  

Landslide Risk Assessment for Saint Lucia's Primary Road Network

Hurricane Tomas Rehabilitation and Reconstruction
Final Feasibility Report

September 2013

Government of Saint Lucia

Mott MacDonald

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Ministry of Infrastructure, Port Services and Transport
Union Office Complex
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Contents

Executive Summary

Introduction

The Government of Saint Lucia (GoSL) Ministry of Infrastructure, Port Services and Transport (MIPS&T, 'the Ministry'), has obtained a loan from the Caribbean Development Bank (CDB) for Natural Disaster Management – Rehabilitation and Reconstruction (Hurricane Tomas) and has applied a portion of the loan to finance this Landslide Risk Assessment for Saint Lucia's Primary Road Network.

Mott MacDonald has been commissioned by the GoSL to provide technical assistance to reduce the landslide risk to the primary road network of Saint Lucia, through the analysing and assessing of slope stability, drainage and geotechnical conditions; mapping levels of risk; identifying primary and secondary causal factors of slope movement; and cost effective slope stabilisation, protection and landslide remediation measures. The project is expected to enhance the capacity of the GoSL to manage landslide hazards.

This report follows the feasibility phase of works and will:
- describe the landslide hazard assessments completed;
- describe the landslide risk analysis methodology and derivation;
- present the landslide hazard and risk mapping;
- discuss the landslide risk in relation to the road network and appropriate management / stabilisation options; and
- provide feasibility level detail including assessment of appropriate management / stabilisation options for sites assessed as high risk and priority.

Hurricane Tomas

Hurricane Tomas passed just south of Saint Lucia on 31st October 2010 with winds up to 160km/h and rainfall of up to 668mm in the 24 hour period between Saturday 30th and Sunday 31st (ECLAC, 2011). Hurricane Tomas was unprecedented in terms of the amount of rainfall, and possibly also in the widespread occurrence of the rainfall. Analysis of the rainfall records suggests a return-period in the region 200 years for the quantities experienced during Tomas.

Two persons were confirmed dead and three persons missing at Colombette and four persons dead and one person missing at Fond St. Jacques as a result of landslide activity during Hurricane Tomas. Major sections of the primary road network were impassable because of landslides, damaged bridges, fallen trees and utility poles. Some communities were completely isolated or partially accessible overland for several days (FDL, 2010).

Landslides in Saint Lucia

Landslides impact the primary road network in two main ways:

- inconvenience and disruption by preventing movement of goods or people; and
- expenditure.

DeGraff (1985) notes that 2 to 6 % of the annual government maintenance budget is spent on removing debris and repairing damage to the roads to restore their use following landslides. The Economic Commission for Latin America and the Caribbean (ECLAC, 2011) estimate that Hurricane Tomas caused EC$121 million (US$45) worth of damage to the road transport sector, accounting for approximately 13.3% of the total monetary impact of Hurricane Tomas.

The disaster history of Saint Lucia presented in O'Keefe and Conway (1977) indicates that there were at least 13 major landslide producing storm events on the island from 1938 to 1976. The eyes of 18 tropical storms/hurricanes are recorded to have occurred within 50 nautical miles of Saint Lucia over the years 1938 to 1976 (NOAA, 2013). From 1976 to the present day, the eyes of 13 tropical storms/hurricanes have passed within 50 nautical miles of Saint Lucia. Notable landslides occurred during at least six of these events. In addition to these, landslides invariably develop on an annual basis during the rainy season (July to December) or during high rainfall periods of non-storm years. The high frequency and widespread distribution of these slope failures are evidence that landsliding is a dominant erosional process on the island.

Several types of landslides have been documented in Saint Lucia, including debris flows, debris slides, rockfalls, rock slides and landslide complexes (e.g. DeGraff, 1985). Of the several landslide types, debris flows are the most common and are the main contributor to land degradation. These flows occur in soil or weathered rock, are typically small in size and are initiated as shallow failures in the upper regions of the slope. The failed material, saturated with water becomes mobilized, flows downslope and carves deep erosion channels. Debris flows also erode the upper slopes of road beds, leading to the collapse of road foundations. The significant volume of soil and other landslide debris carried by these flows to streams result in increased sedimentation of rivers, the coastline and contributes to flooding downstream.

A summary of significant landslide events that have occurred in Saint Lucia is presented and each significant event is associated with heavy rainfall. Most of the landslides that occur are shallow, between 1-3m, and many landslides go unreported since in most cases they have little impact on communities.

Geology, Hydrogeology and Seismicity

Saint Lucia is almost entirely volcanic with the oldest rocks, largely rhyolite, andesite and various basalt lavas, dating from the early Tertiary period about 50 million years ago. The geological divisions of Newman (1965) are used and summarised. A brief description of recent deposits such as colluvium, weathering process and residual soils, and their distribution in relation to the primary road network and association with landsliding is presented.

The presence of springs in or near the areas prone to landslides is highlighted.

Seismic events in the Eastern Caribbean are principally associated with a subduction zone at the junction of the Caribbean Plate and the North American Plate.

The University of the West Indies Seismic Research Centre reports that there have been at least five swarms of shallow earthquakes in Saint Lucia in the last 100 years. They occurred in 1906, 1986, 1990, 1999 and 2000. At least three of these swarms seem to have been triggered by a larger tectonic earthquake. The most recent tectonic earthquake of note was of magnitude 7.75 in 1953 and caused partial collapse of buildings previously damaged by fire and caused some damaged to buildings in Castries.

Based on the expected peak ground acceleration (PGA) potentially caused by an earthquake and the geological environment, a preliminary risk assessment has been performed to indicate if landslides are likely to be triggered by earthquakes in Saint Lucia. There are no reports of any historical landslides being associated with ground shaking in this region. At the PGS expected in an earthquake with a 475-year return period the risk of triggering a landslide is considered low. The probability of a large earthquake and extreme rainfall event occurring at the same time is very low and so earthquakes are not being considered as triggers for landslides as part of the project.

Stakeholder engagement

Information disclosure and consultation have been guided by the Stakeholder Engagement Plan (SEP) which was submitted to MIPS&T in March 2013. Based on the SEP, the main activities undertaken to date have been:

- preliminary key stakeholder meetings to introduce the Project;
- seminars on GIS based hazard analysis, risk assessment and by the project peer reviewers;
- a workshop on slope stability;
- distribution of a Project brochure with requests for data and opinions to a range of stakeholders; and
- risk matrix training at sites along roads with zone engineers.

The engagement process is on-going and will continue throughout the project.

Landslide hazard assessment

Landslide hazard assessment has been completed at a network scale and site specific scale in a number of stages to allow a comprehensive understanding of the landslide hazard to be developed. Regional landslide hazard assessments have been previously completed by several authors based on the available landslide inventory. A landslide susceptibility map has been created using the existing database within the geographical information system (GIS) to assist with targeting more detailed assessments for the road network.

At the network scale a density analysis of the landslides that occurred in response to different storm events has been attempted to try and evaluate the hazard that is caused by different storm events. The assessment reviewed landsliding following Hurricane Allen and Hurricane Tomas and presents the results as the density of landsliding along different sections of road following the different events. The results show many more landslides occurred along the primary road network during Hurricane Tomas compared to Hurricane Allen which may be a result of the higher rainfall during Hurricane Tomas.

At the site scale a geomorphological assessment has been completed by interpretation of 2009 air photographs to identify historical and recent landslides along the network. This air photograph interpretation was then ground truthed by visiting the sites to confirm the desk based assessment was correct and to improve the accuracy of the mapping. Areas along the primary road network have also been zoned to identify slopes adjacent to the road where similar ground conditions, environments and morphology may lead to similar landslide events and ground movements. The zones can assist in highlighting landslide hazards in areas of slopes that may be identified as low landslide risk using the risk matrix approach described below. The zones will assist with network management.

The information from the hazard assessments is included within the project geographical information system (GIS).

Vulnerability analysis

A lack of quantitative data means that a quantitative assessment of the primary road network's vulnerability is not possible. Therefore, for the purpose of the study, vulnerability is accounted for in two ways:

- within the risk matrix developed for the project in terms of severity of damage/loss to a section of the road; and

- within zones around the primary road network for which specific vulnerability levels have been determined based on subjective assessments of traffic and alternative routes.

The risk matrix is discussed in the next section.

The subjective assessment of traffic and alternative routes has resulted in different zones of 'vulnerability' being assigned to parts of the network. This information has been mapped and is presented as a layer within the project GIS. The landslide risk determined from the risk matrix is compared to these zones in later sections of the report.

Landslide risk assessment

All societies have limited resources available to minimise natural hazards. Therefore, some risk must be accepted. Bunce et al. (1997) state that if a risk is lower than that accepted by society, the expenditure of resources to reduce that risk may not be appropriate. Alternatively, if a risk is higher than the accepted level, we require a method of assessing how best to allocate effort to achieve the greatest benefit.

Probability-loss analysis to determine the varying financial impact of rainfall events and associated landslides on the primary road is discussed but was not completed owing to a lack of information on the costs of previous landslide events.

A landslide risk matrix has been developed to assess landslide risk to the primary road network based on the frequency of a potential slope failure and the severity of damage such a failure would cause to the road. The entire primary road network has been assessed and the results mapped as a layer within the project GIS. In total, 290km of risk mapping has been completed along the primary road network, including slopes on either side of the road. A relatively small proportion of the primary road network is classified to be medium or high landslide risk.

In summary:

- 194km (67%) of the slopes are classified as negligible or very low landslide risk;

- 83km (29%) are classified as low landslide risk;
- 11km (4%) are classified as medium landslide risk; and
- 0.96km (0.3%) are classified as high landslide risk.

A discussion of the level of landslide risk that can be accepted by society and the basis for a design rainfall event is presented. Design rainfall with a return period somewhere between 1 in 10 years and 1 in 50 years is considered applicable, and a 1 in 20 year return period is recommended for most roadside drainage.

Network management and slope management / stabilisation options

A slope management approach based on the results of the landslide risk assessment is proposed. Where the landslide risk has been assessed as being 'as low as reasonably practicable' (ALARP) it is considered that the Ministry should:

- accept the risk;
- reassess risk level at low and medium risk sites following large storm events;
- regularly inspect structures and drainage and maintain as required; and
- respond to events as they occur.

Where the landslide risk has been assessed as high, it is considered high priority remedial works should be carried out or preventative measures put in place. It may not be practical to make a slope physically more stable and therefore ways of reducing the risk may include monitoring or improving risk awareness.

Slopes assessed with landslide risks between 'high' and 'ALARP' can be managed in different ways. Either the risk can be accepted, slopes/associated structures regularly monitored and events responded to as they occur, or mitigation measures / remedial works can be carried out to reduce the risk level. Areas shall be looked at on a zone basis to determine the appropriate options for final reporting.

Land management and runoff control are discussed and considered to be especially applicable in areas of the Barre De L'Isle and the West Coast Road.

Land management would require close cross Ministry cooperation and enforcement backed by political will.

Twelve priority slope stabilisation sites are identified. One of which is currently being remediated by others. Immediate actions are recommended at nine of the sites, typically comprising cleaning of drains or improving the drainage to prevent water infiltration to slopes and prevent water being directed onto slopes or sealing up cracks in the road to prevent water ingress.

Ground investigations

Ground investigation have been completed at several of the high priority sites to allow for determination of the most appropriate slope stabilisation/management option and conceptual/preliminary remedial design as appropriate. Ground investigation works have included geomorphological mapping, topographical surveys, wash-boring, test pitting and associated laboratory testing.

On-going studies

The following stages of the project are on-going at the issue of the final feasibility report:

- Stakeholder engagement.
- Finalising the landslide risk management capacity strengthening plan.
- Conceptual design at the high priority sites.

A revised project programme is presented based on the actual date of commencement and current status. The project is currently due for completion at the mid-December 2013.

1 Introduction

1.1 Terms of reference

The Government of Saint Lucia (GoSL) Ministry of Infrastructure, Port Services and Transport (MIPS&T, 'the Ministry'), has obtained a loan from the Caribbean Development Bank (CDB) for Natural Disaster Management – Rehabilitation and Reconstruction (Hurricane Tomas) and has applied a portion of the loan to finance this Landslide Risk Assessment for Saint Lucia's Primary Road Network.

Mott MacDonald has been commissioned by the GoSL to provide technical assistance to reduce the landslide risk to the primary road network of Saint Lucia, through the analysing and assessing of slope stability, drainage and geotechnical conditions; mapping levels of risk; identifying primary and secondary causal factors of slope movement; and cost effective slope stabilisation, protection and landslide remediation measures. The project is expected to enhance the capacity of the GoSL to manage landslide hazards.

The Contract for the project was signed on the 4th January 2013. Prior to signing, Mott MacDonald completed the inception stage with the aim of completing the project by the target date of September 2013.

The project deliverables are:

- an inception report that was submitted on the 14th December 2012, prior to Contract signing, and has been accepted by the GoSL and the CDB;
- draft and final feasibility reports;
- draft and final landslide risk management and capacity strengthening plan; and
- draft and final conceptual design reports.

The dates for submission of the deliverables are shown on the updated project programme presented within Section 11.

This report follows the feasibility phase of works and will:

- describe the landslide hazard assessments completed;
- describe the landslide risk analysis methodology and derivation;
- present the landslide hazard and risk mapping;
- discuss the landslide risk in relation to the road network and appropriate management / stabilisation options; and
- provide feasibility level detail including assessment of appropriate management / stabilisation options for sites assessed as high risk and priority.

1.2 Background

The primary road network was defined within the inception report to be comprised of:

- the A11 and A12 roads north of Castries;
- the east coast road (A32, A33, A34, A35, A36 and A37);
- the west coast road (A51, A52, A53, A54, A45, A44, A43, A42 and A41);
- the Barre de L'isle (A31 and A32);

- the Morne (A23);
- the Millennium Highway (A20);
- Bois Cachet road; and
- La Toc (A21).

To assist site location and descriptions within the report, a chainage system has been developed for the following road sections:

- Main line – starting at Chainage (Ch.) 0m from the Cap Estate Roundabout in the north, over the Morne, down the West Coast Road past Vieux Fort, up the East Coast Road and across the Barre de L'Isle, finishing at the Cul de Sac junction at Ch. 136,046m.
- Bois Cachet (Old Morne Road) – starting at Ch. 0m at the northerly lower junction with Morne Road and finishing at the southerly higher junction with Morne Road at Ch. 647m.
- La Toc – starting at Ch. 0m from the junction with Mandel Street and finishing at Ch. 3,581m at the junction with Morne Road
- Millennium Highway – starting at Ch. 0m from the Millennium Highway/La Toc roundabout and finishing at Ch. 6,164m at the Cul de Sac junction.

An overview map showing the primary road network is presented as Figure 1.1.

Figure 1.1: Overview map of the primary road network

Not to scale.

The primary road network roads are typically single carriageway. There are no standard drainage details and so a variety of different drain types, sizes and qualities are present around the network. The primary road network has existed in approximately its current alignment for in excess of 50 years. The west coast road was constructed in the 1950's and underwent improvement works in the 1980's and 1990's (Brown and Clark, 1995).

1.2.1 Landslides along roads

Landslides impact the primary road network in two main ways:
- inconvenience and disruption by preventing movement of goods or people; and
- expenditure.

Landslides can either block roads by putting debris upon the carriageway (Figure 1.2), or undermine roads, for example where a road is on side long ground or on ridges that are actively degrading (Figure 1.3 & Figure 1.4). This activity can be sudden and rapid or on-going and slow movement depending on the type of failure that occurs. Landslides occur at a wide variety of scales from events with debris <1m³ to those with debris in excess of 10,000m³. This range of activities and size requires different management responses to different events.

Figure 1.2: Small rock fall onto the highway in zone 7

Figure 1.3: Arcuate crack and depression in road caused by landslide at Ti Colon (Ch 22955 – 23000 SB)

Figure 1.4: Shallow slope failure along road at Site 9 on the Barre de L'isle (Ch 125295 – 125340 WB)

DeGraff (1985) notes that 2 to 6 % of the annual government maintenance budget is spent on removing debris and repairing damage to the roads to restore their use following landslides. The Economic Commission for Latin America and the Caribbean (ECLAC, 2011) estimate that Hurricane Tomas caused EC$121 million (US$45) worth of damage to the road transport sector, accounting for approximately 13.3% of the total monetary impact of Hurricane Tomas. This figure does not include damage to bridges as a result of flooding or damage to forest roads.

1.3 Related initiatives in Saint Lucia and the Caribbean

Several landslide studies have been completed in Saint Lucia in recent times:

- DeGraff (1985) completed a landslide hazard zonation study;
- Rogers (1995) completed a debris flow hazard assessment following Tropical Storm Debbie;
- A watershed and environmental management project was completed following Tropical Storm Debbie with some information on landsliding (Hunting Technical Services / Mott MacDonald, 1998);
- Management of Slope Stability in Communities (MoSSaiC) pilot projects 2004 – 2010 (Anderson and Holcombe, 2013); and
- CDB/CDERA landslide hazard maps for St. Lucia and Grenada, 2006.

A more detailed review of the available information on these studies is provided in Section 2. The information in these reports has been utilised and referenced where relevant within this study.

A review of other studies taking place in Saint Lucia and the Caribbean that may be relevant to this landslide risk assessment has also been completed. The main relevant activities are summarised below:

Roads

- Post-Hurricane Tomas Recovery Project:
  - Barre de L'Isle remedial design of high risk sites by FDL Consult Inc.; and

  - the West Coast Road Rehabilitation project currently being procured.
- Strategic planning proposal for the Saint Lucia road network by the Economic Planning Department funded by the World Bank.

Disaster risk management

- The Saint Lucia National Emergency Management Organisation (NEMO) undertook a review of its response to Hurricane Tomas. NEMO also produced a country profile and action plan with European Union funding in collaboration with the UN Office for Disaster Risk Reduction. NEMO is currently in the midst of a twelve month process to update its National Emergency Management Plan. The Plan will incorporate lessons learned and new thinking around emergency management.

Climate change

Climate change adaptation is important to island countries like Saint Lucia. Soon after Hurricane Tomas, climate change and its effects was a focus of efforts for many governmental and non-governmental organisations.

- There is a National Climate Change Committee and Sustainable Development Department which are responsible for Saint Lucia's commitments under the United Nations Framework Convention on Climate Change.
- Civil society, through the organising efforts of the Caribbean Natural Resources Institute (CANARI), produced an agenda for climate change in 2011.
- In March 2012, the CARIBSAVE Partnership with funding from the United Kingdom's Department for International Development (DFID) and the Australian Agency for International Development produced the "CARIBSAVE Climate Change Risk Profile for Saint Lucia".
- As part of the CARICOM countries, Saint Lucia has a roles and responsibilities outlined in the 'Implementation Plan for the Regional Framework for Achieving Development Resilient to Climate Change'. The Implementation Plan was developed by the Caribbean Community Climate Change Centre with funding support from the DfID. Following extensive in-country discussions with stakeholders, the Implementation Plan was approved by the CARICOM Heads of Government in March 2012.

Other

- To support community resilience, the Ministry of Physical Development, Housing and Urban Renewal is using World Bank funding to implement The World Bank's Open Data for Resilience Initiative (OpenDRI) initiated in March 2012. The idea is that access to the right data and information using the geospatial data web application will help inform good local decisions. The GoSL has launched the Saint Lucia Integrated National GeoNode (SLiNG) as a result of this initiative. The GIS data collected from this landslide assessment could feed into such activities.

1.4 Report layout

The final feasibility report is presented as follows:

- Introduction – putting the project in context and discussing in relation to other initiatives.

- Background and previous studies – briefly describing Hurricane Tomas and its impacts, historical landsliding in Saint Lucia and summarising previous relevant studies on landslides in Saint Lucia.
- Geology, hydrogeology and seismicity – provides an overview of the information relevant to landsliding around the primary road network.
- Stakeholder engagement – discussing the stakeholder engagement process and current status.
- Landslide hazard assessment – describing the various scale assessments completed and results.
- Network vulnerability analysis – describing the vulnerability analysis completed and the results.
- Landslide risk assessment – describing the assessments completed and the results.
- Slope management / stabilisation options – discussing the optioneering process and summarising the priority sites.
- Network management – discussing the landslide risk assessment results in terms of network management.
- Proposed investigations – summarising the proposed investigations to be completed for the on-going works.
- On-going works – summarising the work currently being completed and future work required as part of the project.

2 Background and previous studies

2.1 Hurricane Tomas

Hurricane Tomas passed just south of Saint Lucia on 31st October 2010 with winds up to 160km/h and rainfall of up to 668mm in the 24 hour period between Saturday 30th and Sunday 31st (ECLAC, 2011). Hurricane Tomas was unprecedented in terms of the amount of rainfall, and possibly also in the widespread occurrence of the rainfall. Analysis of the rainfall records suggests a return-period in the region 200 years for the quantities experienced during Tomas (see Appendix A).

Two persons were confirmed dead and three persons missing at Colombette and four persons dead and one person missing at Fond St. Jacques as a result of landslide activity during Hurricane Tomas. Major sections of the primary road network were impassable because of landslides, damaged bridges, fallen trees and utility poles. Some communities were completely isolated or partially accessible overland for several days (FDL, 2010).

A damage assessment was were completed immediately following Hurricane Tomas by FDL Consult Inc. on behalf of the Ministry to facilitate the clean-up and reconstruction process. A summary of the critical damage to the primary road network caused by landslides is presented as Table 2.1.

Table 2.1: Summary of critical damage to the primary road network by landslides immediately post-Tomas

Road	Description of damage	Outcome
Cul de Sac – Ravine Poisson	Landslips and heavy siltation	Route impassable
Barre de Lisle – Hill top Dennery	Major landslides, fallen telecommunication lines. Bridge at Grand Ravine overtopped with 3m of debris	Route impassable
Quarte Chemin – Soufriere	Major landslides - fatalities	Route impassable
Choiseul Village Bridge – Myers Bridge	Major landslides between Ravine Cacoa and Myers bridge	Route impassable from Victoria to Myers Bridge
(Anse La Raye – Canaries)	Major Landslide(Anse La Verdue); collapsed culvert at Anse Gallet	Road impassable
Myers Bridge – Soufriere	Major landslides	Road impassable

Source: Extract from Table 1 of Hurricane Tomas Damage Assessment Report, FDL Consult Inc. 2010.

Total damage and loss to the entire road network was estimated in the region of EC$121M (US$45M) (ECLAC, 2011).

2.2 History of landslide in Saint Lucia (1938 – 2010)

Information on the problem of land degradation due to landslides on the island of Saint Lucia is well documented in published and unpublished reports, including DeGraff (1985), DeGraff et al. (1989) and Prior and Ho (1972). The disaster history of Saint Lucia presented in O'Keefe and Conway (1977) indicates that there were at least 13 major landslide producing storm events on the island from 1938 to 1976. The eyes of 18 tropical storms/hurricanes are recorded to have occurred within 50 nautical miles of

Saint Lucia over the years 1938 to 1976 (NOAA, 2013 - Appendix B). From 1976 to the present day, the eyes of 13 tropical storms/hurricanes have passed within 50 nautical miles of Saint Lucia. Notable landslide occurred during at least six of these events. In addition to these, landslides invariably develop on an annual basis during the rainy season (July to December) or during high rainfall periods of non-storm years of the type experienced at high frequency and widespread distribution of these slope failures are evidence that landsliding is a dominant erosional process on the island.

Several types of landslides have been documented in Saint Lucia, including debris flows, debris slides, rockfalls, rock slides and landslide complexes (e.g. DeGraff, 1985). Of the several landslide types, debris flows are the most common and are the main contributor to land degradation. These flows occur in soil or weathered rock, are typically small in size and are initiated as shallow failures in the upper regions of the slope. The failed material, saturated with water becomes mobilized, flows downslope and carves deep erosion channels. Debris flows also erode the upper slopes of road beds, leading to the collapse of road foundations. The significant volume of soil and other landslide debris carried by these flows to streams result in increased sedimentation of rivers, the coastline and contributes to flooding downstream.

Landuse is an important factor in slope stability. O'Keefe and Conway (1977), highlighted the importance of the banana industry on the macro-economics of the island. However, the natural rugged topography of the island does not ideally favour the cultivation and transport and thus the delivery of the banana crop.

Much of the cultivation of the banana crop is done on hillslopes which suffer from highly variable rainfall. Banana cultivation on these steep slopes is very difficult and requires the clearing of all permanent, woody trees. This results in a disturbance of the ecological environment by the development of stagnant rivers, low water tables, soil erosion and flash floods which result from the changes in vegetation.

The clearing of the permanent vegetation on hillslopes for banana cultivation presents a high potential for rainfall induced landslides. The roots of the banana plant are shallow and provide little resistance to slope instability during periods of heavy rainfall.

A summary of significant landslide events that have occurred in Saint Lucia is presented in Table 2.2 and further details are provided in Appendix B. In Table 2.2, each significant event is associated with heavy rainfall. Other factors such as leaky drainage may have contributed but the trigger in each case is heavy rainfall. During the wet season the island experiences frequent periods of intensive rainfall especially during the passage of hurricanes and storms. The hillside streams and ravines draining the steep catchment slopes quickly become swollen with runoff and sometimes the roads become watercourses themselves. Whilst the storm lasts, which may be several hours or even days, affected slopes that are not well-built or well-maintained become susceptible to water-induced landslips either through surface erosion or saturation due to matrix suction in the subsoil.

Most of the landslides that occur are shallow, between 1-3m. Many unreported landslides are known to occur on undeveloped natural terrain subjected to intensive rainfall, being visible at a distance on hillslopes and in aerial photographs. These landslides usually go unreported since in most cases they have little impact on communities.

Landsliding is also influenced by man-made processes such as cut slopes, fill slopes, clearing of lands for farming and retaining walls created by the process of hillside development.

Development pressures resulting from constant population growth in the recent past in a limited land area have led to intensive human settlement of hill slopes in many parts of the island. Slopes have been terraced for roads and buildings and the streams and rivers culverted and much of the marginal lands are occupied by squatter villages. Inadequacies of hillside development works along with the lack of subsequent maintenance of constructed slope works can increase the landslide hazard.

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Table 2.2: Summary of major landslide events in Saint Lucia – further details for some of the more recent events are provided in Appendix B.

Date	Landslide location / name	Associated rain event	Description	Source
1894	Unknown	'Tropical storm'*	'Heavy landslides - incalculable damage to crops'	O'Keefe and Conway, 1977
11th September 1897	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide	O'Keefe and Conway, 1977
10th September 1921	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide	O'Keefe and Conway, 1977
19th September 1928	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide. 'Roads destroyed in Rosseau'	O'Keefe and Conway, 1977
21st November 1938	Ravine Poisson / Ravine Crebiche	Eight days continuous rainfall	Around 26 days prior to the main slide, eight days of continuous rainfall had caused the Barre De L'Isle to be blocked by landslides. The Barre De L'Isle had been blocked for 18 days and a large workforce of local people had mobilised to clear the blockage. Two landslides occurred on the morning of Monday 21st November, one into the area where workmen were clearing previous landslide debris. A third landslide occurred nearby early the following morning. This was one of the worst disasters in terms of loss of life on Saint Lucia, with 60 people known to have died and estimates of missing workers as high as 250 persons.	O'Keefe and Conway, 1977
7th January 1939	Unknown	'Tropical storm'*	Three villages destroyed by a tropical storm with 100 persons reported dead. Limited data on landslide and location.	O'Keefe and Conway, 1977
7th August 1940	Ravine Poisson, Barre De L'Isle, Labayee		Communities badly damaged by a tropical storm*. Extensive damage to livestock, plantations, and roads and retaining walls built in following the 1939 storm were destroyed. Limited data on landslides and location.	O'Keefe and Conway, 1977
12th December 1954	Ravine Poisson		Farmers severely affected by this storm event which destroyed a years output of staple crops and bananas. Recorded rainfall for the year was 3,277mm. Ravine Poisson badly affected by landslides.	O'Keefe and Conway, 1977
4th July 1958	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide	O'Keefe and Conway, 1977
10th July 1960	Fond St. Jacques	Hurricane Abby	Crops destroyed, damage to roads, bridges and electricity supply. Landslide at Fond St. Jacques	O'Keefe and Conway, 1977; NEMO, 2011.
1966 (June onwards)	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide. 'Road communication seriously affected'.	O'Keefe and Conway, 1977
8th September 1967	Unknown	Hurricane Beulah	'Collapse of the road system'	O'Keefe and Conway, 1977
2nd October 1970	Unknown	'Tropical storm'*	Damage by water (or by water together with wind) causing landslide	O'Keefe and Conway, 1977
3rd August 1980		Hurricane Allen	Caused widespread landsliding. Particularly, landslides on the Barre De L'Isle blocked (and	SECL

Date	Landslide location / name	Associated rain event	Description	Source
			undermined?) the main road. Clearing the road did not restore access and construction of a masonry wall at the toe of the slide and three gabion structures within the failed area were required to stabilise the slopes.	
6th November 1990	Morne du Don		Landslide making 68 homeless.	NEMO, 2011
29th November 1992	Bocaye		Landslide affecting 10 families (36 persons).	NEMO, 2011
9th – 10th September 1994	Various	Tropical Storm Debby	More than 400 landslides were reported to have occurred as a result of TSD. More than 90% of the landslides occurred in the upper areas of watersheds. A large portion of the landslides were shallow debris flows, 10 to 20 metres in width, originating close to ridge crests. Debris and rock slides occurred principally along roads.	SECL
September 1995	Millet Primary School		Following a period of prolonged heavy rain associated with Hurricane Iris a large landslide occurred at Millet Primary School. A large debris flow occurred above the school and the toe butted up against the southwestern section of the building. Slope debris was inclined at 17° and the crest of the failure was located around 33m upslope. Groundwater seepage was observed through cracks and fissures in the slope debris. A retaining wall was constructed to stabilise the failed slope and adjacent slopes were also stabilised.	SECL
September 1998	Boguis		Residents reported feeling earthquake tremors prior to the disturbing appearance of cracks in the walls of masonry structures and tension cracks on the ground surface. Slope instability and cracking at a health centre located at the toe of the slope was reported to have been occurring for about four years prior to the main event. Poor waste water disposal and a period of incessant rainfall are understood to have contributed to the failure.	SECL
7th October 1999	Black Mallet / Maynard Hill		80,000 cubic metres of colluvial material “flowed” downslope towards the Marchand river causing the destruction of several residences and rupturing public utilities. Investigations indicated the slope was subject to soil creep and slow gravitational movement for several years prior to the main failure event. Contributory factors were noted to include: poor surface water drainage; leaking septic tanks; liquefaction of a confined sand aquifer owing to an increase in pore water pressure; low shear strength of colluvial materials at the site; and a seismic event prior to and at the time of the failure.	SECL
26th September 2004	Tapion		1800 cubic metres of colluvial material flowed downslope and destroyed two residences and led to adjacent residences being abandoned. Contributory factors noted to include: poorly maintained surface drains at the crest of the slope; seismic event; ongoing creep of slope.	SECL
July 2005	Barre De L’Isle			SECL
July 2005	Windjammer Landing Beach Resort		Ground conditions in this location were investigated and found to comprise colluvium interbedded with slickensided layers of volcanic ash overlying highly weathered basalt bedrock. This led to a relatively low shear strength of the slope mass. Periods of heavy rainfall occurred in the months prior to the failure.	SECL
30th – 31st October 2010	Various	Hurricane Tomas	Many landslides occurred as a result of intensive and prolonged rainfall saturating the subsurface soils resulting in a rise in groundwater level and associated increase in soil pore	SECL

Date	Landslide location / name	Associated rain event	Description	Source
			water pressure, leading to a loss in shear strength of the subsoils. Six people were killed and four remain missing as a result of landslide activity. The major landslides occurred at Colombette, Fond St. Jacques, along the Barre De L'Isle, at Millet and on the hills to the east and south of Castries.	

N.b.: * no tropical storms or hurricanes are recorded to occur in this year in Saint Lucia by the National Oceanic and Atmospheric Administration.

2.3 Previous studies

2.3.1 1985 – Landslide hazard on St. Lucia, West Indies, Final Report. DeGraff.

The DeGraff report was completed for the Department of Regional Development, Organisation of American States. The report provides a background to landsliding and landslide hazard zonation and states why hazard zonation maps can be useful for regional planning – in that they allow zones of landslide hazard to be avoided for development; and zonation permits comparison of landslide hazard between different developments.

The report presents maps of landslides detected through interpretation of 1:15000 scale black and white aerial photography taken in 1977 and 1981 combined with field study in selected areas. Landslides were classified based on Varnes (1978). Debris flows, debris slides, rockfalls and slides, and landslide complexes were mapped. The report notes the features are generally shallow-seated failures. A few deep-seated failures, classified as rockslides or earthflows, are also present.

The report highlights the fact that not all past landslides have been mapped either because they:
- could not be identified at the scale of aerial photography used;
- rapid revegetation and natural erosion of landslide can obscure features;
- agricultural practices such as terracing can obliterate evidence; or
- slides have occurred since the air photographs were taken.

Complex landslides are only found in a few locations along the southern and eastern coast, such as the complex at Moule a Chique on the southern tip of the island. The report cites Prior and Ho (1972) who describe the features as having usually shallow failure surfaces coinciding with discrete clay horizons.

Rockfall and rockslides are concentrated along the coastal bluffs, with failure typically as translational movement along bedding planes or joints.

Debris flows are noted as the most common type of landslide on Saint Lucia. They are stated to have widespread occurrence with greater frequency on the steep slopes in the central part of the island than on the shallower slopes at either end. The majority of debris flows are described to occur on slopes immediately upslope from active stream channels meaning the debris flow deposits are usually rapidly eroded and transported by the stream.

DeGraff notes that the government has expended 2 to 6 percent of the annual maintenance budget on the costs of clearing slope debris from roads and reinstating sections of damaged road. The 1979 Barre de L'Isle landslide on a switchback removed around 100m of road and required complex stabilisation works that took from November 1980 to September 1982 and cost in excess of $1 million.

DeGraff describes the hazard mapping process. The different geological units of the island were combined to generate a map with only 11 bedrock units based on their similar description and ages, slope angle was classified into three units – 0-20%, 20-60% and >60%. No discernible coincidence between landslide occurrence and 'life zones' or annual rainfall distribution was found, contrary to the clear association between precipitation and occurrence of debris flows. DeGraff suggests that a representation of precipitation intensity per unit of time or similar may have been useful, but this information was not available.

The bedrock map, soils map and landslide inventory maps were overlain to determine bedrock and slope combinations associated with mapped landslides. The proportion of each combination subject to past landslide activity was calculated, with values ranging from 0.01 to 0.16. Four hazard groups were defined from non-hierarchical cluster analysis – low for combinations not associated with past landslide activity, moderate for proportions between 0.1 and 0.4, high for proportions between 0.6 and 0.8, and very high for proportions between 0.12 and 0.16.

The hazard maps show high and extreme hazard along the Barre de L'Isle and in the region around Soufrière. It is noted that the methodology provides no prediction capability, and that it is entirely possible to have a major failure occur in a moderate hazard zone. DeGraff emphasises that hazard zonation is not a substitute for detailed investigation of landslide hazard.

The use of the maps is discussed in relation to development and planning. Recommendations on vegetation of slopes and other landslide hazard reduction methods are presented. However, it is not known whether the DeGraff maps were ever incorporated into planning/development policy. The Rogers study (see below) notes they were not significantly utilised.

2.3.2 1995 – Post Tropical Storm Debbie landslide hazard assessment study of St. Lucia. Rogers.

The Post Tropical storm Debby landslide hazard assessment study of St. Lucia by Cassandra Rogers (1995) could not be found. A subsequent paper by Rogers (1997) that summarises the 1995 study has been obtained.

The purpose of the study was to enable users who were not landslide specialists to include landslide hazard data in land use and development decisions. The paper notes that the existing DeGraff landslide hazard maps (1985) have not been significantly utilised by the planning department or other agencies.

The study covered eleven of the islands watersheds that were identified as priority areas by the Ministries of Planning and Agriculture. The paper describes the landslide hazard information package generated by the study which included:

- an annotated landslide inventory map;
- an annotated debris flow hazard map;
- an annotated map of primary debris flow initiation sites in the upper watershed of rivers and potential debris flow runout areas; and

- an associated guidance document to accompany the map.

The study concentrated on the upper regions of watersheds, focused on debris flow hazard and was based on 1:25000 scale regional mapping.

The landslide inventory was compiled using data from several sources:

- the 1985 DeGraff data;
- a review of the 1991 black and white aerial photography coverage of the coastal areas; and
- field mapping of landslides initiated by the 1994 Tropical Storm Debby focusing on the upper regions of watersheds.

For the study, landslides were classified into the same categories as DeGraff (1985).

The hazard was evaluated based on four factors assumed to be the critical factors influencing debris hazard: slope gradient; slope curvature; mean annual rainfall; and soil type. Each factor was divided into factor classes, and each factor and factor class subjectively assigned a relative weight. Factor classes associated with the four factors were grouped into factor combinations and hazard ratios calculated.

The debris flow hazard map is split into four hazard categories – low, moderate, high and extreme. The limitations of the maps are recognised to include:

- only debris flow hazard is identified;
- only hazard associated with debris flow initiation sites is identified, there is no indication of runout hazard;
- hazard level does not consider flow size;
- the resolution of the hazard grid is coarse (200m x 200m) and generalises the hazard; and
- hazard donations do not account for human factors.

The maps showing primary areas of debris flow initiation were created for areas of high and extreme hazard. Probable initiation sites were assessed to be topographical locations that occur at the concave heads of channelled drainages, along concave sections of hillslopes. Runout paths were defined by the steepest slopes and deposition areas where the flow encounters a decrease in slope gradient or enters a major stream channel.

The paper also notes GIS technology is being used to generate debris flow hazard data for the watersheds not covered by the study and to prepare vulnerability and risk maps for the island.

It is understood that the Rogers' maps were used by the Ministry of Planning and Agriculture but the value derived and their impact on policy is not known.

2.3.3 1998 – Watershed and Environmental Management Plan Phase II Final Report. Hunting Technical Services and Mott MacDonald.

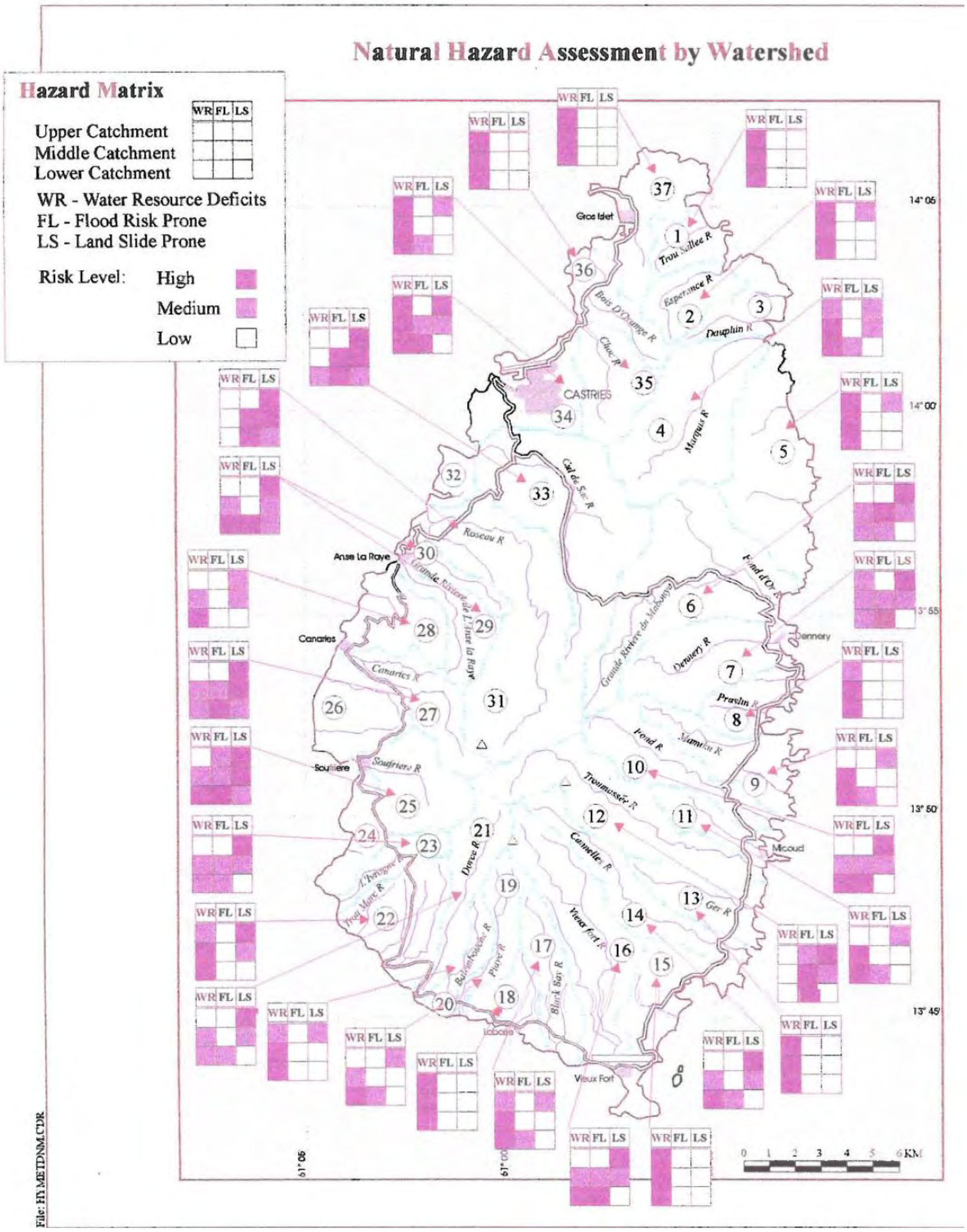
The Watershed and Environmental Management Project was proposed by the World Bank following Tropical Storm Debbie (sic). The project comprised a two stage strategy: phase one of priority repair works to rivers and drainage systems; and phase two to provide pilot watershed management plans to assist long term environmental management.

The Phase II report was sent to the Permanent Secretary of the Ministry of Finance, Planning, Information Services and Public Services in October 1998, as well as the British Development Division in the Caribbean (BDDC). A seminar on the report was completed in July 1998 and was attended by the Prime Minister of the time, Kenny Anthony who is also the current Prime Minister, Permanent Secretaries and Senior Technical staff from the government and representatives of the World Bank, BDDC, The Caribbean Development Bank and the OECS.

The report for phase two includes a section on landslide hazard and risk.

This report summarises the DeGraff and Rogers work. The report notes the lack of topographical data at appropriate scale prevented preparation of a landslide hazard map at 1:10,000 scale. A figure is presented and reproduced here as Figure 2.1 that summarises the natural hazard by watershed, including landslide hazards in the upper, middle and lower catchments of each of the watersheds around the island.

Figure 2.1: Natural hazard assessment by watershed



Source: Reproduced from Annex 6 Landslide Hazard Mapping Figure 4, WEMP

The report discusses the possible correlation between rainfall intensity/duration and landslide incidence. Most landslides are noted to occur in the rainy season, and whether a landslide develops is a function of both the pre-storm rainfall and the rainfall intensity during the storm.

In the absence of detailed rainfall intensity data for Saint Lucia, the report uses daily rainfall records as an approximate representation of rainfall intensity. However, there was poor correlation between the estimated intensity and landslide density, attributed to a bias landslide inventory and limitations in the use of maximum daily rainfall as an estimate of landslide intensity.

The report recommends development of a comprehensive landslide management plan for the island. Including a GIS based management system to organise and manage data, a decision support system to help users generate hazard data for decision making, priority given to data collection including rainfall intensity data and documentation of landslides triggered by individual storms, warning systems put in place, and education and training of staff.

A trial landslide hazard warning system was put in place for a populated area. Five standpipe piezometers and four slope inclinometers were installed at strategic locations at the crest of steep slopes on the Chopin ridge near Bexon and the San de Feur ridge near Ravine Poisson in the Cul de Sac watershed 12km south of Castries. Borehole logs, results of laboratory testing and base readings from the inclinometers are included. Only one set of monitoring data is presented in the report so it is not known whether the study anticipated any failures. The main report notes that no significant movements occurred over the project period, over a drier wet season than normal. No records of ongoing monitoring were found. A visit to the locations during this study located several on the instruments. None of the located instruments were functioning and one location had been subject to a recent shallow failure leaving the instrument exposed as shown in Figure 2.2.

Figure 2.2: Installation completed for 1998 WEMP project recently exposed by a landslide

The study was wide-ranging with several recommendations for government. It is not known whether these recommendations were adopted.

2.3.4 2006 – MoSSaiC. Anderson et al.

MoSSaiC, Management of Slope Stability in Communities, was a government led, World Bank funded project that used a community-based and scientific approach for delivering landslide hazard reduction measures in five vulnerable communities. Results were documented in academic journal articles and in a new book recently published in January 2013. The programme aimed to identify the causes of slope instability and the vulnerability of the elements at risk at hillside and community scale, to allow appropriate landslide hazard reduction measures to be determined and constructed by the community (Holcombe et al., 2011). Slope instability was found to be predominantly controlled by the interaction of surface-water infiltration and anthropogenic influences on slope hydrology. Therefore, the risk management strategy adopted was to design and build surface-water drains and connect the buildings to the drains.

The effectiveness of the mitigation measures was assessed and the increase in slope stability calculated. A benefit-cost analysis of the mitigation measures showed a benefit-cost ratio of 2.7:1 with maintenance and 1.7:1 without maintenance.

It is understood that there are no MoSSaiC projects currently active or planned in Saint Lucia. The MoSSaiC methodology is considered a potential remedial measure for landslide hazard to the primary road network in the appropriate situation.

2.3.5 2006 – Final Project Report Development of Landslide Hazard Maps for St. Lucia and Grenada. CDB/CDERA.

To support the creation of hazard mitigation plans in Saint Lucia, Grenada and Belize, the Caribbean Development Bank (CDB) through the Disaster Mitigation Facility for the Caribbean (DMFC), and the Caribbean Disaster Emergency Response Management Agency (CDERA) through the Caribbean Hazard Mitigation Capacity Building Program (CHAMP) worked together to complete hazard mapping and vulnerability assessments.

The study investigated a pilot area of the Castries watershed and an area to the north of Castries where landslides were known to have occurred. A short period of field reconnaissance was completed to locate recent and historical landslides and evaluate the physiographic, geological and human factors that may have influence landslide formation. 14 landslides were identified during the field reconnaissance, divided into the following slide types: rock slide, rock fall, debris slide (shallow / deep seated), debris flow and creep. Study time limitations enabled on limited information on each slide could be collected.

Landslide susceptibility maps were prepared using a geographic information system (GIS) using the five factors noted above. 10m raster grids were used for the data.

From a review of previous studies and evaluation of the spatial distribution of landslides, the report identifies five factors as most important: slope gradient, slope aspect, elevation, geology and soil type. The report states that during mapping the consultant project team noticed landslide frequency was closely related to increases in elevation and in the study area slope 'class' (understood to be slope gradient) was the most important factor in determining landslide occurrence. The report also notes that andesite rock type dominates basaltic types in landslide prone areas owing to a greater susceptibility to weathering.

The report ranked elevation in 50m increments, slope angle in 10% increments and slope aspect depending on whether the slope was in the lee of the prevailing wind, in the prevailing with direction, or neither. Given the limited data in the study area, the report assessed geology and soils using the island wide inventory prepared by DeGraff (1985).

The susceptibility level mapping was derived by adding the susceptibility ranking values for the factors noted using the GIS. Each of the factors was given equal weighting in the analysis. The obtained numbering classification was then reclassified into five susceptibility classes –very low, low, moderate, high and severe.

The report describes some development planning considerations to be taken into account for major and minor developments. The report recommendations include completing island wide mapping of landslides at least every 10 years, and to conduct an investigation of the primary road network for landslide hazard.

Limitations of the analysis are noted to include:

- that it may underestimate the true potential for landslides because the analysis is based on an incomplete record of historical landslide events; and
- only physiographic data was used in the model, therefore human influence was not taken into account.

Maps were provided to the Government of Saint Lucia in GIS format and hard copy at 1:10000 scale. The maps are not included in the copy of the report available and have not been found. Therefore, the maps have not been consulted for the current report.

The project is discussed within the current GoSL Landslide Response Plan but the hazard maps within that plan are from DeGraff (1985) and Rogers (1995). The CDB/CDERA report and maps do not appear to have significantly improved on the regional scale mapping completed previously. This may be because they use the same landslide inventory with only minor additions.

2.3.6 2012 – Landslide susceptibility and risk in Saint Lucia. Quinn.

This draft paper submitted to the Canadian Geotechnical Journal shows development of a landslide susceptibility map on a regional scale based on the inventory used in the CDB/CDERA study. Quinn interrogated the data using a GIS and weights-of-evidence model to devise a landslide susceptibility map. Based on inferred population density, a qualitative landslide risk to human habitation map was also created.

Quinn notes that slope angle is the most significant factor in predicting landslide incidence. Bedrock mapping was not included in the study but it is noted that it may improve the model. The susceptibility map produced is significantly higher 'resolution' than previous landslide hazard maps, showing much more variation in hazard level around the island. However, areas of high and extreme hazard/susceptibility are generally similar to maps by DeGraff. From a regional planning view-point, the susceptibility map may be too detailed, and may require generalising for use.

2.3.7 Discussion of previous studies

The several landslide hazard studies that have been completed previously at a regional scale do not necessarily seem to have improved in detail or accuracy, probably owing to all of the studies using a similar landslide inventory.

Studies that required on-going commitment following completion of the consultants' input, such as parts of the WEMP, do not appear to have been continued by the GoSL. Also, the level of integration of various study recommendations with government policy is not currently known.

3 Geology and seismicity

3.1 Geology of Saint Lucia

Saint Lucia is almost entirely volcanic with the oldest rocks, largely rhyolite, andesite and various basalt lavas, dating from the early Tertiary period about 50 million years ago.

Newman, (1965) divided the volcanic rock formations in Saint Lucia into three broad categories, from oldest to youngest, namely: the Northern Series, the Central Series and the Southern Series with respect to their predominant locations in the northern, central and southern parts of the island. A simplified version of the geological map is presented as Figure 3.1.

Lindsey et al. (2002) note that subsequent age dating of the rocks indicates several centres in the Southern Series are more likely to correspond to older centres in the Northern Series. For the purposes of a volcanic hazard assessment, Lindsey et al. (2002) preferred to use a revised grouping of volcanic rocks on Saint Lucia as follows:

- eroded basalt and andesite centres (a revision of the Northern Series of Newman, 1965), this is subdivided into northern and southern series;
- dissected andesite centres (Central Series of Newman, 1965); and
- Soufrière Volcanic Centre (a revision of the Southern Series of Newman, 1965).

For the purpose of the landslide risk assessment, the 1984 map has been used. The reclassification by Lindsey et al. does not change the description of the rocks, nor the likely behaviour and influence on landsliding.

A summary of the series' is provided below:

The Northern Series

These deposits consist of deformed and eroded basalts and andesite lavas and pyroclastic deposits. The oldest of these represent the earliest volcanic activity on the island of Saint Lucia.

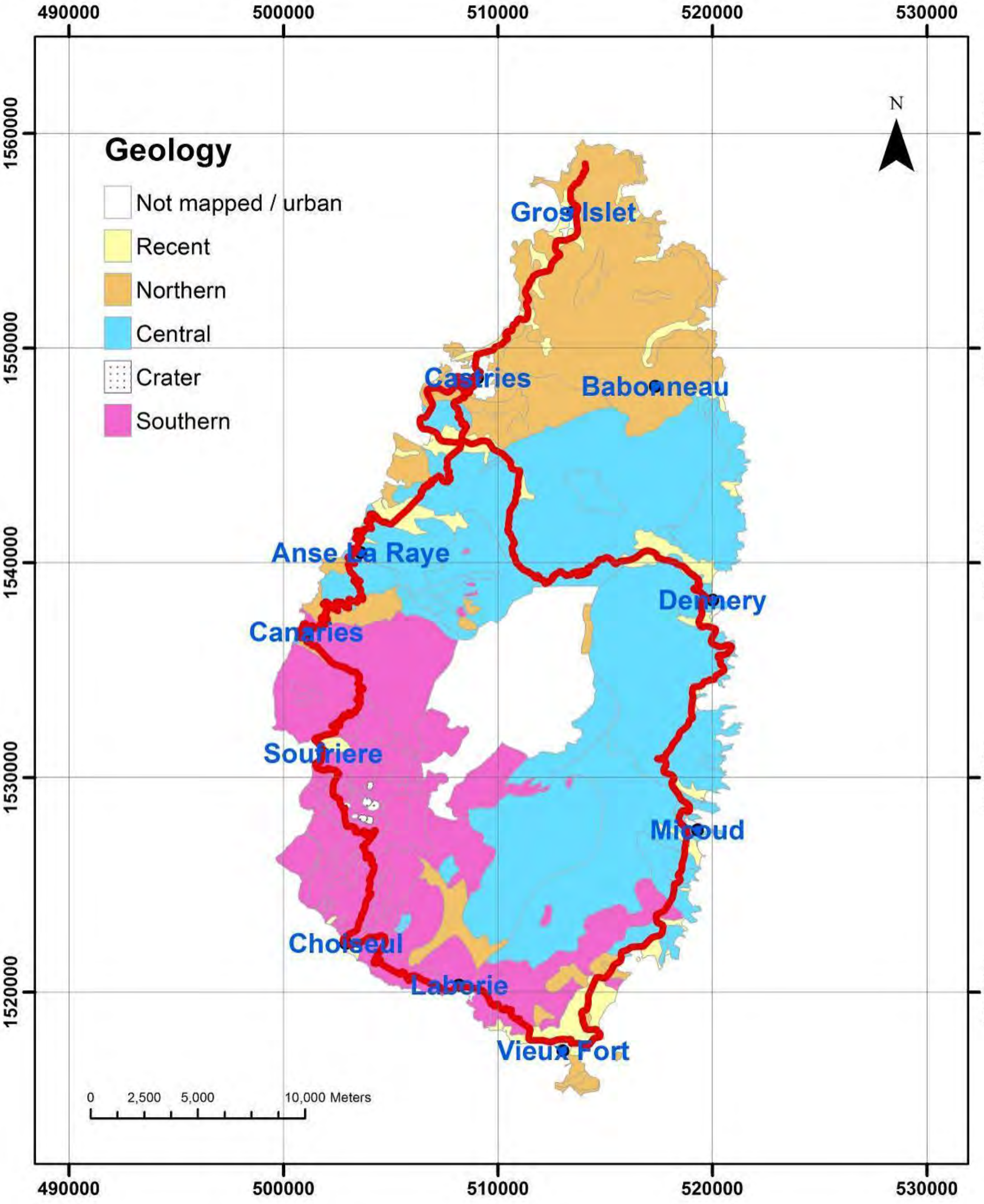
The northern parts of the primary road network, from Cap Estate to the Morne Fortune, are within the Northern Series. Small areas of outcropping northern series are also present on the western coast around Marigot, Anse La Verdure and Canaries, and in the far south.

The Central Series

Mainly andesite lavas and clastic deposits are found in the central part of the island. They extend along the southeast coast and appear to be younger than the deformed basaltic rocks in the northern series but are not of recent origin. The rocks of this series were deposited following an increase in sea level across the Lesser Antilles approximately 25 million years ago. During this period of general submergence, there was a development of coral reefs which were later uplifted above sea level (Newman, 1965). These are present as small outcrops of limestone in the northeast of the island. The primary road network is not shown to encounter any limestone bedrock on the published mapping.

The Barre De L'Isle and majority of the east coast road are within the Central Series. The Barre De L'Isle is shown on the published map to be within andesite ash and altered andesite deposits, and the east coast road mainly within andesite agglomerate and mud flow deposits.

Figure 3.1: Simplified geological map



Source: After Saint Lucia Geology 1:50 000, OAS, 1984; and Geological map of Saint Lucia (West Indies), United Nations, 1965.

The Southern Series

Many small basaltic andesite lava deposits are found in the southern part of Saint Lucia.

They were deposited 5 – 10 million years ago. The relatively young age and limited uplift and erosion have led to the subdued topography of the landforms in this series. There are hot fumaroles associated with this series. There are several instances of 'cold' fumarolic activity and gas vents located in areas of highly altered rock within the southern series.

The most recent centre of volcanic activity in Saint Lucia is in the Southern Series, to the south of the town of Soufriere, within what appears to be remnants of a caldera. It consists of a series of volcanic vents and a vigorous high temperature geothermal field associated with the Qualibou depression, a large arcuate structure that formed in southwest Saint Lucia about 300 thousand years ago as a result of a huge landslide or structural collapse (Lindsay et al, 2002).

3.1.1 Recent deposits

No quaternary or superficial geological map exists of Saint Lucia. Alluvium, beach and terrace sands deposits are shown on the 1:50 000 scale map but are not distinguished. Colluvial deposits are not mapped but are often associated with landsliding. A brief discussion of the superficial deposits present on Saint Lucia is provided.

3.1.1.1 Beach deposits

Beach deposits are located in certain bays along the coast. No raised beach deposits have been identified to date. Most beach sands are a mixture of calcareous coral and shell fragments and particles derived from the volcanic rocks. The primary road network does not encounter beach deposits.

3.1.1.2 Alluvium

The primary road encircles the island and is often relatively close to the coast. As such the primary road traverses or follows many valleys. Some of the major valleys crossed and significant alluvial plains include:

- the area of Ravine Castagne, Bonne Terre, Beausejour, Reduit and the Marina;
- Bois d'Orange River;
- Choc River;
- Cul De Sac River;
- Roseau River;
- Anse La Raye;
- Canaries;
- Soufrière;

- Choisel;
- Grande Rivière de Vieux Fort and the surrounding area;
- Rouarne River;
- Troumassée River;
- Fond River;
- Dennery River; and
- Fond D'Or River and Grand Rivière Du Mabouya.

Deep alluvial deposits are likely to be present in most of these area.

The alluvium is likely to comprise various grain sized material, potentially with some ash interbeds. Grain size will depend on the environment of deposition. In the higher energy upper parts of the river valleys, coarser deposits are likely, with finer material deposited nearer the coast. However, high energy flood events will deposit coarser grained material further down the river system.

Deposits will be normally consolidated and are likely to be highly compressible. Peat deposits may also occur. Alluvial deposits are usually present in relatively flat and low lying areas that are not susceptible to landslides. Hazards such as flooding and liquefaction of normally consolidated sands during earthquakes are likely in alluvial areas. However, landslide debris from flow type slides may reach the alluvial plains in the correct conditions.

3.1.1.3 Colluvium

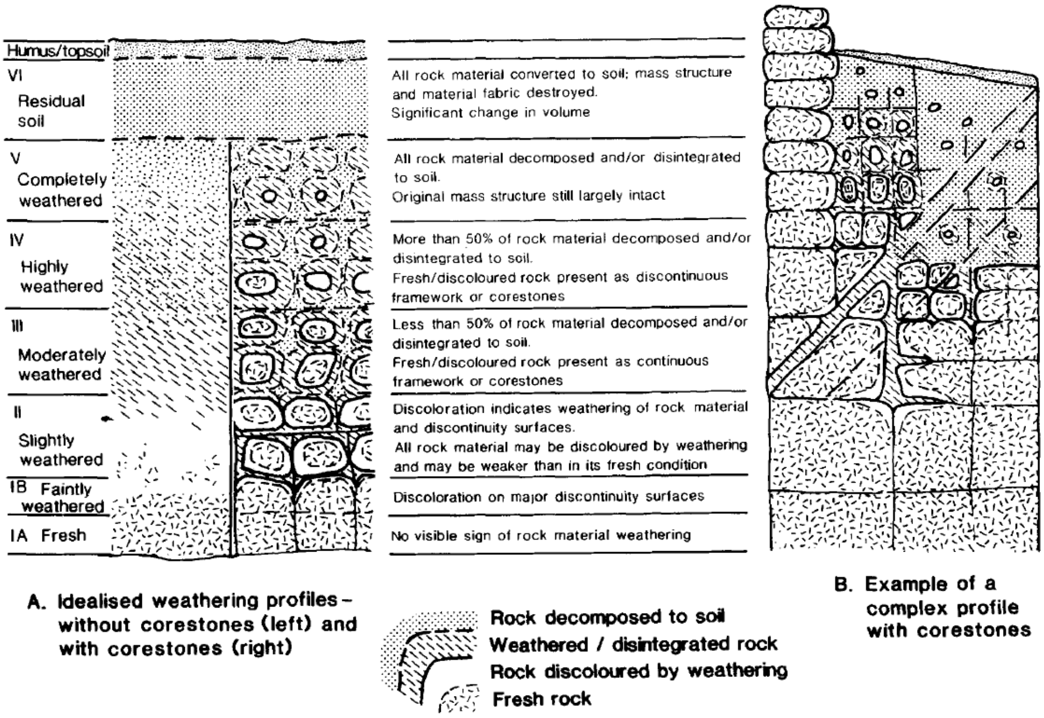
Colluvium is a material that has been transported by gravity. It can be variable in composition, grading and density (Huntley et al., 1981). Colluvium is typically a poorly sorted mixture of angular rock fragments and fine-grained materials (TRB, 1996). Colluvium often accumulates as fans at the base of slopes or within hollows or gullies on slopes.

Debris flows are a common failure type within colluvial materials (Ellen, 1988).

3.1.1.4 Weathering and residual soils

Weathered bedrock and residual soils are common in Saint Lucia. The tropical weathering profile presented within the Geological Society Professional Handbook on Tropical Residual Soils (Fookes, 1997) is considered a suitable classification framework and has been reproduced as Figure 3.2. Tropical red clays are present in several areas around the primary road network, particularly on the Barre de L'isle and some areas along the west coast road.

Figure 3.2: Weathering profiles and classification in tropical climates



Source: Reproduced from Fookes, 1997.

3.1.1.5 Made ground / fill

No significant areas of made ground are known underlying the primary road network. Fill was often used to construct roads in the mountainous areas. It is understood the fill was typically sourced from the cut slope excavated for road construction.

3.2 Hydrogeology

Saint Lucia is one of the volcanic windward islands and the rivers generally radiate out from the highlands in the centre of the island. The andesitic and basaltic bedrock are jointed rockmasses, and groundwater permeability in these are likely to be via fissure or fracture flow, whereas the dominant permeability within the agglomerates is likely to be a combination of fissure/ fracture flow where there are joints and intergranular diffuse flow in the less jointed areas.

To date, no aquifer maps or maps showing the locations of springs have been found for St Lucia. The famous Sulphur Springs are located near Soufriere. These are thought to have resulted from groundwater heating up due to the cooling magma body in the volcanic centre of the island which leads to the water becoming hot and buoyant, rising back to the surface along discontinuities. Other springs were noted in the fieldwork to be primarily along the upper section of the Barre de L'isle.

Geophysical studies both before and after Hurricane Tomas by Agramakova (2011) identify a small aquifer beneath the Thomazo River in the Fond D'Or watershed. The results of this study show that there is a 15% increase in the groundwater level in the ‘wet season’ after Hurricane Tomas. It is not certain if this can be equated to the increase in groundwater in other aquifers elsewhere on the island, but it indicates that there is a significant difference and possibly a fast response rate in St Lucia to the storm events. This increase in the groundwater may correlate with increasing porewater pressure, which is likely to have an effect on the landslides on the island.

The soils on the island are noted in places to have a high clay content associated with the ash content or breakdown of the feldspatic minerals in the volcanic bedrock. As a result there may be areas of low permeability soils and these may be associated with perched water tables.

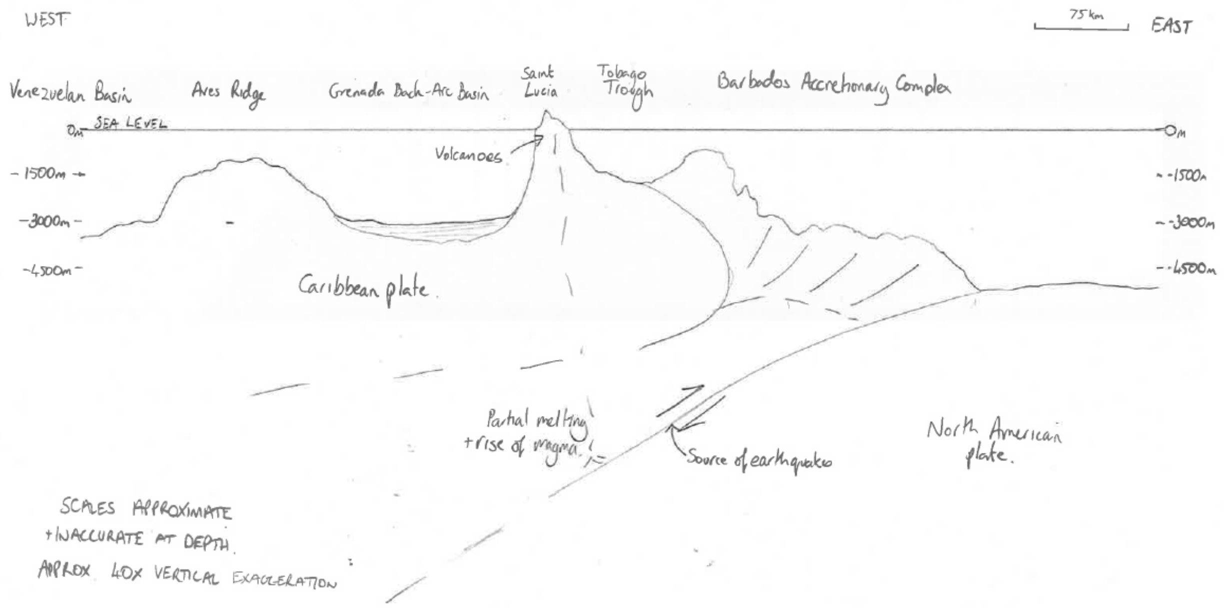
Springs were noted in the fieldwork at the top of the Barre de L’Isle, at this particular location they were also associated with slope failures. The Colombette slide is considered by some to be related to a spring as well (Personal communication with R Issac, 2013) although access to the top of the slide was not done in the first stage of the field mapping and this has not yet been substantiated.

3.3 Seismicity

3.3.1 General

Seismic events in the Eastern Caribbean are principally associated with a subduction zone at the junction of the Caribbean Plate and the North American Plate as shown in Figure 3.3. The Caribbean Plate is moving eastward relative to the North American Plate at a rate of about 20mm per year (USGS, 2013). The North American Plate dips from east to west beneath the Caribbean Plate along a north-south line approximately 150km east of St Lucia. This leads to a moderate level of inter-plate seismicity in the vicinity of St Lucia. Volcanic and seismic activity in Saint Lucia is monitored by the Seismic Research Unit at the University of the West Indies in St. Augustine, Trinidad and Tobago.

Figure 3.3: Regional tectonic setting of Saint Lucia



3.3.2 A Review of earthquake events in Saint Lucia

The Seismic Research Centre (http://www.uwiseismic.com/) reports that there have been at least five swarms of shallow earthquakes in Saint Lucia in the last 100 years. They occurred in 1906, 1986, 1990, 1999 and 2000. At least three of these swarms seem to have been triggered by a larger tectonic earthquake. The most recent tectonic earthquake of note was of magnitude 7.75 in 1953 and caused partial collapse of buildings previously damaged by fire and caused some damaged to buildings in the capital city of Castries.

In 1906, Saint Lucia was shaken by a large tectonic earthquake which was felt in the neighbouring islands of Grenada and Dominica. Numerous aftershocks and tremors were felt in the neighbouring islands for several months following the event.

There have been periods of low seismic activity interrupted by shallow earthquakes since 1986 when there were 12 earthquakes occurred in a single day of which four were felt.

In May and June of 1990, there were shallow earthquakes felt, the largest was of magnitude 4.5 on the Richter scale. Little damage resulted in the vicinity of the epicenter which was located at Mount Gomier in the southern part of Saint Lucia.

Between April and June of 1999, 105 volcanic earthquakes were recorded in southern Saint Lucia. They were recorded at only one station and none were reported felt.

Between July and November 2000 another swarm of earthquakes occurred, and on one day 27 earthquakes occurred. None of these earthquake events were directly related to the Soufriere Sulphur Springs, the area of most recent volcanic activity on the island. Most of these earthquakes were from older basaltic centres which were previously regarded as being extinct.

A magnitude 7.4 event occurred in November 2007 located off the coast of Martinique. The shock was felt throughout the Caribbean and in Saint Lucia caused minor damage to some structures.

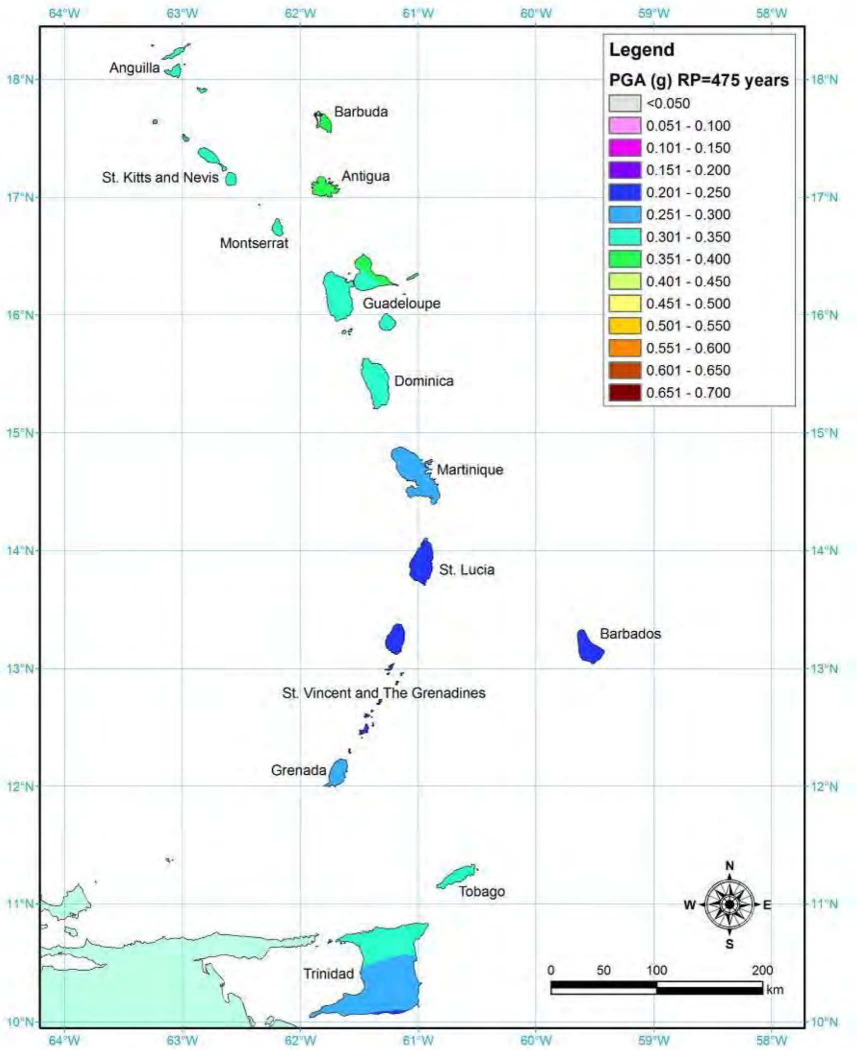
A review of seismological data from Gutenberg and Richter indicates several historical earthquakes with magnitude 7.0 to 7.7 on the Richter scale within 100 kilometres of Saint Lucia. It should be noted that none of the mentioned earthquakes have ever triggered any landslide or caused a loss of life in St Lucia.

3.3.3 Seismic hazard Studies

Several seismic hazard studies have been performed for the region. The most recent study was performed by Bozzoni et al. (2011) who published seismic hazard maps for the region. The analysis has been conducted using a standard logic tree approach which allowed taking into account systematically the model-based (i.e. epistemic) uncertainty and its influence on the computed ground motion parameters. Figure 3.4 presents the Peak ground acceleration for the region for 475 year return period. This equates to a 10% chance of being exceeded during the design life of the structure (which is likely to be 50 years). The PGA for St Lucia varies between 0.2 to 0.25g. This would probably equate to a magnitude 6.5 earthquake at a distance at a distance of 25 to 100km.

The great majority of the historical and recorded earthquakes used in the probabilistic analysis were tectonic earthquakes. There have been some earthquakes in the region associated with volcanic activity and eruptions, for example on Dominica and Montserrat. Earthquakes of this type can do a great deal of damage, but their effects are generally confined to a local area, thought usually to be less than 2 kilometres in radius. Robson (1964) does attribute a long series of small earthquakes felt in Saint Lucia in 1906 to possible volcanic activity, but Saint Lucia is not considered to be significantly at risk from this type of earthquake (Shepherd et al. 1997).

Figure 3.4: Variation of PGA from seismic hazard assessment (Bozzoni et al. (2011) for 475 year return period



The Association of Caribbean states have provided a model seismic code which is intended for the design and construction of new buildings in seismic regions, as well as for the retrofitting of existing buildings. They have divided the country into different zones, associated with maximum horizontal ground acceleration with 10% probability of exceedance in 50 years, as shown in Table 3.1. St Lucia would fall with Zone 3 based on this table. The major contributor to the seismic hazard is a large magnitude earthquake occurring in the northern segment of the Lesser Antilles subduction zone.

Table 3.1: Summary of the Association of Caribbean States model design code seismic zones

Seismic zone	Maximum horizontal ground acceleration with 10 % exceedance probability in 50 years	Value of a_g
1	> 0.30 g	0.35 g
2	0.20-0.30 g	0.25 g
3	0.10-0.20 g	0.15 g
4	<0.10 g	0.05 g

3.3.4 Landslides triggered by seismic forces

Major earthquakes have historically caused widespread landsliding. Topographic slopes fail during earthquakes because addition of gravitational and seismic accelerations causes short lived stresses in excess of the combined cohesive and frictional strength of underlying rock and soils. This is a function of the earthquake magnitude and the slope angles. Keeper (1984) studied data from 40 historical world-wide earthquakes to determine the characteristics, geologic environments, and hazards of landslides caused by seismic events. According to him four types of internally disrupted landslides—rock falls, rock slides, soil falls, and disrupted soil slides—are initiated by the weakest shaking. More coherent, deeper-seated slides require stronger shaking; lateral spreads and flows require shaking that is stronger still; and the strongest shaking is probably required for very highly disrupted rock avalanches and soil avalanches.

A study of historically triggered landslides has concluded that strong earthquakes, steep topography and fragile geological environment are main reasons responsible for serious landslides in seismic regions. Materials most susceptible to earthquake-induced landslides include weakly cemented rocks, more-indurated rocks with prominent or pervasive discontinuities, residual and colluvial sand, volcanic soils containing sensitive clay, loess, cemented soils, granular alluvium, granular deltaic deposits, and granular man-made fill.

The stability of a slope can be seriously affected by the shaking caused by earthquakes. The effect of the earthquake may be twofold; firstly, the accelerations caused by the ground movement will induce an inertial force into the slope material which will provide an extra overturning moment, and secondly, the vibration may cause pore pressure build up in the slope thus causing loss of frictional strength. Both effects will reduce the factor of safety of the slope and may lead to failure if the slope is subject to ground movement of sufficient magnitude and duration.

Based on the expected PGA level and the geological environment a preliminary risk assessment has been performed for the area as presented in Table 3.2. This is following a broad brush approach at this stage to understand if landslide can be triggered by earthquakes as well as induced by rainfall.

Table 3.2: Subjective assessment of landslide risk related to earthquake and slope conditions

Topography	PGA	Geological Environment	Risk on Macroscopic scale Comments
Slope angle less than 20°	Less than 0.3g	Rockfall	Low
		Colluvial Soils	Low
		Residual	Low
	Greater than 0.3g	Rockfall	Low
		Colluvial Soils	Low
		Residual	Low
Slope angle between 20° to 40°	Less than 0.3g	Rockfall	Low
		Colluvial Soils	Low
		Residual	Low
	Greater than 0.3g	Rockfall	Moderate
		Colluvial Soils	Moderate
		Residual	Moderate
Slope angle greater than 40°	Less than 0.3g	Rockfall	Moderate
		Colluvial Soils	Moderate
		Residual	Moderate
	Greater than 0.3g	Rockfall	High
		Colluvial Soils	High
		Residual	High

3.3.5 Conclusions

Earthquakes and volcanic activity are recognized as triggers for landslides which might affect this region. Landslides are relatively common on the eastern Caribbean island of Saint Lucia, being most frequently associated with heavy rainfall. There are no reports of any historical landslides being associated with ground shaking in this region. The probability of a big earthquake triggering a landslide which is also associated with heavy rainfall is low for the region based on the expected seismicity of the area. If there is an earthquake in the dry season it is unlikely that this will cause a landslide. A deeper earthquake can possibly cause some damage if the geological and the topographical conditions are favourable.

In summary, no landslides are known to have been triggered by earthquakes in Saint Lucia and at the PGS expected in an event with a 475-year return period the risk of triggering a landslide is considered low. The probability of a large earthquake and extreme rainfall event occurring at the same time is very low. Therefore, earthquakes will not be considered as triggers for landslides as part of the landslide risk assessment for the project.

4 Stakeholder engagement

4.1 Introduction

This section identifies relevant stakeholders and describes the consultation, participation and disclosure activities that have been undertaken during the first part of the Project.

Information disclosure and consultation have been guided by the Stakeholder Engagement Plan (SEP) which was submitted to MIPS&T in March 2013. The SEP outlines a programme for meaningful stakeholder engagement throughout the assessment period, expected to be about nine months.

This section describes the:
- principles guiding the information disclosure, consultation and participation activities;
- consultation process methodology; and,
- consultation results to date.

4.2 Principles guiding the project's stakeholder engagement

Stakeholder engagement is essential for effective planning and implementation of most infrastructure projects. The consultation and participation activities described in this chapter have aimed to ensure adequate and timely information is provided to stakeholders so that they have sufficient opportunity to present their opinions and concerns. The stakeholder engagement approach for this Project is based on the following commitments:
- stakeholders will be informed why consultation is taking place and how their views will be taken into account;
- a wide spectrum of community and stakeholder groups will be involved in the consultations;
- consultation activities will be organised in ways that are convenient and accessible for the people whose views are sought; and
- results of consultation activities will be reported along with how the results have been used.

Meaningful consultation is proposed. "Meaningful" refers to "free" (free of external manipulation, interference or coercion, and intimidation), "prior" (timely disclosure of information) and "informed" (relevant, understandable and accessible information).

The results of the consultation and participation activities have informed the Draft Feasibility Report and Final Feasibility Report.

4.3 Stakeholders

Stakeholder identification and analysis was undertaken to inform the SEP. Stakeholders' interests and influence were considered in order to analyse the best means of effectively engaging them and the most appropriate type and format of information to disclose to them. Table 4-1 below identifies the stakeholders identified at the planning stage.

Table 4-1: Stakeholders

Key stakeholders	
Government Authorities	**Road User Representatives**
Ministry of Infrastructure, Port Services and Transport (MIPS&T)	National Taxi Association, National Association of Public Transport
National Emergency Management Organisation (NEMO)	Saint Lucia Chamber of Commence
Priority Ministerial Departments: Forestry, Environmental and Sustainability, Water Resources Department; Physical Planning	
Other Ministries and Departments (meteorology, tourism, health, education)	**Non-governmental Organisations**
City, Town, District and Village Councils	Environmental Groups – Saint Lucia National Trust, Caribbean Environmental Health Institute, Caribbean Natural Resources Institute (CANARI) etc.
Utilities and Private Sector	Association of Professional Engineers
LUCELEC &WASCO	
Telephone companies (Karib Cable, Digicel, Lime)	**Others**
Saint Lucia Hotel and Tourism Association	Emergency Services (police, fire, ambulance)
Road construction companies	Organisations and projects with similar focuses in road sector or disaster preparedness (e.g. MoSSaiC, Caribsave, Caribbean Community Climate Change Centre, etc)

4.4 Approach to engagement for the landslide risk assessment and feasibility stage of the project

Based on the SEP, the main activities undertaken to date have been:

- preliminary key stakeholder meetings to introduce the Project;
- seminars on GIS based hazard analysis, risk assessment and by the project peer reviewers;
- workshop on slope stability;
- distribution of a Project brochure with requests for data and opinions to a range of stakeholders. The brochure is attached in Appendix C;
- risk matrix training at sites along roads with zone engineers; and
- workshop to present and discuss the draft risk assessment findings.

4.5 Summary of stakeholder engagement results to date

This section summarises the outcomes of the information disclosure and consultation activities and key facts, namely date, venue, and participant numbers. Table 4-2 summarises the results of key informant meetings and email exchanges during the assessment phase.

Table 4-2: Consultations during the land risk assessment and feasibility stage

Stakeholder	Key Issues	Comments /How addressed in study
NEMO	Results of interest to NEMO; prediction of less hurricane events but they will be	Frequency of hurricane events addressed in Section 2.2

Stakeholder	Key Issues	Comments /How addressed in study
	stronger, key utility service is water, seismic factors (volcanic and tectonic) and drought also as causes of landslides	Seismic factors discussed in Section 3.3 MIPS&T could share GIS data with them
Forestry Department	Bioengineering and potential for methodology to be transferred to forest road network of interest	Bioengineering discussed in Section 9
WASCO	Limited response	
LUCELEC	Have conducted their own vulnerability assessment of their network	Have not provided their vulnerability assessment.
Physical Planning Department	Results would help their mandate to better plan access to individual lots	MIPS&T could share GIS data with them
Meteorology Department	Statistical analysis at regional level; good met data from 3 stations for sharing	
National Association of Public Transportation	Signage and safety are important, should look for low cost maintenance options including cleaning of drainage	Signage is mentioned in Section 8 Maintenance issues are discussed in Sections 8 and 9
Saint Lucia National Trust	More concerned about new roads opening new areas; important to not compromise endemic species; other known disaster management projects are with Caribsave and a recently approved EU project	Other projects were consulted
Caribbean Environmental Health Institute (CEHI)	Bioengineering activities are of interest; are looking at environmental protection activities in the Soufriere area and could potentially pilot some study recommendations	When study recommendations are more concrete, MIPS&T may wish to consult with them again

5 Hazard assessment

5.1 Introduction

Landslide hazard assessment has been completed at a network scale and site specific scale in a number of stages to allow a comprehensive understanding of the landslide hazard to be developed. Regional landslide hazard assessments have been previously completed by several authors based on the available landslide inventory (e.g. DeGraff, Rogers, Quinn). A similar GIS based assessment has been completed as presented in Appendix D. As the landslide inventory is essentially the same in each assessment, they have similar results.

At the network specific scale a density analysis of the landslides the occurred in response to different storm events has been attempted to try and evaluate the hazard that is caused by different storm events.

At the site scale a geomorphological assessment has been completed by interpretation of 2009 air photographs to identify historical and recent landslides along the network and ground truthing of the air photograph interpretation.

This section describes the methodologies used and presents the results of the hazard assessment.

5.2 Network scale density analysis

5.2.1 Methodology

The density analysis aims to examine the relationship between different storm events and the landslides that occurred following these events at a broad network scale. To do this, an assessment of the number of landslides that have occurred during two different storm events has been made. The number of landslides that occurred during each event was assessed as discussed in Section 5.2.2. Each landslide has been added as a point to a map of St Lucia with x and y co-ordinates using ESRI ArcGIS version 10.1. Landslides that are not considered to affect the primary road network have been removed from the dataset. The number of landslide occurrences along a defined road section was then totalled for each of the datasets and a density calculated per km of road section. The results are presented in Section 5.2.3 and the different road sections areas are shown in the map in Figure 5.1. Road sections were defined based on the land morphology and locations of main towns.

5.2.2 Data

In order to examine the relationship between severe storm events and consequential landslide events two different data sources have been analysed. The data sources comprise:

- landslide mapping produced by DeGraff (1985), following Hurricane Allen in 1980;
- a currently up to date landslide inventory compiled by Ms Abraham since Hurricane Tomas in 2010.

Owing to Ms Abraham's lack of confidence with her assessment, it has been reviewed and updated by a Mott MacDonald (MM) engineering geologist based on Rapid Eye satellite images taken recently after Hurricane Tomas (the exact date of this images is not currently known). Rapid Eye satellite images are 5m resolution and therefore features of slope failure can be difficult to distinguish from unrelated features within the landscape. Judgement has been made based on comparison with earlier, better quality aerial photography (taken prior to Hurricane Tomas) and consultation of GIS layers detailing slope gradients.

DeGraff's mapping was produced based on air photos from 1977, before Hurricane Allen, and 1981, after Hurricane Allen. Therefore, some of the landslides may not have been triggered by the hurricane. However, it is considered the analysis will give a broadly accurate representation of landsliding during Hurricane Allen.

The 'Saint Lucia Landslide Inventory' compiled by Rogers (1997) does not allow differentiation between events recorded by DeGraff following Hurricane Allen and events recorded by Rogers following Tropical Storm Debby. Therefore, a comparison can only be made between events following Hurricane Allen and events following Hurricane Tomas. Ms Rogers has been contacted in order to see if this can be ascertained, if a response is gained prior to the final reporting then we will be able to include this data into the results.

Assumptions and limitations

- All landslides identified were as a result of the storm event, i.e. it does not account for those initiated by human influence.
- All landslides that have been identified are a point on the density map, not a polygon and therefore this does not take into account the size or magnitude of the landslide
- It does not take into account the impact of the landslide on the road. Judgement by an engineering geologist as to the location of landslides relative to the road has been taken to remove those landslides not considered to impact on the road.
- Landslide features approximately less than 30m across cannot be identified as part of this assessment because of the resolution of the images.

5.2.3 Results

Landslides considered to have the potential to affect the primary road network have been identified from each data source and recorded according to their corresponding road section. The number of landslides recorded for each road section and the calculated landslide densities for each section are presented in Table 5.1 below and the sections are presented in Figure 5.1. A comparison between the Abraham (2010) and DeGraff (1985) datasets can be seen in Figure 5.2 and Figure 5.3 respectively.

Table 5.1: Landslide density following Hurricane Allen and Hurricane Tomas along the Primary Road Network

		Number of landslides observed		Landslide density (No./km of road)	
Road section	Section length (Km)	DeGraff	Abraham/MM	DeGraff	Abraham/MM
Barre de L'Isle	5.46	15	67	2.75 (1)	12.27
Soufriere - Canaries	11.69	15	33	1.28 (2)	2.82
Castries – Barre de L'Isle	8.34	2	23	0.24 (9)	2.76

		Number of landslides observed		Landslide density (No./km of road)	
Road section	Section length (Km)	DeGraff	Abraham/MM	DeGraff	Abraham/MM
Choiseul - Soufriere	14.17	5	32	0.35 (8)	2.26
Anse La Raye – Castries	10.91	4	14	0.37(7)	1.28
Canaries - Anse La Raye	11.91	5	14	0.42(6)	1.18
Laborie – Choiseul	8.54	6	7	0.70 (3)	0.82
Vieux Fort – Laborie	7.02	0	5	0.00 (11)	0.71
Dennery – Micoud	16.47	4	8	0.24 (9)	0.49
Castries	14.03	3	6	0.21 (10)	0.43
Grand Riviere - Dennery	7.41	5	3	0.67 (4)	0.40
Micoud - Vieux Fort	15.08	7	4	0.46 (5)	0.27
Castries - Gros Islet	15.34	0	0	0.00 (11)	0.00

Note: DeGraff records events around the time of Hurricane Allen (1980); and Abraham/MM record events initiated by Hurricane Tomas (2010). The table is ranked according to the Abraham / MM data. The bracketed data for DeGraff shows the ranking from most dense to least dense landsliding observed by DeGraff.

Figure 5.1: Density analysis for the primary road network

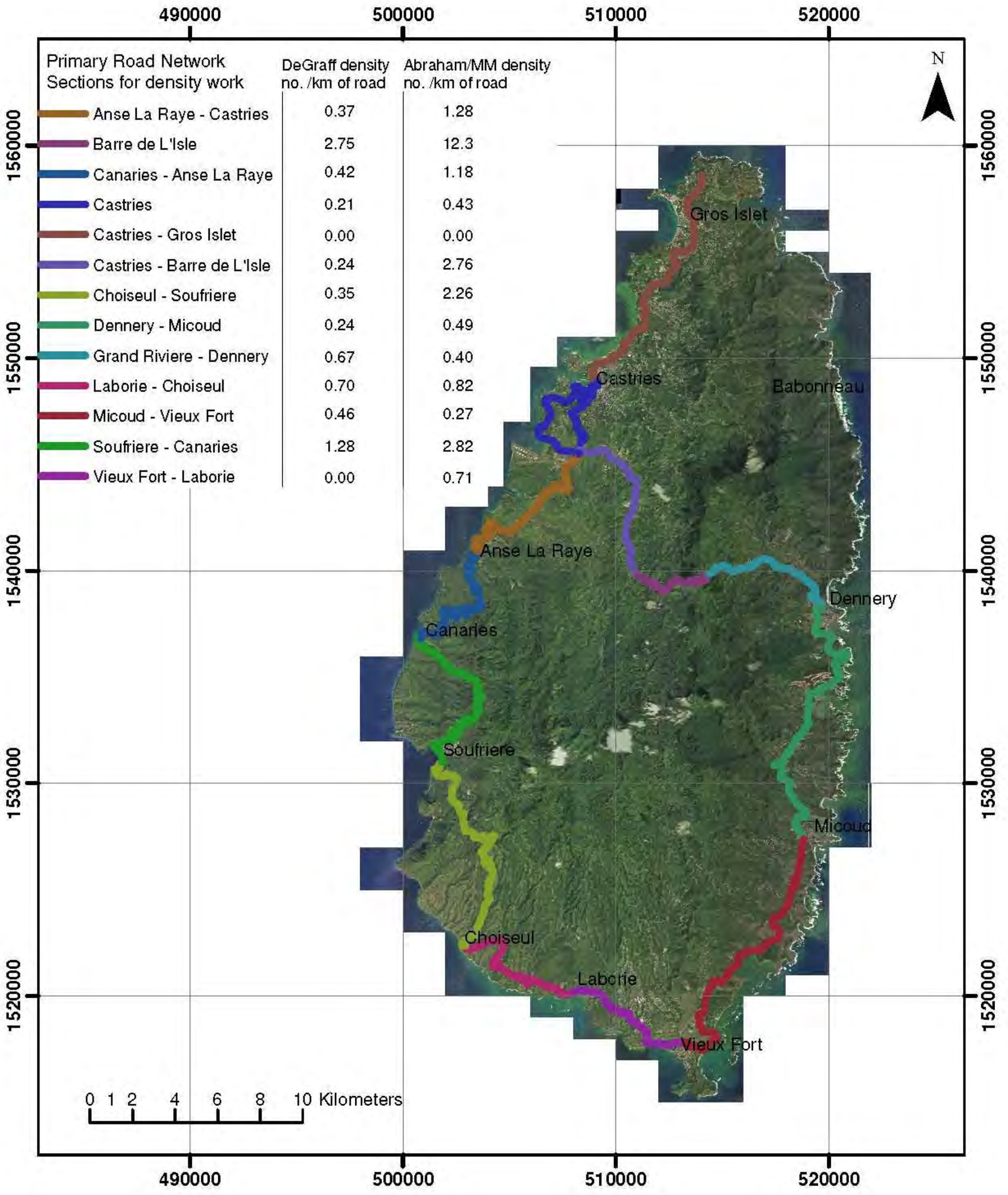


Figure 5.2: Landslide density per km of road - Post Hurricane Tomas

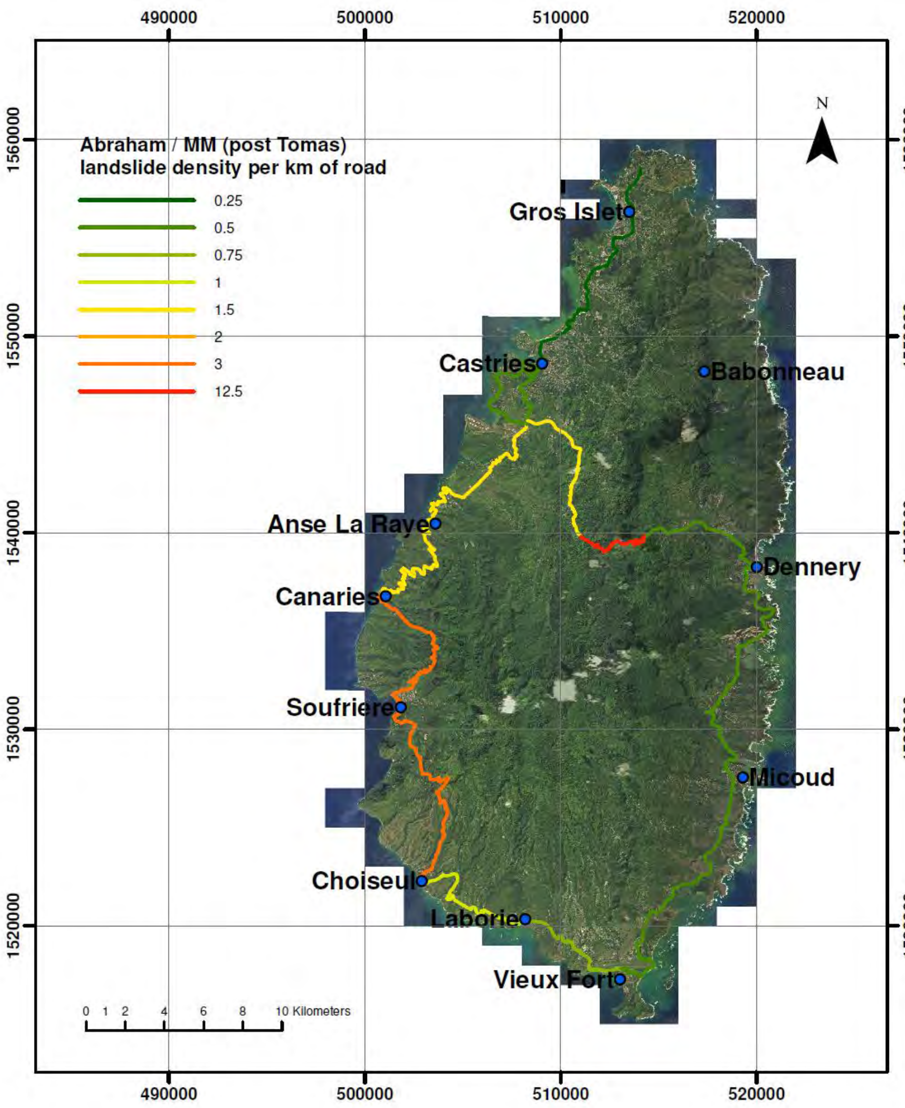
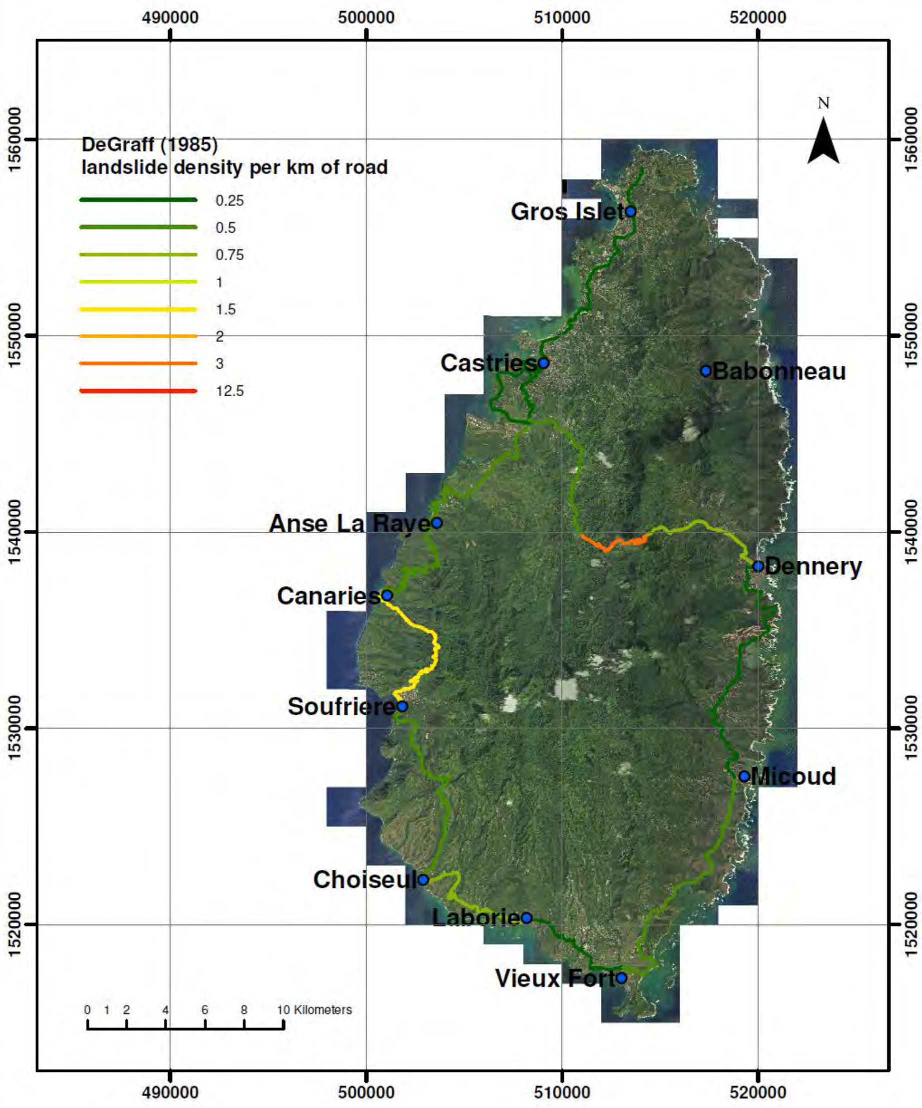


Figure 5.3: Landslide density per km of road – Post Hurricane Allen



5.2.4 Assessment of results

5.2.4.1 Differences between the Hurricane events

Hurricane Allen was a Category 5 Hurricane, recording winds of up to 130 mph (HurricaneCity.com, 1997-2012), whilst Hurricane Tomas was a Category 2 Hurricane, recording lesser wind speeds of up to 80 mph (HurricaneCity.com, 1997-2012). It is apparent from the literature and from discussions with the government and local people who lived through the events that Hurricane Tomas resulted in much greater rainfall in Saint Lucia than Hurricane Allen. During Tomas up to 668mm of rain fell on the island in under 24 hours (ECLAC, 2011). During Hurricane Allen the maximum rainfall was 127mm in 24 hours according to data provided by the GoSL.

5.2.4.2 Analysis of the results

The most striking difference between the different datasets is that there were many more landslides identified as part of the Abraham/MM assessment than the DeGraff assessment following Hurricane Allan. For example, the highest density landsliding from Abraham's data is 12.5 landslide/km, more than four times the density of the highest landslide density area from the DeGraff dataset, 3 landslide/km. This may be a result of the mapping works on Abraham's dataset picking up more smaller landslide features, whereas DeGraff's mapping shows much spatially larger landslides and few small features. This is probably related to the scale of mapping and quality and time available for the landslide interpretation. Alternatively this could indicate that the landsliding resulting from Hurricane Tomas was more intense, with more landslide events occurring as a result of the increased rain.

Both the DeGraff and Abraham datasets show that the highest density of landsliding was found along the Barre de L'Isle, the second densest area between Soufriere and Canaries is also the same for both datasets, with values of 1.5 and 3 landslides per km respectively. This information corresponds with the fieldwork mapping (see Section 5.4) and suggests that these areas along the network suffer most from landsliding following a tropical storm or hurricane.

The area between Dennery and Micoud and the area around Castries is ranked 9th and then 10th respectively by both DeGraff and Abraham. However, the landslides identified in the fieldwork suggest that Castries may have more landslides than suggested by this assessment and they may therefore be not only related to storm events, but may be related to anthropogenic activities, such as drainage blockage and land use. It is also possible that the scale of mapping would not allow the smaller features identified in the fieldwork to be identified.

Neither DeGraff nor Abraham identified any landslides in the road section to the north of the island between Castries and beyond Gros Islet. DeGraff also did not identify any landslides along the primary road in the area between Laborie and Vieux Fort. It is considered that rockfalls in this area may have increased the density in Abrahams's data.

Some landslides have occurred in exactly the same place after both Hurricane Allen and Hurricane Tomas. Therefore, some landslides that occurred during Hurricane Tomas may represent reactivation of earlier landslides. However, in a large number of instances slopes that failed following Hurricane Allen, do not appear to have failed again following Hurricane Tomas. This may be due to the fact that the failed slopes have reached equilibrium and therefore are relatively stable; alternatively it may be that movement following Hurricane Tomas is not visible on the 5m resolution Rapid Eye imagery available.

In summary, network landslide density analysis confirms the most landslide prone areas are the Barre de L'isle and from Soufriere to Canaries. The analysis also suggests that more landslides occur in response to higher intensity rainfall events.

5.3 Site scale geomorphological assessment

5.3.1 Initial air photo interpretation

To assist with understanding the landslide hazard to the primary road network, an initial desk based landslide assessment was completed along the road network by interpreting aerial photography of the island combined with a Digital Elevation Model (DEM). The aerial photographs were taken between December 2008 and February 2009, prior to Hurricane Tomas and have a resolution of 0.25m for the whole island and 0.125m for the main areas of population (Fugro, 2011). The extents of possible historical and current landsliding were traced over the images using ESRI ArcGIS software. Owing to the rapid re-growth of vegetation, the extents of landsliding were principally based on the morphology and landforms that typically demonstrate historical and active landslides at various scales as well as any more recently visible scarps. The assessment was completed at various scales along the road network between 1:10,000 and 1:2,000 in order to identify some of the smaller features. The aerial photographic interpretation was completed by 3 experienced engineering geologists. Some of the features that help identify a potential landslide are described in Turner and Shuster (1996).

Each landslide was classified in the GIS using the scheme proposed by Varnes (1978) primarily using type of movement and nature of displaced material to define landslide types. The probable type of material was also noted to further categorise each landslide. A summary of the classification scheme is provided in

Table 5.2: Landslide classification scheme

			Type of material		
				Engineering soils	
Type of movement			Bedrock	Predominantly coarse (DEBRIS)	Predominantly fine (EARTH)
1. Falls			Rock fall	Debris fall	Earth fall
2. Topples			Rock topple	Debris topple	Earth topple
3. Slides	a. Rotational	i. Few units	Rock slump	Debris slump	Earth slump
	b. Translational		Rock block slide	Debris block slide	Earth block slide
		ii. Many	Rock slide	Debris slide	Earth slide

Type of movement		Type of material		
			Engineering soils	
		Bedrock	Predominantly coarse (DEBRIS)	Predominantly fine (EARTH)
	units			
4. Lateral spreads		Rock spread	Debris spread	Earth spread
5. Flows		-	Debris flow	Earth flow
6. Complex		Combination of two or more types of movement		

Source: after Varnes, 1978

Both DeGraff (1980) and Rogers (1997) also based their classification on the terms defined by Varnes (1978).

Other information assessed and entered into the GIS for each landslide included:

- Area of the landslide being recorded:
  - the head and main body (h);
  - the foot (t);
  - or the entire area (a).
- Relative age:
  - young (y) with fresh features such as a well defined steep backscarp with little degradation;
  - old (o) with low vegetation cover and a degraded backscarp; or
  - historic (h) with high vegetation cover and features that are highly degraded / difficult to make out.
- Activity of the landslide:
  - stable (s) with areas of movement in the past but is currently well vegetated and appears to be stable; or
  - active (a) with clear signs of recent movement.
- Relative depth of the feature:
  - surficial (s); or
  - deep (d).
- An assessment of the level of confidence in the interpretation:
  - poor/unconfident;
  - moderate confidence; or
  - certain / highly confident.

Some of the definitions for the features above are presented within Cruden and Varnes (1996) and the IAEG Commission on Landslide (1990).

Air photo interpretation is time effective and allows larger areas to be viewed than would be possible in the field alone. However, air photograph interpretation should always be backed up by ground truthing in the field to confirm the interpretation is accurate. Ground truthing is especially important for the project because :

- not all features will have been identified in the air photo interpretation as the photographs were taken prior to Hurricane Tomas;

- some of the features will not be visible on the air photos and changes will have occurred since the photographs were taken, due to rapid re-vegetation, erosion and agricultural practices;
- discreet landslide or rock or debris events due to their small size may not be picked up; and
- discreet, slow moving landslides may not be identified due to the lack of visible features that one would look for in the aerial photographic analysis such as displaced ground, change in vegetation cover etc.

The initial air photo interpretation is provided as part of the GIS package included on CD within Appendix D. For information, overview maps at 1:70,000 scale have also been produced as a visual aid and are presented in Appendix E.1 of this report.

5.3.2 Fieldwork

Following the desk based air photo interpretation, field reconnaissance was undertaken in February 2013 and a number of features in the desk based assessment were refined, some features were removed and some new landslide features were added.

The field assessment was restricted to approximately 250m either side of the centreline of the road or the crest of the nearest slope from the road. Significant features outside of this area were also noted if it was considered to impact the road network.

In addition to refining the landslide areas, new scarps and areas where retaining walls were noted to be damaged or drainage was blocked were added to the GIS database. This was not a systematic condition assessment of the drainage and structures and does not constitute a full record of the problems associated with drainage and structures around the primary road network.

The fieldwork is provided as part of the GIS package included on CD within Appendix D. For information, overview maps at 1:70,000 scale have also been produced and are presented in Appendix E.2.

5.3.3 Fieldwork zones

As has been identified by DeGraff (1980) not all past landslides can be identified on aerial photographs or in the field and neither can all future landslides be predicted. Rapid re-vegetation, natural erosion and agricultural practices can obscure landslide features. As a result, a fieldwork zone study aimed to identify slopes adjacent to the road where similar ground conditions, environments and morphology may lead to similar landslide events and ground movements.

The assessment of the fieldwork zones was initiated in parallel with the site specific ground truthing fieldwork. These areas have been grouped based on one or more of the following categories; vegetation cover, climate, slope angles, geology, surface water paths and the road’s situation on the slope and location relative to the watershed. One hypothesis raised from this is that where a certain failure i.e. debris flow or translational failure has occurred in the past, similar failures may have the potential to occur elsewhere within this zone. This can be used to aid planning for future landslide events, prioritisation of preventative works and on-going network management.

The fieldwork zones are described in Table 5.3 and figures showing their location along the primary road network are presented in Appendix E.3 at 1:70,000 scale.

Mott MacDonald

Table 5.3: Fieldwork zones

Zone	Location	Terrain description	Watershed1	Geology2	Slope processes observed associated with the road
A	West Coast Road between Soufriere and Canaries	Sub-tropical wet forested areas. Steep terrain slopes of >45 degrees often encountered. Streams and gullies often dry / ephemeral.	Upper catchment of 26 and mid to lower catchment of 27	Andesite Agglomerate	Debris flows and translational failures occur on the steep slopes and road cuttings where springs may emerge. Rockfalls from steep cuttings in the agglomerate may also occur.
B	West Coast Road between Canaries and Anse La Raye	Dry sub-tropical, thin soils and bedrock frequently exposed in cuttings along the road. Vegetation growth here is less than in the forested wet area of area A. Ephemeral streams.	Mid catchment 28	Andesite Agglomerate and Andesite Tuffs	Surface erosion on the over steepened cut slopes may lead to shallow translational failures. Potential for debris flows. Occasional rock falls observed in the agglomerate.
C	West Coast Road south of Anse La Raye	Dry scrub land with some sub-tropical low height vegetation growth. Valley located below the road. Slope angles generally between 20 and 35 degrees.	Lower to mid catchment 29	Andesite Agglomerate and Basalt Andesite Agglomerate Tuff.	Localised area along the road where rockfall / colluvium is observed in the side slope north of the area.
D	Cul de sac to Ravine Poisson and the base of the Barre de L'isle	Steep variably vegetated slopes with dwellings generally situated along the crest of the slopes and at the foot. Gullies and streams drain surface water towards the River.	Mid to Upper catchment areas of watershed 33.	Andesite Ash altered And Porphyritic Andesite	Shallow translational movements in the upper catchments of the streams can combine with others and form channelised debris avalanches/ debris flows onto the valley floor.
E	Immediately south of Anse La Raye	Dry sub-tropical area, the north and southern areas are bound by relatively flat bottomed river valleys. The side slopes of which are between 28 and 35 degrees. The road generally cuts into these slopes. On top the area forms an approximately 500m wide gently westward sloping (<0.5 degrees) plateau, where dwellings and farms are located and three evenly spaced tributaries.	Lower catchments of watersheds 28 and 29	Andesite Ash altered Andesite Agglomerate	In the cut slopes there are rockfalls and topple failures. Surface erosion is also known to occur causing vegetation slumping in the roads on the steeper slopes. On the plateau there is little slope movement identified.
F	West Coast Road, North of Anse La Raye and south of the Rosseau Valley	Dry sub-tropical area, vegetated slopes with some dwellings located on the higher ground. Rock cuttings occur where the road cuts a slope. Similar terrain to E with a plateau bound to the north and south by river valleys, however the plateau is more disrupted due to the presence of a number of NE-SW trending tributary valleys with approximately 10-15 degree side slopes.	Lower catchment of watershed 31 and upper catchment of watershed 32.	Andesite Ash altered	Bedrock outcrops of agglomerate and andesite causes localised rockfall to occur in places. Where vegetated over the slopes, occasional localised translational failures in the residual soils at the side of the roadside may occur.
G	Between the Cul de Sac River valley (the Hess oil terminal) and the Rosseau Valley	Sub-tropical area with a number of dwellings and gardens with local farmed areas. Tropical vegetation where there are no dwellings. This area represents a section of a NW/SE trending ridge line with tributary valleys of the main rivers draining both to the north and south, giving varied slope angles and directions along the road section in this area. The slopes above and below the road can be up to 50 degrees, generally, they are more likely to be 30 to 35 degrees.	Lower catchment of watershed 33	Andesite Ash altered Andesite Tuff Agglomerate	Small areas of gully erosion and drainage problems along the road have caused some localised sub-rotational failures o at the edges of the road. Translational failures from heavily vegetated over-steepened residual soil slopes above the road have also caused problems here in the past. Rock cuttings present rockfall and topple hazards in small locations along the ridge top.
H	North of Canaries	Slopes north of Canaries generally between 20 and 30 degrees, with a number of dwellings on the lower slopes.	Lower catchment of 28	Andesite Agglomerate and an area at the foot of the slope denoted as being 'unclassified'	Few noted. Rockfalls from the road cuttings.
I	Alluvial / Coastal Plains Along major river valleys and near the coast	Flat alluvial plains / coastal plains. Low flat land in valley bases or near the coast. Often farmed and often with dwellings located on them.	6 to 37	Alluvial and river terrace superficial material	None noted. May be a deposition area of channelised flow deposits.
J	Immediately south of Soufriere town	Sub-tropical trees occupy areas that are unfarmed. This section along the road is variably steep towards the coast and in places the road cuts into the bedrock. This section of the road leads from the town of Soufriere up slope to around a small headland which juts out to the south of Soufriere. It is drained by steep sided gullies leading to the NW and then to the south east (around a small peak which forms one of the volcanic cones).	Mid to upper catchment of watershed 24.	Dark Andesite cones and Aphyric Basalt	Shallow translational failures of the seaward edge of a steep (38-50 degree) slope adjacent to the road noted. Also surface erosion and drainage issues leading to small localised areas of failure below the road. Soil erosion from the densely vegetated slopes above the road as well may form localised shallow translation failures. Where the bedrock is cut, localised topple and rockfall may occur.
K	Volcanic centre West coast road, south of Soufriere	This area is the volcanic centre of the island and so the terrain is typified with high peaks, steep vegetated slopes and flat bottomed craters. The road here goes around the peaks and generally attempts to follows the contours on sidelong ground.	Upper catchment of watershed 24 and lower catchment of watershed 25.	Craters, Piton Agglomerate, Dark Andesitic Cones and Belfond Pumice fall and Piton Dome Lava.	Shallow translational failures may occur.
L	Millennium Highway - Castries	This is the northern portion of the millennium highway. The rock cut slopes are generally not as high and where vegetated form shallower vegetated slopes. The area as with all of Castries is populated by dwellings and farmed fields. Drainage channels run towards the north and west.	Lower catchment of watershed 34	Andesite Agglomerate	Localised rock and boulder fall from the larger clasts within the agglomerate onto the roadside the rock cuttings.
LL	Millennium Highway South	The southern part of the millennium highway comprised of rock cut slopes generally unvegetated and benched. On the southern portion there are some vegetated slopes up to 50 degrees in slope angle. The area as with all of Castries is populated by dwellings and farmed fields. Drainage channels run towards the west.	Lower catchment of watershed 34	Altered Andesite Porphyry	Rockfall and topple, with potential for localised translational slides on the vegetated steep slopes along the south.
M	South coast road near the airport	Rounded peak in the alluvial / coastal planes of the south of the island. Slopes adjacent to the road are between 10 and 30 degrees, the northern end is currently quarried. Where it is not quarries, the vegetation suggests a semi-arid climate.	Lower catchment of watershed 17	Basalt Andesite Agglomerate Tuff	Small area with localised rock fall where exposed and over steepened slopes may provide some shallow translational failures in the residual soils.
N	Laborie	Steeper slopes (between 25 and 30 degrees) form this area related to the hill of basalt agglomerate	Lower catchment of watershed 18	Porphyritic Basalt	Some shallow residual soil erosion seen possibly leading to

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Zone	Location	Terrain description	Watershed1	Geology2	Slope processes observed associated with the road
		north of the road. Vegetation comprises semi-arid dry shrubby material. Coastal slopes present below the road. Surface streams drain the slope towards the south.			translational failures in the slopes above the road. Some coastal erosion may also occur.
O	Vieux Fort town	Similar terrain to P south island lowlands, predominantly Belfond Pumice Flow Tuff, low angle slopes with shallow residual soils and shrubby vegetation. More tributaries leading towards the south and an increased number of dwellings and farm land.	Lower catchment of watershed 17	Belfond pumice flow tuff	Ground movements are minimal and comprise a low volume of material of rockfall and localised shallow soil translational failures in superficial deposits.
P	South coast Choiseul to the edge of Laborie	South island lowlands - Predominantly agglomerate / pumice flow bedrock low angle slopes (generally <5degrees towards the south) with some shallow residual soils and shrubby vegetation. Interspersed with marginally steeper tributary valleys which drain towards the south and southwest.	Lower catchments of watersheds 18, 19, 20 and 21.	Belfond Pumice Ash Flow and Andesite Agglomerate	Ground movements are minimal and comprise a low volume of material of rockfall and localised shallow soil translational failures in superficial deposits.
Q	West coast, from an area south of Soufriere to Choiseul.	This section of the road follows along a ridge top of the various flows to the south west of the island. Drainage is generally towards the south. Shallow vegetated residual soils.	Mid catchment of watershed 23 and low mid and upper catchments of watershed 22.	Belfond Pumice fall, Piton Agglomerate, Andesite Pumice Flows, Andesite Agglomerate,	Translational failures may occur either side of this area reducing the ridge top space available for the road.
R	East Coast, Dennery to Vieux Fort	Predominantly agglomerate tuff bedrock slopes of shallow angles between 5 and 30 degrees with some shallow residual soils and shrubby semi-arid vegetation. This is a big zone covering most of the east coast. There are some areas where the road is closer to the coast and therefore closer to the steeper sea cliff slopes. There are a number of river valleys and coastal plains which intersperse this zone, which drain towards the Atlantic Ocean (east of the island).	Lower catchment of watersheds 6 to 15.	Andesite porphyritic, Belfond Pumice Flow, Agglomerates and Mudstone.	Ground movements are minimal. Where there are rock cuttings there may be localised boulder fall / rockfall as the larger clasts of agglomerate weather out. Also along ephemeral streams minor translational / channelised flows may occur, but this was not seen in the field. The sea cliffs may be subject to undercutting by wave erosion and therefore may regress with rockfalls, however normally the road is quite far back from the cliff edges.
S	West of Dennery	Small village called La Caye, in the Dennery valley with rock cuttings and shallow (10 to 30 degree slopes) generally farmed.	Mid to lower catchment of watershed 6	Andesite Agglomerate	Minor rockfall and localised shallow translational failures in superficial deposits.
T	Barre de L'isle (east)	Eastern side of the Barre de L'isle comprising forested sub-tropical vegetated slopes and bedrock cuttings. Gully's / head catchments of tributaries form alongside the roads here.	Upper catchment of watershed 33	Andesite Ash altered and Porphyritic Andesite	Shallow translational failures, and channelised debris flows along stream paths.
U	Barre de L'isle (top/middle)	Top of the Barre de L'isle and some plateaued areas and lack of steep slopes. Generally farmed.	Uppermost catchments of both watersheds 33 and 6.	Andesite Ash altered and… And Porphyritic Andesite	Deeper more complex slow moving slides have occurred in the past here. Also some channelised debris flows on the lower slopes after Hurricane Tomas.
V	Barre de L'isle (west)	Western side of the Barre de L'isle and the road drops down via a number of hairpin bends some areas are farmed and vegetation is not as dense tropical forest as on the western side. Slopes angles vary but generally are generally greater than 30 degrees. Gully's / tributary slopes can be steeper up to 60 degrees.	Upper to middle catchments of watershed 6.	Andesite Ash altered And Porphyritic Andesite	On the tributary side slopes, translational failures can occur displacing the road. Shallow translational movements also observed in the superficial materials and cut slopes. Channelised flow along gullies has occurred.
W	The slopes around Grand Rivier	This zone comprises the side slopes in the lower eastern side of the Barre de L'isle. Generally vegetated with sub-tropical trees and shrubs.	Middle catchment of watershed 6.	Andesite Ash altered And Porphyritic Andesite	Localised shallow translational slides within superficial deposits.
X	Castries (top of The Morne)	Plateau of the Morne Area of flatter ground at the top of the Morne highway. Houses constructed here, no bedrock observed.	Upper catchment of watershed 34	Altered Andesite Porphyry and Basalt Agglomerate.	No slope stability issues noted here.
XX	Castries (the Morne North)	Northern slope of the Morne slopes northwards from the plateau. There are more benches on this side of the Morne, possibly a function of the increased number of dwellings. Drainage channels mainly run towards the NW.	Upper catchment of watershed 34	Basalt Agglomerate, Andesite and Unclassified.	Complex failures, rotational failures and translational failures observed.
Y	Castries (Castries and the north)	Castries and the North- This is a large zone covering the flatter densely populated areas of Castries and leading to Gros Islet. The area has an increased number of dwellings, farms and hotels in it than other areas. The vegetation therefore is sparse relative to the rest of the island, with sub-tropical plants growing where possible. In the very north, the vegetation growth becomes semi-arid with gently convex slopes. The distinction between these has not been made owing to the lack of effect it has on the road. Slope angles do not generally exceed 35 degrees unless it is a cut slope.	Lower catchments of watersheds 34, 35, 36 and 37.	Basalt Agglomerate and Basalt Agglomerate Andesite Tuff	No major slope instabilities noted here. Minor rockfall from rock cuttings and minor localised sub-rotational slides on small roadside embankments related to drainage.
Z	Castries (the Morne South)	Southern side of the Morne highway the road is generally on sidelong ground. There is sparse vegetation due to the number of dwellings dwellings. Slope angles are generally between 20 to 35 degrees with some slopes up to 45 degrees. Drainage channels run towards the south west feeding the Cul de Sac River Valley	Middle portion of watershed 33 and possibly the upper catchment of watershed 34	Altered Andesite Porphyry	Shallow translational slope failures in the superficial materials related to drainage concentration along relict valleys and on over steepened slopes.

1 - Watershed zones taken from the 1998 St Lucia watershed and environmental project report. 2 - Geology data taken from the GIS geological map. 3 - We have only considered Watersheds 6 to 36. Others were not on the Primary Road Network. 4 - Vegetation descriptions for areas A, B, C, H are amended from Brown and Clark (1995). 5 - There are 2 sections in the Cul de Sac Valley which are given a risk rating of 13, these are not landslides, but slope stability issues related to erosion of the river causing instability of the road embankment.

5.3.4 Air photo interpretation and fieldwork analysis

The initial air photo interpretation identified a total of 763 features and most of these were considered to be translational landslides with few units. The fieldwork generally reduced / refined the size of those features seen in the aerial photograph interpretation. A number of features were deleted as the initial air photo interpretation picked out small agricultural fields on slopes rather than locations of slope failures. There were also some failures identified which were too far from the road to cause any impact on it. In these cases the features were removed from the dataset. Many of the clearly identified backscarps on the air photo interpretation were re-vegetated when visited in the field. Some new features were added during the ground truthing, especially along the Barre de L'Isle, where vegetation cover and the slow moving nature of the complex slides were not captured in the air photo interpretation. Not all features identified in the air photo interpretation were visited during the ground truthing due to access and visual constraints such as vegetation cover. These were noted in the GIS database and left in the inventory if they were considered to have a potential impact on the road. The fieldwork reduced the features identified to a total of 570 features. We did not distinguish between first time slides or reactivations of existing slides unless these were particularly obvious.

Table 5.4 presents the ranges and averages for each of the landslide types of failure, against the areas, activity, age and confidence, as derived from the project GIS.

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Table 5.4: Fieldwork analysis of landslide type vs. activity, age, area and confidence.

Landslide feature type	Total number of landslide features (% of all features identified)	Confidence with the assessment		Activity – number of landslide units		Relative Age - Number of landslide units			Area (m2)		
		Good / Certain	Moderate / Poor	Active	Stable	Historic	Old	Young	maximum	minimum	average
Rockfall / Topple	190 (33%)	142	48	162 (85%)	28 (15%)	1	16	173	7,469	17	829
Slide, Rotational, few units	18 (3%)	3	15	4 (22%)	14 (78%)	11	5	2	66,221	141	11,546
Slide, Rotational, many units	11 (2%)	2	9	6 (55%)	5 (45%)	1	6	4	37,458	97	5,947
Slide, Translational, few units	254 (45%)	76	178	74 (29%)	180 (71%)	37	139	78	46,210	22	2,684
Slide Translational, many units	8 (1%)	1	7	4 (50%)	4 (50%)	1	6	1	18,472	374	9,556
Lateral Spread	0 (0%)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Flow	87 (15%)	8	79	25 (29%)	62 (71%)	21	37	29	29,508	18	4,869
Complex	2 (0.4%)	1	1	0 (0%)	2 (100%)	1	1	0	146,621	8,454	n/a

5.3.4.1 Rockfall and topple failures

These have been grouped into one type of movement since the resulting impacts on the primary road network are considered to be the same. In addition, distinguishing between the two would take a more detailed assessment involving rock mass mapping / scan-line discontinuity surveys which is not considered necessary for this stage of the works. Primarily these are rock based failures and they are a minor nuisance over most of the island occurring generally in the cut rock slopes for the primary road network. As was also noted by DeGraff (1980), more rockfall and topple occurrences are noted along the east coast of the island. This may be due to the higher number of bedrock exposures and therefore the higher chance of the road passing through a steep rock slope or cutting. There are other areas with rockfall and topple occurrences such as along the Millennium Highway in Castries where there are large benched cut slopes along the roadside and also along the west coast road where bedrock is exposed on steep sometimes near vertical cut slopes.

Two main mechanisms for rockfall/topple were identified during field mapping. These were:

- failures along discontinuities, including faults, joints, bedding planes, flow boundaries or man-made induced fractures, and
- rockfall / topple related to the composition of the bedrock. It was noted that where the bedrock was a tuff agglomerate or andesite agglomerate with a weaker matrix, the matrix often degraded quicker than the boulders and cobbles of igneous rock and results in sub-rounded boulders and cobbles falling onto the road.

This distinction is particularly visible on the Millennium Highway where rockfall in fieldwork zone L (to the north) comprised of sub-rounded boulders falling/rolling onto the road due to the agglomerate geology of the slopes (see figure 5.4). However, the southern section of the Millennium Highway, suffers from minor rockfall failures due to the discontinuity orientations. Figure 5.5 shows an area where wedge type rockfall failure occurs in the andesite geology due to the intersection of 3 discontinuity planes.

Figure 5.4: The Millennium highway rock slope failure in zone L (north) rockfall type related to the geology.

View approximately SE

Figure 5.5: The Millennium Highway rock slope failure in zone LL (south) rockfall related to discontinuities

View towards the NNE

Table 5.4 shows that rockfall is the second most common type of failure along the primary road network. The average area of a rockfall slope calculated in the GIS is 829m² with the smallest being 17m². The average value is not representative of reality on the island since actual rockfalls are generally only small and localised. However, owing to the scale of mapping rockfall/topple features were not generally individually identified rather a length of rock slope was identified. Rockfall/topple areas shown in the GIS represent areas where rockfall/topple failures occur, rather than individual failures. Most areas were noted in the field to be <10m³ of rockfall / topple material visibly affecting the road. Rockfall / topple areas were mostly identified as being young. Generally only young / recently active rockfall / topple areas are noted in the field since the debris is relatively easy to clear off the roads and often no trace is left. Areas where there were large potholes in the road considered to be associated with boulder fall were identified as being ‘old’. This often occurs in cut slope agglomerate outcrops, for example along parts of the road north of Soufriere. Generally where rockfall does affect the road pavement, the damage is repaired relatively quickly. Therefore the frequency and potentially the location of these events may be masked by the repairs.

5.3.4.2 Rotational failures

Rotational failures were mostly observed to occur along the Barre de L’Isle and in locations where the residual soils are deeper. This may be a function of the geology as over 80% of the Barre de L’Isle road sections are shown in the geological map to comprise agglomerate bedrock geology.

A total of 18 rotational slides with few units were identified in the ground truthing which equates to only 3% of all landslides identified. Of these, the areas ranged between 141m² and 66,221m², with an average area of 11,546m². This average area is much more than for landslide flows and translational slides. Some of the largest rotational slides are related to sea cliff erosion and are areas which are currently being undermined by the sea, however often these are quite far from the road and are not likely to impact on the primary road network in the near future. Generally, the rotational slides observed are small localised ‘slumps’ comprising debris or soil. They were identified due to the back tilted vegetation, back tilted benches and a rounded bowl shaped backscarp area. It is considered possible some of the translational slides may have a component of rotation within them in the upper slopes of the Barre de L’Isle, where the residual soils appear to be deeper. The confidences ratings given are mostly moderate or poor, indicating lack of certainty even when ground truthing of the extent and physical location of these landslides. This is in part due to them being quickly obscured by rapid vegetation growth.

5.3.4.3 Translational failures

Table 5.4 shows that the main type of failure observed in St Lucia during the fieldwork is planar translational failures, with a total of 262 individual features in the ground truth mapping. This is 72 fewer than the original air photo interpretation because some slides noted in the air photograph interpretation were too far from the road to be an impact and so were removed from the dataset (i.e. were in a different valley) also in some locations farmed fields were mistaken for translational scarps slopes. More recent slides not visible on the older aerial photographs that occurred following Hurricane Tomas were added. It should be noted that distinguishing between rotational and translational slides in the air photo interpretation was difficult as the most visible and distinguishable portion of the slide is the scarp and often the difference between these is difficult to pick out without field mapping of recent failures.

Translational landslides are found island-wide and are the most common type observed being a total of 46% of all the landslide types. They are more numerous in the area of the Barre de L'Isle, on the West Coast road and around Castries, but smaller localised translational slides are also mapped between the Rousseau Valley and Anse La Raye, and also occasionally minor slides are identified near the East Coast Road.

The slides comprised a mixture of vegetation debris, rock and soil. They are either localised shallow failures in residual soils which result in debris on the road such as the translational slips as shown in Figure 5.6, or they can be initiated from the road level so that the backscarp is on the road edge, resulting in carriageway loss. This is observed regularly at the top of the Barre de L'Isle (see Figure 5.7). Generally translational slides seem to occur on the steep slopes with thin soil/vegetation cover or on slopes with relatively shallow residual soil at the change in weathering grade from residual soil to highly weathered rock. The predominantly bedrock slopes on the east coast have far fewer translational landslides as there is little soil coverage and lower angle slopes. Also the low angle slopes of the south lowlands (zone P) also have fewer landslides generally.

Figure 5.6: Translational slides on the west of the Barre de L'Isle resulting in debris on the road

Source: Photograph taken facing approximately NW

Figure 5.7: translational slide on top of the Barre de L'Isle showing loss of carriageway

Source: Photograph taken facing approximately NW

Based on the GIS database, the plan area the translational slides ranged between 22m² and 46,210m² with an average of 2,684m² for slide with few units. Of the 262 translational slides identified, 8 were denoted as comprising many units and their minimum area is 374m², larger than translational slides of few units. Translational slides were generally shallow features with the upper residual soils forming the bulk of the landslide material. The confidence rating given for the translational landslides is 29% good / certain. The number of active slides was totalled at 29% for the 'few units' and 50% for the 'many units'. This may be the reason for the lack of confidence as when the slides are a less active they are more difficult to discern from ongoing erosion features. Often the volume of material resulting from these slides was minimal since they were just shallow slips of vegetation and shallow soil from a road cutting for example. In some cases translational slides may coalesce at the head catchment of a tributary / gully. If this is triggered by extreme rainfall conditions, then the combined slide masses may provide enough sediment supply to cause debris / mud flow to develop in the lower channels.

5.3.4.4 Lateral spread

No lateral spread failures were noted along the primary road network in St Lucia. Spreading requires generally low angle slopes where extension of a cohesive soil or rock mass is combined with general subsidence of the fractured mass into softer underlying material (Lee and Jones, 2004). This type of failure is only considered likely to occur potentially on coastal planes, in river valleys, or in the south or south eastern parts of the island or where the slopes are typically shallow.

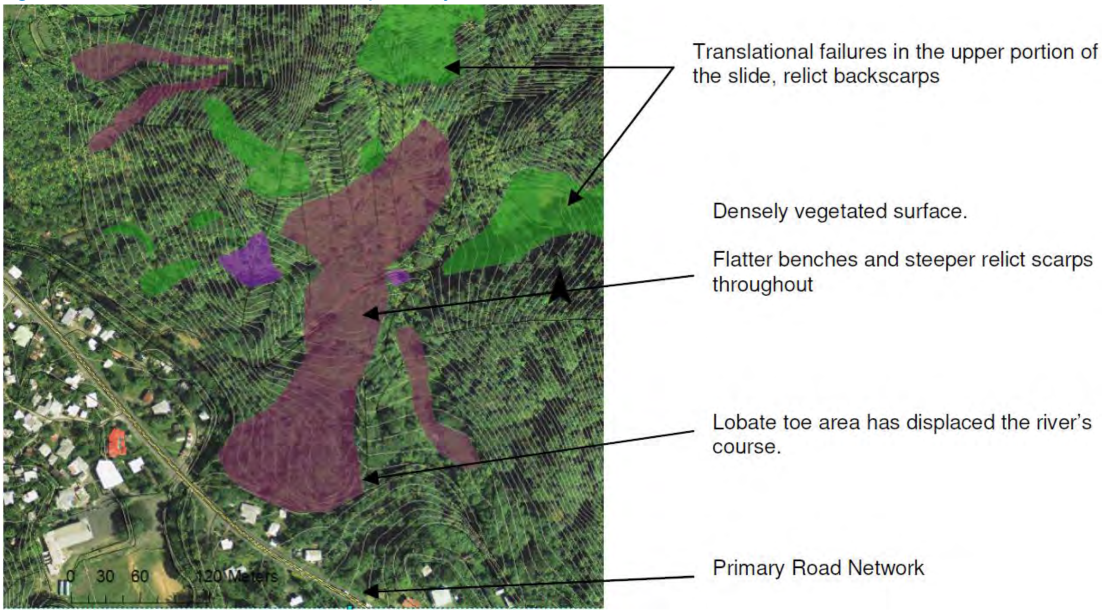
5.3.4.5 Flows

A total of 194 possible flow type failures were identified during the air photograph interpretation, this was reduced to 87 following the fieldwork ground truthing assessment. The size of the flows in plan varied between 18m² and 29,508m², with an average of nearly 5000m². These areas typically include both source and deposition areas. This wide spatial range is considered to be related to the volume of failed material and the downslope momentum of that material. For example, if the flow is constrained in a narrow and/or steep river valley and travels a significant distance, the plan area of the flow may be much bigger than other types of landslides. There does not appear to be a relationship between the geology and the locations of flows.

71% of the flows identified were considered to be currently stable. 67% of the flows identified were considered to be historic or old. This may be an under estimate since not all historic or old flows would be identified owing to the rapid re-vegetation of ground surfaces following landslide events. Also since flows often follow channels / stream valleys, their deposited materials are likely to be subsequently eroded.

Flows were generally noted to comprise a mixture of soil and rock and were classified as debris flows. In Zone D (Cul de Sac to Ravine Poisson and the base of the Barre de L'Isle), some flows are described as 'relict mud flows' indicating less rock content and generally occupying areas within the lower watersheds, often following pre-existing surface water flow paths such as tributary valleys. There is also evidence of an historic debris flow in Zone D as presented in Figure 5.8. This particular flow may be a relic of the large Ravine Poisson landslide that occurred in November 1938 and is reported to have caused 96 fatalities (NEMO, 2010). The flow material comprised a mixture of soil and large boulders, the toe appears to have displaced the river course. The backscarp currently shows signs of small incipient failures, likely related to farming and not an indicator that the bulk of the debris material is active. Therefore, this is considered to be currently stable and not a risk to the road network. This area has been grouped to form Fieldwork Zone D (Cul de Sac to Ravine Poisson and the base of the Barre de L'Isle).

Figure 5.8: Historic debris flow – possibly related to the Ravine Poisson slides that occurred in 1938



Source: Extract from project GIS database. Flows are shown in brown, translational failures in green and rockfall / topple areas in purple. The centre coordinates for the image are at 511226, 1539905 (BWI grid 1955). The contours are at 5m intervals.

Generally the flows identified in the air photo interpretation along the Barre de L'Isle (zones T, U and V) were situated in the lower slopes of channelised streams and gullies. They are likely to have originated in the head catchments of streams and gullies as several translational failures that coalesced to form a flow. On the West Coast more flows were observed some being recently active.

One major flow that affected the primary road network during Hurricane Tomas was at Colombette between Canaries and Soufriere (Figure 5.9). The entire flow, including the deposition area, is estimated to be 450m long by 150m wide and forms an area of approximately 67,500m². This particular slide was a first time slide and was not distinguishable in the 2009 aerial photographs. As a result, this area of the road network is grouped into Zone A (West Coast road between Soufriere and Canaries), as there may be potential for another similar debris slide in this section under similar circumstances as Hurricane Tomas. The section of the road immediately north of the Colombette slide is considered particularly susceptible and small failures have already occurred. Some of the existing slopes on the Colombette slide are currently not in equilibrium, evidenced by localised rockfalls and debris on the road and the lack of vegetation growth. It is considered that further sections of this slide may fail again, therefore, the slide is being considered as part of the preliminary design works for the study.

Figure 5.9: Recent debris flow - Colombette

Photograph taken facing approximately east,

5.3.4.6 Complex failures

Two complex failures were identified during the ground truthing. One, known as Site 1, is located on the top of the Barre de L'Isle in fieldwork Zone U and is considered to be a slow moving slip within the thick residual soil, possibly that responds to porewater pressures within a sand layer. The second is located in Castries and this area will be subject to further more detailed geomorphological mapping.

6 Vulnerability analysis

Vulnerability is the degree of loss to a given 'element' or set of 'elements', such as the road, pedestrians, vehicle users or other infrastructure, resulting from the occurrence of the landsliding event. Typically expressed on a scale from 0 (no damage) to 1 (total loss) (Varnes, 1984). Vulnerability is a measure of the primary road network's susceptibility to frequency of landslide events and the style of event.

For the purpose of the study, vulnerability is accounted for in two ways:
- within the risk matrix in terms of severity of damage/loss to a section of the road as discussed in Section 7; and
- within zones around the primary road network for which specific vulnerability levels/weightings have been determined based on subjective assessments of traffic and alternative routes as discussed below.

A lack of quantitative data means that a quantitative assessment of the primary road network's vulnerability is not possible. To enable a quantitative assessment to be completed at least the following information would be required:
- traffic flows;
- delay times caused by landslides/rockfalls;
- accident rates caused by landslides/rockfalls; and
- location/date of landslides/rockfalls along the road network.

As part of the capacity strengthening plan, recommendations will be made and proformas developed to record this information to allow more detailed assessments of vulnerability to be completed in the future.

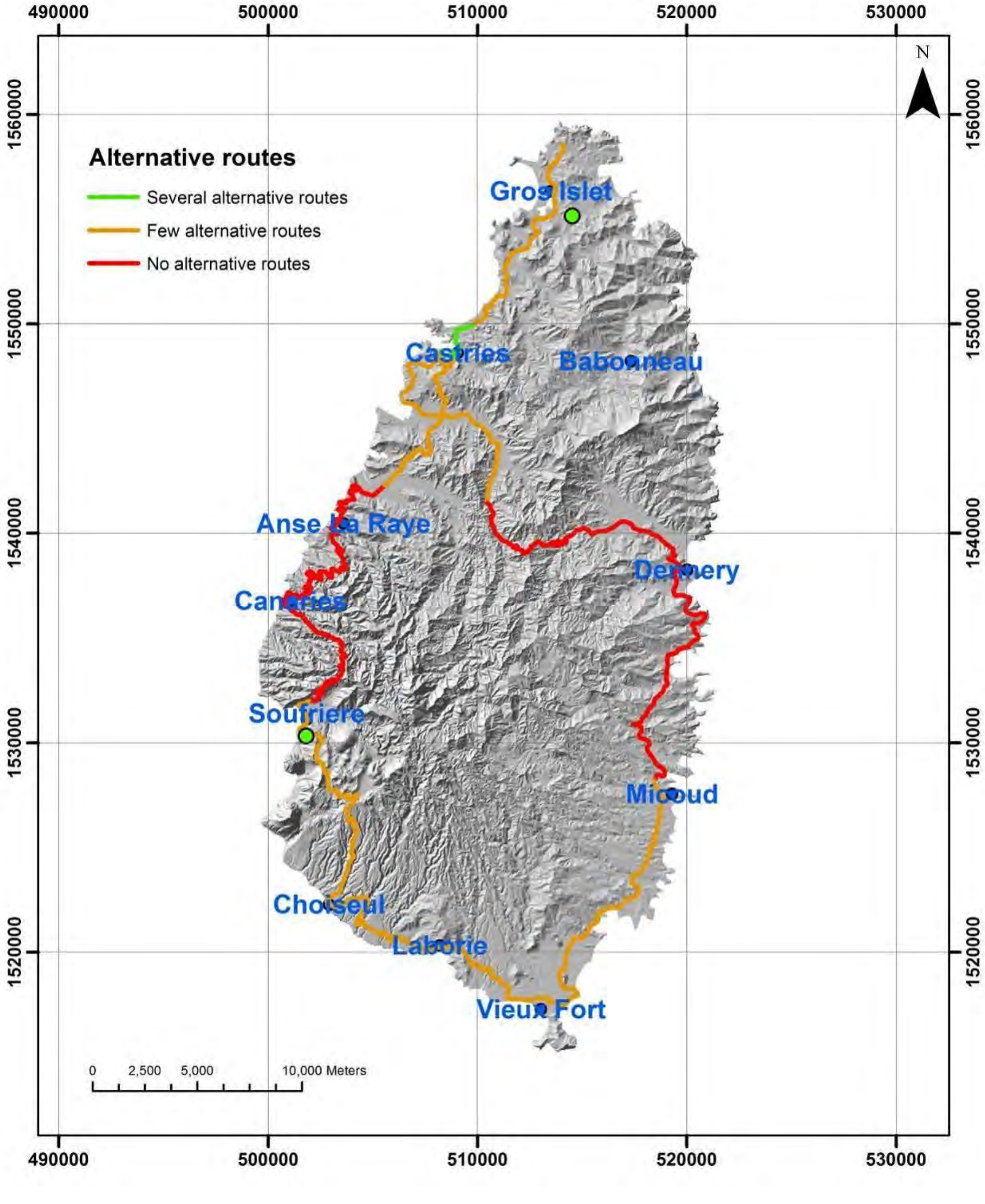
Bunce et al. (1997) show how a quantitative risk assessment can be completed for a rock cutting. Similar assessments could be completed for high risk cuttings or landslide prone slopes along the primary road network once sufficient data has been collected.

6.1 Network analysis of alternative routes

An analysis of the primary road network and viable alternative routes was completed in conjunction with the Ministry zone engineers in February 2013. The primary road and connecting secondary roads were reviewed to determine the locations along the primary road where there are either:
- several alternative routes;
- few alternative routes; or
- no alternative routes.

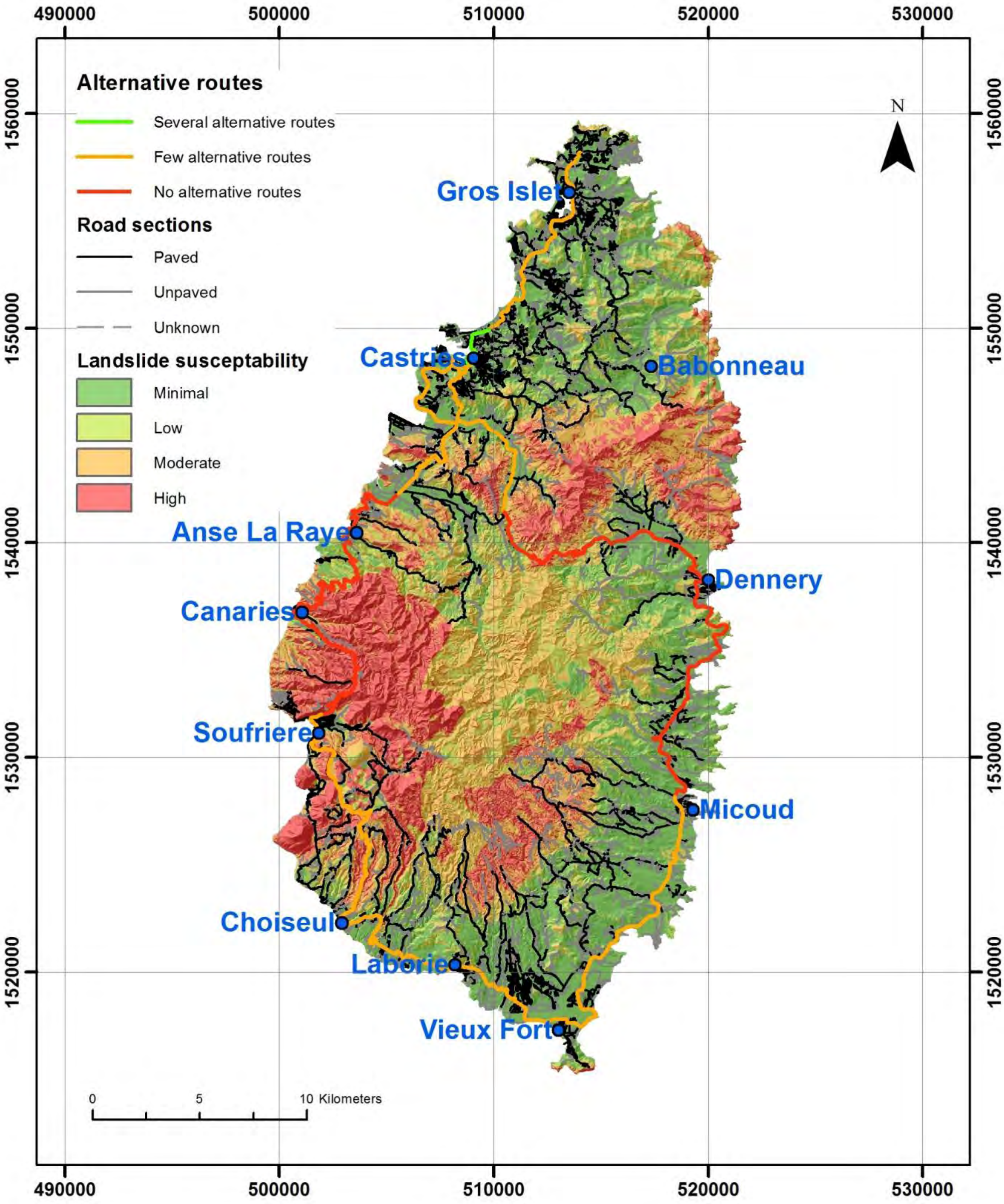
A plan showing the analysis is presented as Figure 6.1.

Figure 6.1: Primary road network vulnerability with respect to alternative routes



The analysis is basic and assumes that the alternative routes are viable alternatives when the primary road network has been blocked, and have not been blocked by landslides themselves. Comparing the alternative routes map with the regional scale landslide susceptibility map this appears to be a reasonable assumption in Castries, north of Castries, on the East Coast road and in the south where landslide susceptibility is shown as 'low' to 'medium'. However, south of Castries, and on the West Coast Road, landslide susceptibility is 'low' to 'high', therefore the secondary and tertiary road networks in these locations are more likely to be affected by landslides than in the areas previously mentioned.

Figure 6.2: Alternative routes and the secondary and tertiary road network overlain on the landslide susceptibility map



6.2 Traffic flow

Based on experience of the traffic during a 10-week period on the island late January to the end of March 2013 and discussion with the Ministry and regular road users, a subjective assessment of the traffic has been made. The subjective assessment has three categories of traffic flow:

- high flow – considered to be Castries and associated commuter zones where traffic jams occur Monday to Friday;
- moderate flow – considered to be outside Castries but including popular commuting belts and tourist routes; and
- low flow – considered to be beyond regular tourist routes and commuting routes to Castries.

Average annual daily traffic (AADT) values for 2002 were provided by the GoSL for the network, excluding the west coast south of Soufriere, on the 5th June 2013. The values generally agree with the subjective assessment made at draft issue. However, for the final feasibility report the subjective traffic flow has been amended to take the AADT data into account as follows:

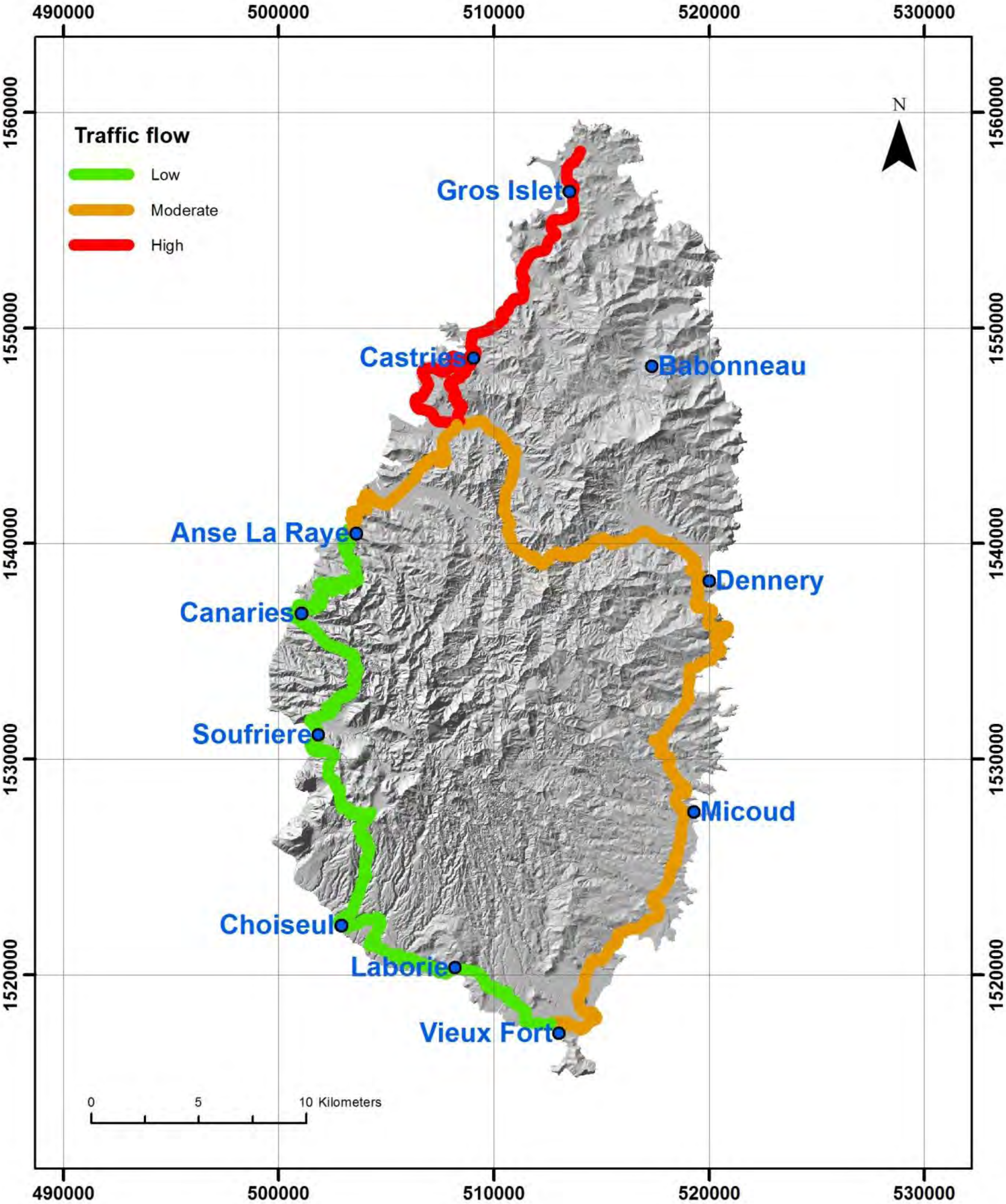
- from Cap Estate to Union the subjective assessment has been increased to 'high'; and
- the location of the change from 'moderate' to 'low' flow on the West Coast Road has been changed from Soufriere to Anse La Raye.

A summary of the assessment is presented in Table 6.1 and a plan showing the zones is presented as Figure 6.3.

Table 6.1: Subjective traffic flow analysis summary

Location	Subjective traffic flow	Ranking
Cap Estate – Gros Islet / Edge Water	High (formerly low)	1
Gros Islet / Edge Water – Union	High (formerly moderate)	1
Union – Cul De Sac	High	1
Cul De Sac – Vieux Fort (East Coast Road)	Moderate	2
Cul De Sac – Anse La Raye	Moderate	2
Anse La Raye – Vieux Fort	Low	3

Figure 6.3: Plan showing subjective traffic flow summary



6.3 Essential facilities

Hospitals and schools along the primary road network are typically located in population centres. Therefore, a temporary break in the network will typically mean longer travel time for persons not within the population centre.

The facilities have not been taken into account as part of the subjective network vulnerability assessment.

6.4 Subjective network vulnerability assessment

The alternative route categories and traffic flow categories have been created as separate layers within the GIS environment and assigned a number as summarised in Table 6.2.

Table 6.2: Alternative route and traffic flow categories

Alternative route category	Traffic flow category	Number assigned
Several alternative routes	Low flow	1
Few alternative routes	Moderate flow	2
No alternative routes	High flow	3

Within the GIS, the numbers assigned to each of the layers have been multiplied to obtain a relative vulnerability number for sections of the primary road network. A matrix showing the resultant numbers is presented as Table 6.3.

Table 6.3: Vulnerability matrix

<table>
<tr><th colspan="2" rowspan="2">Vulnerability matrix</th><th colspan="3">Traffic flow category</th></tr>
<tr><th>Low flow</th><th>Moderate flow</th><th>High flow</th></tr>
<tr><th rowspan="3">Alternative route category</th><td>Several alternative routes</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td>Few alternative routes</td><td>2</td><td>4</td><td>6</td></tr>
<tr><td>No alternative routes</td><td>3</td><td>6</td><td>9</td></tr>
</table>

This information has also been mapped within the GIS. The resultant map is presented as Figure 6.4 and a summary of the vulnerability zones is presented as Table 6.4.

Figure 6.4: Subjective vulnerability assessment

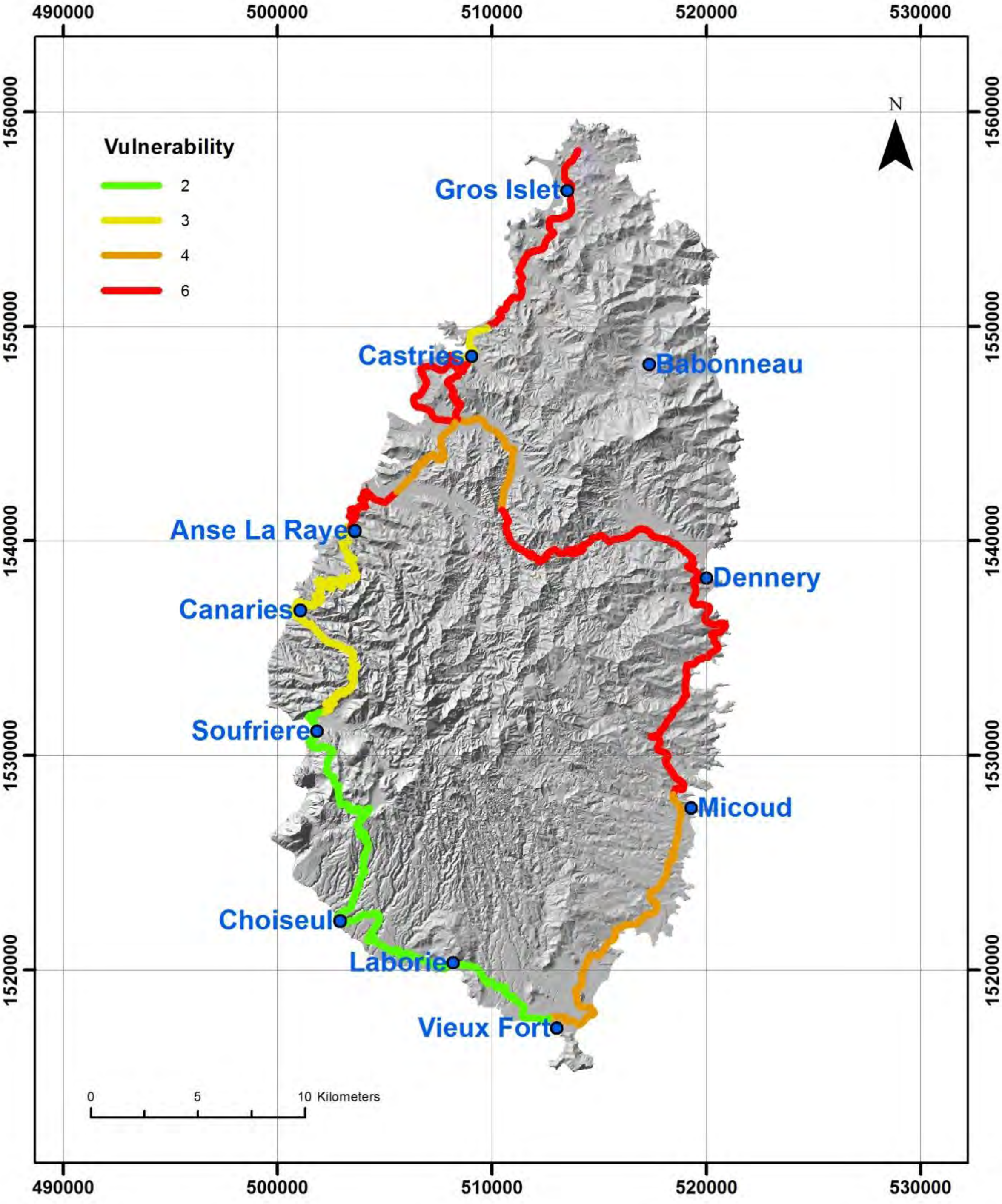


Table 6.4: Summary of vulnerability zones

Zone	From (CH m)	To (CH m)	Vulnerability level
1	Cap Estate (0)	Vigie (11550)	6
2	Vigie (11950)	Morne Road / Bridge Street (14180) And La Toc / Millennium Highway roundabout	3
3	Morne Road / Bridge Street (14180) And La Toc / Millennium Highway roundabout	Cul de Sac (19035 / 135925)	6
4	Cul de Sac (19035)	Rosseau Valley (24690)	4
5	Rosseau Valley (24690)	Anse La Raye (30095)	6
6	Anse La Raye (30095)	Fond Bernier (51975)	3
7	Fond Bernier (54610)	Vieux Fort / Laborie Highway (82755)	2
8	Vieux Fort / Laborie Highway (82755)	Volet (99285)	4
9	Volet (99285)	Bexon (129585)	6
10	Bexon (129585)	Cul de Sac (135925)	4

7 Risk assessment

All societies have limited resources available to minimise natural hazards. Therefore, some risk must be accepted. Bunce et al. (1997) state that if a risk is lower than that accepted by society, the expenditure of resources to reduce that risk may not be appropriate. Alternatively, if a risk is higher than the accepted level, we require a method of assessing how best to allocate effort to achieve the greatest benefit.

The aim of the risk assessment process is to categorise the slopes of the primary road network in terms of landslide risk to the road. This will allow an understanding of the variation of landslide risk to the network to be developed, assist the process of determining a level of acceptable risk, and allow network management to be improved and targeted remedial works to be completed.

Two levels of risk assessment are discussed:

- a network scale probability-loss analysis; and
- a site scale approach using a custom developed risk matrix.

7.1 Risk definitions

The following definitions of hazard and risk are used throughout the report.

Hazard: The probability of occurrence of a damaging landslide within a specified area over a given period of time (Varnes, 1984). **Within the risk matrix this is considered under the event frequency.**

Element at Risk: Meaning the population, buildings and engineering works, economic activities, public services utilities and infrastructure in the area potentially affected by landslides (IUGS Working Group on Landslides, 1997). **For the purpose of the study, the main element at risk is considered to be the primary road network and structures supporting the network.**

Vulnerability: The degree of loss to a given 'element' or set of 'elements' resulting from the occurrence of the landsliding event. Typically expressed on a scale from 0 (no damage) to 1 (total loss) (Varnes, 1984). **For the purpose of the study, vulnerability is accounted for in two ways:**

a. **Within the risk matrix in terms of severity of damage/loss to a section of the road; and**
b. **Within zones around the primary road network for which specific vulnerability levels/weightings have been determined as discussed in Section 6.**

Specific Risk: The expected degree of loss due to a particular magnitude of landslide. It may be expressed by the product of hazard and vulnerability (Varnes, 1984). **This is the number derived from the project risk matrix. For the purposes of the study this is a qualitative assessment.**

Total Risk:	The expected number of lives lost, persons injured, damage to property or disruption to economic activity caused by a landslide. It is the produce of specific risk and elements at risk (Varnes, 1984). **For the purposes of the study this is the ranking process that is carried out for each of the vulnerability zones.**
Acceptable risk:	A risk for which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risk justifiable (IUGS Working Group on Landslides, 1997).
ALARP (as low as reasonably practicable):	The risk is regarded as tolerable only if risk reduction is impracticable or if the cost is grossly disproportionate to the improvement gained. This involves determining (HSE, 1992): c. whether a given risk is so great or the outcome so unacceptable that it must be refused altogether; or d. whether the risk is, or has been made, so small that no further precaution is necessary; or e. if a risk falls between these two states, that it has been reduced to the lowest level practicable, bearing in mind the benefits flowing from its acceptance and taking into account the costs of any further reduction. The injunction laid down in UK safety law is that any risk must be reduced so far as reasonably practicable, or to a level which is 'as low as reasonably practicable'.

7.2 Network scale risk assessment

The financial impact of landsliding on the primary road network can be assessed using probability-loss analysis. This analysis requires information on the likelihood of a particular size/intensity of event occurring, in this case a rainfall event.

The analysis also requires an estimation of the costs associated with such an event. At the time of writing, no information on annual maintenance costs or event clean-up and reconstruction costs has been made available by the Ministry. Therefore, accurate probability/loss analysis is not possible. To allow analysis to be completed, the Ministry is required to provide the information presented in Table 7.1.

Table 7.1: Information required for basic probability-loss analysis

Event	Ministry actions required	Other sources
'Normal' year (1 in 1 year)	Ministry to provide typical annual primary road maintenance budget with respect to landslides – to include broken down costs for clearing debris, drainage maintenance, repairing/repaving roads damaged by landslides, reconstructing roads damaged by landslides	None known
Intense rain	Ministry to provide costs of clearing debris and reinstating roads following	None known

Event	Ministry actions required	Other sources
storm (1 in 10 years)	significant storm event	
Tropical storm Debbie (1 in 50 years)	Ministry to provide costs of clearing debris and reinstating roads following major tropical storm	None known
Hurricane Tomas (<1 in 200 years)	If Ministry agrees with ECLAC estimate, no further information required.	Caused EC$121 million (US$45M) damage to road network (ECLAC, 2011)

It may not be possible for the government to provide this information. If the information is not available, it may be possible for the Ministry to complete this analysis at a later stage.

7.3 Site specific risk assessment

7.3.1 Development of the risk matrix

Landslide risk to the primary road network has been assessed using a matrix approach developed specifically for the project with the assistance of Dr Mark Lee of Ebor Geoscience Limited. The matrix was developed during the landslide ground truthing process. The matrix is intended to be simple to allow the assessment process to be repeated by engineers with relatively minimal training and supervision.

The matrix approach has been used to ‘score’ the slopes adjacent to the primary road network based on the frequency of slope failure (the hazard) and the severity of damage to the road (the vulnerability).

More quantitative risk assessments, such as the process used for assessing landslide risk in Hong Kong, are not currently possible in Saint Lucia. This style of risk assessment is reliant on analysis of a large database of failures to derive information such as volume of failure, expected width of failure, travel distance of debris and annual failure frequency for different types of slope. In Hong Kong a database or this information exists from 1984 – present. This database of information does not currently exist in Saint Lucia. However, as part of the capacity building part of the study, standard proformas to allow recording of this information about failures will be developed to enable this information required to develop quantitative risk assessment processes to be built up. Given the similar conditions on other nearby Caribbean islands, it may be appropriate to extend this to a regional methodology to allow a large database to be built up relatively rapidly enabling initial quantitative assessments to be made in a shorter timeframe.

7.3.1.1 Frequency (the hazard)

The frequency of slope failure is assessed using two approaches – triggering event frequency and a slope condition assessment. A summary of the rationale behind the assessment is presented as Table 7.2.

Table 7.2: Rationale of slope failure frequency assessment

Class	Trigger	Slope condition	Rationale	Indicative annual probability
1	Event likely to occur during "normal" rain storm event	Event likely to occur in next 1-2 years. Slope in very poor condition and expected to deteriorate	Failure appears imminent and could be triggered by <100mm/day storm	P = 1 (1 in 1 year)
2	Event likely to occur in intense rainstorm event, possibly in combination with earthquake	Event likely to occur in next 5-10 years. Slope in poor condition and expected to deteriorate	Failure expected in short-term and could be triggered by <250mm/day storm	P = 0.2 – 0.1 (1 in 5 to 1 in 10 years)
3	Event likely to occur in a major tropical storm (e.g. Debby), once every 50 to 100 years	Event likely to occur in next 10-50 years. Slope in moderately poor condition and expected to deteriorate	Marginally stable slopes where failure could be triggered by >400mm/day rain storm event (1 event in 50 years at Barre de L'Isle, excluding Hurricane Tomas)	P = 0.1 – 0.02 (1 in 10 to 1 in 50 years)
4	Event likely to occur in prolonged, near-stationary Hurricane event (e.g. Tomas), once every 100+ years	Signs of slope distress, but landslide is conditional on failure of a man-made structure (e.g. retaining wall)	Relatively stable slopes where failure is conditional on exceptional rainfall (>500mm/day rain storm) or retaining wall failure	P = 0.02 – 0.002 (1 in 50 to 1 in 500 years)
5	Event possible, but has no precedent in the historical record	Slope in good condition. Failure might occur in exceptional circumstances	Relatively stable slopes where failure is conditional on a combination of events such as M>7 earthquake, exceptional rainfall (>500mm/day rain storm) and retaining wall failure	P = <0.002 (<1 in 500 years)

The rationale was based on analysis of the available rainfall data as presented in Appendix A and field assessment of some of the structures and slopes around the network in combination with engineering judgement.

Landslides along the primary road network are triggered by rainfall as discussed in Section 2.2. The probability of an earthquake triggering a landslide is so low as to be impractical to take into account during the assessment. The probably of a significant earthquake occurring during a rainfall event has been discussed in Section 3.3 and is considered to be an unprecedented event with an annual probability of occurrence of P<0.002, or less than 1 in 500 years.

7.3.1.2 Severity (the vulnerability)

The severity of damage to the road forms the opposing axis to the matrix. The severity levels were developed based on visual assessment of failures along the primary road network and site visits with the Ministry zone engineers who highlighted their main concerns and on-going maintenance difficulties with the road network. The minutes of these site meetings are included within Appendix F. Five severity levels have been assigned:

- A. Complete loss of road. Road not serviceable.
- B. Loss of outer carriageway fill or deformation/settlement of road surface. Road serviceable, but one-lane traffic flows.

- C. Partial loss of outer carriageway fill. Temporary blockage of 2 carriageways, road out-of-service.
- D. Temporary blockage of inner carriageway. One-lane traffic flows.
- E. Debris on road e.g. rocks or soil. Damage to inner carriageway road drain. Road remains usable.

In the field, an assessment of the severity of a slope failure on the network is made by the engineer. This is based on the experience of the engineer and therefore new assessors should be accompanied by an experienced assessor until they are 'calibrated'. Some guidance on the assessment is provided in Table 7.3.

Table 7.3: Initial guidance on severity level assessment

Feature	What it shows	Typical values
Slope height above road	Extent of debris on the road following failure	Depends on type of failure and slope material. A small cutting (say <2m vertical height) is only likely to put a small amount of debris on the road, whereas a larger cutting (say 5-10m vertical height) is likely to cover one carriageway. If the slope is high (i.e. road on sidelong ground of significant hill) then the failure may original from above the visible cut slope, these situations are likely to cover the both carriageways.
Slope material	Extent of debris on the road following failure	Different materials will fail in different ways and have different travel distances. For example, a rock cut will likely fail as individual boulders or slabs which may stop on impact. However, if they are spherical or fall from a significant height they may roll, bounce or explode on impact spreading debris. Residual soil slopes travel distance will depend on the height of the slope. This table does not take into account the possibility of rainfall spreading debris along the road.
Structure height/width above/below road	Extent of debris on the road / loss of carriageway following failure	Different size structures are supporting different amounts of material. For example, a small retaining wall, say 5m across, is likely to undermine the road less than a larger retaining wall, say 20m across.
Location of cracking in the road	Extent of loss of carriageway following failure	Where the slope below the road is failing, cracking is often visible in the road pavement. If the cracking is near the edge of the pavement it indicates only partial loss of the outer carriageway is likely, whereas if the cracking is near the centreline of the pavement, it indicates loss of the outer carriageway is likely.

Note: Table for guidance only – other indicators of severity of failure exist and are not shown in the table. The assessment should be completed by engineers experienced in this type of assessment. New staff should be trained in the assessment process by those with previous experience to ensure the assessments are comparable.

It is recognised that the damage to the road may not reflect the wider societal damage that may occur as a result of a landslide. Within the matrix the severity does not take several important aspects into account including traffic flows, presence of alternative routes and access to emergency facilities. These are assessed in section 7.3.4 using the vulnerability determined in Section 6.

7.3.2 Risk matrix

A relative risk rating is determined on a matrix comparing the frequency and severity. The risk matrix developed is presented as Figure 7.1.

Uses

The matrix is intended for use on the primary road network of Saint Lucia only. It should be tailored to suit the purpose of the risk assessment if it is to be used on other roads in Saint Lucia. The matrix and assessment are relatively simple to facilitate use by the Ministry. Training in the use of the matrix will be given during the capacity building/training phase of the study. It is considered that a repeat assessment of the entire primary road network should be carried out at approximately 5 year intervals and along selected areas of the network following major tropical storms or hurricanes.

Assessments should be carried out on foot and in pairs. The assessment is not just of the slopes immediately above and below the road, but for the entire slope above and below. Appropriate health and safety precautions should be planned prior to the assessment and implemented during fieldwork.

Limitations

The risk matrix does not define whether an event will occur and it’s impact on society, just the relative likelihood and impact on the road structure at that location. Some high risk slopes may not fail within the timeframes estimated by the visual inspection, and some low risk slopes will fail before expected.

Figure 7.1: Landslide risk matrix developed for Saint Lucia's primary road network

	FREQUENCY					
LANDSLIDE RISK MATRIX FOR SAINT LUCIA'S PRIMARY ROAD NETWORK	Event considered possible, but has no precedent in the historical record	Event likely to occur in prolonged, near-stationary Hurricane event (e.g. Tomas), once every 100+ years	Event likely to occur in a major tropical storm (e.g. Debby), once every 50 to 100 years	Event likely to occur in intense rainstorm event, possibly in combination with earthquake	Event likely to occur during "normal" rain storm event	**Rainfall and/or hurricane triggering events**
SEVERITY LEVEL: Direct Impact on Road. *Notes: outer carriageway is typically constructed of fill. Debris on road may include trees and shrubs*	Slope in good condition. Failure might occur in exceptional circumstances e.g. landslide is conditional on failure of a man-made structure	Mature trees present. Signs of slope distress, but landslide is conditional on failure of a man-made structure (e.g. retaining wall)	Event likely to occur in next 10-50 years. Slope in moderately poor condition and expected to deteriorate	Event likely to occur in next 5-10 years. Slope in poor condition and expected to deteriorate	Event likely to occur in next 1-2 years. Slope in very poor condition and expected to deteriorate	**Slope condition assessment**
A. Complete loss of road. Road not serviceable.	11	16	20	23	25	*Note all Severity Levels include the possibility of fatalities/injury for landslide impact to traffic*
B. Loss of outer carriageway fill or deformation/settlement of road surface. Road serviceable, but one-lane traffic flows.	7	12	17	21	24	
C. Partial loss of outer carriageway fill. Temporary blockage of 2 carriageways, road out-of-service.	4	8	13	18	22	
D. Temporary blockage of inner carriageway. One-lane traffic flows.	2	5	9	14	19	
E. Debris on road e.g. rocks or soil. Damage to inner carriageway road drain. Road remains usable.	1	3	6	10	15	
	P <0.002 (< 1 in 500 years)	P = 0.02 - 0.002 (1 in 50 to 1 in 500 years)	P = 0.1 - 0.02 (1 in 10 to 1 in 50 years)	P = 0.2 - 0.1 (1 in 5 to 1 in 10 years)	P = 1 (1 in 1 year)	**Indicative Annual Probability of Event**
	ANNUAL PROBABILITY					

Decreasing Severity of Damage/Loss

Use both approaches to estimate frequency of slope failure

- High Risk
- Medium Risk
- Low Risk
- Very Low Risk

0 = Negligible Risk

Hatched fill signifies risk level considered 'as low as reasonably practicable'

7.3.2.1 Basis for design rainfall event

The risk assessment approach is an important part of determining what level of risk can be accepted by society, what level of risk is "as low as reasonably practicable", and what level of risk is unacceptable and requires measures to bring that risk to within acceptable levels.

In terms of the primary road network, it will not be practical to design the entire network to withstand rainfall events of the scale of Hurricane Tomas or larger. **Individual structures along the network such as retaining walls and bridges should be designed to the codes and current practice within Saint Lucia.** The drainage of landslide prone watersheds along the road network is being analysed in further detail to further support the design rainfall event recommended.

In terms of the frequency used within the risk matrix, it is not considered viable to design highway drainage for events that are 'considered possible but has no precedent in the historical record' or 'prolonged, near stationary hurricane' events similar to Tomas, i.e. those with a return period less than 1 in 50 years. Risk at these levels is considered to be as low as reasonably practicable for the primary road network.

It is considered that the highway drainage should be designed for "normal" rain storm events and intense rainfall events, i.e. those with a return period of 1 in 10 years or more frequent.

Therefore, the design rainfall event is considered to fall between rainfall return periods of 1 in 10 years and 1 in 50 years. Runoff modelling presented in Appendix A recommends:

- drainage infrastructure should generally be designed for a 20-year return period rainfall intensity;
- a 30-minute duration is appropriate for determining the rainfall intensity;
- the estimated 30-minute 1-in-20 year rainfall intensity is 133mm/hour, considered to be appropriate for use throughout the primary road network; and
- peak flow should be estimated using the Rational formula, with appropriate average curve number.

For information, a comparison of different rainfall return periods used for design of various structures associated with slope stability in other countries is presented in Table 7.4.

Table 7.4: Rainfall return periods used for design in Hong Kong and the UK

Country / facility	Structure	Rainfall return period	Reference
Hong Kong	Drainage	200 years	Geotechnical Manual for Slopes. Jan 2011. Pp. 97
	Soil nails	10 years	Geoguide 7. Guide to soil nail design and construction. March 2008. Pp. 42.
	Retaining walls	Return period to obtain 'worst credible' water conditions on a case by case basis – guidance of 1 in 1000 years where phreatic surface exhibits a storm response	Geoguide 1. Guide to retaining wall design. August 2000. Pp. XX
U.K.	Highway drainage	Intercept and remove rainfall from short duration, high intensity events with return	Design manual for roads and bridges. Volume 4 Geotechnics and drainage.

Country / facility	Structure	Rainfall return period	Reference
		periods of 1 year (for no surcharge of piped systems or road-edge channels) or 5 years for no flooding of the carriageway. Flow rates from natural catchments without defined watercourses should be assessed for design storms with a return period of 75 years. For culverts that convey permanent watercourses beneath roads, the flow rates should be assessed for return periods that can vary between 25 and 100 years depending on the implications of flooding.	Section 2 Drainage. Part 1. HA106/04. Drainage of runoff from natural catchments. Return periods are to prevent/minimise flooding of the road, not specifically for slope stability.

7.3.3 Risk maps

As part of the study a risk assessment of the entire primary road network using the risk matrix approach has been completed. Engineers from the project walked the network assessing the slopes above and below the road. The matrix number assessed was recorded on paper mapping at 1:5000 scale and transferred into a layer within the study GIS. In future, a GIS based system may be possible and this will be discussed further in the capacity strengthening plan.

Location and boundaries of risk units are based on mapping at 1:5000 scale. It is considered accuracy will typically be ±20m. Therefore, some risk zones may need to be truthed prior to specifying locations of further investigations.

The potential risks implied on the map may not affect the whole unit; the map merely indicates that a certain landslide risk may exist within a designated area.

The risk layer is included within the accompanying GIS package included on CD within Appendix D. Printed maps of key areas at 1:5000 scale are presented within Appendix G.

7.3.4 Risk register and summary of results

Table 7.5 presents the risk information for each of the vulnerability categories developed in Section 6 of this report. 290km of risk mapping has been completed along the primary road network, including slopes on either side of the road. 194km (67%) of the slopes are classified as negligible or very low landslide risk, 83km (29%) are classified as low landslide risk, 11km (4%) are classified as medium risk and 0.96km (0.3%) are classified as high landslide risk. Therefore, a relatively small proportion of the primary road network is classified to be medium or high landslide risk.

Table 7.5: Summary of lengths of landslide risk rating assigned to slopes in different vulnerability zones

	Location	Approximate chainage (m)		Ministry zones	Vulnerability level	Kilometers of road slide at noted landslide risk rating																										
		From	To			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total
1	Cap Estate to Vigie	0	11550	1	2	20.87	0.82	0.45	0.14	0.66		0.07				0.04					0.16											23.22
2	Vigie to Morne Road / Bridge Street	11550	14180	1	4	6.13	0.73		0.31	1.09		0.13		0.57				0.14														9.10
3	Morne Road / Bridge Street to Cul de Sac	14180	19035	8A	6	9.24	3.39	0.94	1.93	3.78	0.36	0.76	0.13	0.82	0.14		0.48	0.14	0.50			0.07		0.07		0.29						23.04
4	Cul de Sac to Rosseau Valley	19035	24690	8A	3	5.24	0.18	0.16	1.18	1.04	0.56		0.10	1.47	0.66				0.40	0.04			0.04	0.25			0.05					11.37
5	Rosseau Valley to Anse La Raye	24690	30095	8A	6	5.66	0.71		0.47	2.47	0.03	0.59		0.10	0.09	0.61			0.01	0.11												10.84
6	Anse La Raye to Fond Bernier	30095	51975	7	4	9.65	1.51	0.11	1.82	8.72	1.25	5.94	0.10	5.58	3.35	0.91		0.26	3.13	0.71	0.21		0.05	0.39	0.10			0.06				43.85
7	Fond Bernier to Vieux Fort / Laborie Highway	51975	82755	7 & 6B	6	33.60	2.33	0.02	4.87	8.18	0.45	5.25		2.96	2.23	0.28	0.10		0.99	0.08			0.08	0.14			0.08	0.01				61.65
8	Vieux Fort/Laborie Highway to Volet	82755	99285	6B	4	28.55	1.19		0.89	0.42		2.09																				33.15
9	Volet to Bexon	99285	129585	6B, 6A, 5C & 5B	2	32.84	2.38	0.24	4.91	6.81	0.68	4.55	0.28	3.15	1.76	0.11		0.16	1.83	0.30			0.06	0.13			0.40	0.08				60.66
10	Bexon to Cul de Sac	129585	135925	5A & 4B	4	10.38	0.35					0.77		0.99					0.22													12.70
					Total	162.16	13.58	1.92	16.52	33.18	3.33	20.14	0.61	15.64	8.23	1.95	0.58	0.70	7.08	1.24	0.37	0.07	0.23	0.98	0.10	0.29	0.52	0.15	0.00	0.00	0.00	289.59

Key:

Vulnerability level	6	Higher vulnerability area of network
	4	
	3	
	2	Lower vulnerability area of network
Risk level	(red)	High risk
	(yellow)	Medium risk
	(dark green)	Low risk
	(light green)	Very low risk
	0	Negligible risk

N.b. hatched shading indicates risk levels which are not within the determined design events.

The high and medium risk sections of the primary road network for each vulnerability zone are presented in the following tables.

A section of the network with a higher network vulnerability may be considered more critical to the network function than an area with lower network vulnerability. Therefore, equivalent risk matrix values assigned within a section of the network with higher network vulnerability may be considered to be more important to address than those in an area of lower network vulnerability.

For example, from Cap Estate in the north of the network to Vigie (near the airport), only one 160m section of road was assigned a medium risk value, 15, in the area where a rock cut is very close to the edge of the road where it was considered minor debris is likely to fall on the road on a regular basis. The ministry may consider it more important to address this risk in some way, such as reducing it by netting or making the public more aware with signage, rather than a similar risk level on an area of the network assigned a lower vulnerability.

Based on the available information, the current network assessment is based on traffic and alternative routes only. Therefore, the Ministry will need to decide if it is representative. The Ministry could re-evaluate the vulnerability to account for other conditions (e.g. based on other factors such as proximity to emergency facilities, tourist routes etc.).

Further discussion of appropriate slope stabilisation / management for various risk levels is discussed in Section 9.

Table 7.6: High and medium landslide risk sites in vulnerability zone 1

Risk level	Site location	Approximate chainage	Coordinates
15	A12 Sunny Acres / Choc	9725 - 9820 SB	510,733mE, 1,551,075mN
10	A12 Sunny Acres / Choc	10225 – 10270 SB	510,463mE, 1,550,776mN

Table 7.7: High and medium landslide risk sites in vulnerability zone 3

Risk level	Site location	Approximate chainage	Coordinates
20	Bois Cachet - long stretch on downside below old restaurant	75 – 260 (Bois Cachet)	508,676mE, 1,548,047mN
20	Bois Cachet – lower hairpin below road	330 – 385 (Bois Cachet)	508,641mE, 1,547,930mN
20	Bois Cachet – upper hairpin below road	390 – 445 (Bois Cachet)	508,623mE, 1,547,930mN
18	Ravine Grognette (bottom of Morne Road)	14215 – 14250 SB	508,853mE, 1,548,214mN
18	Morne Road (hairpin north of Government House)	15360 – 15375 NB	508,217mE, 1,548,202mN
16	Bois Cachet - following up from long stretch on downside below old restaurant	260 – 325 (Bois Cachet)	508,663mE, 1,547,921mN
13	Ravine Grognette (bottom of Morne Road)	14180 – 14215 SB	508,863mE, 1,548,249mN
13	Bois Cachet - long stretch on upside below old restaurant	65 – 330 (Bois Cachet)	508,668mE, 1,548,030mN
13	Bois Cachet – lower hairpin above road	325 – 390 (Bois Cachet)	508,632mE, 1,547,925mN
13	Top of the Morne – on the northbound side, north of the bakery	16335 – 16380 NB	508,102mE, 1,547,554mN
13	Goodlands (south side of the Morne) on NB carriageway	17800 – 17855 NB	508,328mE, 1,546,434mN
13	Goodlands (south side of the Morne) on NB carriageway	17885 – 17945 NB	508,409mE, 1,546,447mN
12	Bois Cachet – slope below road above the hairpins	445 – 580 (Bois Cachet)	508,561mE, 1,547,897mN
12	La Toc Road – slope below road on stretch above Bananes Bay	2075 – 2215 SB (La Toc)	507,583mE, 1,548,688mN
11	Morne Road – just south of Ravine Grognette both sides of road	14290 - 14530	508,763mE, 1,548,171mN

Table 7.8: High and medium landslide risk sites in vulnerability zone 4

Risk level	Site location	Approximate chainage	Coordinates
21	Ticolon (north of La Croix Maingot)	20325 - 20370 SB	507,632mE, 1,544,482mN
18	La Croix Maignot – just west of below	21375 - 21410 SB	507,560mE, 1,543,763mN
18	La Croix Maignot – failure by the coke hut at the top	21290 - 21310 SB	507,646mE, 1,543,757mN
18	La Croix Maignot – just east of above	21120 - 21160 SB	507,735mE, 1,543,847mN
18	Marigot	22825 - 22905 SB	506,675mE, 1,543,533mN

Risk level	Site location	Approximate chainage	Coordinates
18	La Perle (near Marigot Bay)	23175 - 23210 SB	506,496mE, 1,543,370mN
17	Ticolon (north of La Croix Maingot) - N of level 21 site	20210 - 20250 SB	507,640mE, 1,544,599mN
13	Ticolon (north of La Crox Maingot) – just south of above	20250 - 20290 SB	507,642mE, 1,544,551mN
13	Ticolon	20500 - 20525 SB	507,645mE, 1,544,339mN
13	Ticolon	20565 - 20625 SB	507,705mE, 1,544,285mN
13	Ticolon	20855 - 20985 NB	507,705mE, 1,543,988mN
13	Ticolon	21005 - 21020 SB	507,790mE, 1,543,957mN
13	La Croix Maignot	21970 - 22099 SB	507,162mE, 1,543,975mN
13	La Croix Maignot	22270 - 22315 SB	506,939mE, 1,543,826mN
13	La Croix Maignot	22400 - 22445 SB	506,902mE, 1,543,756mN

Table 7.9: High and medium landslide risk sites in vulnerability zone 5

Risk level	Site location	Approximate chainage	Coordinates
14	Au Tabor (north of Anse La Raye)	29335 – 29435 SB	503,548mE, 1,541,194mN

Table 7.10: High and medium landslide risk sites in vulnerability zone 6

Risk level	Site location	Approximate chainage	Coordinates
22	Ravine Joseph (north of Anse La Verdure)	35915 - 35940 SB	503,014mE, 1,537,881mN
22	North part of the Colombette landslide	48440 - 48470 SB	503,373mE, 1,533,155mN
19	Anse Galet (south of Anse La Raye)	31230 - 31260 SB	503,071mE, 1,540,171mN
19	Upslope part of Colombette landslide	48495 - 48565 SB	503,367mE, 1,533,100mN
18	Saurot (south of Anse La Raye) – tributary to Anse Cochon river	34395 - 34405 SB	503,696mE, 1,538,321mN
18	Ravine Joseph (north of Anse La Verdure) – associated with a high risk 22	35940 - 36060 SB	502,944mE, 1,537,901mN
18	Ravine Joseph (north of Anse La Verdure) – further west than above site	36180 - 36200 NB	502,836mE, 1,538,046mN
18	Ravine Joseph (north of Anse La Verdure) – further west than above site	36250 - 36275 NB	502,799mE, 1,538,101mN
18	Anse La Verdure (just south of town)	38860 - 38935 NB	501,966mE, 1,537,520mN

Risk level	Site location	Approximate chainage	Coordinates
18	Anse La Verdure – east of above site	39000 - 39030 NB	502,013mE, 1,537,416mN
18	South of Belvadere – near tributary to Mahout river	45975 - 45990 NB	503,527mE, 1,534,742mN
17	Ravine Joseph (north of Anse La Verdue) – associated with high risk 22	35905 - 35960 NB	503,008mE, 1,537,894mN
15	Anse Galet (south of Anse La Raye)	31595 - 31635 NB	503,292mE, 1,539,967mN
15	Near Ravine Joseph (north of Anse La Verdue)	35710 - 35780 SB	503,037mE, 1,538,027mN
14	Au Tabor (north of Anse La Raye)	29335 - 29435 SB	503,548mE, 1,541,194mN
14	North of Ravine Joseph	35030 - 35305 SB	503,267mE, 1,538,204mN
14	North of Ravine Joseph	35610 - 35675 SB	503,021mE, 1,538,114mN
14	West of Ravine Joseph	36150 - 36220 SB	502,833mE, 1,538,030mN
14	West of Ravine Joseph	36450 - 36485 SB	502,620mE, 1,538,172mN
14	Anse La Verdue	37765 - 37805 SB	502,077mE, 1,538,125mN
14	Anse La Verdue	38885 - 38910 SB	501,975mE, 1,537,525mN
14	Belvedere (south of Canaries)	42835 - 42890 NB	501,163mE, 1,536,295mN
14	Belvedere (south of Canaries)	46050 - 46115 SB	503,508mE, 1,534,671mN
14	South of Colombette landslide	49450 - 49505 SB	502,830mE, 1,532,915mN
14	N of Soufriere	50270 - 50305 NB	502,445mE, 1,532,531mN
13	Anse Galet	31390 - 31460 SB	503,226mE, 1,540,090mN
13	Anse Galet	31630 - 31670 SB	503,258mE, 1,539,977mN
13	Anse Galet	31775 - 31790 NB	503,144mE, 1,540,032mN
13	Anse Galet	34405 - 34445 NB	503,689mE, 1,538,297mN
13	Anse La Verdue	37290 - 37340 SB	502,405mE, 1,537,843mN
13	Anse La Verdue	37455 - 37520 SB	502,269mE, 1,537,924mN
13	Anse La Verdue	37805 - 37890 SB	502,024mE, 1,538,160mN
13	Anse La Verdue	39110 - 39210 SB	501,979mE, 1,537,354mN
13	Anse La Verdue	39680 - 39730 NB	501,901mE, 1,537,217mN
13	Canaries	39965 - 40060 SB	501,786mE, 1,537,124mN
13	Canaries	40925 - 41125 SB	501,106mE, 1,537,090mN
13	Belvedere	41910 - 41990 SB	500,726mE, 1,536,808mN

Risk level	Site location	Approximate chainage	Coordinates
13	Belvedere	42025 - 42075 NB	500,664mE, 1,536,800mN
13	Belvedere	43600 - 43630 SB	501,718mE, 1,535,918mN
13	Belvedere	43710 - 43805 SB	501,813mE, 1,535,811mN
13	Belvedere	43835 - 43880 SB	501,880mE, 1,535,745mN
13	Belvedere	45100 - 45195 NB	502,888mE, 1,535,122mN
13	Belvedere	45455 - 45485 NB	503,126mE, 1,534,930mN
13	Belvedere	45900 - 45915 NB	503,479mE, 1,534,783mN
13	Belvedere	45930 - 45965 NB	503,513mE, 1,534,763mN
13	Belvedere	46310 - 46390 SB	503,486mE, 1,534,451mN
13	Belvedere	46390 - 46510 SB	503,463mE, 1,534,369mN
13	Central Forest Reserve	46660 - 46850 SB	503,687mE, 1,534,185mN
13	Central Forest Reserve	46930 - 47190 SB	503,511mE, 1,534,081mN
13	Central Forest Reserve	47190 - 47335 SB	503,566mE, 1,533,915mN
13	North of Colombette	47995 - 48020 SB	503,589mE, 1,533,472mN
13	North of Colombette	48050 - 48065 NB	503,542mE, 1,533,449mN
13	North of Colombette	48060 - 48095 SB	503,551mE, 1,533,430mN
13	North of Colombette	48095 - 48435 SB	503,503mE, 1,533,278mN
13	Morne Lastic	50115 - 50270 NB	502,522mE, 1,532,591mN
13	La Haut	50415 - 50500 NB	502,309mE, 1,532,446mN
13	La Haut	50750 - 50925 SB	502,488mE, 1,532,463mN
13	La Haut	51170 - 51245 NB	502,508mE, 1,532,318mN
13	La Haut	51385 - 51415 NB	502,415mE, 1,532,162mN
13	La Haut	51570 - 51670 NB	502,287mE, 1,532,075mN
12	Belvedere	44370 - 44395 SB	502,231mE, 1,535,377mN
12	Belvedere	44770 - 44810 SB	502,581mE, 1,535,217mN
12	Belvedere	44905 - 44950 SB	502,701mE, 1,535,189mN
12	Belvedere	46510 - 46560 NB	503,521mE, 1,534,314mN
12	Bouton	47705 - 47730 NB	503,416mE, 1,533,672mN
12	Colombette – just north of slide slope below road with retaining wall of unknown condition	48440 - 48470 NB	503,365mE, 1,533,162mN

Risk level	Site location	Approximate chainage	Coordinates
12	Colombette – mass below road	48520 - 48580 NB	503,365mE, 1,533,079mN

Table 7.11: High and medium landslide risk sites in vulnerability zone 7

Risk level	Site location	Approximate chainage	Coordinates
22	Calvaire (south of Soufrière)	53810 - 53815 NB	501,700mE, 1,530,841mN
18	Calvaire (south of Soufrière)	53660 - 53720 NB	501,787mE, 1,530,921mN
18	Choisel (north side)	66995 - 67105 NB	502,826mE, 1,522,493mN
17	Choisel (north side)	67145 - 67220 NB	502,782mE, 1,522,436mN
14	Choisel (north side)	67060 - 67155 SB	502,807mE, 1,522,502mN
13	Calvaire (south of Soufrière)	53625 - 53660 NB	501,821mE, 1,530,941mN
13	Calvaire (south of Soufrière)	53900 - 54010 SB	501,705mE, 1,530,729mN
13	Calvaire (south of Soufrière) -	54170 - 54235 NB	501,480mE, 1,530,666mN
13	Plat Pays	55430 - 55515 SB	502,493mE, 1,530,286mN
13	Plat Pays	55785 - 55810 SB	502,491mE, 1,530,035mN
13	South of Sulphur Springs	56605 - 56640 SB	502,311mE, 1,529,260mN
13	Etangs	59895 - 60020 NB	503,932mE, 1,527,353mN
13	Victoria	60995 - 61115 SB	503,908mE, 1,526,959mN
13	Choisel (north side)	67105 - 67145 NB	502,793mE, 1,522,493mN
13	Choisel (south side)	67470 - 67525 SB	502,849mE, 1,522,285mN
13	Choisel (south side)	67540 - 67555 NB	502,817mE, 1,522,265mN
13	River Doree	69980 - 69995 SB	504,695mE, 1,522,217mN
13	River Doree	70435 - 70460 SB	504,446mE, 1,521,832mN
13	River Doree	70570 - 70595 SB	504,361mE, 1,521,733mN
13	River Doree	71160 - 71330 SB	504,391mE, 1,521,428mN
11	Victoria	61120 - 61220 NB	503,813mE, 1,526,921mN

Table 7.12: High and medium landslide risk sites in vulnerability zone 9

Risk level	Site location	Approximate chainage	Coordinates
22	Tomazo (east of Barre De L'Isle)	122120 - 122145 WB	514,532mE, 1,539,915mN
21	Ravine Poisson	127055 - 127070 EB	511,582mE, 1,539,474mN
21	Ravine Cribiche	126555 - 126580 EB	511,819mE, 1,539,401mN

Risk level	Site location	Approximate chainage	Coordinates
21	Barre De L'Isle (site 1)	124915 - 124975 EB	512,874mE, 1,539,587mN
21	Barre De L'Isle (site 1)	124915 - 124975 WB	512,884mE, 1,539,577mN
21	Barre De L'Isle (sites 2 and 3)	124480 - 124635	513,190mE, 1,539,413mN
18	Thomazo (east of Barre De L'Isle)	122480 - 122510 WB	514,187mE, 1,539,753mN
18	Thomazo (east of Barre De L'Isle)	122215 - 122320 EB	514,370mE, 1,539,856mN
17	Tomazo (east of Barre De L'Isle) N side of hairpin – site6	123725 - 123755 EB	513,937mE, 1,539,623mN
17	Tomazo (east of Barre De L'Isle) S side of hairpin – site7	123645 - 123670 EB	513,978mE, 1,539,586mN
14	Tomazo	122380 - 122420 EB	514,268mE, 1,539,792mN
14	Ravine Cribiche	126380 - 126435 EB	511,936mE, 1,539,322mN
14	Ravine Cribiche	126440 - 126645 WB	511,836mE, 1,539,406mN
13	Mamiku	105800 - 105870 SB	518,921mE, 1,532,643mN
13	Anse Canot	112510 - 112605 NB	520,132mE, 1,536,902mN
13	Anse Canot	113120 - 113160 SB	519,591mE, 1,537,025mN
13	Tomazo (east of Barre De L'Isle) hairpin	123390 - 123645 EB	513,849mE, 1,539,526mN
13	Tomazo (east of Barre De L'Isle) hairpin	123325 - 123520 WB	513,780mE, 1,539,496mN
13	Tomazo (east of Barre De L'Isle) hairpin	123690 - 123725 EB	513,968mE, 1,539,628mN
13	Tomazo (east of Barre De L'Isle) hairpin	123755 - 123875 EB	513,862mE, 1,539,612mN
13	Tomazo (east of Barre De L'Isle) hairpin	123905 - 123945 EB	513,760mE, 1,539,581mN
13	Tomazo (east of Barre De L'Isle) hairpin	123940 - 123970 WB	513,737mE, 1,539,557mN
13	Barre de L'isle	125040 - 125140 EB	512,747mE, 1,539,517mN
13	Barre de L'isle	125215 - 125310 EB	512,624mE, 1,539,411mN
13	Barre de L'isle	125415 - 125530 WB	512,553mE, 1,539,250mN
13	Barre de L'isle	125975 - 126015 WB	512,169mE, 1,539,057mN
13	Barre de L'isle	126165 - 126300 WB	512,024mE, 1,539,205mN
13	Ravine Poisson	126730 - 127155 WB	511,668mE, 1,539,378mN
13	Ravine Poisson	127230 - 127270 WB	511,422mE, 1,539,569mN
12	Barre de L'isle	125360 - 125410 EB	512,545mE, 1,539,339mN
12	Barre de L'isle	125730 - 125765 EB	512,359mE, 1,539,096mN
12	Barre de L'isle	126165 - 126240 EB	512,065mE, 1,539,201mN

Table 7.13: High and medium landslide risk sites in vulnerability zone 10

Risk level	Site location	Approximate chainage	Coordinates
13	Bexon	129990 - 130045 SB	510,492mE, 1,541,828mN
13	Bexon	130435 - 130525 SB	510,533mE, 1,542,290mN
13	Bexon	133930 - 133955 EB	510,131mE, 1,545,122mN
13	Bexon	134175 - 134225 EB	509,902mE, 1,545,232mN

7.3.5 Risk relative to fieldwork zones

The data from the risk assessment has been compared to the fieldwork zones discussed in Section 5.3.3. The length of medium and high risk levels in each fieldwork zone has been calculated within the GIS and the zones ranked in order from those with highest proportions of medium and high risk levels to those with lower proportions of medium and high risk levels.

The results from the fieldwork zones ranking are shown in Table 7.14 and shown in Figure 7.2. Zones were ranked based on the following proportions:

- 1 – Greater than 25% of the roadside was assigned a medium / high risk.
- 2 – Between 10% and 25% of the roadside was assigned a medium / high risk.
- 3 – Between 5% and 10% of the roadside was assigned a medium / high risk.
- 4 – Less than 5% of the roadside was assigned a medium / high risk.
- 5 – No medium or high risks identified in the zone.

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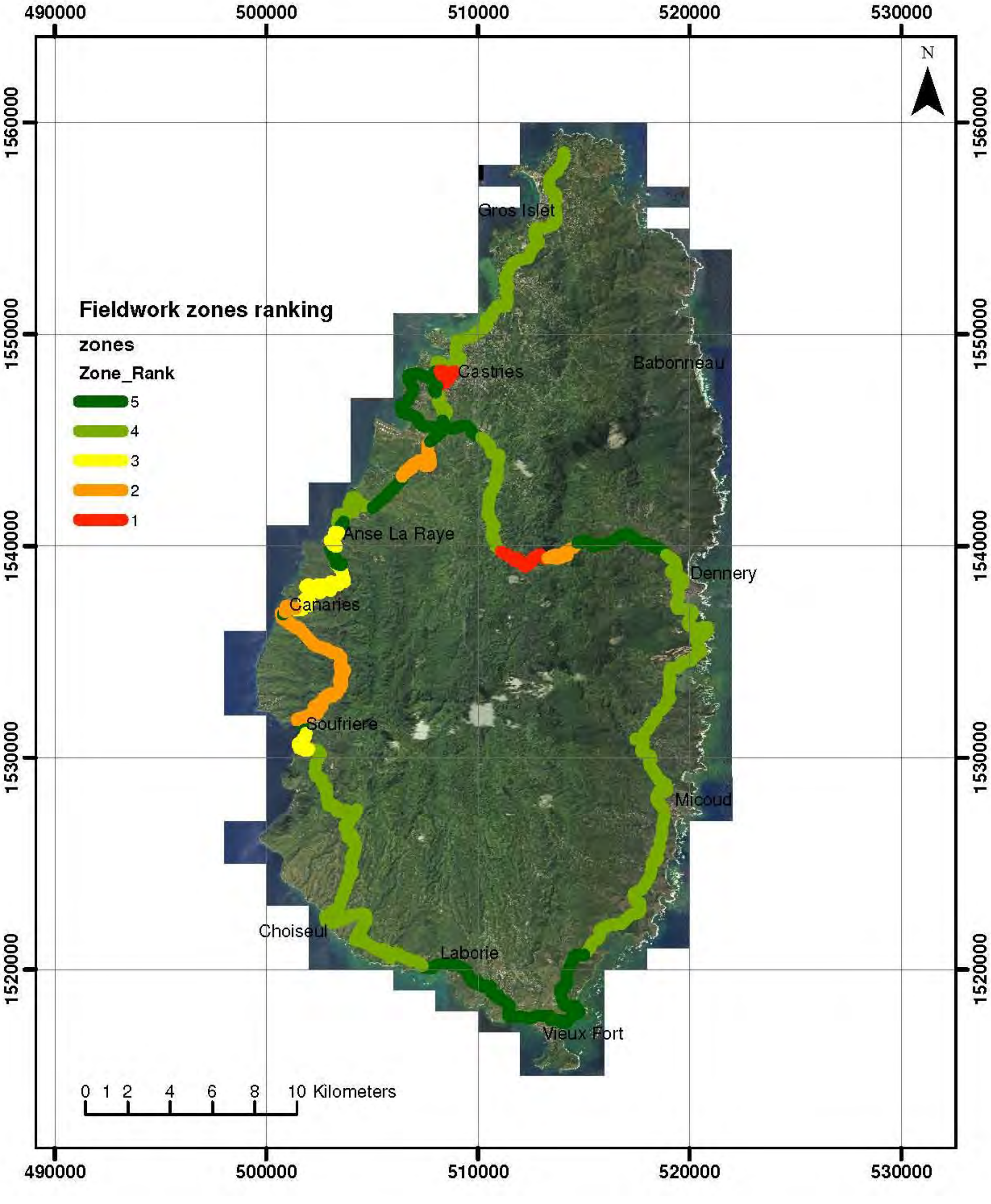
Table 7.14: Ranked fieldwork zones according to the risk.

Zone	Location	Range in risk level recorded along the zone	Typical (modal) risk	Length of medium / high risk within the zone1	Total length of zone	Length of medium / high risk as a % of the length of road2	Zone rank
A	West coast road between Soufriere and Canaries	0 – 22	4 / 8	2936m	10.7km	13.7%	2
B	West coast road between Canaries and Anse La Raye	0 – 22	0 / 6	1467m	7.4km	9.9%	3
C	West coast road south of Anse La Raye	0 – 10	0	0m	1.4km	0%	5
D	Cul de Sac to Ravine Poisson and the base of the Barre de L'Isle	0 – 13	8	167m	6.3km	1.3%	4
E	Immediately south of Anse La Raye	0 – 19	0 / 4	194m	1.7km	5.7%	3
F	North of Anse La Raye and south of the Rosseau Valley	0 – 14	0 / 4	124m	4.1km	1.5%	4
G	Between the Cul de Sac River valley (the Hess oil terminal) and the Rosseau Valley	0 – 21	4	711m	3.5km	10.2%	2
H	North of Canaries	0 – 13	0	202m	1.0km	10.1%	2
I	Along major river valleys and near the coast	0 –13	5	0m	18.6km	0%	5
J	Immediately south of Soufriere town	0 – 22	0 / 6	291m	1.6km	9.1%	3
K	West coast road, south of Soufriere	0 – 13	0 / 4	152m	2.7km	2.8%	4
L	North Millennium Highway - Castries	0 – 6	1	0m	2.2km	0%	5
LL	South Millennium Highway - Castries	0 – 6	0	0m	2.3km	0%	5
M	South coast near the airport	0	0	0m	0.9km	0%	5
N	Laborie	0 – 9	4	21m	2.7km	0%	5
O	Vieux Fort town	0 – 8	0	0m	2.2km	0%	5
P	South coast Choiseul to the edge of Laborie	0 – 13	0 / 4	231m	7.8km	1.5%	4
Q	West coast, from an area south of Soufriere to Choiseul	0 –18	4	729m	10km	3.6%	4
R	East Coast, Dennery to Vieux Fort	0 – 13	0 or 3	189m	27.7km	0.3%	4
S	West of Dennery	0 – 9	4?	0m	0.9km	0%	5
T	Barre de L'isle (east)	0 – 21	8	1385m	2.6km	26.6%	1
U	Barre de L'isle (middle)	0 – 21	21	356m	0.5km	35.6%	1

Zone	Location	Range in risk level recorded along the zone	Typical (modal) risk	Length of medium / high risk within the zone1	Total length of zone	Length of medium / high risk as a % of the length of road2	Zone rank
V	Barre de L'isle (west)	0 – 22	8	932m	2.6km	17.9%	2
W	The slopes around Grand Rivier	0 – 9	0	0m	0.8km	0%	5
X	Top of The Morne Castries	0 – 1	0	0m	0.4km	0%	5
XX	The Morne North Castries	0 – 20	4 or 8	1406m	2.8km	25.1%	1
Y	Castries and the North	0 – 15	0	307m	15.9km	0.9%	4
Z	The Morne South Castries	0 – 13	4	110m	1.8km	3.1%	4

1 This is based on the Mott MacDonald risk assessment (see Section 7) and does not include the unclassified sections that are to be revisited.
2 The risk assessment was done on both sides of the road and therefore the % is calculated from twice the total length of the road in the zone.
N.b. unclassified areas will be assessed prior to final report.

Figure 7.2: Fieldwork zones ranked relative to the medium and high risk assessment



8 Network management

As discussed in Section 7, the slopes on the primary road network have been classified in a risk framework to facilitate management of the network. The classification of the slopes in this way allows areas and slopes to be prioritised for remedial/stabilisation measures, monitoring or ongoing management.

As low as reasonably practicable

Where risk is considered as low as reasonably practicable (ALARP), further reduction of the risk by stabilisation is not considered viable. For discussion, the ALARP level on the risk matrix is considered to be where the annual probability of an event is less than 1 in 50 years ($P < 0.02$). For the purpose of network management, all very low and low risk sites are probably at a risk level that is ALARP. However, this may depend on the vulnerability of the network and should be considered on that basis. For example, an event that is likely to put debris on the road in the next 5-10 years (risk level 10) may be considered to require some mitigation in areas of high traffic flow to prevent accidents, but may not be considered to require mitigation in areas of low traffic flow. Where risk is considered ALARP, risk communication to the network users allows individuals to be aware of the risks associated with travelling along a section of the network or stopping in particular places. This can be in the form of signage warning of rock fall or landslide potential.

Maintenance

Road maintenance, especially drainage maintenance, is a vital tool in managing the landslide risk to the primary road network. Rainfall and poor drainage are significant contributory factors in all of the medium and high risk sites. Drainage is variable and in some places formal drainage is not present around the network. However, the MIPS&T does have standard design guidance for road drainage and conceptual design for most locations could proceed using the existing guidance. Requirements for designers and contractors to make sure drainage for new works is tied in to the existing network and will not overload the network would also be beneficial. Maintenance and drainage is discussed in further detail in the Landslide Risk Management Capacity Strengthening Plan.

Warning systems

Landslide warning systems, potentially based on antecedent rainfall and predicted event rainfall intensity, is discussed in more detail within the Landslide Risk Management Capacity Strengthening Plan. In Hong Kong, two types of landslide warning system have developed: detailed warning systems for specific sites based on piezometer readings and slope stability analysis; and more regional warnings based on rainfall which alert when a significant number of landslides are likely to occur. These warning systems are probably add most value in populated areas and may not be relevant for the primary road network. However, they may be able to give an indication of where more landslides are expected during storms and therefore where resources can be targeted prior to and after the event. This may not necessarily be an improvement on the current landslide response.

8.1 Climate change

Climate change is important to consider when looking to develop and improve ways of managing infrastructure in the long term. The National Climate Change Policy and Adaptation Plan (2003) notes the GoSL in collaboration with other relevant entities will “ensure that national infrastructure standards (jetties, roads, bridges etc.) are adequate to withstand the impacts of climate change”.

Climate modelling projections for Saint Lucia reported in the Second National Communication on Climate Change for Saint Lucia (2011) predict:

- reduced average annual rainfall;
- an increase in mean annual temperature; and
- potential for an increase in the intensity of tropical storms.

The predicted reduction in annual rainfall may lead to a general lowering of the water table and may actually increase slope stability.

If tropical storms become more intense that may lead to more landsliding during these storm events, i.e. the frequency of ‘extreme’ events such as Tomas may increase. However, it would be prohibitively expensive to design all structures on the primary road network to withstand such storm events. Therefore, it would be more appropriate to develop an enhanced capacity for warning systems along the network with respect to public safety. If an increase in the frequency of extreme events does occur, maintenance costs for the primary road network are likely to increase.

9 Slope management/stabilisation options

9.1 Overview

The main types of landslide that affect the primary road network are:

- relatively small translational slides that put debris on the road or undermine the road;
- debris flows that cover the road and may destroy parts of the road;
- occasional larger deeper seated failures;
- rockfall.

The majority of failures are relatively small scale and many are related to failure of a structure or lack of formal slope and roadside drainage. Structural failures, such as crest/retaining wall failure, are usually not related to landsliding but caused by poor maintenance and inadequate drainage.

Large, rapid failures, such as the debris flow at Colombette or the channelized debris flows at Fond St. Jacques are difficult to manage in that they cannot be identified prior to occurrence. However, the areas where such events are likely can be identified. Along the primary road network these areas are a significant length and measures to prevent such events from causing damage to the road would be prohibitively expensive. These events are fortunately very rare and the primary road network has been able to be repaired following such events. Loss of life from such events is highly unlikely to be road users, as the failures typically occur in heavy rainfall when there will be less people using the road. Loss of life is more likely to be related to buildings constructed in areas where this type of failure is possible. It may be appropriate to relocate structures that are in the zones with the potential for this type of failure. This is a public safety issue beyond the scope of this report.

The current Ministry slope management system is understood to be reactive to failures. Relatively little proactive maintenance of structures or drainage is completed. However, drainage is cleared annually prior to or during the rainy season.

9.2 Slope management based on risk assessment results

Slopes around the network have been assessed based on a risk matrix approach as discussed in Section 7. A slope management strategy using the risk levels and based on this assessment is presented as Table 9.1.

Table 9.1: Management strategy for different landslide risk levels

Risk level	Management strategy
ALARP 0 (negligible) 1 to 3 (very low) 4, 5, 7, 8 (low) 11, 12, 16 (medium)	Accept the risk Reassess risk level at low and medium risk sites following large storm events Regularly inspect structures and drainage and maintain as required Respond to events as they occur
6, 9, 10 (low) 13 to 15 (medium) 17 to 19 (medium)	Either Accept the risk Regular monitoring of slopes/associated structures

Risk level	Management strategy
20 to 22 (high)	Respond to events as they occur Or Mitigation/remedial works in selected cases Depending on assessment of individual sites
23 to 25 (high)	High priority remedial works / preventative measures required

9.2.1 Management strategies

A discussion of the different management strategies suggested is presented below.

9.2.1.1 Accepting the risk

Accepting the risk does not mean ignoring it. The risk is usually accepted because it is ‘as low as reasonably practicable’ in that risk reduction is impractical or the cost of risk reduction would be grossly disproportionate to the improvement gained. Where risk is accepted, risk communication to the network users allows individuals to be aware of the risks associated with travelling along a section of the network or stopping in particular places. This could be in the form of signage warning of rock fall or landslide potential in appropriate locations.

9.2.1.2 Reassessing the risk

The landslide risk level of slopes will change. For example, following a significant storm a slope previously considered to be in ‘moderately poor’ condition may have deteriorated and look like a failure is possible in the next storm event. Slopes may also degrade on a more gradual basis in response to normal climatic conditions and geological processes. Landslide risk level may also change because of human influence such as removal of vegetation, construction works surcharging a slope or a retaining wall improving stability. Therefore, the risk level should be reassessed by the zone engineers on a regular basis.

The suggested timeframe for reassessing the entire network is once every five years. Medium and high risk zones should be reassessed following major tropical storms and hurricanes.

Updating of the risk assessment is important and keeping a record of changes, reasoning and a centralised up-to-date version of the risk assessment is critical. This process is discussed in the landslide risk management capacity strengthening plan.

9.2.1.3 Drainage inspections and maintenance

Regular inspections of drainage should be carried out to ensure it is functioning and adequate for purpose. Drainage should be integrated and not allowed to discharge uncontrolled on to slopes. Maintenance and improvement of existing drainage is important for controlling landslide risk.

9.2.1.4 Monitoring

It may be appropriate to monitor certain slopes for movement or changes in pore water pressure rather than carry out significant mitigation works. Monitoring can allow a better understanding of the failure and the risk posed to the network. It may allow the risk level to be reduced or can provide a warning of failure. Monitoring is usually more appropriate for slides with structures involved or deeper seated slides, rather than small shallow translational slides.

Monitoring can be done in many different ways and the technique should be chosen to suit the aims of the monitoring. A summary of some potential techniques is presented in Table 9.2.

Table 9.2: Possible slope monitoring techniques and uses

Monitoring technique	Uses	Pros	Cons
Surface measurements			
Visual inspection	Identifies human observable scales of changes Can record deterioration/development of movement indicators such as cracks	Relatively cheap Does not require any equipment	Needs regular visits, preferably by the same person Can be subjective
Regular survey of appropriately placed survey points	Measures small surface movements of placed survey points Can show amount and direction of movement Process can be automated but this requires specialist equipment, is expensive and prone to vandalism	Relatively cheap Accurate	Requires regular visits and data interpretation
Ground-displacement measurements			
Slope inclinometers	Measures differential subsurface displacement Can show depth of failure plane, rate and quantity of movement	Accurate and provides detailed information on landslide for modelling	Relatively expensive Requires a borehole Needs regular visits to record measurements, however in place inclinometers that automate the process are available
Slope piezometers	Measures groundwater level and pressure Assists in determining slope stability and can show if groundwater rises to unsafe levels Several different types available, the most common for slope monitoring include standpipe, pneumatic and electric piezometers	Various accuracy depending on type Provide detailed information for landslide modelling	Relatively expensive Requires a borehole May require regular visits to record measurements, however data loggers can automate the measurement process.
Extensometers	Measures increase in length of a wire/rod anchored to two points in the ground Can show depth of failure plan and	Can show larger displacements than slope inclinometers	Relatively expensive Requires regular visits unless automated recording

Monitoring technique	Uses	Pros	Cons
	quantity of movement		

9.2.1.5 Respond

Response to events by the Ministry is understood to depend on the size, location and type of event. For example, along the west coast road, minor slope failures into drainage may be left until there are several such failures to justify calling a Contractor to come and clear all of the failures. Larger failures will be cleared as required.

The response of the Ministry to major events is discussed in more detail within the landslide risk management capacity strengthening plan. However, based on discussions with the Ministry to date, the response to such events seems good.

9.2.1.6 Mitigation works

Mitigation works may be required in some locations to reduce the risk to an acceptable level. Potential mitigation measures are discussed on a case-by-case basis.

Currently, the typical mitigation/remedial measure used most frequently are gabion baskets. It is understood that these are usually preferred because they are relatively cheap and Contractors on the island have significant experience with them.

9.2.1.7 Land management and runoff control

Land management, including restricting development and controlling tree felling in landslide prone areas, and requiring any development or landscaping not to contribute to slope instability can assist in reducing the likelihood of landslides and can reduce the loss associated with landslides. Land management would require a close cross ministry cooperation, combined with enforcement backed by laws and political will.

Controlling and reducing runoff from hillsides onto the primary road network would assist in reducing the landslide hazard, particularly in large storm events, by reducing the amount of water the drainage systems need to manage, and reducing uncontrolled runoff. Installation of crest drains, maintenance of forested land, planting trees on farmed land in critical locations and making sure farmed land is constantly cropped can assist with controlling runoff.

Critical areas of the network that may be considered for such measures include the Barre De L'Isle and sections of the West Coast Road.

9.3 Priority slope stabilisation/management sites

The priority sites are those with high risk levels based on the landslide risk matrix, or sites agreed with the Ministry. A description of each of the high risk sites and priority sites is presented in Appendix H and a summary of the sites is presented in Table 9.3.

Table 9.3: Summary of priority slope stabilisation/management sites

Site	Approximate chainage	Coordinates	Risk	Ministry zone	Immediate actions recommended
Bois Cachet – straight	BC 70 – 260m	508,676mE; 1,548,047mN	20 / 13	8A	Seal tension cracks on road surface; clear existing drains.
Bois Cachet – hairpin	BC 260 – 440m	508,630mE; 1,547,930mN	9 to 20	8A	Seal tension cracks on road surface; clear existing drains.
The Morne (near Eudovic Studios)	17885 – 17945 NB	508,410mE; 1,546,455mN	13	8A	Seal tension cracks on road surface; clear existing drains.
Ticolon	20320 – 20370 SB	507,632mE; 1,544,482mN	21	7	Seal tension cracks on road surface; clear existing drains.
Barre de L'isle – site 1	124905 – 124965	502,880mE; 1,539,580mN	22	8B	None
Barre de L'isle / Tomazo (sites 6, 7, 9 and 10)	various	various	17 or 22	3	It is considered the findings and recommendations of the FDL report should be progressed.
Ravine Cribiche	126540 – 126565 EB	511,819mE; 1,539,401mN	21	8B	Improve drainage to prevent infiltration behind the remaining retaining wall and prevent surface flow off the slope beneath the retaining wall and in failed area.
Ravine Poisson	127040 – 127055 EB	511,582mE; 1,539,474mN	21	8B	Redirect drainage to prevent discharge directly onto failed area.
Ravine Joseph	35910 – 35940 SB	503,014mE; 1,537,881mN	22	7	None
Colombette	48435 – 48575	503,360E; 1,533,110mN	0 to 22	6B	Condition survey of retaining wall and drainage on the north side of the slide
Calvaire 1	53800 - 53805 NB	501,700mE; 1,530,841mN	22	6B	Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.
Calvaire 2	53650 – 53710 NB	501,780mE; 1,530,920mN	18	6B	Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.
Road past the turn off to Sulphur Springs	55750 – 56550	502,330mE; 1,529,755mN	4 to 9	6B	None
Laborie	75755 - 75800	507,650mE; 1,520,080mN	21	5C	None

10 Site investigations

A summary of the investigations completed at the priority sites is presented in Table 10.1.

Table 10.1: Summary of proposed investigations

Site	Risk	Ministry zone	Investigation completed
Bois Cachet – straight	20 / 13	8A	Detailed geomorphological/damage mapping of the area to define the type and extents of landslide
Bois Cachet – hairpin	9 to 20	8A	Detailed geomorphological/damage mapping of the area to define the type and extents of landslide.
The Morne (near Eudovic Studios)	13	8A	None
Barre de L'isle – site 1	22	8B	Detailed geomorphological survey to define boundaries and improve understanding of landslide.
Ticolon	21	7	Topographical survey of the site. Two test pits in road side to define ground conditions in the slide area and outside. Shallow borehole to investigate ground conditions and allow installation of a piezometer to determine groundwater level. Disturbed and undisturbed sampling for shear strength testing and index properties.
Ravine Poisson	21	8B	Topographical survey.
Ravine Cribiche	21	8B	Topographical survey.
Ravine Joseph	22	7	None
Colombette	0 to 22	6B	Topographical survey of the area followed by detailed geomorphological mapping to define the type and extents of landslide, location of bedrock, thickness of deposits, material in the backscarp, surface water drainage and ongoing morphological processes. Series of test pits on slope above road to determine thickness of colluvial material to allow stability of mass to be confirmed and options for high risk area on the north side of the slide to be investigated. A condition survey of retaining wall and drainage on the north of the slide is recommended but is not considered within the scope of this project.
Calvaire	22	6B	Topographical survey of the site.
Calvaire	18	6B	Topographical survey of the site.
Road past the turn off to Sulphur Springs	4 to 9	6B	None.
Laborie	21	5C	Topographical survey of the site. Two test pits in road side to define ground conditions in the slide area and outside. Shallow borehole to investigate ground conditions and allow installation of a piezometer to determine groundwater level. Disturbed and undisturbed sampling for shear strength testing and index properties.

11 On-going studies

The status of deliverables at the time of issue of this final feasibility report is summarised in Table 11.1.

Table 11.1: Status of project deliverables

Item / deliverable	Issue date	Status
Inception report	Issued 14th December 2012	Accepted by GoSL and CDB
Draft feasibility report	Issued 24th April 2013	Comments provided by GoSL and CDB incorporated into this final issue.
Final feasibility report	Issued 23rd September 2013	Issued
Draft landslide risk management capacity strengthening plan	Issued 26th June 2013	Issued
Final landslide risk management capacity strengthening plan	To be issued within one month of receipt of comments	Awaiting comments from GoSL and CDB
Draft conceptual design report	To be issued 1st November 2013	In progress
Final conceptual design report	To be issued within one month of receipt of comments	

An updated project programme based on project commencement dates and current project status is presented as Figure 11.1.

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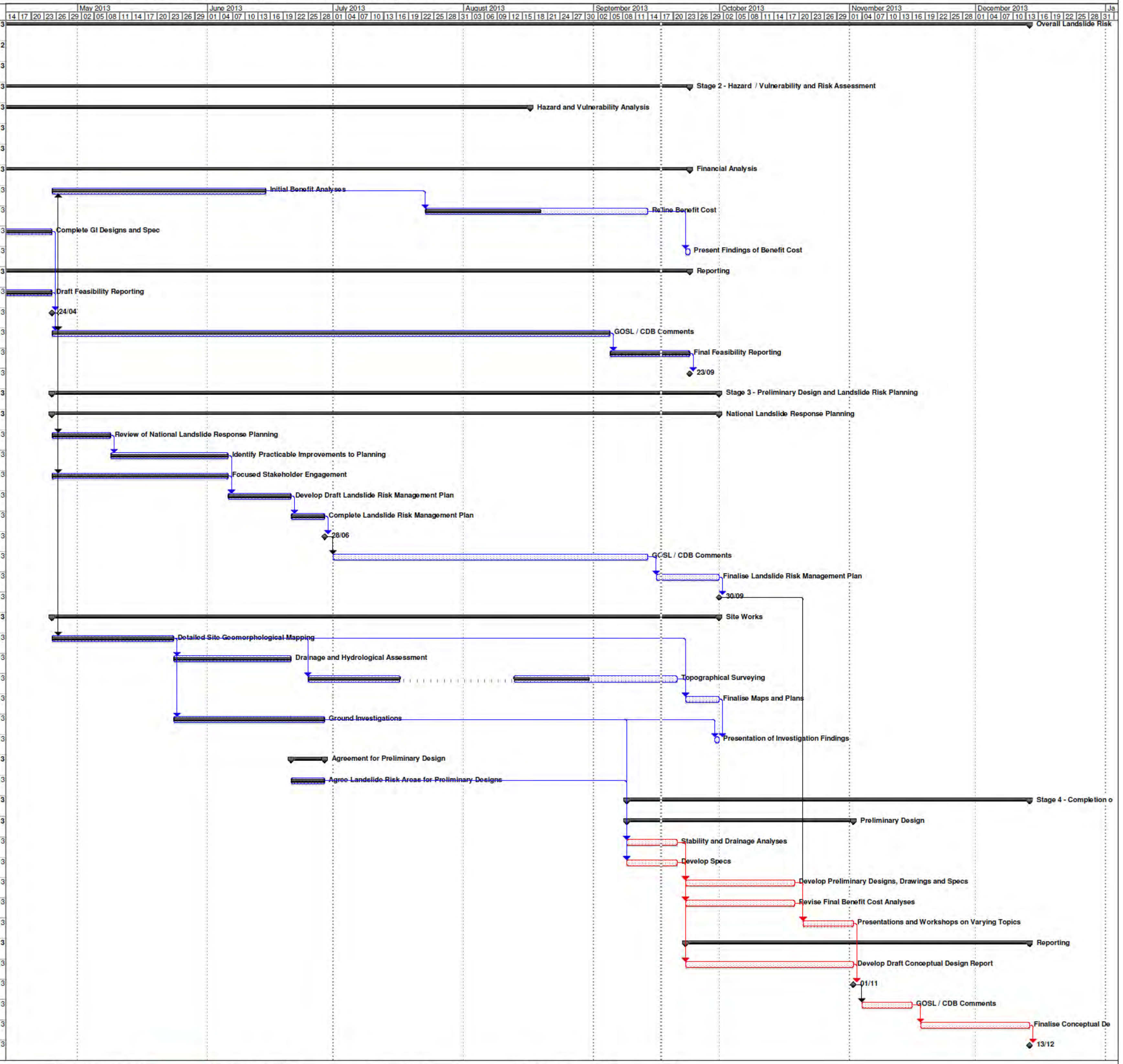
Figure 11.1: Updated project programme

Landslide Risk Assessment for Saint Lucia's Primary Road Network
Mott MacDonald Team Programme - Revised 06 September 2013

ID	Task Name	Duration	Start	Finish
1	**Overall Landslide Risk Assessment**	**254 days?**	**Mon 03/12/12**	**Fri 13/12/13**
2	**Meetings**	**1 day?**	**Mon 03/12/12**	**Mon 03/12/12**
11	**Stage 1 - Inception**	**19 days**	**Tue 04/12/12**	**Mon 21/01/13**
18	**Stage 2 - Hazard / Vulnerability and Risk Assessment**	**185 days**	**Tue 08/01/13**	**Mon 23/09/13**
19	**Hazard and Vulnerability Analysis**	**159 days**	**Tue 08/01/13**	**Fri 16/08/13**
30	**Risk Assessment**	**34 days**	**Tue 05/02/13**	**Fri 22/03/13**
35	**Optioneering**	**22 days**	**Tue 05/02/13**	**Wed 06/03/13**
39	**Financial Analysis**	**131 days**	**Mon 25/03/13**	**Mon 23/09/13**
40	Initial Benefit Analyses	37 days	Thu 25/04/13	Fri 14/06/13
41	Refine Benefit Cost	39 days	Tue 23/07/13	Fri 13/09/13
42	Complete GI Designs and Spec	23 days	Mon 25/03/13	Wed 24/04/13
43	Present Findings of Benefit Cost	1 day	Mon 23/09/13	Mon 23/09/13
44	**Reporting**	**143 days**	**Thu 07/03/13**	**Mon 23/09/13**
45	Draft Feasibility Reporting	35 days	Thu 07/03/13	Wed 24/04/13
46	Issue Draft Feasibility Report	0 days	Wed 24/04/13	Wed 24/04/13
47	GOSL / CDB Comments	95 days	Thu 25/04/13	Wed 04/09/13
48	Final Feasibility Reporting	13 days	Thu 05/09/13	Mon 23/09/13
49	Issue Final Feasibility Report	0 days	Mon 23/09/13	Mon 23/09/13
50	**Stage 3 - Preliminary Design and Landslide Risk Planning**	**113 days**	**Thu 25/04/13**	**Mon 30/09/13**
51	**National Landslide Response Planning**	**113 days**	**Thu 25/04/13**	**Mon 30/09/13**
52	Review of National Landslide Response Planning	10 days	Thu 25/04/13	Wed 08/05/13
53	Identify Practicable Improvements to Planning	20 days	Thu 09/05/13	Wed 05/06/13
54	Focused Stakeholder Engagement	30 days	Thu 25/04/13	Wed 05/06/13
55	Develop Draft Landslide Risk Management Plan	11 days	Thu 06/06/13	Thu 20/06/13
56	Complete Landslide Risk Management Plan	6 days	Fri 21/06/13	Fri 28/06/13
57	Issue Draft Landslide Risk Management Plan	0 days	Fri 28/06/13	Fri 28/06/13
58	GOSL / CDB Comments	55 days	Mon 01/07/13	Fri 13/09/13
59	Finalise Landslide Risk Management Plan	11 days	Mon 16/09/13	Mon 30/09/13
60	Issue Final Landslide Risk Management Plan	0 days	Mon 30/09/13	Mon 30/09/13
61	**Site Works**	**113 days**	**Thu 25/04/13**	**Mon 30/09/13**
62	Detailed Site Geomorphological Mapping	21 days	Thu 25/04/13	Thu 23/05/13
63	Drainage and Hydrological Assessment	20 days	Fri 24/05/13	Thu 20/06/13
64	Topographical Surveying	45 days	Tue 25/06/13	Fri 20/09/13
65	Finalise Maps and Plans	6 days	Mon 23/09/13	Mon 30/09/13
66	Ground Investigations	26 days	Fri 24/05/13	Fri 28/06/13
67	Presentation of Investigation Findings	1 day	Mon 30/09/13	Mon 30/09/13
68	**Agreement for Preliminary Design**	**6 days**	**Fri 21/06/13**	**Fri 28/06/13**
69	Agree Landslide Risk Areas for Preliminary Designs	6 days	Fri 21/06/13	Fri 28/06/13
70	**Stage 4 - Completion of Preliminary Designs**	**70 days**	**Mon 09/09/13**	**Fri 13/12/13**
71	**Preliminary Design**	**40 days**	**Mon 09/09/13**	**Fri 01/11/13**
72	Stability and Drainage Analyses	10 days	Mon 09/09/13	Fri 20/09/13
73	Develop Specs	10 days	Mon 09/09/13	Fri 20/09/13
74	Develop Preliminary Designs, Drawings and Specs	20 days	Mon 23/09/13	Fri 18/10/13
75	Revise Final Benefit Cost Analyses	20 days	Mon 23/09/13	Fri 18/10/13
76	Presentations and Workshops on Varying Topics	10 days	Mon 21/10/13	Fri 01/11/13
77	**Reporting**	**60 days**	**Mon 23/09/13**	**Fri 13/12/13**
78	Develop Draft Conceptual Design Report	30 days	Mon 23/09/13	Fri 01/11/13
79	Issue Draft Conceptual Design Report	0 days	Fri 01/11/13	Fri 01/11/13
80	GOSL / CDB Comments	10 days	Mon 04/11/13	Fri 15/11/13
81	Finalise Conceptual Design Report	20 days	Mon 18/11/13	Fri 13/12/13
82	Issue Final Conceptual Design Report	0 days	Fri 13/12/13	Fri 13/12/13



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Date: Tue 17/09/13

Task; Progress; Summary; Rolled Up Critical Task; Rolled Up Progress; External Tasks; Group By Summary
Critical Task; Milestone; Rolled Up Task; Rolled Up Milestone; Split; Project Summary; Deadline

Page 1

295680/MNC/FNG/007/B 23 September 2013
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Appendices

Appendix A. Rainfall and runoff review

A.1 Hurricane severity assessment

A.1.1 Hurricane Tomas, October 2010

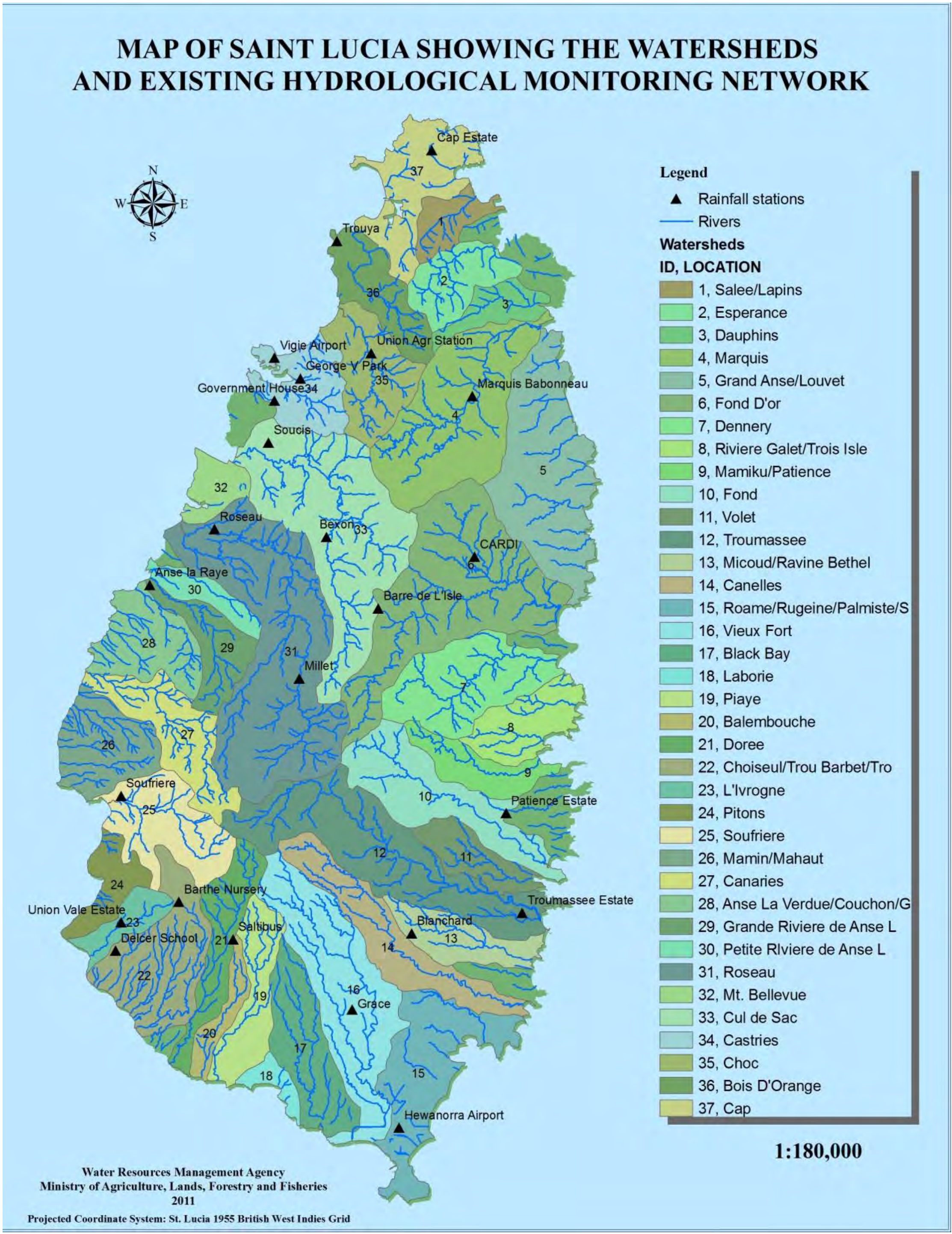
A.1.1.1 Scale of event

There appear to have been 7 raingauges operating on October 30th 2010. These recorded between 358 and 593mm, with an average of 499mm (see Table A.1). The gauges were spread across the island, from Hewanorra Airport in the south to Vigie (George Charles) Airport in the north-west. The highest recorded value was at Hewanorra and the lowest at Anse la Raye – the latter is on the west coast where there may have been some rain shadow effect. (An eighth gauge, Trouya, does show data, but with a value of just 19mm it seems unlikely to be a true record.) Gauge locations are shown in Figure A.1. Sub-daily data (actually to the nearest minute) was obtained from the Ministry of Water Resources for four of these gauges; this allows the profile of the event to be derived (see section A.1.1.4).

Table A.1: Recorded rainfall on 30th October 2010

Station	Rainfall (mm)	Sub-daily data
Union Agricultural Station	549	No
George Charles (Vigie) Airport	533	No
Marquis Babonneau	437	Yes
Cardi	541	Yes
Anse la Raye	358	Yes
Patience Estate	480	Yes
Hewanorra Airport	593	No
Average	499	

Figure A.1: Rainfall stations in St Lucia



Source: Ministry of Agriculture, Lands, Forestry and Fisheries, 2011; estimated scale on this page 1:230,000

In the available rainfall data for over 30 stations over the period since 1955 there are no other believable records of over 500mm in a day (some higher values have been discounted, including a significant number at one station where the record includes several values of 2000mm or more, higher than the world maximum daily rainfall). Of the rare occasions where a value of over 400mm has been recorded there are no instances (apart from Tomas) of this occurring at more than one gauge, let alone spread widely across the island.

It is clear that the 2010 event was unprecedented in the amount of rainfall, and possibly also in its widespread occurrence.

A.1.1.2 Previous analysis

A Note was prepared by the Economic Commission for Latin America and the Caribbean (ECLAC). This included an analysis of annual maximum daily rainfall for George Charles Airport for the period 2000-2009, i.e. just prior to the Tomas event, and gave an estimated 1-in-100 year rainfall of 155mm. The 10-year period of data is very short for estimating a 100-year event, so the estimate should be treated with caution. The annual maxima ranged from 61 to 105mm, with an average of 85mm; the limited range means that the extrapolated extreme value curve is quite “flat” and hence the 100-year value is not very much higher than the maximum observed in the 10-year period. The Note reported comments from the St Lucia Met Office that in terms of total daily rainfall Hurricane Tomas was classified as a 1-in-180 year event; in view of the difference between the 100-year estimate (155mm) and the recorded rainfall (533mm) this return period might be considered an underestimate. (However, there is no indication that the Met Office assessment was based on the same 10-year period of data, or just this station.)

The data for George Charles actually starts in 1985; study of this shows that the period analysed is not representative of longer-term conditions, as illustrated in Table A.2 below. Over the 25-year period to 2009 the range is much wider, with the average more than 25% higher. Analysis of this data would suggest a 100-year rainfall in the region of 300mm. Analysis of the full data to 2012 inevitably suggests a much higher value, possibly in excess of 500mm. However, extrapolating from a 28-year dataset is subject to large uncertainties, particularly when it includes one value which is so much higher than all the others.

Table A.2: Annual Maximum Daily rainfall at Georges Charles Airport (mm)

Period	minimum	mean	maximum
2000-2009	61	85	105
1985-2009	51	108	270
1985-2012	51	122	533

A.1.1.3 Available rainfall data

As noted, there is extensive rainfall data for St Lucia. Digital records from 1955 to 2012 have been made available, though it may be noted that a previous report[1] refers to several gauges being installed more than

[1] St Lucia Watershed and Environmental Management Plan, Hunting Technical Services, 1998

100 years ago, with George V Park in 1890 the earliest. Seven stations have 45 years or more of data within the 58-year period, but only three of those have data for Hurricane Tomas in 2010. These are Union Agricultural Station and Marquis Babonneau in the north of the island and Patience Estate on the east. Key points from the data are shown in Table A.3. The comparison with the previous highest rainfall illustrates the exceptional nature of the 2010 event, particularly for Patience Estate.

Table A.3: Summary data for long-term stations with data in 2010

	Union Agricultural Station	Patience Estate	Marquis Babonneau
Years data	57	51	45
Maximum (2010)	549 mm	480 mm	437 mm
2nd highest	293 mm	183 mm	301 mm
Average	124 mm	108 mm	121 mm
Minimum	53 mm	50 mm	57 mm

Extreme value analysis of the Union Agricultural Station series shows a reasonable fit to a Generalised Extreme Value (GEV) Type 3 curve (Figure A.2); the 2010 event lies outside the 95% confidence limits, but is plausibly part of the same distribution. Similar analysis for Patience Estate (Figure A.3) suggests that the 2010 event forms part of a different distribution. Marquis Babonneau (Figure A.4) fits the distribution, with the 2010 event only marginally outside the confidence limits. The other stations with 2010 data have less than 30 years data, and extreme value analysis is difficult, particularly bearing in mind the extreme nature of the 2010 event.

The two long-term station curves that show reasonable fit to the data are very similar (Figure A.5), and provide a degree of confidence that that they provide a satisfactory representation of conditions in St Lucia. The estimates for a range of return periods are summarized in Table A.4.

Figure A.2: Extreme Value Analysis of Annual Maximum Daily Rainfall, Union Agricultural Station

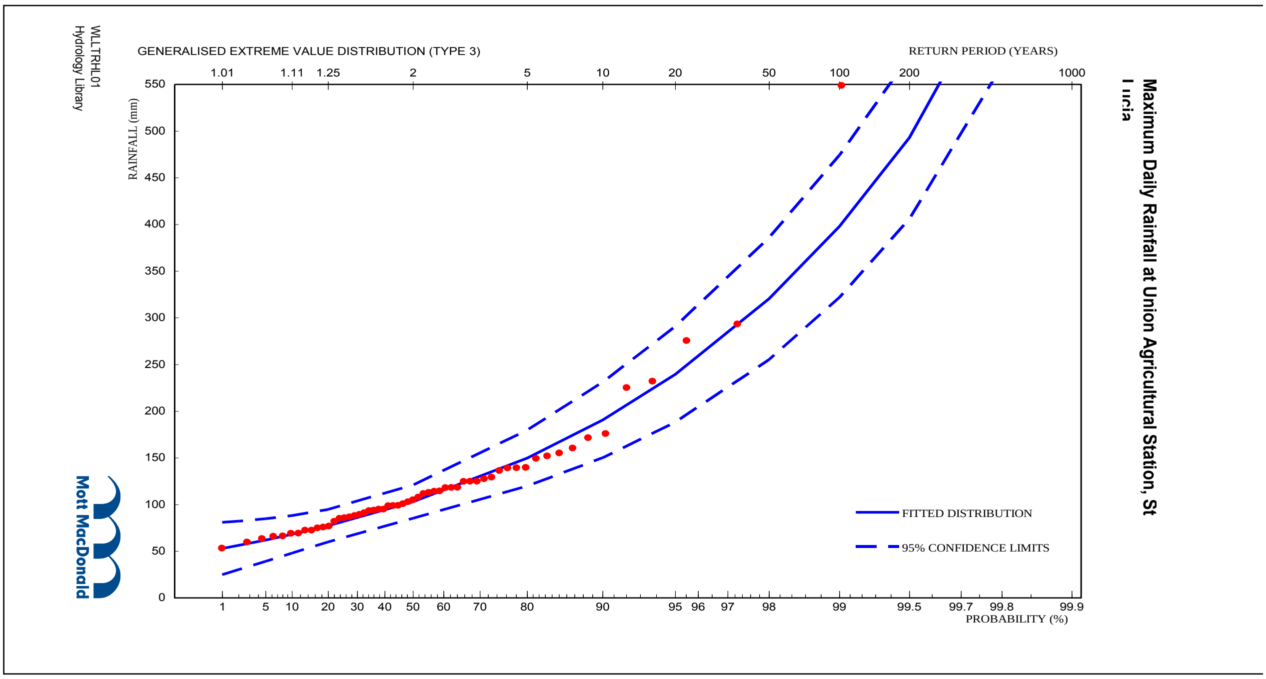


Figure A.3: Extreme Value Analysis of Annual Maximum Daily Rainfall, Patience Estate

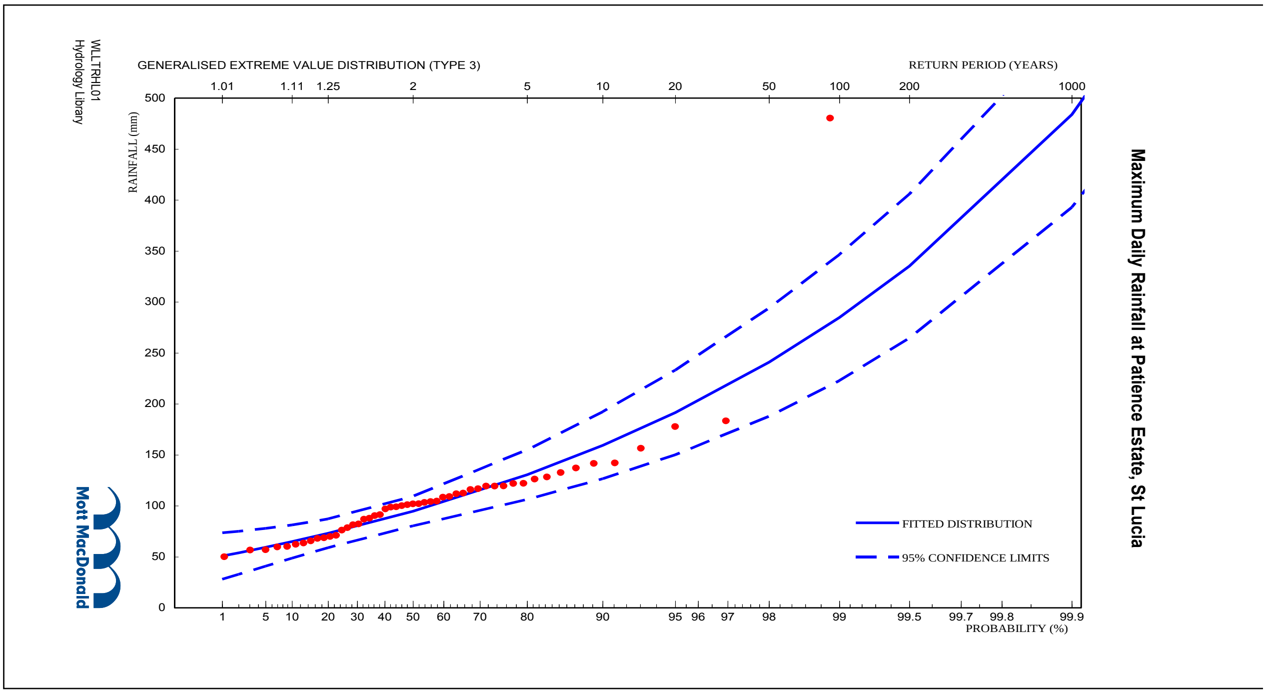


Figure A.4: Extreme Value Analysis of Annual Maximum Daily Rainfall, Marquis Babonneau

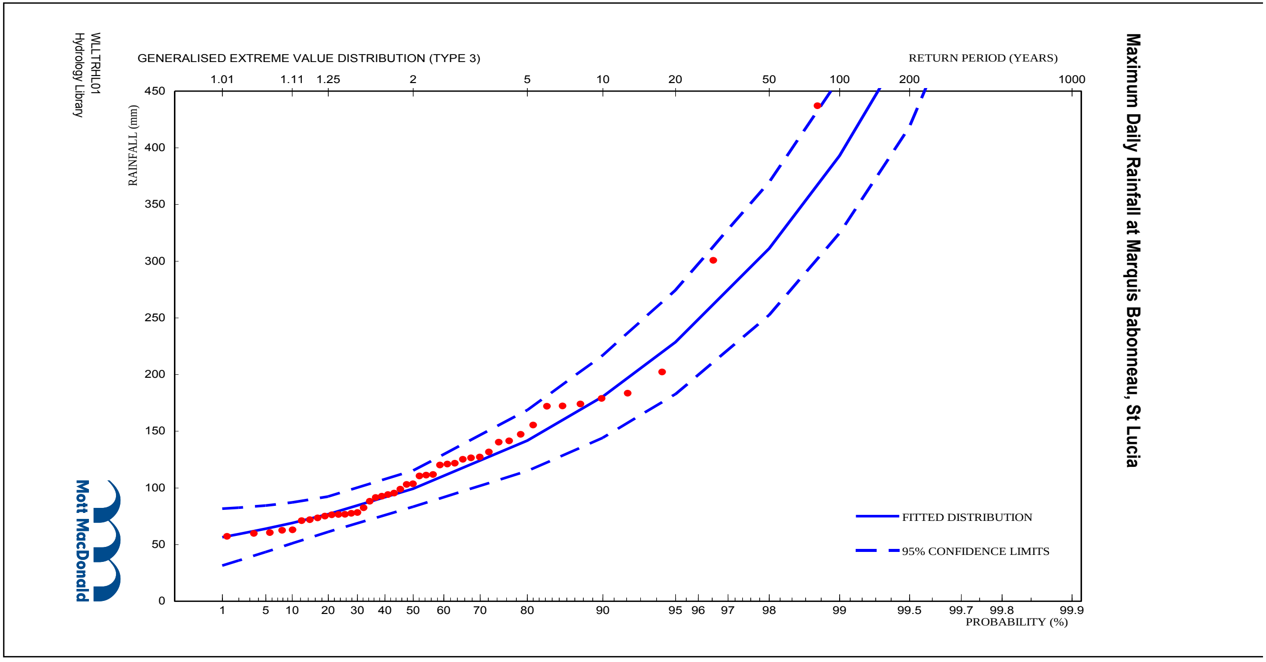


Figure A.5: Derived Extreme Value Curves

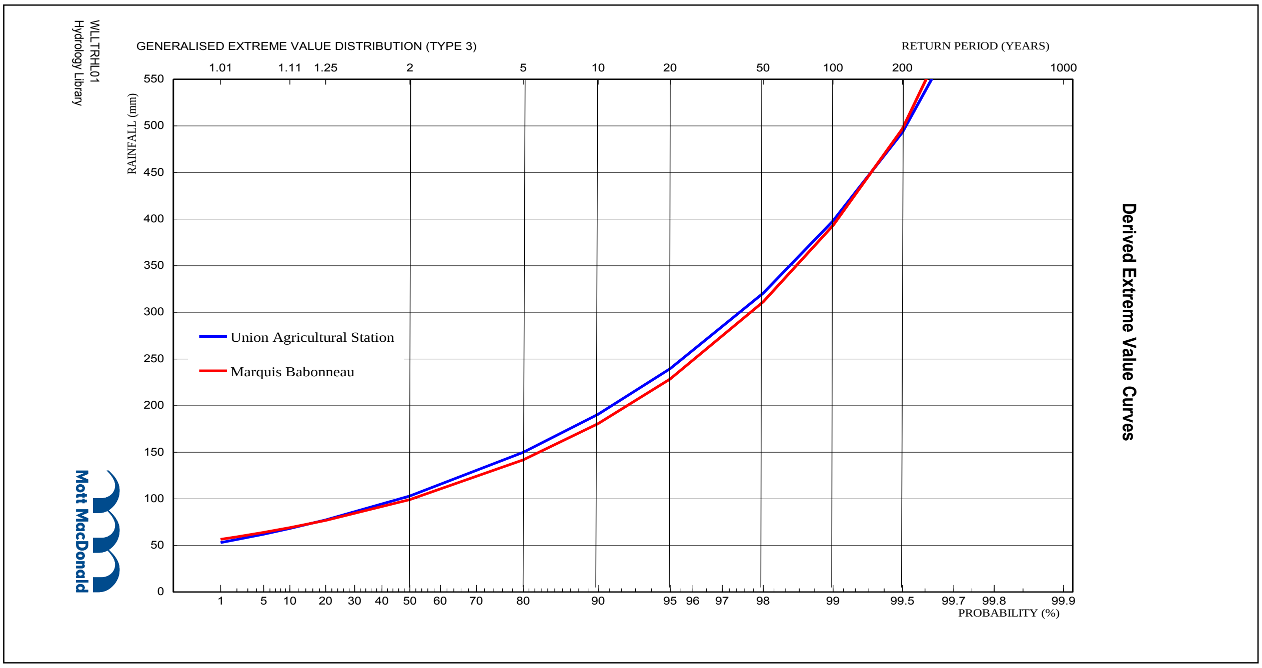


Table A.4: Estimated Daily Rainfall for a range of Return Periods (mm)

Return period (years)	Union Agricultural Station	Marquis Babonneau	Average
2	103	99	101
5	150	142	146
10	191	181	186
20	239	228	234
50	321	311	316
100	398	393	395
200	493	497	495

The average rainfall across the seven stations on 30th October 2010 was 499mm. The analysis suggests that this might correspond to a return period in the region of 200 years. This essentially considers point rainfall; the return period of such rainfall occurring across the island would be higher, but it is difficult to say by how much.

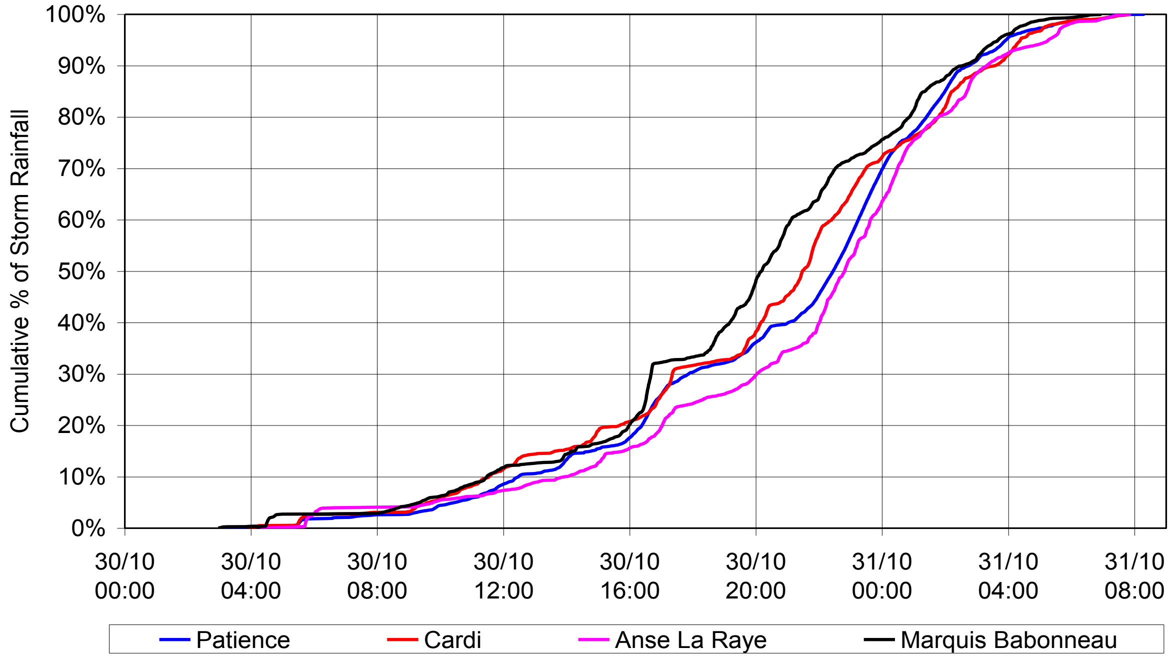
Maximum 24-hour rainfalls are generally higher than maximum daily values because the storm may not neatly fit within the standard rainday (the 24 –hour period ending at 0900). A factor may therefore be applied to derived daily rainfall values to obtain estimated 24-hour values for use in flood estimation; a major US study[2], determined a factor of 1.13, and this has been adopted in some other parts of the world. However, it may not be appropriate to do so here; as will be shown below, in Tomas the peak 24-hour rainfall was virtually the same as the peak daily (see section A.1.1.4), and for some other events/stations the recorded peak daily rainfall may in fact represent a cumulative total (see section A.1.2).

A.1.1.4 Storm profile

Many of the raingauges in St Lucia are recording gauges that produce data on rainfall in 1-minute increments. However, it is understood that only four of these gauges were operating during Tomas. Three of these gauges are in the eastern half of the island, with one on the west. The timing of the storm and various peak rainfalls are shown in Table A.5, and the cumulative rainfall is illustrated in Figure A.6. To aid comparison between the locations the graph shows each station’s rainfall as a percentage of the total storm rainfall. The graph shows a particularly intense period of rainfall at Marquis Babonneau at about 16:30 on October 30th (over 35mm in 15 minutes or more than 140mm/hour). The other stations also show increased intensity (though not to the same extent, and with a slight time delay). The main period of prolonged intense rainfall at Marquis Babonneau occurred between about 18:30 and 22:45 when the intensity averaged nearly 40mm/hour. The intense period occurred progressively later at Cardi, Patience and Anse La Raye; relating this to the gauge locations (Figure A.1) suggests that the intense rainfall arrived from approximately the north-east. Given that the eye of the storm passed to the south of St Lucia and winds circulate counter-clockwise around the eye, the arrival of the most severe winds (and perhaps therefore the most intense rainfall) would be expected to be roughly from that direction.

[2] Rainfall Frequency Atlas of the United States, Weather Bureau Technical Paper No 40, Department of Commerce, May 1961

Figure A.6: Cumulative Rainfall During Hurricane Tomas



Source: MM analysis of raw data from Water Resources Department, Ministry of Agriculture, Lands, Forestry and Fisheries

Table A.5: Detailed Rainfall in Hurricane Tomas Event

	Marquis Babonneau	Cardi	Anse La Raye	Patience Estate	Average
Start of rainfall (30/10)	02:58	03:56	04:17	03:09	03:35
End of rainfall (31/10)	06:57	07:52	07:53	08:19	07:45
Total (mm)	457	559	373	494	471
Daily1 (mm)	437	541	358	480	454
Peak 24-hours (mm)	444	542	358	481	456
cf daily	102%	100%	100%	100%	100%
Peak hour (mm)	56	66	48	65	59
cf max 24 hours	13%	12%	13%	13%	13%
Peak 60-mins (mm)	62	72	50	66	62
cf max hourly	110%	108%	105%	101%	106%
Peak minute (mm)	3.0	3.0	1.8	1.2	2.3
Peak 30-mins (mm)	46	44	27	46	38
Peak 120-mins (mm)	94	117	91	121	106
Peak 4-hours (mm)	150	191	153	196	173

	Marquis Babonneau	Cardi	Anse La Raye	Patience Estate	Average
Peak 6-hours (mm)	202	245	201	252	225
Peak 12-hours (mm)	348	399	287	384	355

1 from 0900 on 30/10 to 0900 on 31/10, as shown in Table A.1

The peak 24-hour rainfall was almost the same as the rainfall in the standard rainday (24 hours to 0900) – the average factor between the two was less than 1.005. The peak 60-minute rainfall exceeded the peak clock-hour rainfall by an average factor of 1.06. This compares to 1.13 in the US Weather Bureau report cited above (coincidentally the same factor as for daily to 24-hour values). Given the prolonged nature of the storm the relatively low factor is not unexpected. Similarly, the peak hourly rainfall (average about 60mm) will be shown in section A.2 to be of a much lesser return period than the overall event.

A.1.2 Other notable hurricanes

The National Oceanic and Atmospheric Administration (NOAA) has produced a list of nearly 60 hurricanes over the period from 1872 to 2010. Although not explicitly stated, it is assumed that this list is confined to storms that affected the Windward Islands (many notable hurricanes that affected the northern Caribbean and/or the United States are not listed). The list contains 27 hurricanes in the period for which rainfall data is available. A simple summary of these is shown in Table A.6; this gives the maximum daily rainfall recorded at any gauge in the period, together with the total number of gauges operating and the number that recorded over 100mm on the day of the peak station rainfall. In most cases the peak day of the storm is very clearly indicated by the data, but in a few there were large rainfalls at other gauges on subsequent days – for example in 1984 there were 11 gauges recording over 100mm on either July 25th or 26th. In some others (notably 1988) records for some gauges show zero on the peak day but a large value on a subsequent day, possibly an accumulated total. Consequently, some of the major events may have been more widespread than is indicated by the comparison of the number of gauges and the number recording over 100mm. Conversely, there may be instances where the recorded annual maximum daily rainfall actually represents rainfall from more than one day.

Table A.6: Maximum Rainfall in Hurricane Events 1955 to 2010

Year	Storm name	From	To	Duration (days)	Max rain (mm)	Nr gauges	sites>100mm
1958	Ella	30-Aug	06-Sep	8	113	11	1
1960	Abby	10-Jul	16-Jul	7	193	11	7
1963	Edith	23-Sep	29-Sep	7	121	11	1
1965	Betsy	27-Aug	13-Sep	18	91	11	0
1966	Judith	27-Sep	30-Sep	4	100	11	1
1967	Beulah	05-Sep	22-Sep	18	329	11	10
1967	Edith	26-Sep	01-Oct	6	41	11	0
1969	Unnamed	25-Jul	27-Jul	3	33	9	0
1970	Dorothy	17-Aug	23-Aug	7	36	10	0
1970	Unnamed	23-Sep	11-Oct	19	244	10	7

Year	Storm name	From	To	Duration (days)	Max rain (mm)	Nr gauges	sites>100mm
1971	Chloe	18-Aug	25-Aug	8	76	8	0
1976	Unnamed	03-Oct	12-Oct	10	69	12	0
1979	Ana	19-Jun	24-Jun	6	117	14	1
1980	Allen	31-Jul	11-Aug	12	160	15	1
1983	Unnamed	23-Jul	28-Jul	6	94	17	0
1984	Unnamed	24-Jul	26-Jul	3	183	16	6
1988	Gilbert	08-Sep	20-Sep	13	311	23	14
1993	Cindy	14-Aug	17-Aug	4	58	22	0
1994	Debby	09-Sep	11-Sep	3	450	17	12
1995	Iris	22-Aug	07-Sep	17	182	23	2
2001	Chantal	14-Aug	22-Aug	9	61	28	0
2001	Iris/Jerry	04-Oct	09-Oct	6	102	25	1
2003	Claudette	07-Jul	17-Jul	11	71	29	0
2004	Bonnie	03-Aug	14-Aug	12	47	29	0
2007	Dean	13-Aug	23-Aug	11	181	24	10
2010	Tomas	30-Oct	27-Nov	29	593	8	7

The table shows five events (1967, 1970, 1988, 1994 and 2010) where the maximum daily rainfall was over 200mm (in all cases occurring at 4 or more stations), with several more having widespread rainfall of over 100mm. Three of the five events (1967, 1988 and 2010) showed all except one raingauge having a daily value of over 100mm, and in the other two a majority of the stations exceeded 100mm. The data therefore suggests that severe and widespread events might have a return period of in the region of 10 years.

Table A.7 summarizes the data for the five severe events, showing the maximum daily rainfall recorded against any day within the period (of up to 4 days). This effectively allows for the fact that rainfall on the key day may only have been read a day or two later. This confirms the widespread nature of the events, with generally only one gauge not showing the severe rainfall. Further study of the data for these exception gauges strongly suggests that the record (generally zero for an extended period) is erroneous.

Table A.7: Daily Rainfall in the Five Biggest Hurricane Events

Date	Max rain (mm)	Nr gauges	sites>100	sites>200	sites>300	sites>400	sites>500
Sep-1967	329	11	10	7	3	0	0
Oct-1970	244	10	7	5	0	0	0
Sep-1988	311	23	22	16	3	1	0
Sep-1994	450	17	16	13	4	1	0
Oct-2010	593	8	7	7	6	6	4

A.1.3 Conclusions

The key conclusions from the analysis are as follows:

- The Hurricane Tomas event in 2010 showed daily rainfalls of 400-600mm over a wide part of the island.
- The return period of the Hurricane Tomas rainfall event is estimated to be in excess of 200 years.
- Island-wide storms with daily rainfall in excess of 100mm may be expected to occur roughly once every 10 years on average.
- The 1-in-10 year rainfall at a point is likely to be in the region of 150-200mm.
- Although there is a significant variation in annual average rainfall across the island, there is less variation in extreme rainfalls; high rainfalls (whether from “normal” storms or exceptional hurricane events) can occur at any location.

A.2 Additional rainfall assessment

A.2.1 Return period rainfall curves

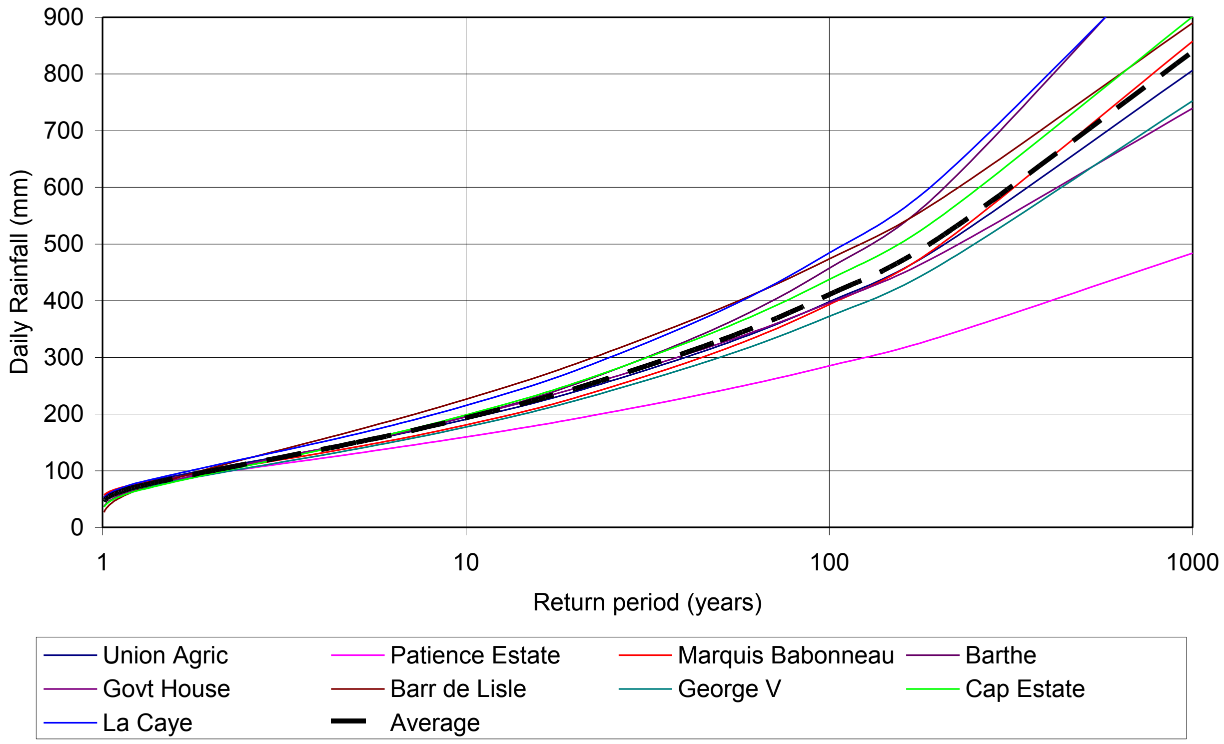
There are 9 stations with annual maximum series covering over 40 years, 3 of which contained data for the Hurricane Tomas event.

Estimated 200-year rainfalls range from 300 to 497mm, and 50-year from 223 to 340mm. As already noted, the highest 200-year is for Marquis Babonneau which had Tomas data. However, the highest 50-year estimate is for Barre de Lisle which has no data for 2010. This gauge is centrally located very close to the east-west catchment divide, and may be a key location for assessing runoff from the mountains.

Given the widespread and extreme nature of Tomas rainfall it is unsatisfactory to be comparing gauges that have data for that event with others that do not. In view of the observation that very high rainfalls were recorded across the island, further analysis was undertaken for the 6 gauges without Tomas data, assuming that the annual maximum for 2010 was equal to the average of the 7 stations with data (i.e. 499mm, Table A.1). The 200-year range is then 335 to 613mm (average 510mm) and the 50-year range is 241 to 386mm (average 330mm). These averages are slightly higher than the average of two stations shown in Table A.4.

There is inevitably a lot of scatter in the curves, particularly at high return periods (Figure A.7). (Note that this has been plotted with the return period on a log scale rather than the probability scale of the earlier graphs.)

Figure A.7: Return Period Curves for Daily Rainfall for Long-term Stations



The key question regarding rainfall-runoff modelling is whether the variation in estimated rainfalls across the group of stations represents a genuine variation in rainfall or whether it arises from chance variations in the data (including the impact of periods of missing data at particular stations) and in the extreme value analysis. The lowest curve is for Patience Estate which is close to the east coast and the two highest are for La Caye (also close to the east coast, around 9km north of Patience Estate) and Barre de L'isle in the central mountains. The group of four stations towards the north of the island (Government House etc.) show very consistent results (50-year ranging from 300 to 324mm). It would not be surprising if the relatively remote stations had more variable data.

It is considered reasonable to adopt the average curve shown in Figure A.7 for all catchments across the island. The values are tabulated later (Table A.9).

A.2.2 Areal reduction factor

Rainfall magnitudes derived from raingauge data relate to rainfall at a point. The average rainfall over a catchment area will be lower, with the difference described by the areal reduction factor (ARF). The ARF is close to 1 for a long duration and small area, and reduces as either the area increases or the duration decreases. The UK's Flood Estimation Handbook[3] includes a set of equations to derive the ARF from the area and duration. Whilst this is based on UK rainfall conditions the results are similar to the curves presented by the World Meteorological Organization (1983)[4]. Figures for a range of areas and durations are shown in Table A.8. The largest catchments in St Lucia are in the range 25-50 km², and for these the critical storm duration (in terms of maximum flood flow) is likely to be 4-6 hours. At many drainage points the catchment area will be very small, usually much less than 1 km², and these will be susceptible to intense short duration storms, typically an hour or less. In both of these cases the ARF is in the region of 0.95; bearing in mind the uncertainties involved in the rainfall analysis it is considered reasonable to apply a fixed ARF of 0.95 in flood estimation for all catchments. The effect of this on design rainfalls is shown in Table A.9.

Table A.8: Areal Reduction Factors

	Storm Duration (hours)					
Area (km2)	0.5	1	2	4	6	12
1	0.949	0.961	0.950	0.976	0.980	0.984
2	0.935	0.950	0.961	0.970	0.974	0.980
5	0.910	0.930	0.946	0.959	0.965	0.973
10	0.884	0.911	0.932	0.948	0.955	0.966
25	0.838	0.877	0.906	0.929	0.939	0.954
50	0.793	0.843	0.881	0.909	0.923	0.941

Table A.9: Recommended design daily rainfalls (mm)

Return period (years)	Point rainfall	Catchment rainfall
2	100	95
2.33	109	104
5	150	142
10	193	183
20	245	232
50	330	313
100	411	390
200	510	485

Note: 2.33 year event represents the mean annual event.

24-hour rainfall may be higher than daily rainfall because the latter is based on a specific 24-hour period (typically from 0900 on one day to 0900 on the following day), and this may not encompass the full duration of a specific storm event. However, for the reasons outlined earlier it is believed that any adjustment for St Lucia would be quite small, and for this study no factoring has been applied.

[3] Flood Estimation Handbook, Vol 4; Institute of Hydrology, 1999

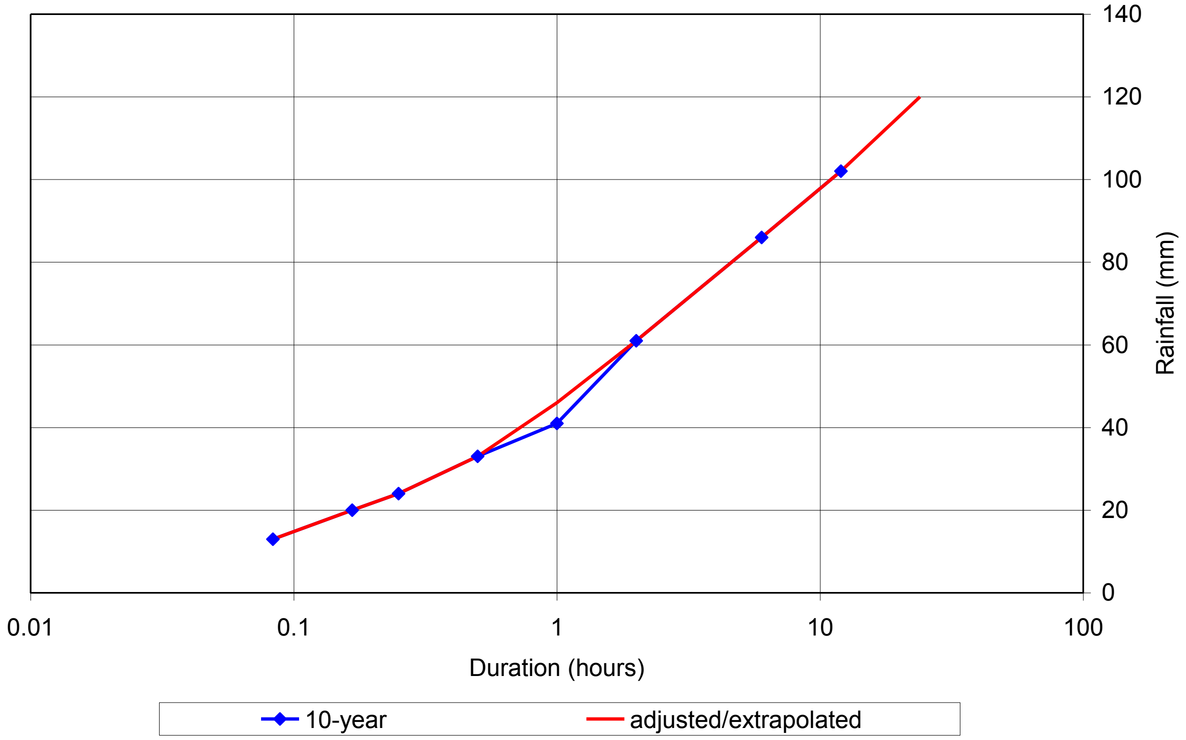
[4] Reproduced from Technical Paper 29, US Weather Bureau, 1958

A.2.3 Storm profiles

All the rainfall data referred to above is from daily raingauges. Shorter-duration information is required for assessing flood runoff in the small catchments in St Lucia. As noted above, a number of raingauges in St Lucia have sub-daily data, and the data for gauges operating during Hurricane Tomas has been analysed (section A.1.1.4). Some earlier data for one station (Union Agricultural Station) was analysed for a previous paper by Acreman and Boorman[5]. Acreman and Boorman presented relationships between rainfall and return period for a range of durations from 5 minutes to 12 hours, based on data for the period 1979-1987. The values for a 10-year return period are illustrated in Figure A.8. This includes a suggested adjustment where the 1-hour value seems to be on the low side, and extrapolation from 12 to 24 hours.

It is noted that the 24-hour estimate of 120mm is well below that found by analysing the full period of daily data (191mm, Table A.4). This reflects the period of data analysed; the average annual maximum rainfall in the period analysed was 102mm compared to 124mm for the full data set, and the short period did not include any extreme hurricane event. The full 57-year data set includes seven values between 172 and 549mm, whereas the highest in the period 1979-87 was 161mm.

Figure A.8: 10-year Rainfall for Union Agricultural Station for durations up to 24 hours

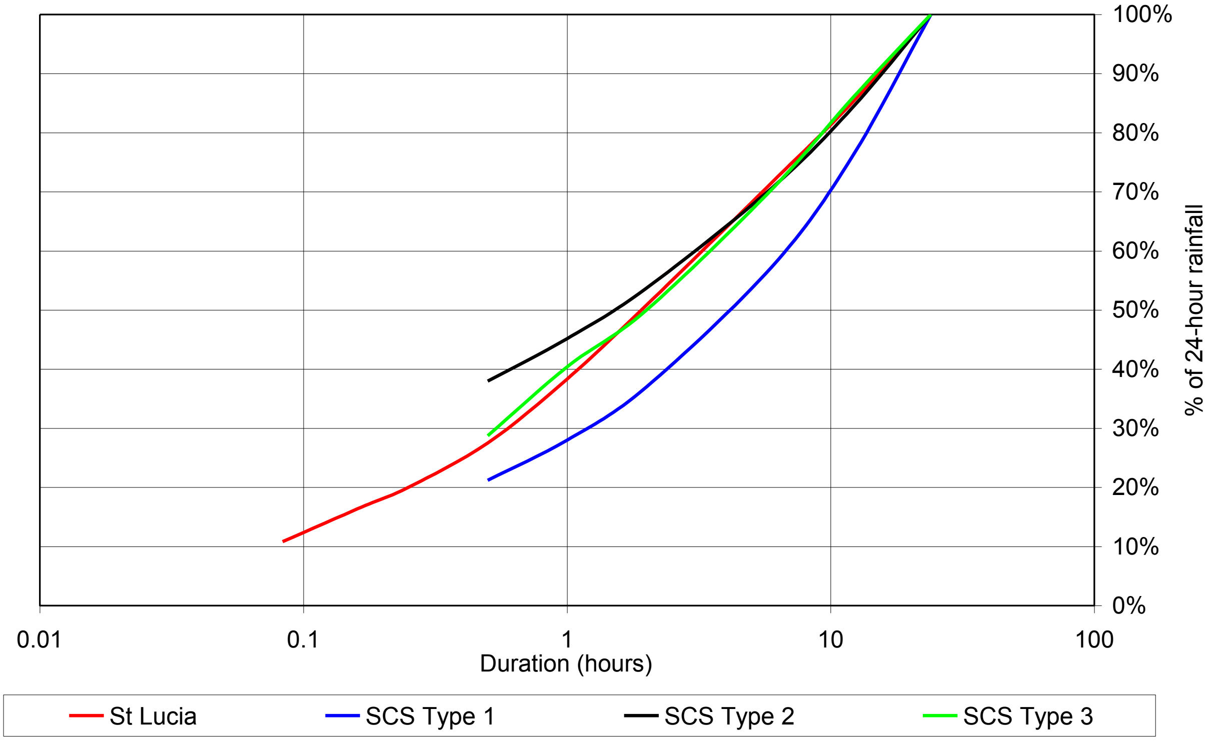


[5] Flood frequency analysis of the Cul de Sac River, St Lucia, using joint probabilities of rainfall and antecedent conditions; Acreman, MC and Boorman, DB; Hydrology of Warm Humid Regions (Proceedings of the Yokohama Symposium, July 1993), IAHS publication no. 216, 1993.

Source: Values abstracted from Acreman & Boorman (1993)

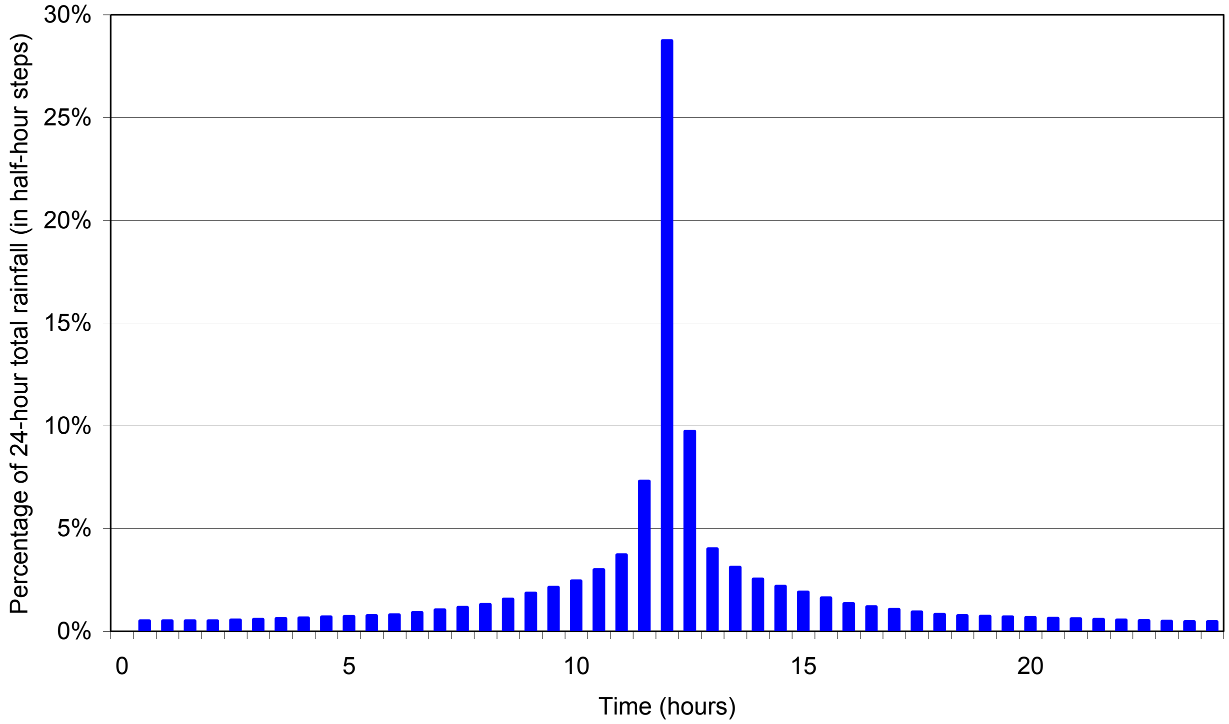
The adjusted profile of the Union Agricultural Station data is compared to the profiles of the widely-used SCS method (named from the former United States Soil Conservation Service) in Figure A.9, with the information presented as a percentage of the 24-hour rainfall. There are three standard SCS profiles; the local data closely follows the Type 3 curve which was set up to represent areas susceptible to tropical storms. If there had been no local data the Type 3 curve would have been chosen, but it is useful to have an indication that local data fits that curve.

Figure A.9: Comparison of St Lucia data to SCS Storm Profiles



In the SCS method the storm profile within the 24-hour period is arranged in such a way that the storm includes the relevant rainfall quantity (% of 24-hour total) for all durations from 0.5 to 24 hours. This “nested” half-hourly profile is illustrated in Figure A.10.

Figure A.10: Increments of 24-hour storm



Source: SCS Type 3 curve

The data for the four raingauges with data during Tomas was for a relatively short period and was evidently not complete, so analysis is subject to considerable uncertainty. The information is summarised in Table A.10; the annual rainfall is included because it gives an indication of years/stations with significant missing data during the year. All four records include data up to the beginning of July 2012; since most of that year's wet season was yet to come it is quite likely that the maximum hourly values from the data do not represent true annual maxima for 2012.

Table A.10: Annual and Maximum Hourly Rainfall from Recording Raingauge Data

	Marquis Babonneau		Cardi		Anse la Raye		Patience Estate	
Year	total	max hour	total	max hour	total	max hour	total	max hour
2003	1098	28	1199	25	1237	39		
2004			426	24	14	3		
2005								
2006								
2007								
2008			124	27				
2009	478	26	1789	43	1297	42	1002	46

	Marquis Babonneau		Cardi		Anse la Raye		Patience Estate	
2010	2835	56	3493	66	1704	49	2613	65
2011	2242	62	2006	33	1364	29	2672	44
2012	945	45	879	28	421	20	969	62

Excluding just 2004 at Cardi where the gauge appears to have ceased operating on 5th January, the median annual maximum hourly rainfall across the four stations is 42mm, and the mean is 41mm. Since there are considerable periods of missing data (most of 2009 at Marquis Babonneau, most of 2004 and 2008 at Cardi and most of the 2012 wet season at all four sites) it is possible that the true average values would be higher.

Compared to the derived island values shown in Figure A.7 and Table A.9, the mean value is about 37% of the daily total, and the median about 42%. These are broadly similar to the older St Lucia data and the SCS Type 3 curve (shown in Figure A.9). This provides further support for using the Type 3 curve in runoff assessment.

A.2.4 Severity of Tomas rainfall over a range of durations

On the assumption that the SCS Type 3 curve is generally applicable in St Lucia, it is possible to approximately estimate the return period of the Tomas rainfall for a range of durations, using the average values in Table A.5. The results are shown in Table A.11; the estimated return period rises steadily from 5 years for the 30-minute duration to 170 years for 12 hours (and about 200 years for daily rainfall, as previously noted). For the purposes of this table the Tomas rainfall has been adjusted to reflect the fact that the average rainfall at the four gauges with sub-daily data was lower than at all seven that had daily data.

Table A.11: Approximate Return Period of Tomas Rainfall

	30-mins	60-mins	120-mins	4-hrs	6-hrs	12-hrs
2-year	27	38	47	59	67	81
5-year	41	57	71	88	101	122
10-year	53	74	92	114	130	157
20-year	67	94	116	144	165	199
50-year	90	127	157	195	222	268
100-year	112	158	195	243	276	334
200-year	139	196	242	302	343	415
Tomas (adjusted)	41	68	116	190	247	390
approx RP	5	8	20	45	70	170

For small catchment areas (for example small hillsides draining to the road, or a length of road itself) the peak runoff is likely to arise from intense rainfall over a very short period, typically no more than 30 minutes. In this respect, therefore, Hurricane Tomas was in no way exceptional as its peak rainfall intensity would be expected to occur about once every five years on average. However, because of the prolonged nature of the storm, and the high total rainfall, this intensity on already saturated ground was sufficient to trigger landslides.

A.3 Flooding and drainage

A.3.1 Available information

It is understood that there are no currently-operating gauging stations with significant length of record. The Cul de Sac river was gauged at Ferrand Bridge from 1985, as reported by Acreman and Boorman (1993). From the available data an annual maximum flood series was derived; this gave a mean annual flood (MAF) of 29 m^3/s. A slightly higher figure of 30 m^3/s was derived from peaks-over-threshold (POT) analysis. This is presumed to also be an estimate of the MAF, though the text is slightly unclear. The paper states that floods of higher return period could not be derived with confidence because of a number of gaps in the record and several truncated peaks. There were also no high flow measurements available for the derivation of the rating curve. Although it was stated that an acceptable flood rating curve was derived there must be considerable uncertainty about the derived estimates of MAF.

Acreman and Boorman used a rainfall-runoff model to derive flood estimates for a 50-year flood. This showed a growth factor of only 1.6 between the MAF and the 50-year flood. This broadly reflects the ratio from the rainfall data used in the analysis. This growth factor is much lower than found from the analysis of annual maximum daily rainfall (2.6), perhaps because of the short period of sub-daily data on which the analysis was based. It should also be noted that it is normal for flood growth factors to be greater than rainfall growth factors because initial rainfall losses become proportionally less significant as rainfall increases.

The period for which the rainfall data was analysed (1979-87) appears to have had less severe rainfall events than the long-term average (mean annual maximum daily rainfall 105mm and maximum 161mm, compared to 124mm and 549mm for the full period of record).

Acreman and Boorman used the model to derive flood estimates for a development site 2km downstream of the gauging station. Based on this and survey of the channel it was estimated that floodplain inundation would occur on average about once every 50-60 years. Such a severe flood would not be accommodated by a natural river channel, but it is difficult to comment in this case because of channelization and flood levee construction work undertaken in 1987. However, the levees are well downstream of the gauging station site, and further upstream the channel remains substantially natural. Here there is likely to be substantial floodplain storage and perhaps significant attenuation of the flood peak. Satellite images taken after Hurricane Tomas confirm very substantial flooded areas within the catchment, but there is no information on the severity of that event in terms of runoff.

It may be noted that the Acreman and Boorman study originated because an initial estimate of the 5-year flood was exceeded on 10 separate occasions during a 5-month period. Their study raised the 5-year estimate by 54%, but did not comment on how many of the 10 events (if any) exceeded this revised figure.

From the information presented by Acreman and Boorman it seems possible that the estimated MAF is too low (intermittent flow data, uncertainty about the flood rating curve and a drier-than-average period), and probable that the growth factor is too low (comparison to rainfall growth factor). Taken together, it is very likely that the 50-year flood figures shown in the paper are too low, possibly by a substantial margin.

A.3.2 Rainfall-runoff modelling

A.3.2.1 Background

The SCS method (originally from the United States Soil Conservation Service) has been used to derive flood estimates. This uses catchment information (area, stream length and slope), design rainfall, storm profile (SCS Type 3 preferred, as shown above) and a curve number based on land use. The curve number is critical, particularly for events of moderate rather than extreme severity. Standard curve number tables give the curve number for a range of land uses for four soil groups that reflect the potential for infiltration. In some cases the hydrological condition is also taken into account, with “poor” condition having a higher curve number than “fair” or “good” condition. A higher curve number means higher runoff.

A.3.2.2 Ferrand Bridge catchment

For the Ferrand Bridge catchment the area is 26.8 km², longest drainage path 14.8km and the 1085 slope (calculated between the 10% and 85% points on the drainage path, measured from the outlet) is 0.0176. The land use is shown in Table A.12, together with the curve numbers for three of the soil groups. Group A was excluded because it is for high infiltration even when wet, and is considered inappropriate. The other three (B, C and D) are successively moderate, slow and very slow infiltration when thoroughly wet. The average curve number for the whole catchment ranges from 48 to 80 for the total catchment area.

Table A.12: Land Use and Curve Number for Ferrand Bridge Catchment

Land Use	Area (Ha)	Share	Adopted SCS category	CN (B)	CN (C)	CN (D)
Bare Ground/Scrub	6.77	0.3%	fallow, bare soil	86	91	94
Built-up Area	391.44	14.6%	second smallest category of plot size	75	83	87
Densely Vegetated Farming	1402.69	52.3%	continuous forage, good condition	35	70	79
Forest Reserve	628.57	23.4%	woods, fair condition	60	73	79
Grassland	4.21	0.2%	meadow	58	71	78
Intensive Farming	118.51	4.4%	continuous forage, good condition	35	70	79
Natural Tropical Forest	70.96	2.6%	woods, good condition	55	70	77
Other Vegetation	58.48	2.2%	brush, fair condition	56	70	77
Ponds	1.70	0.1%	impervious (gives high "runoff")	98	98	98
Total/average	2683.33	100.0 %		48	73	80

Using a 12-hour storm duration, the peak flows for the 2.33-year (mean annual) and 100-year events are as shown in Table A.13.

Table A.13: Ferrand Bridge Flood Estimates (m^3/s)

	Rainfall (mm)	For Soil Group B	For Soil Group C	For Soil Group D
2.33 year event	89	6	56	80
100-year event	334	266	480	529
Growth factor	3.8	47.6	8.6	6.6

Source: SCS calculations, storm duration 12 hours

Soil group B gives an extremely low mean annual flood because the curve number means that the model assumes most of the rainfall to be taken up by initial losses and ongoing infiltration, and the comparison with the recorded data indicates that group B could not be appropriate. Furthermore, local observation shows that streams and rivers respond quite quickly to heavy rainfall. Consequently, either group C or D is considered applicable. In both cases the mean annual flood figure is substantially higher than that from the data; however, as discussed above, the value from the data may well be too low. It is noted that a recent study by a local company for the Choc River[6] assumed soil group D.

Application of the model with the actual Tomas event rainfall (taken as the average of values for Marquis Babonneau, Cardi and Anse La Raye which are spread around the catchment and are roughly equidistant from the centre of the catchment) yielded a peak flow of 278 m^3/s. This is approximately the same as the 20-year flood calculated on the basis of the standard storm profile. With the calculated time-to-peak for the catchment being 105 minutes this result is reasonably close to the assessment of the rainfall (Table A.11) where the 120-minute rainfall was estimated to have a return period of about 20 years.

A.3.2.3 Road crossings in Cul-de-Sac watershed area

The length of the Primary Road Network within the Cul-de-Sac catchment has been studied and a total of 22 potential drainage crossing points identified along the length upstream of Ferrand Bridge. Apart from the river draining the southern part of the catchment (area 5.2 km^2) the drainage areas are very small (maximum less than 0.5 km^2), with runoff coming from the mountain ridge to the west of the road. The catchments are marked in Figure A.11, where the dots indicate the 10% and 85% points on the drainage path; in many cases the drainage path is so short that the 10% point is marked virtually at the point of the road crossing. The land use and derived curve number (assuming soil group D) is shown in Table A.14. Most of the catchments have a slightly higher curve number than the overall Ferrand Bridge catchment, because of the significant proportion of built-up area.

Table A.14: Land Use and Curve Number for Cul de Sac Cross-drainage Catchments

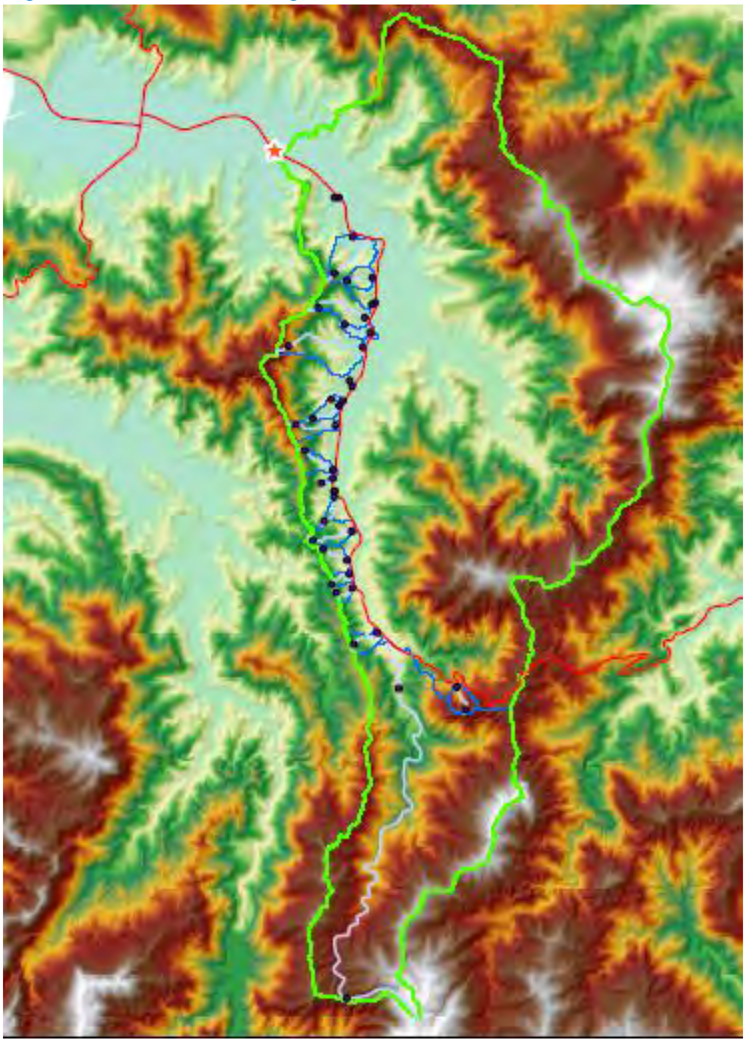
Sub-catchment	Area (km^2)	Built-up Area	Densely Vegetated Farming	Forest Reserve	Other Vegetation	Curve number (D)
1	0.0010	14%	86%	0%	0%	80

[6] Draft Choc Bridge Design Report, FDL Consult Inc, January 2013

Sub-catchment	Area (km²)	Built-up Area	Densely Vegetated Farming	Forest Reserve	Other Vegetation	Curve number (D)
2	0.1964	27%	3%	0%	70%	80
3	0.0675	45%	55%	0%	0%	83
4	0.2050	18%	80%	0%	2%	80
5	0.0010	100%	0%	0%	0%	87
6	0.0431	72%	28%	0%	0%	85
7	0.4475	6%	93%	0%	1%	79
8	0.0012	100%	0%	0%	0%	87
9	0.0058	100%	0%	0%	0%	87
10	0.0524	70%	30%	0%	0%	85
11	0.0946	19%	81%	0%	0%	80
12	0.0744	11%	89%	0%	0%	80
13	0.0056	60%	40%	0%	0%	84
14	0.0156	100%	0%	0%	0%	87
15	0.0001	100%	0%	0%	0%	87
16	0.1130	100%	0%	0%	0%	87
17	0.0912	100%	0%	0%	0%	87
18	0.0321	100%	0%	0%	0%	87
19	0.0357	93%	7%	0%	0%	86
20	0.0710	74%	26%	0%	0%	85
21	5.1598	2%	40%	58%	0%	79
22	0.0760	0%	76%	24%	0%	79

Note: Sub-catchments numbered from north to south along the road.

Figure A.11: Road crossing catchments within Cul-de-Sac Watershed



Source: Project GIS

The SCS method has been applied to these catchments to obtain estimated flood peaks for a range of return periods. However, many of the catchments are too small for the results to be considered reliable. In these cases it would be more appropriate to use the Rational method in which:

$$Q = C_1.C_2.I.\ A$$

Where: Q = discharge

I = rainfall intensity

A = drainage area

C_1 = coefficient of runoff

C_2 = allowance for unit conversion

The rainfall intensity should be that for the period of time required for all parts of the catchment to be contributing to runoff at the catchment outlet (i.e. the road crossing culvert or other structure). In extremely small catchments (and especially urban ones) this might be only a very few minutes, and consequently the rainfall intensity might be exceptionally high. In practice it is usual to limit the assessment to the rainfall intensity over, say, 15 or 30 minutes. The curve number can be taken as the runoff coefficient (as a percentage). The unit adjustment factor is found as follows:

If A is in km² and I is in mm/hour, $C_2 = (10^6 \times 10^{-3}/3600) = 1/3.6$

Adopting the 30-minute rainfall intensity, the rainfall intensities for a range of return periods are as shown in Table A.15. For road drainage it would generally be appropriate to use a 20-year return period; experience shows that anything higher is likely to lead to excessive cost that would not be justified by avoiding surcharging of the drains in occasional more severe events. It is worth noting that in very intense rainfall it is likely that there will be very little traffic using the roads.

Table A.15: Design Rainfall Intensities

Return period (years)	Daily (mm)	Peak 30-mins (mm)	Intensity (mm/hour)
5	142	41	82
10	183	53	105
20	232	67	133
50	313	90	180

Note: Daily values from Table A.9.

The analysis undertaken indicates that the Rational method should be applied for all catchments up to about 0.2 km² or 200,000 m². There are likely to be few (if any) areas greater than this requiring drainage as part of the project, so it is recommended that the Rational method be used throughout. If there should be a catchment larger than 0.2 km2 the effect would be to achieve slightly greater freeboard in the design.

The runoff coefficient (curve number, expressed as a fraction or percentage) should be 0.98 for areas of the road surface. For other areas the curve number can be assessed by determining the land use from the GIS and calculating a weighted average curve number using the areas of each land use category and the CN(D) values from Table A.12. As an alternative to using the GIS, adopting an average curve number of 85 for non-road areas should give a result of sufficient accuracy for the purpose of sizing drainage.

A.3.3 Drainage

Standard details for a range of road drains (including culverts and cross-drains) are contained in a volume produced by the government ministry that preceded the Ministry of Infrastructure, Port Services and Transport (MIPST)[7], and in use by engineers within the MIPST. These should be sufficient for conceptual design of schemes under this project.

Observations around the network show generally satisfactory drainage provision. There are inevitably some issues of channels being partially blocked, but drain clearance teams were seen in action and it is to be hoped that most blockages would be cleared before the main wet season period. Some drains are clearly smaller than shown in the standard drawings, possibly because of space constraints. Of greater concern are channels that are not properly lined, or where sections of drainage are not properly linked together, particularly where this might allow water to flow under the road.

A.3.4 Key recommendations

- Conceptual drainage design should use the standard designs already in use in the MIPST.
- Drainage infrastructure should generally be designed for a 20-year return period rainfall intensity.
- A 30-minute duration is appropriate for determining the rainfall intensity; in more intense shorter duration storms there is likely to be some ponding on the road, but traffic is likely to be minimal at such times.
- The estimated 30-minute 1-in-20 year rainfall intensity is 133 mm/hour. This value is appropriate throughout the Primary Road Network.
- Peak flow should be estimated using the Rational formula.
- The runoff coefficient in the Rational formula should be the average curve number for the area concerned (assuming soil group D), expressed as a percentage.
- The average curve number can be determined from land use categories in the GIS, or may be estimated assuming CN=98 for the road surface and CN=85 for other areas.

[7] Standardized Drawings for Primary and Secondary Roads, Ministry of Communications, Works, Transport and Public Utilities, Government of St Lucia, January 2011

Appendix B. Details of landslides in Saint Lucia

B.1 Historical Hurricane Tracks

Historical Hurricane Tracks

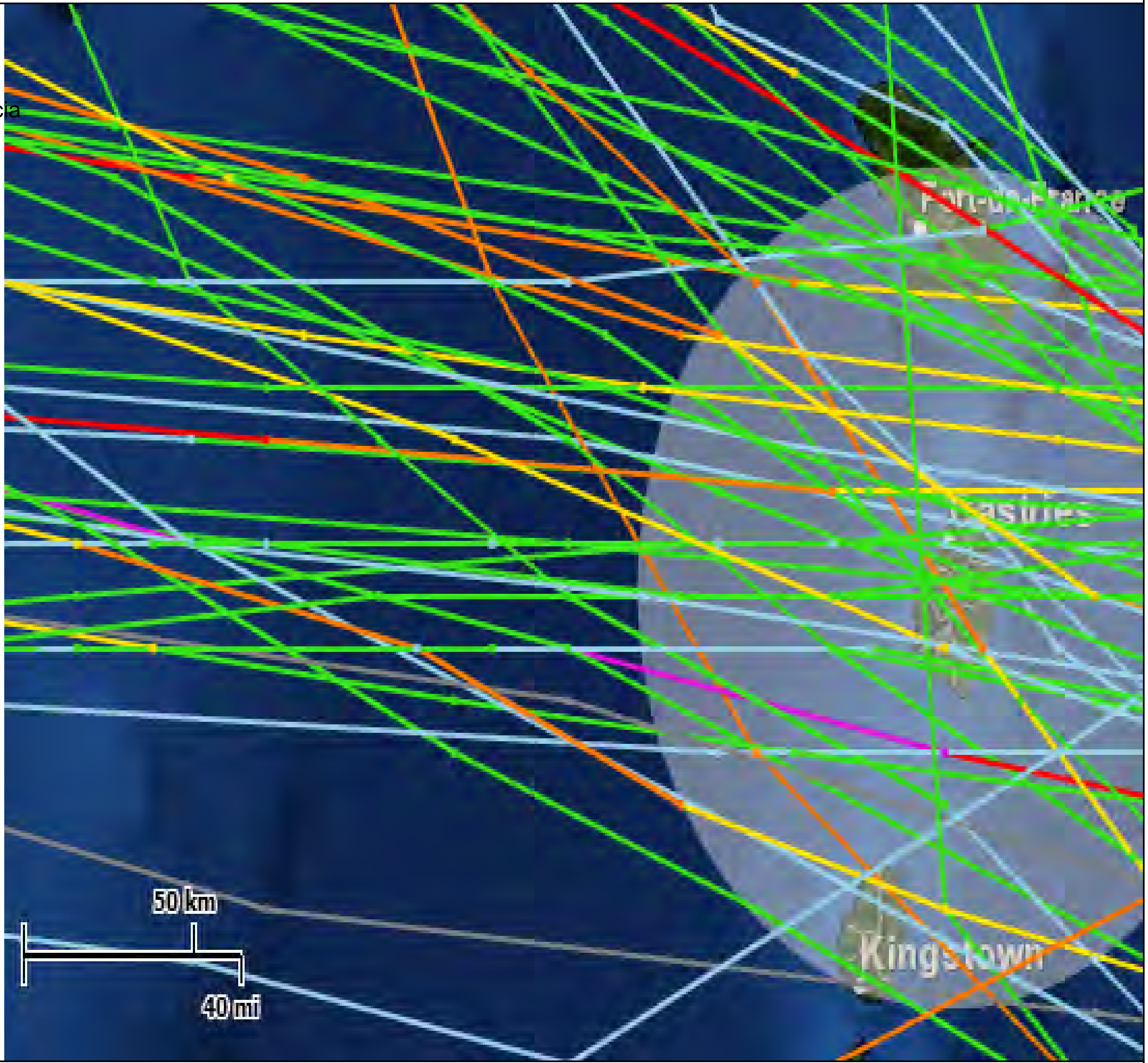
National Oceanic and Atmospheric Administration

Summary of Search:

Location: Saint Lucia Island, island, Saint Lucia
Buffer: 92600 Meters (50 Nautical Miles)
Search was not refined

Summary of Storms

Category	Count
Category 5 (H5)	4
Category 4 (H4)	5
Category 3 (H3)	11
Category 2 (H2)	10
Category 1 (H1)	4
Trop./Sub. Storm (TS/SS)	19
Trop./Sub. Depression (TD/SD)	5
Extratropical (ET)	0
Unknown (N/A)	0



H5 H4 H3 H2 H1 TS/SS TD/SD ET N/A

http://www.csc.noaa.gov/hurricanes

Historical Hurricane Tracks
National Oceanic and Atmospheric Administration

Storm Name	Max Saffir-Simpson	Date
NOT NAMED 1872	H1	Sep. 9, 1872 to Sep. 20, 1872
NOT NAMED 1875	H3	Sep. 8, 1875 to Sep. 18, 1875
NOT NAMED 1876	H2	Sep. 29, 1876 to Oct. 5, 1876
NOT NAMED 1879	TS	Oct. 9, 1879 to Oct. 16, 1879
NOT NAMED 1880	H1	Aug. 15, 1880 to Aug. 20, 1880
NOT NAMED 1886	H3	Aug. 15, 1886 to Aug. 27, 1886
NOT NAMED 1887	TS	Jul. 30, 1887 to Aug. 8, 1887
NOT NAMED 1887	H2	Sep. 11, 1887 to Sep. 22, 1887
NOT NAMED 1888	TS	Nov. 1, 1888 to Nov. 8, 1888
NOT NAMED 1891	H3	Aug. 18, 1891 to Aug. 25, 1891
NOT NAMED 1894	H4	Oct. 11, 1894 to Oct. 20, 1894
NOT NAMED 1895	H2	Aug. 22, 1895 to Aug. 30, 1895
NOT NAMED 1896	H3	Aug. 30, 1896 to Sep. 11, 1896
NOT NAMED 1898	H2	Sep. 5, 1898 to Sep. 20, 1898
NOT NAMED 1901	H1	Jul. 4, 1901 to Jul. 13, 1901
NOT NAMED 1903	H3	Aug. 6, 1903 to Aug. 16, 1903
NOT NAMED 1916	H2	Jul. 10, 1916 to Jul. 22, 1916
NOT NAMED 1916	H4	Aug. 12, 1916 to Aug. 20, 1916
NOT NAMED 1916	H3	Oct. 6, 1916 to Oct. 15, 1916
NOT NAMED 1917	H4	Sep. 20, 1917 to Sep. 30, 1917
NOT NAMED 1918	TS	Sep. 9, 1918 to Sep. 14, 1918
NOT NAMED 1924	H3	Aug. 16, 1924 to Aug. 28, 1924
NOT NAMED 1931	TS	Aug. 10, 1931 to Aug. 18, 1931
NOT NAMED 1931	TS	Aug. 16, 1931 to Aug. 21, 1931
NOT NAMED 1941	H3	Sep. 23, 1941 to Sep. 30, 1941
NOT NAMED 1942	H3	Aug. 21, 1942 to Aug. 31, 1942
NOT NAMED 1942	TS	Sep. 15, 1942 to Sep. 22, 1942
NOT NAMED 1943	H2	Oct. 11, 1943 to Oct. 18, 1943
NOT NAMED 1948	TS	Aug. 31, 1948 to Sep. 1, 1948
NOT NAMED 1949	TS	Aug. 30, 1949 to Sep. 3, 1949
DOG 1951	H3	Aug. 27, 1951 to Sep. 5, 1951
ELLA 1958	H3	Aug. 30, 1958 to Sep. 6, 1958
ABBY 1960	H2	Jul. 10, 1960 to Jul. 16, 1960
EDITH 1963	H2	Sep. 23, 1963 to Sep. 29, 1963
BETSY 1965	H4	Aug. 27, 1965 to Sep. 13, 1965
JUDITH 1966	TS	Sep. 27, 1966 to Sep. 30, 1966
BEULAH 1967	H5	Sep. 5, 1967 to Sep. 22, 1967
EDITH 1967	TS	Sep. 26, 1967 to Oct. 1, 1967
UNNAMED 1969	TD	Jul. 25, 1969 to Jul. 27, 1969
DOROTHY 1970	TS	Aug. 17, 1970 to Aug. 23, 1970
UNNAMED 1970	TD	Sep. 23, 1970 to Oct. 11, 1970
CHLOE 1971	TS	Aug. 18, 1971 to Aug. 25, 1971
UNNAMED 1976	TD	Oct. 3, 1976 to Oct. 12, 1976
ANA 1979	TS	Jun. 19, 1979 to Jun. 24, 1979
ALLEN 1980	H5	Jul. 31, 1980 to Aug. 11, 1980

Historical Hurricane Tracks
National Oceanic and Atmospheric Administration

Storm Name	Max Saffir-Simpson	Date
UNNAMED 1983	TD	Jul. 23, 1983 to Jul. 28, 1983
UNNAMED 1984	TD	Jul. 24, 1984 to Jul. 26, 1984
GILBERT 1988	H5	Sep. 8, 1988 to Sep. 20, 1988
CINDY 1993	TS	Aug. 14, 1993 to Aug. 17, 1993
DEBBY 1994	TS	Sep. 9, 1994 to Sep. 11, 1994
IRIS 1995	H2	Aug. 22, 1995 to Sep. 7, 1995
CHANTAL 2001	TS	Aug. 14, 2001 to Aug. 22, 2001
IRIS 2001	H4	Oct. 4, 2001 to Oct. 9, 2001
JERRY 2001	TS	Oct. 6, 2001 to Oct. 8, 2001
CLAUDETTE 2003	H1	Jul. 7, 2003 to Jul. 17, 2003
BONNIE 2004	TS	Aug. 3, 2004 to Aug. 14, 2004
DEAN 2007	H5	Aug. 13, 2007 to Aug. 23, 2007
TOMAS 2010	H2	Oct. 30, 2010 to Nov. 27, 2010

B.2 Details of selected landslide events

B.2.1 Ravine Poisson/Ravine Crebiche Landslide (1938)

O'Keefe and Conway (1977) reported on natural hazards in the Caribbean from 1938 t0 1954 in a paper titled ' A disaster history of St. Lucia' published by the University of Bradford. They reported that the Ravine Poisson/Ravine Crebiche landslide occurred on November 21, 1938 after the region had experienced 244 mm of rainfall in one day from a tropical storm. Rainfall distribution for the year was irregular and abnormal and was reported at 965 mm above the 50 year average. The Barre de L'isle road was blocked by a landslide. For eighteen days landslides had prevented passage along the road to the southeastern part of the island. A work force of several hundred inhabitants was present near Ravine Crebiche and the neighbouring Ravine Poisson labouring to clear the road. This was the result of eight days of continuous rainfall.

At 9:00 am on Monday, November 21, 1938 a landslide from Ravine Crebiche swept into the area where workmen were clearing the previous landslide debris. An hour later, a second landslide issued from neighbouring Ravine Poisson. The areas engulfed by these landslides was described as "a sea of mud".

The following morning at about 4:00 am, a third landslide covered an area one half mile away. A total of 60 persons are known to have died in these landslides. Another 32 persons were injured and it is unknown if all the injured survived. Estimates of missing workers were as high as 250. an area of 10 square kilometres encompassing the ravines and vicinity was ordered evacuated and resulted in the displacement of some 500 persons. In terms of loss of life, injury and short term disruption of people's lives due to evacuation, the landslide disaster at Ravine Crebiche and Ravine Poisson represent one of the worst experienced in the Eastern Caribbean.

B.2.2 Ravine Poisson, Barre de L'isle and Labayee Landslides (1939 & 1940)

Data on these landslide events is limited and details of the exact location of the landslides are not available. Three villages on the island were destroyed by a tropical storm on January 7, 1939 with 100 persons reported dead. On August 7, 1940 Ravine Poisson, Barre de L'isle and Labayee communities were badly damaged by a tropical storm. There was extensive damage to livestock and plantations. Roads and retaining walls that were built after 1939 were destroyed.

B.2.3 Ravine Poisson Landslide (1954)

Farmers were severely affected by this storm event on December 12, 1954 which totally destroyed a whole year's output of staple crops and bananas. Recorded rainfall for the year was 3,277 mm. ravine Poisson was badly hit by landslides.

B.2.4 Barre de L'isle Landslide (1980)

On August 3, 1980 a landslide was triggered on the Barre de L'isle ridge by the passing of hurricane Allen. The landslide blocked the main road causing a disruption of traffic to the east coast and to the International airport at Vieux Fort. The landslide affected the main road to the extent that clearing the road did not restore access to the southern part of the island.

The road was later restored by the construction of a masonry wall at the toe of the slide and three gabion structures within the failed area in order to stabilize the slope.

B.2.5 Tropical Storm 'Debbie' (1994)

In recent times, landslide events and their impact on the socio-economic structure of the island of Saint Lucia has increased. This is attributed to a) the increase in frequency and severity of low pressure systems which affect the Lesser Antillies and b) the encroachment of forested areas by agricultural farming in particular bananas.

On September 9, 1994, the island was ravaged by Tropical Storm "DEBBIE" For several days a tropical wave had been monitored from satellite observations but there had been no reason to believe that it could develop into a full storm. However, during the night of September 9, when the wave hit Saint Lucia, it developed into rapidly from a tropical wave to a depression and then into a tropical storm.

The most devastating part of Tropical Storm "DEBBIE" was not so much the wind speed, although some wind-related damage did occur, but rather the very intensity rainfall that accompanied it. In particular, in the early hours of September 10, heavy rainfall was experienced in the interior parts of the island.

Six rainfall gauging stations were operational throughout the storm, with recorded 24 hour totals ranging from 230 mm to 360 mm. Maximum recorded one hour rainfall intensities reached 90 mm/hr at Union research Station, with an estimated peak one hour intensity in the Upper Roseau Valley of 141 mm/hr.

The short duration, high intensity rainfall experienced during the storm formed the most critical storm profile type for Saint Lucia's small and steep catchments. This, in combination with the already saturated soil conditions due to antecedent rainfall, resulted in high discharges in the rivers, in particular those whose catchments drain the steep slopes on the central mountain range of Morne Gimie.

The devastating effect of the resulting flood was aggravated by large volumes of debris and sediment that came down the rivers, particularly derived from extensive landslide activity that occurred on steep slopes. Widespread debris flow activity led to the removal of large tracks of forest, the loss of vast acreages of agricultural crops and extensive erosion, particularly in the upper watersheds of the rivers.

More than 400 landslides were reported to have occurred as a result of Tropical Storm "DEBBIE", resulting in loss of soil, trees and crops which contributed to the debris and sediments which dammed the rivers and damaged adjoining farmland. More than 90 per cent of the landslides occurred in the upper reaches of the watersheds with landslides occurring in every main drainage area in some catchments. A large portion of the landslides were shallow debris flows, ten to twenty metres in width, originating close to ridge crests. Debris and rock slides occurred principally along roads.

The floods caused four deaths, twenty four persons were injured, six persons were reported missing, thirty seven were made homeless and five hundred displaced persons had to be accommodated in temporary shelters.

B.2.6 The Millet Primary School Landslide (1995)

During the month of September 1995, a landslide occurred at the Millet Primary School following a period of heavy incessant rainfall triggered by hurricane “IRIS”. The landslide raised some concern about the safety of the students and faculty and an urgent appeal was made by representatives of the Government of Saint Lucia for the implementation of immediate remedial slope stabilization measures to eliminate the risk of further instabilities developing within the slope that may result in serious consequences regarding the school occupants and the facility.

A large flow of slope debris had buttressed against the southwestern section of the building and the toe of the debris flow extended 4.0 m around the southwest corner of the building. The slope debris was inclined at an angle of 17° with the crest located some 33.0 m upslope. Groundwater seepage was observed through cracks and fissures in the slope debris. Walkways and utility lines were damaged as a result of the landslide. The remaining slopes in close proximity of the school building showed signs of instability and had to be stabilized.

An investigation of the cause of the landslide indicated that a retaining wall structure was necessary to stabilize the failed slope.

B.2.7 The Boguis Landslide (1998)

The agricultural community of Boguis located approximately 14 kilometres east of Castries experienced disturbing ground movements in early September 1998 which resulted in the appearance of cracks in the walls of masonry structures and tension cracks on the ground surface. Residents at the site reported feeling earthquake tremors prior to the occurrence of the landslide.

Additional information acquired from local residents indicated that the Boguis Health Centre which was located at the toe of the slope experienced slope instabilities some four years previous and cracks had appeared in the walls of the building.

Several houses were destroyed by the landslide causing the displacement of about four families. The water supply to the community was interrupted as a result of broken water pipes.

The slope instability at Boguis was caused by a change in the groundwater regime due to incessant rainfall and the indiscriminate disposal of waste water by residents.

B.2.8 Black Mallet/Maynard Hill Landslide (1999)

The problem of slope instability at the residential community of Black Mallet/Maynard Hill was brought to public attention with dramatic force on October 7, 1999 when approximately 80,000 cubic metres of colluvial material “flowed” downslope toward the Marchand river causing the destruction of several residences and ruptured public utilities servicing the community.

Large tension cracks developed on the roads in the community and at various locations on hill slopes where there was ground displacement. Several concrete residences showed evidence of distress with numerous cracks developing on walls and several water and sewer mains were ruptured. It was reported by some residents in the community that prior to the main slide event on October 7, minor tension cracks were observed developing on the walls of their homes during late September, 1999. A total of 300 persons were displaced and 60 residences were destroyed as a result of the landslide. No fatalities were reported.

An investigation of the landslide event indicated that the slope was in a steady state of movement for a period of years prior to the failure. This was evident in the presence of old cracks observed on several concrete structures and reports from residents of frequent disturbing noises caused by ground movement during periods of heavy rainfall and earthquake events. Soil creep or slow gravitational movement of the subsurface soils from frequent wetting and drying appeared to have occurred throughout the site.

The main contributing factors which triggered the landslide included the following:

i) poor drainage conditions to divert surface water runoff downslope and away from the site

ii) the existence of leaking septic tanks for human waste disposal from residences

iii) an increased of pore water pressure conditions in a confined sand aquifer in the subsoils which liquefied causing instability in the slope

iv) the low shear strength of the colluvial material at the site

v) seismic events which occurred prior to and at the time of the landslide which triggered slope failure

B.2.9 The Tapion Landslide (2004)

On September 26, 2004 a landslide was triggered in the suburban residential community of Tapion when approximately 1,800 cubic metres of colluvial material flowed downslope and destroyed two residential buildings and adjacent residences had to be abandoned.

An area of about 1,250 square metres was affected by the landslide on a 15o slope which extends eastwards to a very steep cut in weathered rock. Surface runoff was collected by an earth drain located on the east side of an access road which channels waste water to a collector ditch downslope.

Several tension cracks were observed on the access road at the crest of the slope and there was bulging at the toe of the mobilized soil mass. Several utility ducts were ruptured and water flowed freely into the failed soil mass. Overhead power lines were damaged and had to be replaced.

The results of an investigation into the cause of the landslide indicated that the slope had been in a steady state of movement or creep for some period of time. The occupant of one of the damaged buildings had resided at that location for five years and had noticed cracks developing in the walls of his house since 2001. He recalled that on May 2004 he felt a sudden jolt of his building during the late hours of the evening. Some research of the seismic events that occurred during that period revealed that there was an earthquake event of magnitude 4.1 during the month of May 2004.

Soil creep is usually caused by frequent wetting and drying of the soil on a slope and it appears that this had occurred throughout the site. Creep is usually a forewarning of active instability that may be initiated by uncontrolled events. Slopes comprised of colluvium are generally of limiting stability because over geological times the formation of a colluvial soil slope is a dynamic process which naturally involves slope movement by gravity and water.

The main factors that affected landslide initiation at Tapion are as follows:

- the presence of poorly maintained surface drains at the crest of the slope which were incapable of diverting surface run-off away from the slope resulting in rainfall infiltration and saturation of the colluvial material;
- excess pore water pressure build up in the colluvial material due to infiltration or the possible existence of subsurface flow channels;
- the presence of loose, sandy, permeable, and saturated colluvial with a high liquefaction potential;
- ground borne vibrations from recent earthquake activity on the island may have contributed by reducing the shear strength of the saturated colluvium.

B.2.10 The Barre de L’isle Landslide (2005)

During the month of July, 2005 a landslide occurred on the Barre de L’isle ridge causing a disruption of vehicular traffic flow along the main road to the eastern and southern parts of the island. The Barre de L’isle ridge is the main east to west divide of the island with the highest elevation at 440 m. The existing road is steep and tortuous and landslides frequently occur on the slopes during the wet season. The landslide occurred on the eastern slope of the ridge where the road to Dennery converges in a sharp curve with gradual slopes on both sides of the road. Numerous tension cracks had appeared on the road surface and on the adjacent northern and southern slopes of the road cut.

Rainfall data for the Barre de L’isle ridge during the period of January to December 2005 indicated a maximum of 377 mm over a 24 hour period. The slope was instrumented with slope inclinometers and standpipe piezometers to monitor pore water pressures and subsurface movement. An interpretation of the field instrumentation results indicated that remedial slope stabilization should include one or a combination of the following:

i) surface and sub surface drainage facilities

ii) the installation of passive piles on the slope

iii) the installation of soil nails

iv) relocation of the existing roadway to an alternate route to bypass the unstable area

B.2.11 The Windjammer Landing Beach Resort Landslide (2005)

A landslide occurred at the site of the Windjammer Landing Beach Resort during the month of July, 2005 which caused extensive damage to a few high scale villas, roadways, buried utility services, retaining walls and posed an immediate threat to the Administration building and villas upslope.

Previous studies of slope instability at this site had been conducted and reported by engineering consultants from 1989 to 2004.

The general subsoil stratigraphy at the site consisted of colluvium overlying highly weathered basalt bedrock. Field instrumentation of the landslide area consisted of standpipe piezometers, slope inclinometers, dewatering wells, a rain gauge and tensiometers. Artesian pressure was recorded in one of the standpipe piezometers at the crest of the failed slope.

The slope instability problem at this site was caused by several contributing factors.

The presence of interbedded, slickensided layers of volcanic ash in the colluvium was a contributing factor in reducing the shear strength of the colluvial material. Data collected from a Government weather station in the vicinity of the resort showed heavy rainfall occurring during the months prior to the landslide. Other landslide events had occurred at other locations on the island during that same time period e.g. Barre de L'isle.

Remedial slope stabilization works involved soil replacement since it provided the most immediate implementation stabilization method with the equipment and technology available on the island.

B.2.12 Hurricane Tomas (2010)

On Saturday October 30, 2010 Hurricane 'TOMAS' ravaged the island of Saint Lucia with maximum sustained winds of 160 km/hr and rainfall up to 668 mm as a Category 2 system . The hurricane was initially classified as a Category 1 system with sustained winds of 120 km/hr but was later upgraded to a Category 2 system. Strong winds began at about 10:00 am on Saturday and subsided around 8:00 am on Sunday October 31, lasting for a period of 22 hours.

Two (2) persons were confirmed dead and three (3) persons missing at Colombette and four (4) persons dead and one (1) person missing at Fond St. Jacques as a result of landslide activity during hurricane 'TOMAS'.

The Government Meteorological Centre reported rainfall measurements at various locations on the island over a 24 hour period as follows:

Location	Rainfall
Hewanorra International Airport (Vieux Fort – South)	347.3 mm
George F.L.Charles Airport (Castries – West)	533.3 mm
Soufriere (West)	668.0 mm
Forestierre (Castries – Central)	633.0 mm
Windjammer Landing Resort (Gros Islet – North)	130.0 mm

Rooftops, power lines and trees were blown away by the strong winds and several bridges collapsed due to overflowing rivers. The heavy rains caused saturation of the ground and triggered several landslides some more severe than others.

The main triggering mechanism causing the landslides was the intensive and prolonged rainfall which saturated the subsurface soils resulting in an increase of the groundwater regime which in turn caused an increase in the soil pore water pressure. This resulted in a loss in shear strength of the subsoils resulting in the mobilization of the subsoils on slopes.

The most pronounced landslides occurred at Colombette and Fond St. Jacques (Soufriere); the Barre de L'isle Ridge (Dennery) and in communities east and south of the capital city of Castries, such as the Morne, Derriere Fort, Bagatelle, Forestierre, Babonneau, Millet and Marc.

A summary of observations and recommendations for these areas are presented in the following table:

Table B.1: Summary of major landslides triggered by Hurricane 'Tomas' on October 31, 2010

Landslide	Description of Failure Mechanism	Potential Hazards	Proposed Mitigation	Notes/ Comments
Colombette An extensive slide which resulted in loss of life, damage to the main arterial roadway and significant mass wasting.	Very rapid debris avalanche as a result of an increase in the pore water pressure within the subsoils.	The soil mass is likely to expand through increased sliding and creep. This could affect the integrity of the roadway and the utilities within the easement. Soil	**Short Term**: Clear roadway, provide surface drainage, flatten the slope for increase stability and build retaining walls along roadway cuts. **Long Term**: Realign the	The area is unsuitable for development unless a major mitigation project to improve slope stability is undertaken. The risk after

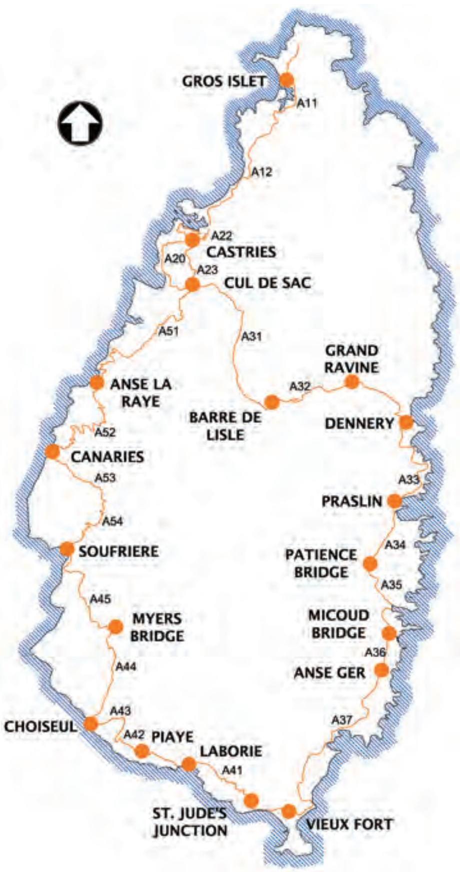
Landslide	Description of Failure Mechanism	Potential Hazards	Proposed Mitigation	Notes/ Comments
		erosion is causing a major environmental impact to the surrounding area including the marine reserve.	roadway, use subsurface drainage, use soil reinforcement and plant trees along the exposed slopes.	development may be higher than usually accepted.
Fond St. Jacques An extensive slide which resulted in loss of life, damage to roadway infrastructure including two bridges, significant mass wasting and the destruction of residence.	Very rapid debris avalanche as a result of an increase in the pore water pressure within the subsoils.	There is evidence of soil creep which could lead to additional slippage at the landslide site. Significant instability may occur during or after extreme rainfall of earthquakes.	**Short Term**: Evacuate area within the slide zone. Provide adequate surface drainage and implement a river training program. **Long Term**: Redesign the landscape to improve slope stability. Evaluate the area for stability of residential settlement. Plant trees on slopes and install relief wells for springs.	Development restrictions are required to limit and control activities which could affect the stability of the area. The potential of other landslides exists for other larger slopes surrounding the area based on a similar mechanism of failure.
Barre D'Isle A series of landslides along the mountains and within the roadway cut and fill sections damaging roadway and utility infrastructure.	Slow to rapid debris flow as a result of an increase in the pore water pressure within the subsurface soil layer	There is evidence of soil creep which could lead to additional slippage along the roadway. Significant instability may occur during or after extreme rainfall or earthquakes.	**Short Term**: Evacuate area within the slide zone. Provide adequate surface drainage and implement a river training program. **Long Term**: Develop an alternate route to by pass area which may require highway bridges and tunnels.	Development and cultivation restrictions may be required.
Millet A series of landslides along the access roadway to the main water supply of St. Lucia.	Slow to rapid debris flow as a result of an increase in the pore water pressure within the subsurface soil layer.	There is evidence of soil creep which could lead to additional slippage along the roadway. Significant instability may occur during or after extreme rainfall or earthquake.	**Short Term**: Clear roadway and provide adequate surface drainage to control storm water. Flatten and or bench slopes to increase slope stability. **Long Term**: Improve slopes along roadway.	The roadway needs to be improved to with a focus of uninterrupted access to the Dam site.
East and South Hills of Castries A series of landslides within residential communities impacting, roadways, utilities and residence.	Slow to rapid debris flow as a result of an increase in the pore water pressure within the subsurface soil layer.	There is historical evidence of creep which became extensive landslides, impacting lives and infrastructure. Significant instability may occur during or after extreme rainfall or earthquakes.	**Short Term**: Clear Roadway and provide adequate surface drainage to control storm water. Flatten and or bench slopes to increase slope stability. **Long Term**: Implement comprehensive storm water management plan.	Residents need to control runoff to reduce creep. Overall strategy on storm water management needs to be implemented.

Landslide	Description of Failure Mechanism	Potential Hazards	Proposed Mitigation	Notes/ Comments
			Improve slopes along roadways along with retaining structures to improve overall stability of area.	

Source: R. Isaac, Strata Engineering Consultants Ltd

Appendix C. Project brochure

LANDSLIDE RISK ASSESSMENT
FOR SAINT LUCIA'S PRIMARY ROAD NETWORK



SAINT LUCIA
Map shows primary road network across the island

The Government of Saint Lucia's Ministry of Infrastructure, Port Services and Transport (MOIPS&T) has obtained a loan from the Caribbean Development Bank for Natural Disaster Management – Rehabilitation and Reconstruction (Hurricane Tomas). A portion of the loan has been applied to finance this Landslide Risk Assessment for Saint Lucia's Primary Road Network.

This brochure provides basic information about the nine month assignment and aims to identity information that may be of use to the assignment held by persons or organisations.

The Primary Road Network of St Lucia is vital for the social, economic and developmental well being of the country. The impacts on the Primary Road Network by Hurricane Tomas were extensive. The overall objective of this assignment is to reduce landslide risk to the primary road network of St Lucia. The project is expected to enhance the capacity of the Government of Saint Lucia to manage landslide hazards.

In agreement with the MOIPS&T, the primary road network has been defined to comprise:

- the A11 & A12 primary roads north of Castries
- the east and west coast roads
- the Barre de L'Isle
- the Morne
- the Millennium Highway
- Bois Cachet
- La Toc

Landslides in Saint Lucia

Climate, ground conditions and steep topography all combine to make the Island of St Lucia susceptible to landslides. The landslide problem in Saint Lucia is often linked to development, for most of the landslides along the road network during Hurricane Tomas resulted from man-made slopes, i.e. cut slopes, fill slopes, clearing of lands for farming and retaining walls created by the process of hillside development. This assignment recognises that landslides can be stabilised, the primary road network and users protected, and remediation implemented. This assignment also recognises financial constraints and that stabilisation may not always be appropriate. Measures should be effective not only in cost but also in the way they increase landslide stability.

Assignment Tasks

A landslide hazard and vulnerability analysis for the primary road network will be produced. The analysis will be used to inform a landslide risk assessment for the primary road network. Engineers and geotechnical specialists will walk the primary network and use a risk matrix to categorise the landslide risk. This will allow ranking of sites in terms of frequency of failure and impact on the primary road network. Cost benefit analysis at the priority sites will be completed to allow informed assessment of the most appropriate management or stabilisation option. Preliminary designs will be prepared where appropriate.

The above activities will feed into a capacity strengthening plan for landslide emergency response and risk management. Training on specific measures will be provided. Throughout the assignment stakeholder consultation will be undertaken to ensure coordination among government and other entities.

Mott MacDonald, a British consultancy, is supported by

Strata Engineering Consultants Ltd. (Saint Lucia), and experts Professor Norbert Morgenstern from the University of Alberta, Canada, Fred Matich, and Dr Mark Lee lecturer at the University of Sussex, UK

Mott MacDonald has been commissioned to provide technical assistance comprising

- analysing and assessing of slope stability, drainage and geotechnical conditions
- mapping levels of risk
- identifying primary and secondary causal factors of slope movement
- identifying cost effective slope stabilisation, protection and landslide remediation measures

PROJECT CONTACTS

If you have data or information that would be useful to the assignment or wish to know more about the results, please contact us.

CHRIS ARNOLD - Mott MacDonald Ltd.
T 758-721-3145
E chris.arnold@mottmac.com

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T 758-484-0377
E geostrata_inc@yahoo.com

JUDE REGIS - MIPS&T
T 758-718-1468
E jude.regis@yahoo.com

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Appendix D. Project GIS

Appendix E. Hazard mapping

E.1 Initial air photo interpretation

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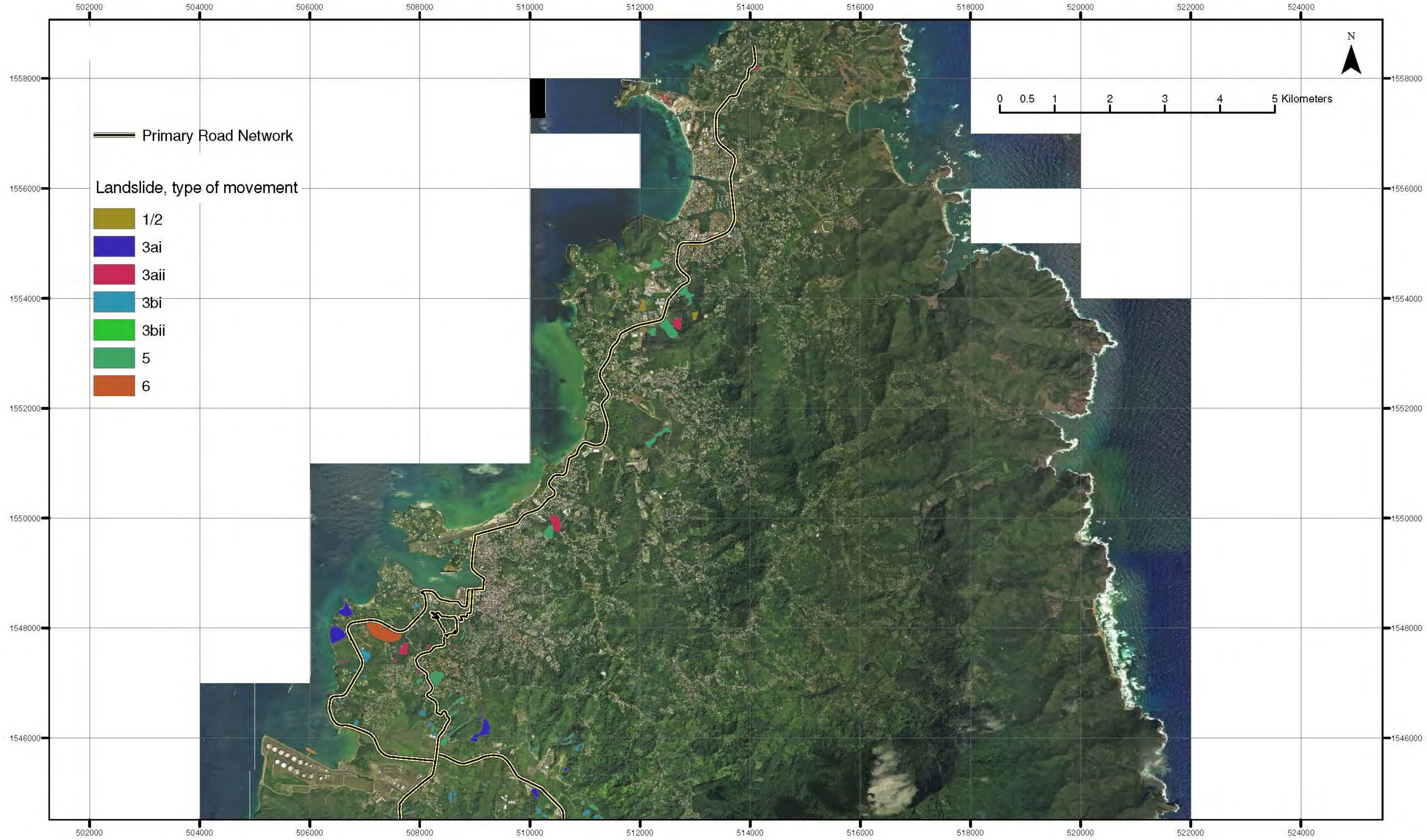
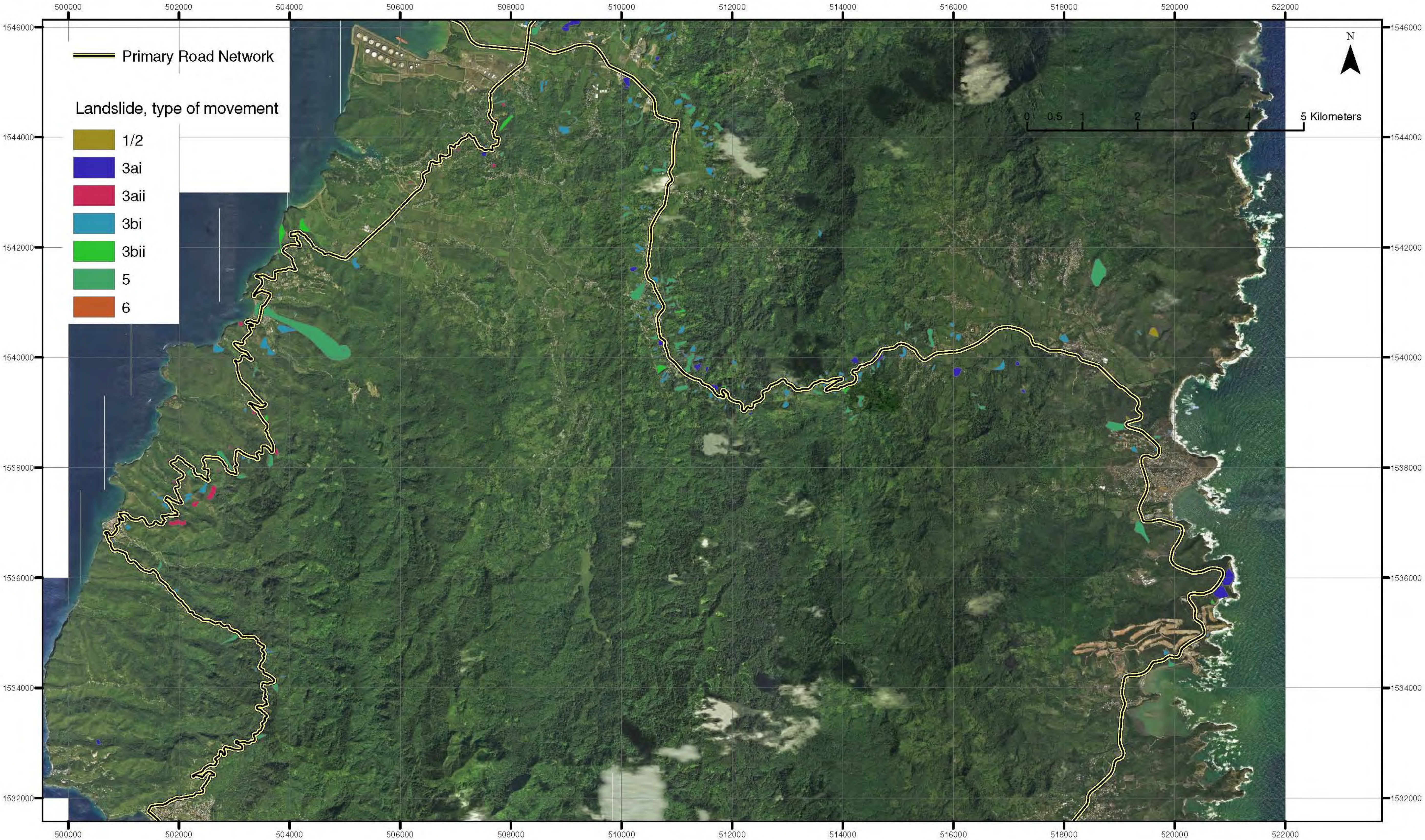
Figure E.1: Initial air photo interpretation Northern St Lucia



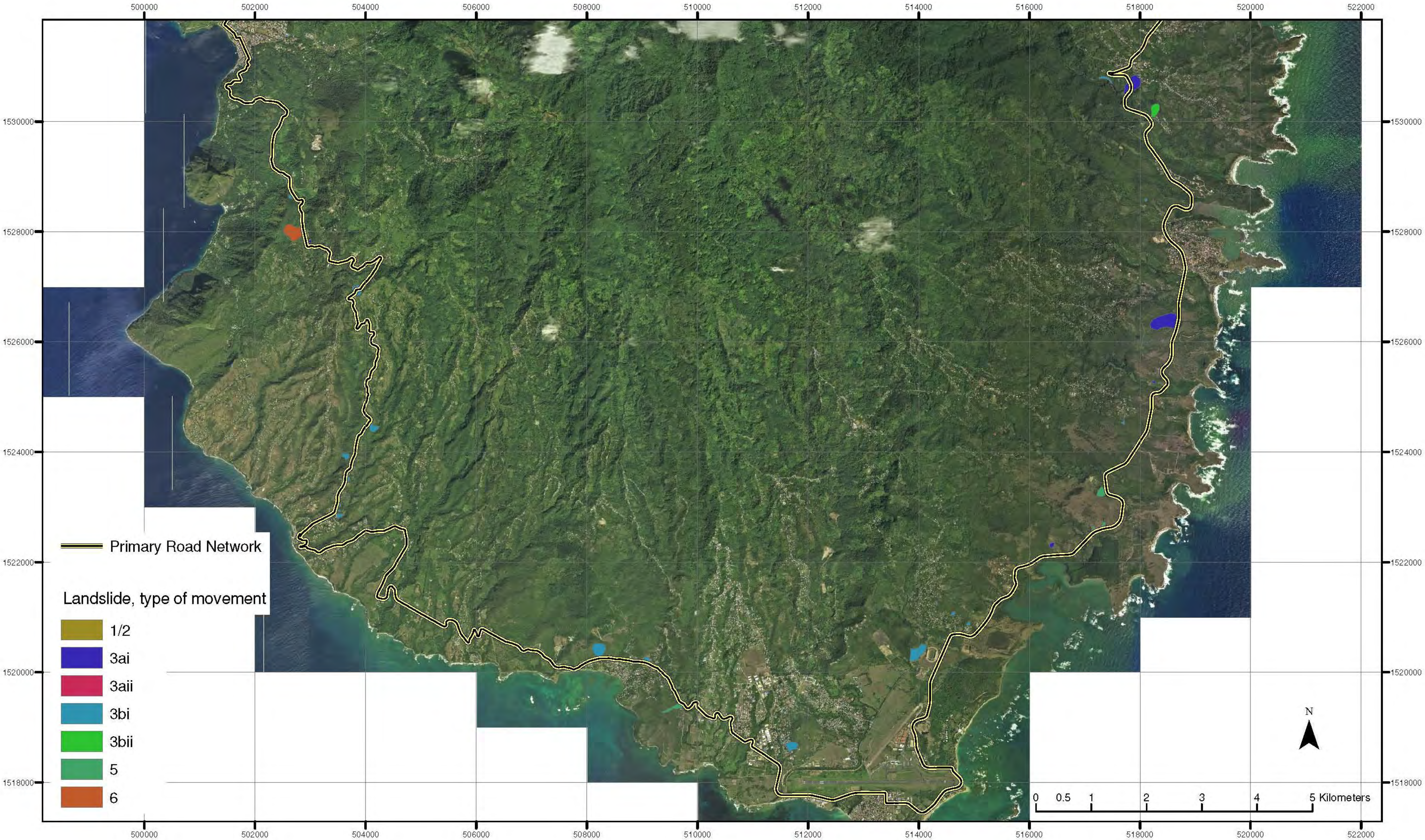
Source: Type of movement after classifications by EPOCH (1993) and Dikau et al (1996) 1 / 2- rockfall or topple failures, 3 – Slides subsets are: a – rotational and b – translational split into i) few units and ii) many units, 4 – Lateral spreads, 5 – Flows and 6- Complex.

Figure E.2: Initial air photo interpretation Middle St Lucia



Source: Type of movement after classifications by EPOCH (1993) and Dikau et al (1996) 1 / 2- rockfall or topple failures, 3 – Slides subsets are: a – rotational and b – translational split into i) few units and ii) many units, 4 – Lateral spreads, 5 – Flows and 6- Complex.

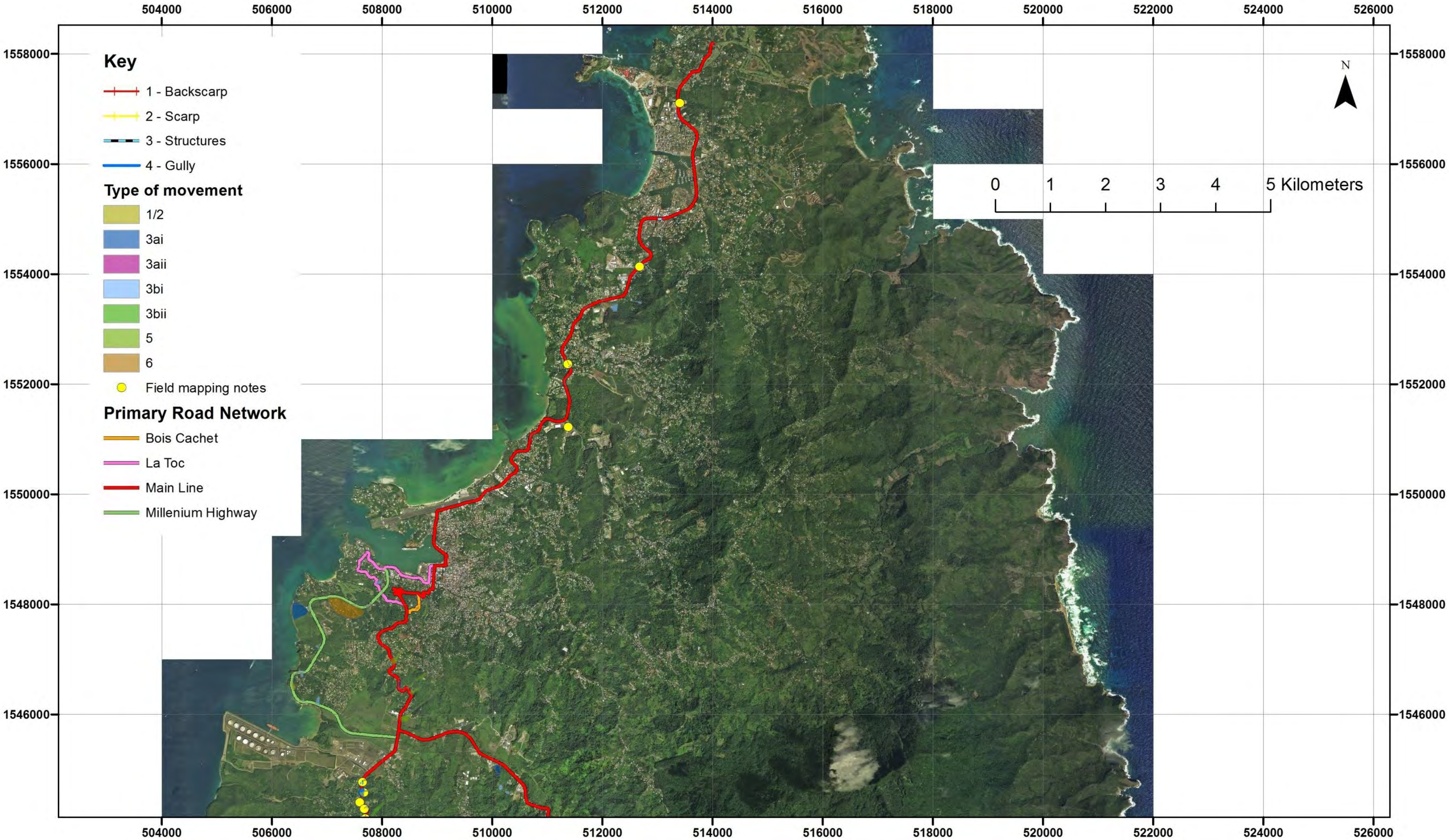
Figure E.3: Initial air photo interpretation Southern St Lucia



Source: Type of movement after classifications by EPOCH (1993) and Dikau et al (1996) 1 / 2- rockfall or topple failures, 3 – Slides subsets are: a – rotational and b – translational split into i) few units and ii) many units, 4 – Lateral spreads, 5 – Flows and 6- Complex.

E.2 Fieldwork

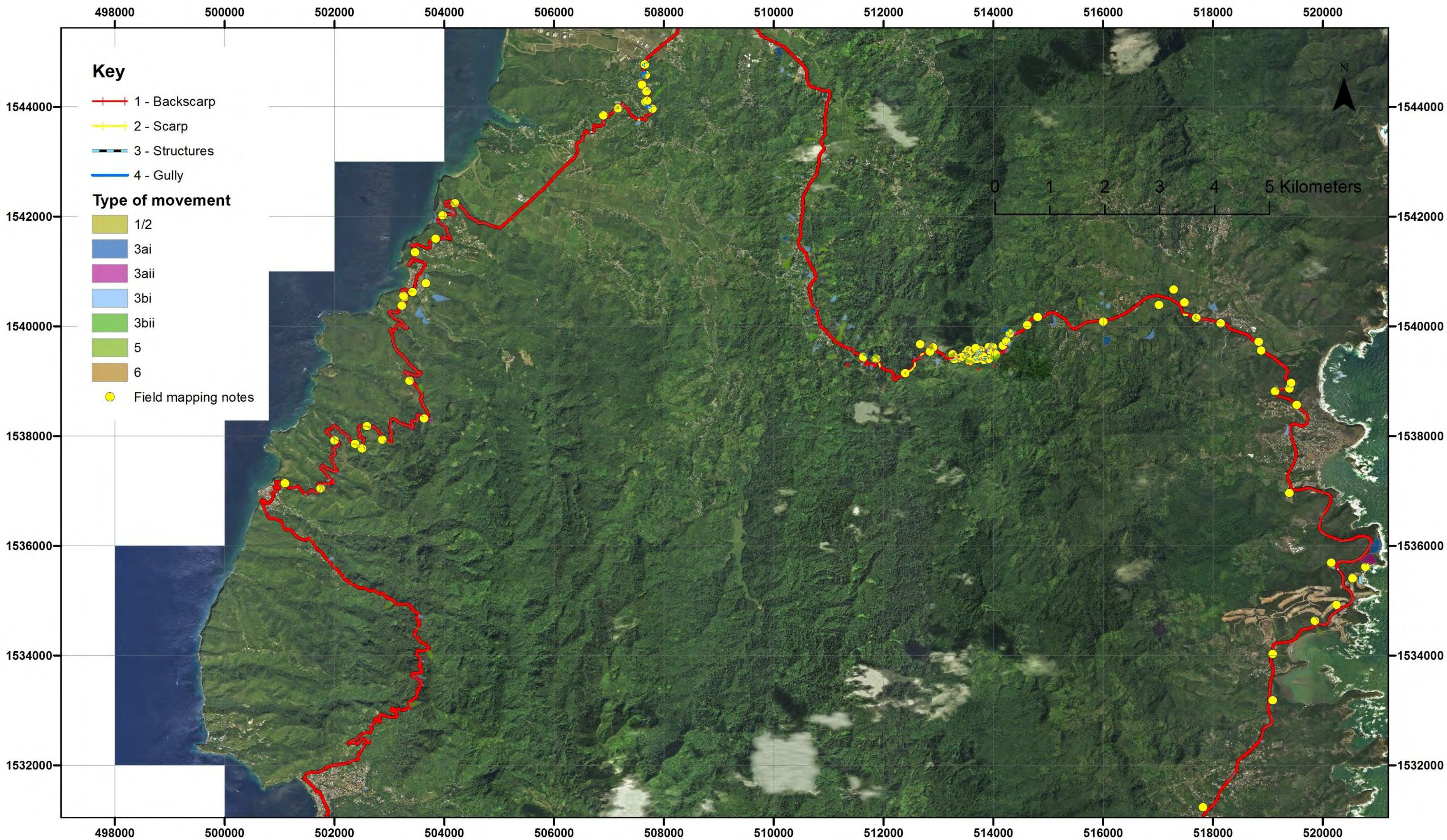
Figure E.4: Fieldwork ground truthing Northern St Lucia



Further detail can be viewed on the GIS database

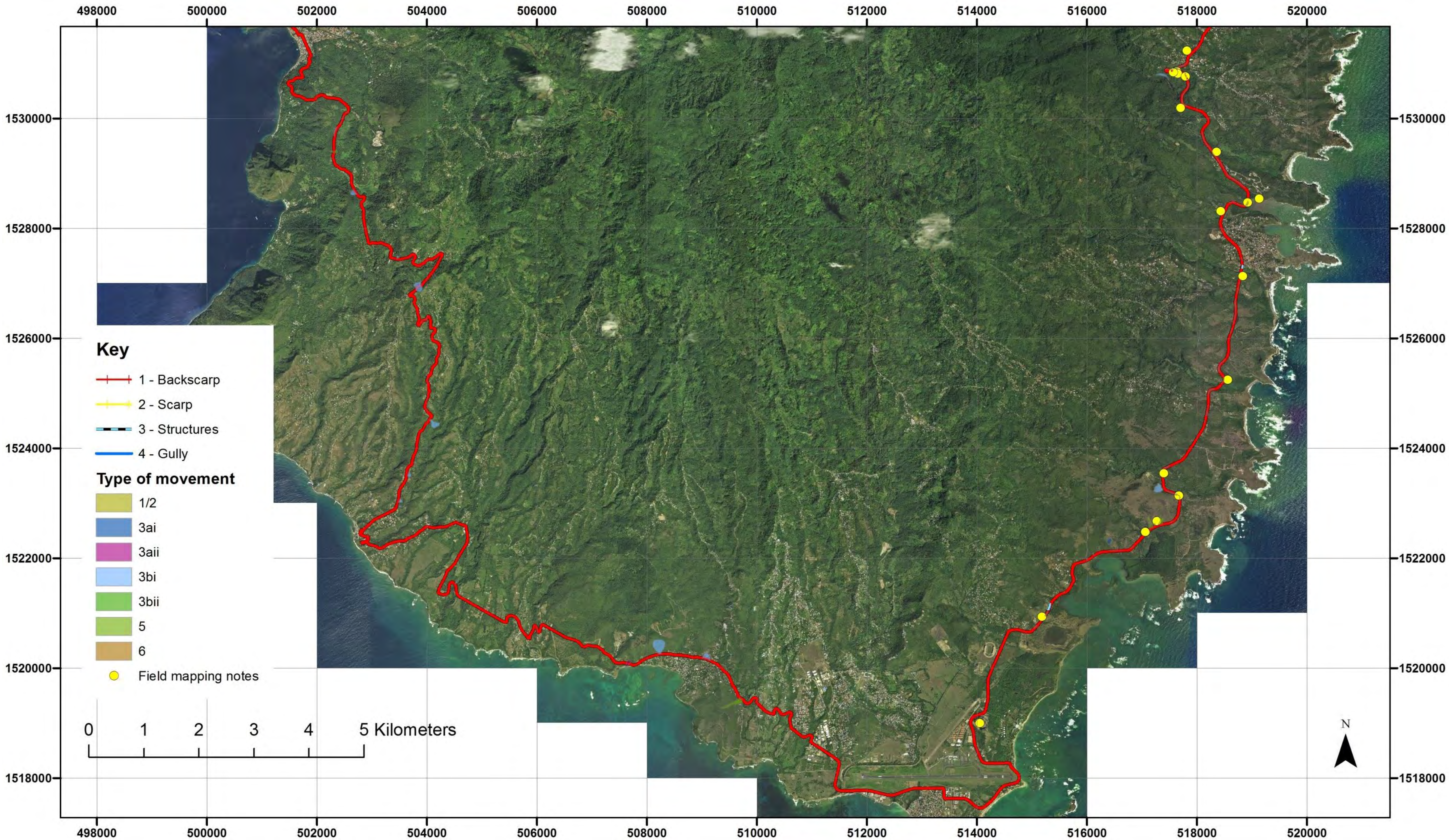
Mott MacDonald

Figure E.5: Fieldwork ground truthing - Middle St Lucia



Further detail can be viewed on the GIS database

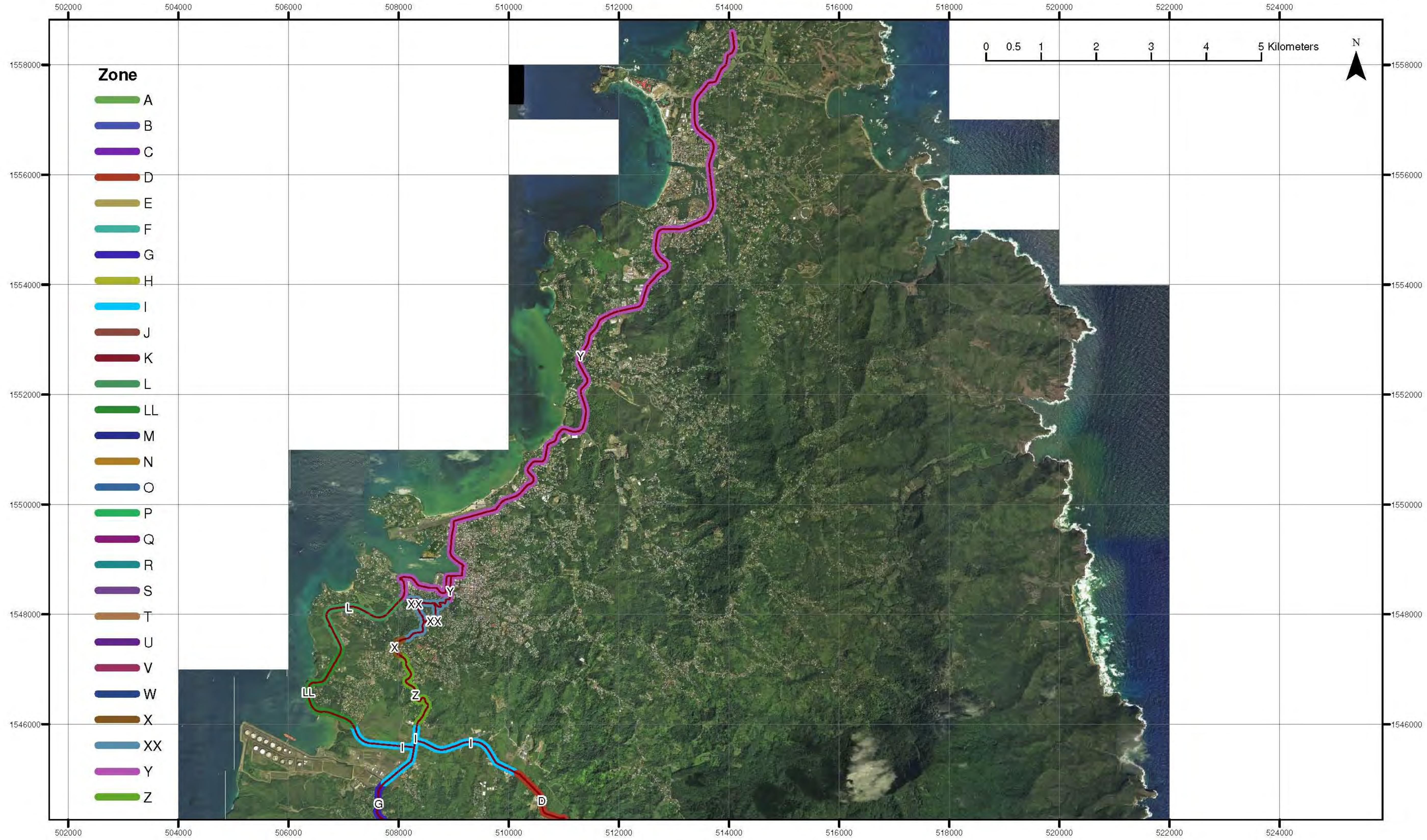
Figure E.6: Fieldwork ground truthing Southern St Lucia



Further detail can be viewed on the GIS database

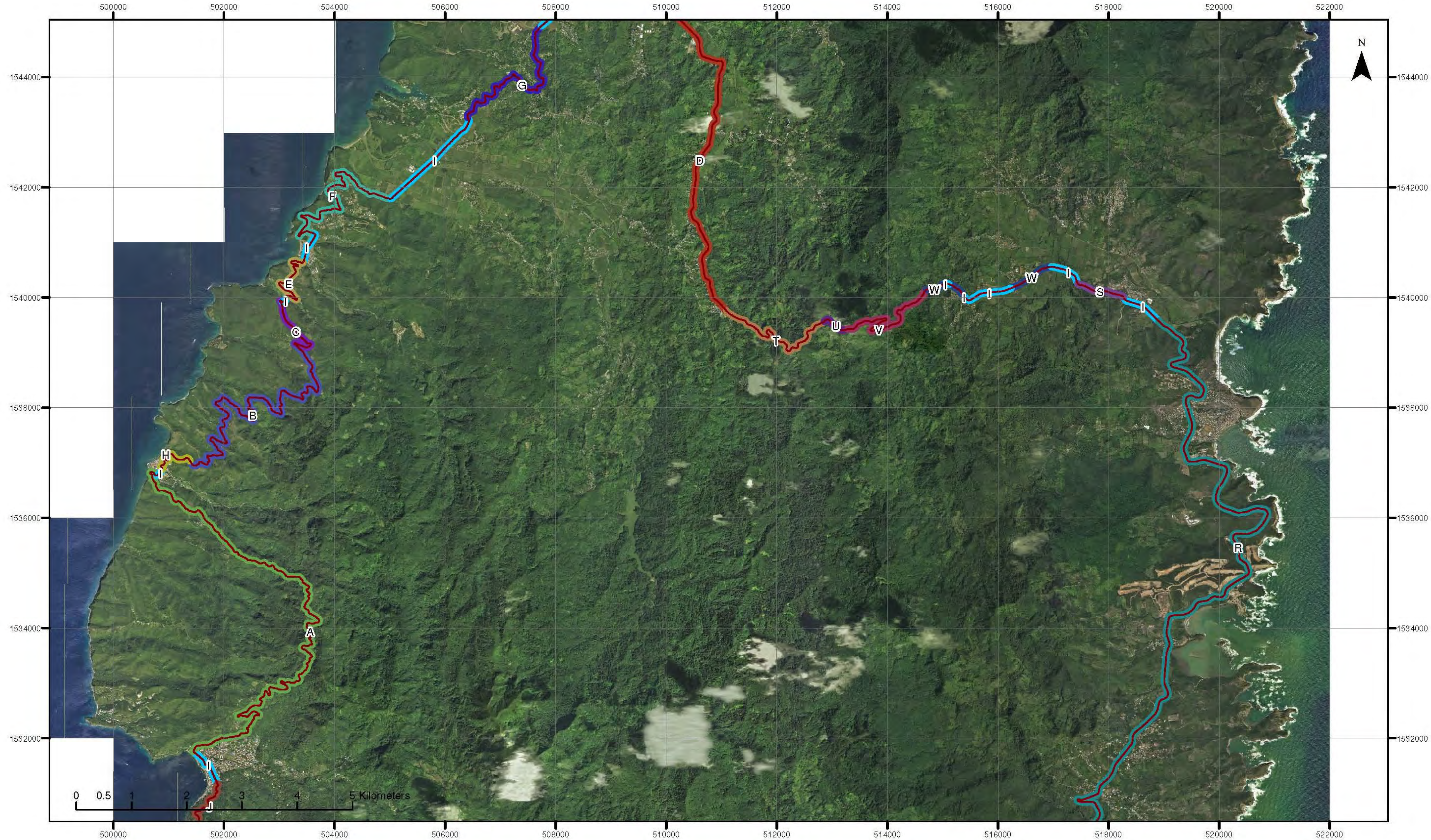
E.3 Fieldwork zones

Figure E.7: Fieldwork Zones - Northern St Lucia



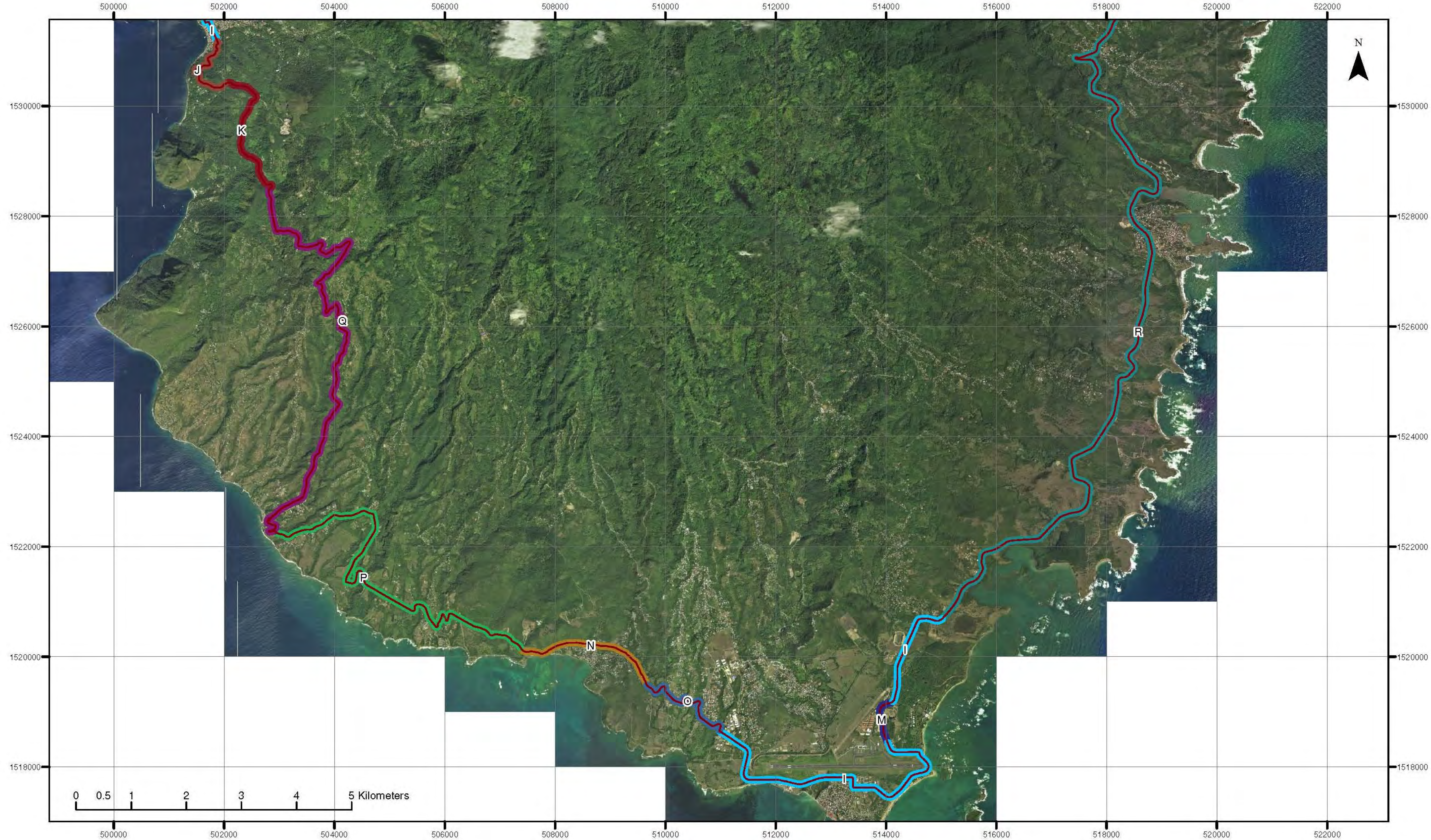
Key in Table 5.3

Figure E.8: Fieldwork Zones - Middle St Lucia



Key in Table 5.3

Figure E.9: Fieldwork Zones - Southern St Lucia



Key in Table 5.3

295680/MNC/FNG/007/B 23 September 2013
PiMS ID: 1542624503

Appendix F. Zone engineer site meeting minutes

Record of meeting/discussion

Mott MacDonald

Project Title	St Lucia Landslide Assessment	Division	
Subject	Landslide effects on Primary Road Network	Project No.	295680
Location	Zones 1 & 8	Date of Meeting	6th February 2012

Present	Peter Gustave (8A)	MIPS&T	Nancy Engerran	MM
	Ronald Harrow (8B)	MIPS&T	Chris Arnold	MM
			Roosevelt Issacs	Strata Engineering

Recorded by	Distribution
NE	Attendees + Jude Regis

Item	Text	Action on
1	**Contact Details** Peter Gustave – 7217682 & jellussee@hotmail.com Ronald Harrow – 7161217 & rharrow@gosl.gov.lc	
2	**Introduction** The aim of the visit was to gain an understanding of the past and future effects of landslide on the priority road network. Roads visited in this visit: • Morne du Don (at request of Chief Engineer – not priority road) • Bois Cachet (not priority road itself but could affect priority road) • The Morne • Bexon Road • 1st section of Barre De L'Isle • The Millenium Highway • La Toc	
3	**Morne du Don** Although not part of the priority road network, the Chief Engineer asked that we also look at the road. This road provides a link to various communities but due to the location of other roads would not be cut-off if part of road closed. Morne du Don was affected following a landslide some 20 years ago and the road itself has been slowly moving over the past 5 years. There is monitoring in place at the critical points. Comment was made that previous issue have been caused by unplanned development and uncontrolled drainage from residential properties.	

Item	Text	Action on
	 	
	It was noted that several of the properties has received some intervention from the MoSSaiC project (EC$200,000) and this area did not suffer too badly from the effects of Tomas (potentially as a result of these interventions)	
		
	Some remedial works costing approx $6,000 have been carried out – patching etc.	
4	**Bois Cachet**	
	Bois Cachet is not on the primary road network but is on the down slope of the Morne which is on the primary road network. There are some major issues here and the slopes were weakened significantly during Tomas. MIPS&T are only monitoring the surface movement.	

Item	Text	Action on
	   	
	Repairs at the start of the road have been carried out by the landowner:	
		
	There are no current remedial works planned – only monitoring.	
	Some sealing of cracks in the pavement has been carried out in the past.	
5	**The Morne**	
	There are generally small slumps which occur along the route during the rain. These are cleared with a day and do not necessarily affect the road function.	

Item	Text	Action on

However there is one location by the Eudovic Art Studio (E508413, N1546456) where there are regular slips. This fails about 3 times a wet season and will costs EC$7,000-$10,000 to clear each time. Generally cleared within 1 day.

The following section near Goodlands Road (Coca Cola hut)(E508231, N1546697) suffered a vertical failure in 2005. The retaining wall has been repaired and no movement has been noted since.

6 **Bexon Road / Ravine Poisson**

The major issue along this road after Tomas was flooding which left 05.m silts along approx 1km of road. This took approx 10 days to clear.

Along this section of road there are regular small slides which are generally cleared the day after

Post Tomas gabion wall remedial works were carried out in 3 locations. Cost for all 3 was EC$120,000.

Item	Text	Action on
	 	
7	**Barre De L'Isle** This covers the section to the top of Barre De L'Isle (Barre De L'Isle Reserve sign). In general slides along this section are more significant and take 1-2 days to clear. During Tomas these were exacerbated. Following Tomas there are significant areas of exposed rock. There are several springs along this section:  There is one section of rock netting in this section which has been installed by others and it is believe that the Special Project Unit (SPU) is carrying out the monitoring:  There is one section of edge failure in this zone for which there are no remedial works currently designed:	

Item	Text	Action on
		
8	**Millennium Highway**	
	Millennium Highway was opened in 2001. No major issues along here just some erosion and minor slides. Construction included reinforced earth walls which has helped. WASCO have a water tank above areas that have seen some minor slumps.	
9	**La Toc**	
	This road forms local access to residential properties only. Governor General property at the top. No major issues along here. There has been minor creep over a number of years.	
10	**Maintenance**	
	Routine maintenance (grass cutting, general clearing of drain and culverts) is carried out under the caretaker system on a 6 month programme. The caretakers are no longer covered under MIPS&T but by Ministry of Social Development.	
	With reactive maintenance issues such as slips or blocked drains and culverts are either picked up on the regular inspections or the local populous has a specific department to receive complaints.	
	Small slips will be covered from the routine maintenance budgets but funds for larger slips can be applied from the Government from the Disaster Relief Budget.	
	There is sufficient equipment locally and the zone engineers have a contract list of people they can call on to provide the relevant services.	
11	**Information required**	
	The following information is requested from MIPS&T:	

Item	Text	Action on
	• Traffic figures for these roads • Accident data for these roads • Annual routine maintenance budget • Annual reactive maintenance budget incl clear up cost following Tomas. • Details of any monitoring in place • Details of remedial works that have been implemented • Costs of remedial works that have been implemented • Any photos of landslides immediately after Tomas • Zonal hurricane response plan • Any zonal reports produced following Tomas.	

Record of meeting/discussion

Project Title	St Lucia Landslide Assessment		Division	
Subject	Landslide effects on Primary Road Network		Project No.	295680
Location	Zone 3		Date of Meeting	6th February 2012
Present	John David	MIPS&T	Nancy Engerran	MM
	Vincent Henry	MIPS&T	Chris Arnold	MM
	Lambert Monoville	MIPS&T	Roosevelt Issacs	Strata Engineering
	Lance Octav	MIPS&T		
	Raymond Mafrin	MIPS&T		

Recorded by	Distribution
NE	Attendees + Jude Regis

Item	Text	Action on
1	**Contact Details**	
	John David – 7205351 & jdavid@gosl.gov.lc	
2	**Introduction**	
	The aim of the visit was to gain an understanding of the past and future effects of landslide on the priority road network. Roads visited in this visit: • Barre De L'Isle from top (Barre De L'Isle Reserve sign) • East coast road to Praslin Bay	
3	**Barre De L'Isle**	
	This road was one of the worst affected roads during Tomas. The original construction involved cut and fill and TOMAS has highlighted the potential weaknesses in the original design/construction. Many if the edges have failed significantly. It is interesting to note that many of the failed slopes had been previously stripped of vegetation for banana farming.	
	Location – Grand Ravine GPS 18 (E 512872, N 1539586)	
	 	
	This section has been repaired 3 times recently – 2006, 2008 & 2012. The road was re-levelled in 2012. The provision of the	

Item	Text	Action on

concrete drain has helped but the whole area is still moving. Special Project Units (SPU) is monitoring the area.

Location – GPS 19 (E 513131, N 1539462)

This is one of the major repair locations. Causes of slide include uncontrolled run-off, poorly compacted fill and lack of drains. This took approximately 1.5 weeks to clear. Interventions include gabions walls, shallower slopes, cascade drains and the use of Vetiver grass. This is WB/CDB funded and is being monitored by SPU. Design details and costs are requested.

Location - GPS 20 (E513787, N 1539593)

This is the first gabion wall to be completed following Tomas. Design details, costs and any monitoring results are requested.

It was noted that there are many issues related to flooding following Tomas. Many of the rivers are still silted so any rain could cause a flood.

Location - GPS 21 (E513953, N 1539637)

This location is being monitored. Results are requested. There are currently no remedial works designed for this location.

Item	Text	Action on


Location - GPS 22 (E 513991, N 1539604)


This location is also being monitored. Results are requested. No current remedial designs.

Location - GPS 23 (E 513700, N 1539415)

At this location the edge slipped due to retaining wall failure. Tomas caused the catastrophic failure but the wall had been moving since 2006. Remedial measure involved realigning the road away from the failed edge and provision of concrete drainage. It should be noted that the edge itself has not been repaired.


Item	Text	Action on
	Designs, costs and any monitoring results are requested.	

Location - GPS 24 (E 514252, N 1539632)

At this location the edge has failed exposing the WASCO water pipe. There is a quarry near this location which uses explosives – any effect?

Location – GPS 25 (E 514517, N 1539920)

Although difficult to see under the vegetation, the retaining wall at this location has shifted causing the edge of the road to fail. No remedial designs currently.

Item	Text	Action on
4	**East Coast Road to Praslin Bay**	
	From Dennery to end of Zone 3 there are no major issues associated with landslides. The major issues in Dennery are caused by flooding as all the run-off from surrounding areas ends up here.	
	There can be minor slips all year round that are cleared within a day.	
5	**Maintenance**	
	Routine maintenance (grass cutting, general clearing of drain and culverts) is carried out under the caretaker system on a 6 month programme. The caretakers are no longer covered under MIPS&T but by Ministry of Social Development.	
	With reactive maintenance issues such as slips or blocked drains and culverts are either picked up on the regular inspections or the local populous has a specific department to receive complaints. Removed material is generally taken to landfill or private land if requested by the landowner.	
	Small slips will be covered from the routine maintenance budgets but funds for larger slips can be applied from the Government from the Disaster Relief Budget.	
	There is sufficient equipment locally and the zone engineers have a contract list of people they can call on to provide the relevant services.	
6	**Information required**	
	The following information is requested from MIPS&T: • Traffic figures for these roads • Accident data for these roads • Annual routine maintenance budget • Annual reactive maintenance budget incl clear up cost following Tomas. • Details of any monitoring in place • Details of remedial works that have been implemented • Costs of remedial works that have been implemented • Any photos of landslides immediately after Tomas • Zonal hurricane response plan • Any zonal reports produced following Tomas.	

Record of meeting/discussion
Continuation sheet

Project No. Date of Meeting

Item	Text	Action on

Record of meeting/discussion

Project Title	St Lucia Landslide Assessment	Division	
Subject	Landslide effects on Primary Road Network	Project No.	295680
Location	Zones 4 & 5	Date of Meeting	8th February 2012

Present	Eddie Parsade	MIPS&T-South	Nancy Engerran	MM
	Alfonse	MIPS&T-South		

Recorded by	Distribution
NE	Attendees + Jude Regis & Chris Arnold

Item	Text	Action on
1	**Contact Details**	
	Eddie Parsade – 7217166 & eparsade@gosl.gov.lc	
2	**Introduction**	
	The aim of the visit was to gain an understanding of the past and future effects of landslide on the priority road network. Roads visited in this visit: • West/east coast highways from Laborie to Praslin Bay	
3	**Site Visit**	
	It is felt that the major cause of concern along this section is flooding. The main effects from Tomas were due to the road washing out as a result of blocked culverts. Two of these have been replaced.	
	 	
	Most of the culverts along this route are ARMCO and have reached the end of their life and are beginning to cause problems such as depressions int he road.	
	Where there are slopes along the route they are generally bedrock so this section only has v minor slips or rockfalls that do not affect the road function.	

Item	Text	Action on
	There was one minor slip during Tomas which has not be cleared as it is not affecting the road:	
		
	The most significant slip during Tomas was at Escap and covered half the road and took approximately 4 days to clear:	
		
4	**Maintenance**	
	Routine maintenance (grass cutting, general clearing of drain and culverts) is carried out under the caretaker system on a 6 month programme. The caretakers are no longer covered under MIPS&T but by Ministry of Social Development.	
	With reactive maintenance issues such as slips or blocked drains and culverts are either picked up on the regular inspections or the local populous has a specific department to receive complaints.	
	Small slips will be covered from the routine maintenance budgets but funds for larger slips can be applied from the Government from the Disaster Relief Budget.	
	There is sufficient equipment locally and the zone engineers have a contract list of people they can call on to provide the relevant services.	

Item	Text	Action on
5	**Information required** The following information is requested from MIPS&T if available: • Traffic figures for these roads • Accident data for these roads • Annual routine maintenance budget • Annual reactive maintenance budget incl clear up cost following Tomas. • Details of any monitoring in place • Details of remedial works that have been implemented • Costs of remedial works that have been implemented • Any photos of landslides immediately after Tomas • Zonal hurricane response plan • Any zonal reports produced following Tomas.	

Record of meeting/discussion

Project Title	St Lucia Landslide Assessment		Division		
Subject	Landslide effects on Primary Road Network		Project No.	295680	
Location	Zone 6		Date of Meeting	7th February 2012	
Present	Kensley Promesse	MIPS&T	Nancy Engerran	MM	
		MIPS&T	Chris Arnold	MM	
		MIPS&T			
		MIPS&T			

Recorded by	Distribution
NE	Attendees + Jude Regis

Item	Text	Action on
1	**Contact Details** Kensley Promesse – 7161648 & kpromesse@gosl.gov.lc	
2	**Introduction** The aim of the visit was to gain an understanding of the past and future effects of landslide on the priority road network. Roads visited in this visit: • West coast road from Colombette to Laborie	
3	**West Coast Road** From Colombette down to Soufriere there are no significant issues – just minor slips. Some of the slopes are stone pitched. *Location – GPS 41 (E 501725 1530907)*  All along this section from Soufriere to the Stonefield Estate turn off is showing signs of distress and pavement creep. There is a lack of drainage channel behind the safety fence along this side and it is causing erosion. *Location – GPS 42 (E 501718, N 1530837)*	

Item	Text	Action on
		
	Complete edge failure as another example along the road from Soufriere.	
	Location - GPS 43 (E501507, N 1530704)	
	 	
	The LH photo shows the slide from the road down to the beach. The RH photo shows the top of the slip on the RH side of the road.	
	On the LHS side of the road along this section are minor slips. There is one section of gabions which have been installed since Tomas. Details and costs requested.	
	Location – GPS 44 (E 501514, N 1530698)	
	.	

Item	Text	Action on
	Around the area of the Piton turn off creep has been showing inthe pavement since Tomas. 3 slips on the LHS have had gabion remedial works installed. Details and cost requested.	
	Location - GPS 45 (E 501514, N 1530698)	
	 	
	This is an historical slip location on LHS and is still considered to be unstable. Berms on RHS will prevent run-off.	
	From here through and through Choiseul the slope are mainly pumice and bed rock and so no significant issues.	
	Location – Sapphire GPS 46 (E507630, N 1520102)	
	 	
	This whole area is continually moving slowly affecting properties, poles, walls and pavement. Way up on the hill above this location is the start of the Gomier Heights Development. It has the drainage and infrastructure in place.	
4	**Maintenance**	
	Routine maintenance (grass cutting, general clearing of drain and culverts) is carried out under the caretaker system on a 6 month programme. The caretakers are no longer covered under MIPS&T but by Ministry of Social Development.	
	With reactive maintenance issues such as slips or blocked drains and culverts are either picked up on the regular inspections or the local populous has a specific department to receive complaints. Removed material is generally taken to landfill or private land if	

Item	Text	Action on
	requested by the landowner. Small slips will be covered from the routine maintenance budgets but funds for larger slips can be applied from the Government from the Recon and Rehab budgets or even the Disaster Recovery Budget. There is sufficient equipment locally and the zone engineers have a contract list of people they can call on to provide the relevant services.	
5	**Information required** The following information is requested from MIPS&T: • Traffic figures for these roads • Accident data for these roads • Annual routine maintenance budget • Annual reactive maintenance budget incl clear up cost following Tomas. • Details of any monitoring in place • Details of remedial works that have been implemented • Costs of remedial works that have been implemented • Any photos of landslides immediately after Tomas • Zonal hurricane response plan • Any zonal reports produced following Tomas.	

Record of meeting/discussion

Mott MacDonald

Project Title	St Lucia Landslide Assessment	Division	
Subject	Landslide effects on Primary Road Network	Project No.	295680
Location	Zone 7	Date of Meeting	7th February 2012
Present	Anseworth Charlemagne MIPS&T Laurna Raoul MIPS&T		Nancy Engerran MM Chris Arnold MM

Recorded by	Distribution
NE	Attendees + Jude Regis

Item	Text	Action on

1 **Contact Details**

Anseworth Charlemagne – 7217208 & acharlemagne@gosl.gov.lc

Laurna Raoul – 7173767 & lraoul@gosl.gov.lc

2 **Introduction**

The aim of the visit was to gain an understanding of the past and future effects of landslide on the priority road network. Roads visited in this visit:

- West coast road from end of Millennium Highway to Columbette

Some of the following locations are referred to by a Wall No. This is reference to the Post Hurricane Tomas Retaining Walls Programme – Zone 7 report provided by A Charlemagne.

3 **West Coast Road**

There were significant slides at various locations along this section, particularly between L'Anse La Raye and Souffriere which took about 2.5 weeks to clear after Tomas.

Location – Ti Colon, Wall 1, GPS 27 (E507638, N 1544503)

Item	Text	Action on
	The ground at this location has been moving slowly for several years but TOMAS made it worse. There is no current monitoring in place or remedial designs. There is uncontrolled over the edge drainage at this location. *Location – Wall 2 – GPS 28 (E507747, N 1544011)*  Repairs in this location have been carried out at a cost of EC$1.3m. Initial estimates were EC$600,000 but the excavation extended during construction and the designs amended. Previous road construction was cut and fill only no edge support. Design details are requested. *Location – La Croix - Wall 3, GPS 29 (E 507768, N 1543880)*  This is a potential future landslide area. A lot of topsoil is ready to fall. Uncontrolled drainage. Culvert under the road at this location. There is a bypass route available for this location (subject to condition). *Location – Wall 10 La Croix Maingot, GPS 30 (E 507674, N 1543766)* Vertical edge failure. Lack of drainage. Previous banana farming on down slope. There is no monitoring in this location. A bit further	

Item	Text	Action on
	along an existing retaining wall is holding up well.	


Location – Wall 4 La Croix, GPS 31 (E507146, N 1543983)


This section is still moving. Cracking in pavement extends some 50m. There is an issue with drainage, run-off from the school above and discharge from school culvert. It has not been possible to install culvert at this location due to private properties on down slope.

Location – Wall 5 Marigot, GPS 32 (E506911, N 1543785)

Item	Text	Action on
	  Localised edge failure. During Tomas significant debris fell from the corner. The contractor placed on the verge to widen but it is unengineered fill. There are several locations along this stretch with small edge failures following Tomas. Uncontrolled run-off along edge. *Location – GPS 33 (E 506494, N 1543388)*  Localised edge failure in this location although installation of 2 new culverts has resolved the run-off issues. From Massacre Ridge to L'Anse La Raye there are minor slips on LHS slide – topsoil and occasional rock slides. Easily cleared. It is felt that if there was another severe hurricane event now both Barre De L'Isle and LA Croix would be seriously affected and cause access problems. However one remedial works have been carried out on Barre De L'Isle this will improve the situation. *Location - Wall 9 before Anse La Verdure, GPS 34 (E 503042, N 1537895)* This location was problem before Tomas but that was the most severe issue. Potentially caused by a spring further up the slope on LHS. No apparent other external influences. This area took 3 days	

Item	Text	Action on
	to clear (2 x 220 excavators, 4 x 20T dump trucks).	


Location – GPS 35 (E 502531, N 1537916)


This section is a recurrent problem and has been blocked twice before Tomas.

Location GPS 36 (E 501626, N 1536058)

This is an example of common localised slips in the area south of Canaries. There is housing at the top of the slope. Maintenance crews my wait until there are 3 or 4 localised slips to clear if not

Item	Text	Action on
	affecting road.	

Location – Wall 19 - Canaries Belvedere Pkg 1, GPS 37 (E 502606, N 1535220)

Previous slip area. There is a culvert discharge point in the location (note water loving fern). Pavement still creeping despite being patched.

From Belvedere to Soufriere was completely blocked after Tomas due to numerous slips from LHS. It took 7 days just to clear a path through. This road surface is now in poor condition due to actions of excavators etc during clearing operation.

Location – Columbette

The Columbette slide was fatal to residents on the down slope from the road during Tomas and took 2 weeks to clear. However since then there have been no problems with the exception of the condition of the road surface. However similar ground conditions exist in the location.

Item	Text	Action on
4	**Maintenance**	
	Routine maintenance (grass cutting, general clearing of drain and culverts) is carried out under the caretaker system on a 6 month programme. The caretakers are no longer covered under MIPS&T but by Ministry of Social Development.	
	With reactive maintenance issues such as slips or blocked drains and culverts are either picked up on the regular inspections or the local populous has a specific department to receive complaints. Removed material is generally taken to landfill or private land if requested by the landowner.	
	Small slips will be covered from the routine maintenance budgets but funds for larger slips can be applied from the Government from the Recon and Rehab budgets or even the Disaster Recovery Budget.	
	There is sufficient equipment locally and the zone engineers have a contract list of people they can call on to provide the relevant services.	
5	**Information required**	
	The following information is requested from MIPS&T: • Traffic figures for these roads • Accident data for these roads • Annual routine maintenance budget • Annual reactive maintenance budget incl clear up cost following Tomas. • Details of any monitoring in place • Details of remedial works that have been implemented • Costs of remedial works that have been implemented • Any photos of landslides immediately after Tomas • Zonal hurricane response plan • Any zonal reports produced following Tomas.	

Appendix G. Example risk maps of key areas

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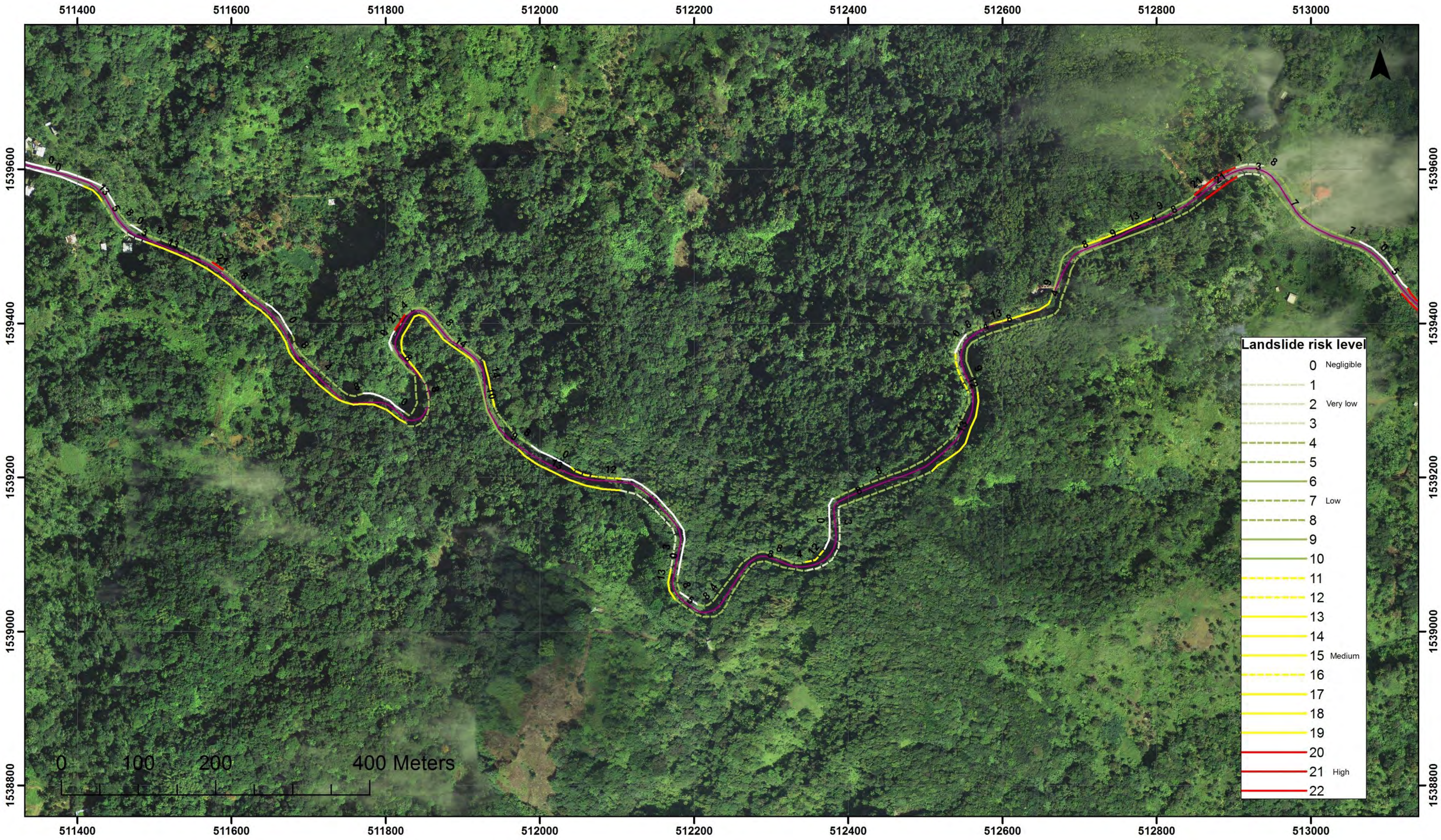
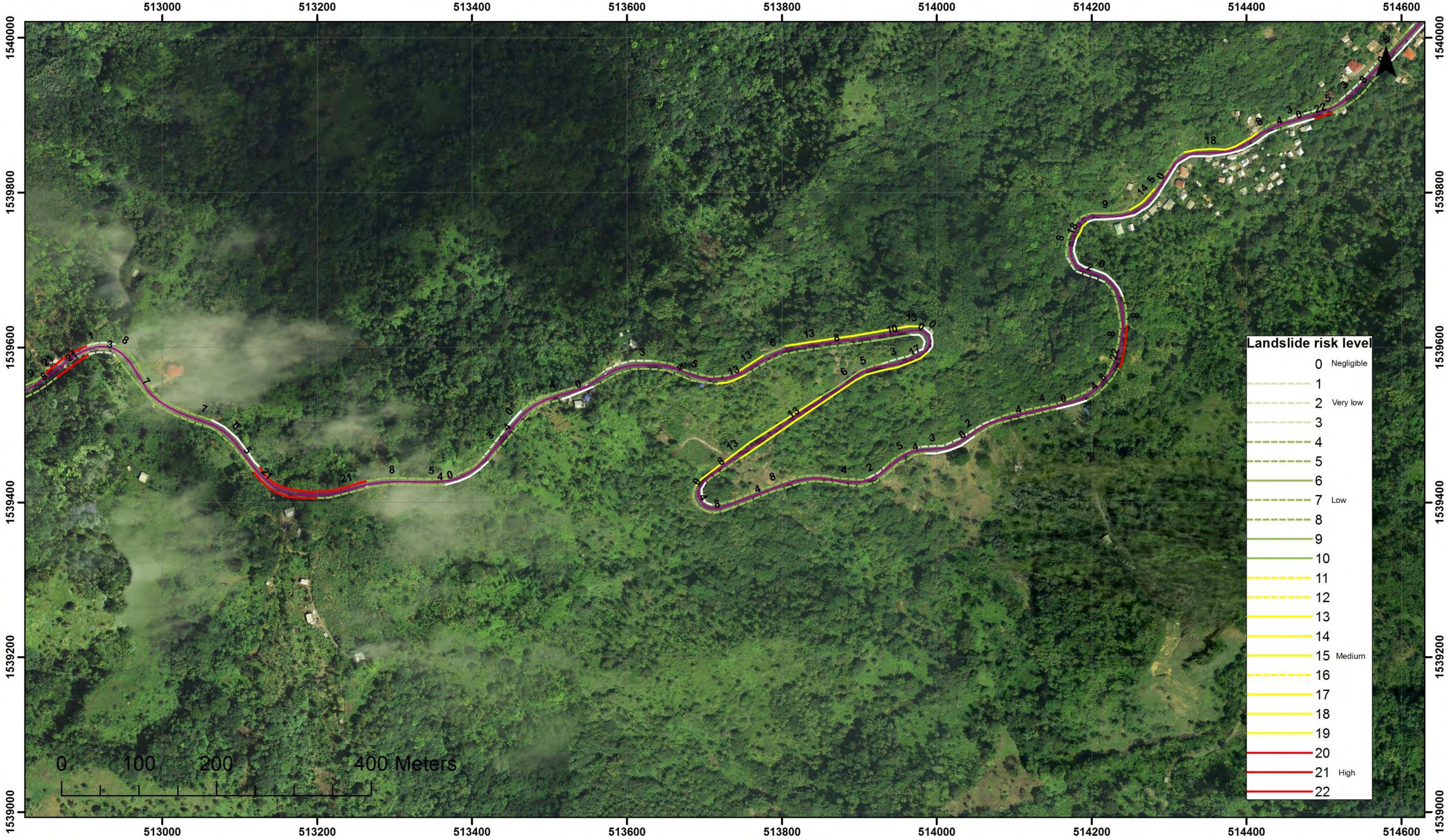
Figure G.1: Example risk map – Barre de L'isle west



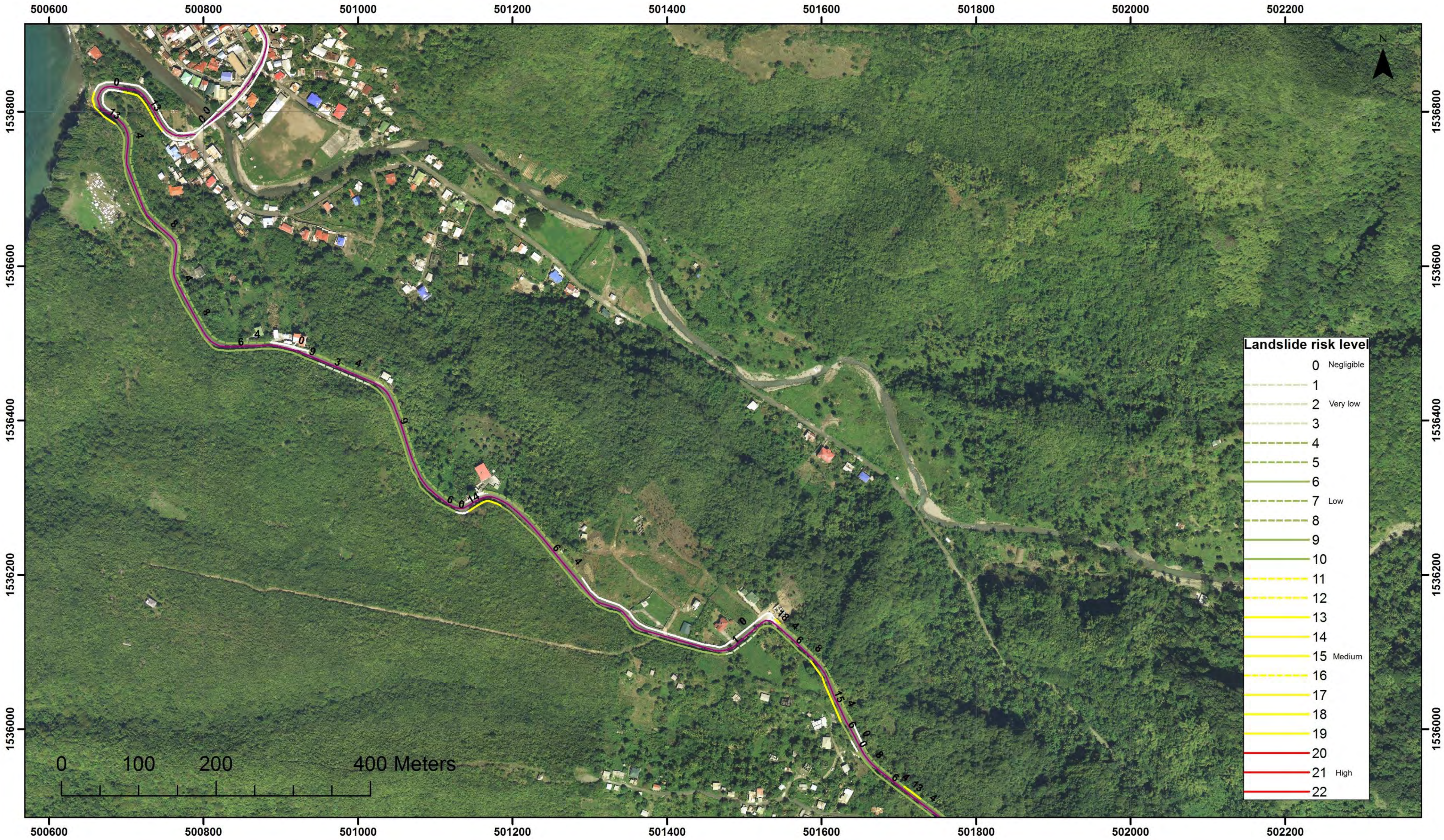
Further detail can be viewed in the GIS presented on the accompanying CD

Figure G.2: Example risk map – Barre de L'isle east



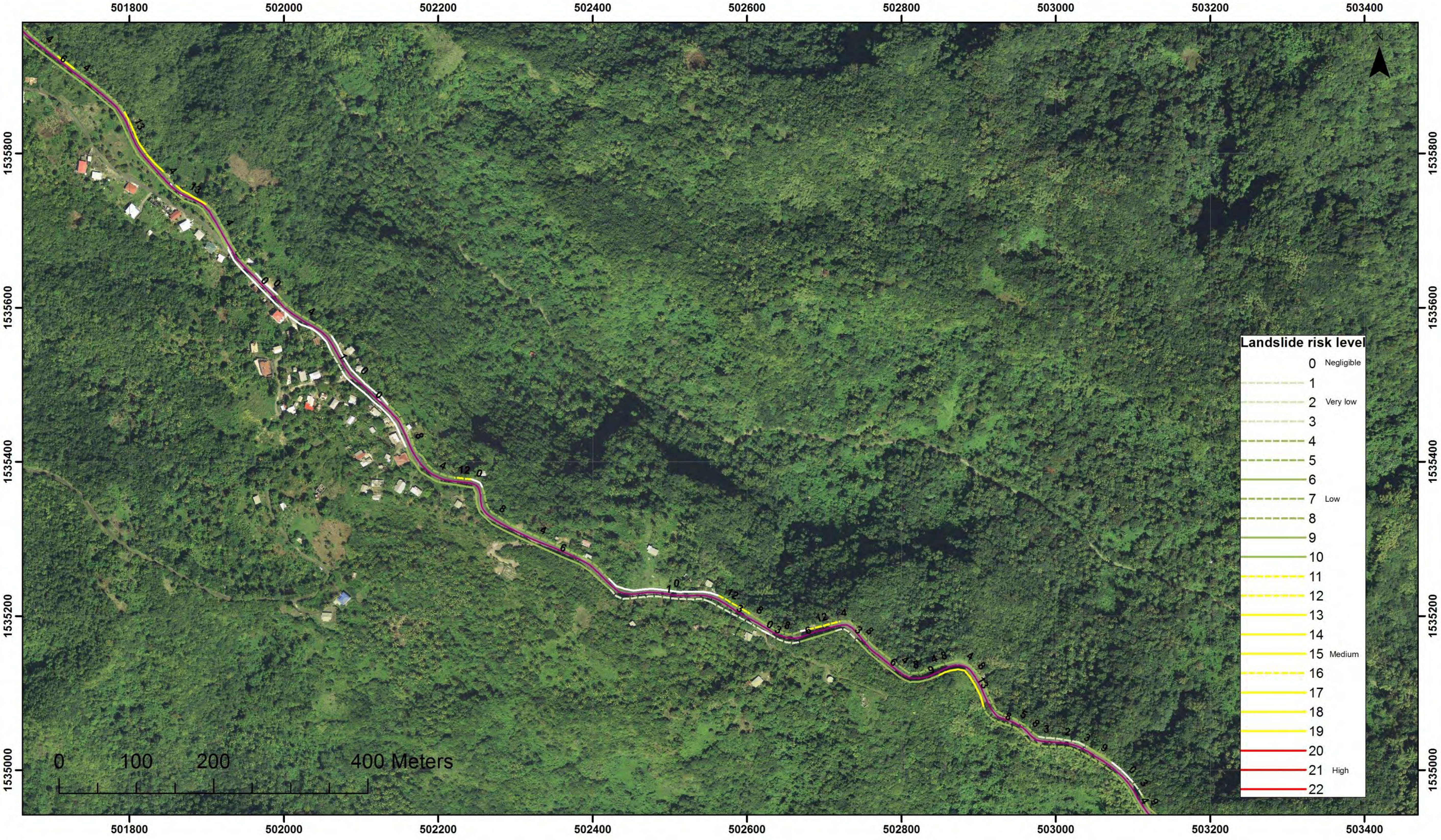
Further detail can be viewed in the GIS presented on the accompanying CD

Figure G.3: Example risk map – Canaries to Soufriere (1 of 7)



Further detail can be viewed in the GIS presented on the accompanying CD

Figure G.4: Example risk map – Canaries to Soufriere (2 of 7)



Further detail can be viewed in the GIS presented on the accompanying CD

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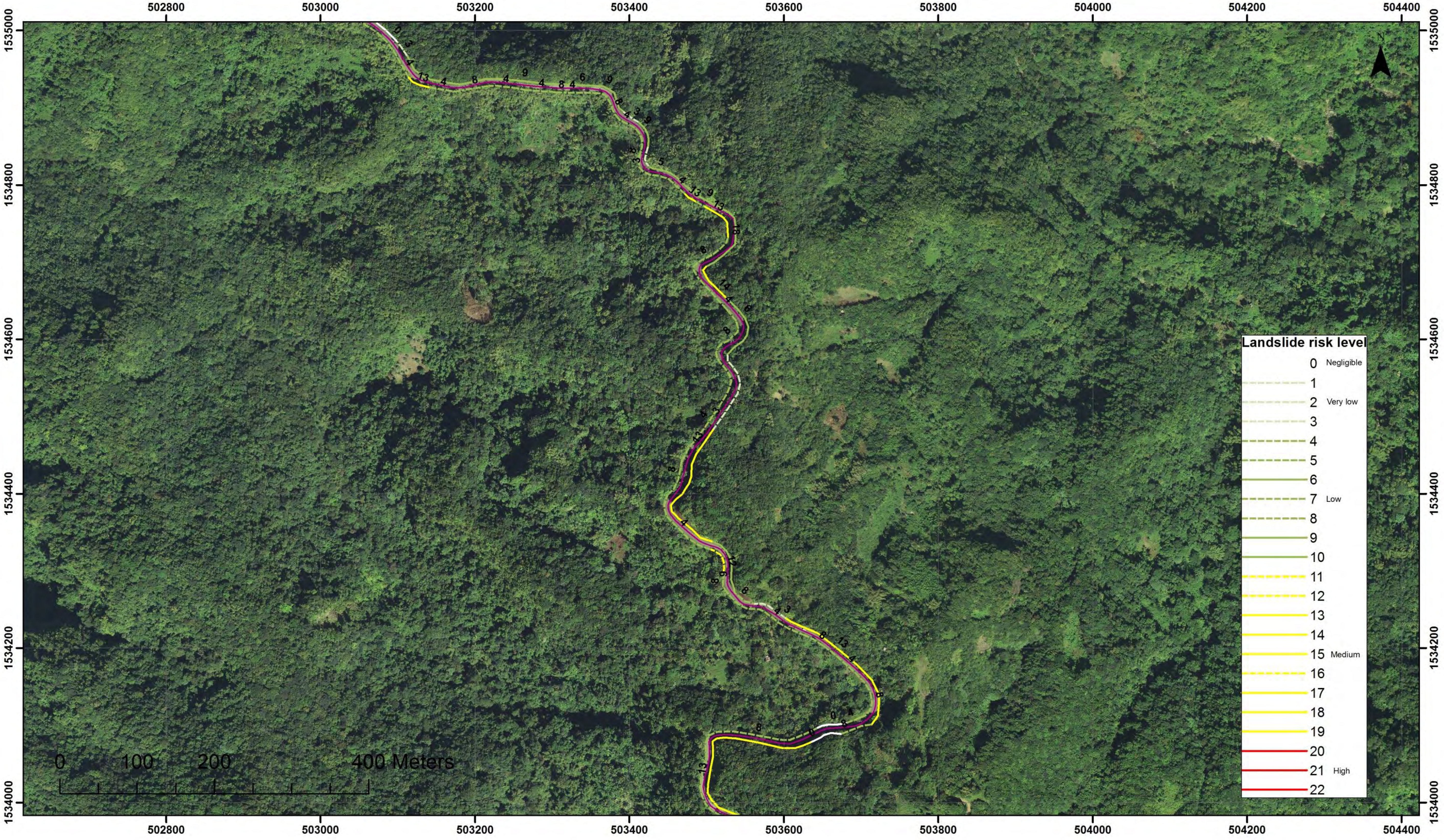
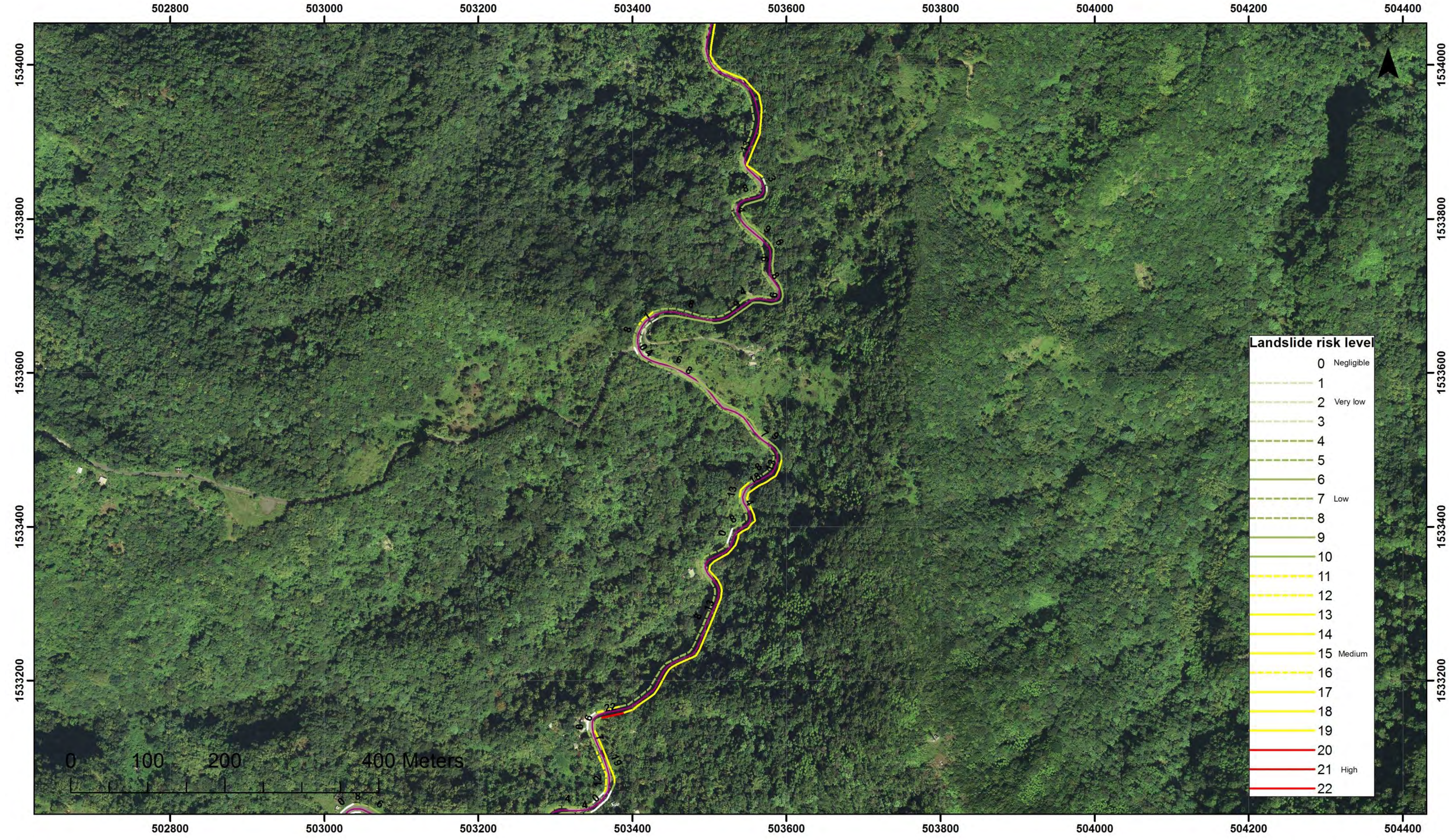
Figure G.5: Example risk map – Canaries to Soufriere (3 of 7)



Further detail can be viewed in the GIS presented on the accompanying CD

Figure G.6: Example risk map – Canaries to Soufriere (4 of 7)



Further detail can be viewed in the GIS presented on the accompanying CD

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Figure G.7: Example risk map – Canaries to Soufriere (5 of 7)

Further detail can be viewed in the GIS presented on the accompanying CD

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Figure G.8: Example risk map – Canaries to Soufriere (6 of 7)

Further detail can be viewed in the GIS presented on the accompanying CD

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Figure G.9: Example risk map – Canaries to Soufriere (7 of 7)

Further detail can be viewed in the GIS presented on the accompanying CD

Appendix H. High risk site descriptions

Site	Approximate chainage	Coordinates	Risk	Ministry zone	Immediate actions recommended
Bois Cachet – straight	BC 70 – 260m	508,676mE; 1,548,047mN	20 / 13	8A	Seal tension cracks on road surface; clear existing drains.
Bois Cachet – hairpin	BC 260 – 440m	508,630mE; 1,547,930mN	9 to 20	8A	Seal tension cracks on road surface; clear existing drains.
The Morne (near Eudovic Studios)	17885 – 17945 NB	508,410mE; 1,546,455mN	13	8A	Seal tension cracks on road surface; clear existing drains.
Ticolon	20320 – 20370 SB	507,632mE; 1,544,482mN	21	7	Seal tension cracks on road surface; clear existing drains.
Barre de L'isle – site 1	124905 – 124965	502,880mE; 1,539,580mN	22	8B	None
Barre de L'isle – sites 2 and 3	124465 – 124620	513,190mE; 1,539,413mN	21	8B	None.
Barre de L'isle / Tomazo (sites 6, 7, 9 and 10)	Various	various	17 or 22	3	It is considered the findings and recommendations of the FDL report should be progressed.
Ravine Cribiche	126540 – 126565 EB	511,819mE; 1,539,401mN	21	8B	Improve drainage to prevent infiltration behind the remaining retaining wall and prevent surface flow off the slope beneath the retaining wall and in failed area.
Ravine Poisson	127040 – 127055 EB	511,582mE; 1,539,474mN	21	8B	Redirect drainage to prevent discharge directly onto failed area.
Ravine Joseph	35910 – 35940 SB	503,014mE; 1,537,881mN	22	7	None
Colombette	48435 – 48575	503,360E; 1,533,110mN	0 to 22	6B	Condition survey of retaining wall and drainage on the north side of the slide
Calvaire	53800 - 53805 NB	501,700mE; 1,530,841mN	22	6B	Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.
Calvaire	53650 – 53710 NB	501,590mE; 1,530,710mN	18	6B	Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.
Road past the turn off to Sulphur Springs	55750 – 56550	502,330mE; 1,529,755mN	4 to 9	6B	None
Laborie	75755 - 75800	507,650mE; 1,520,080mN	21	5C	None

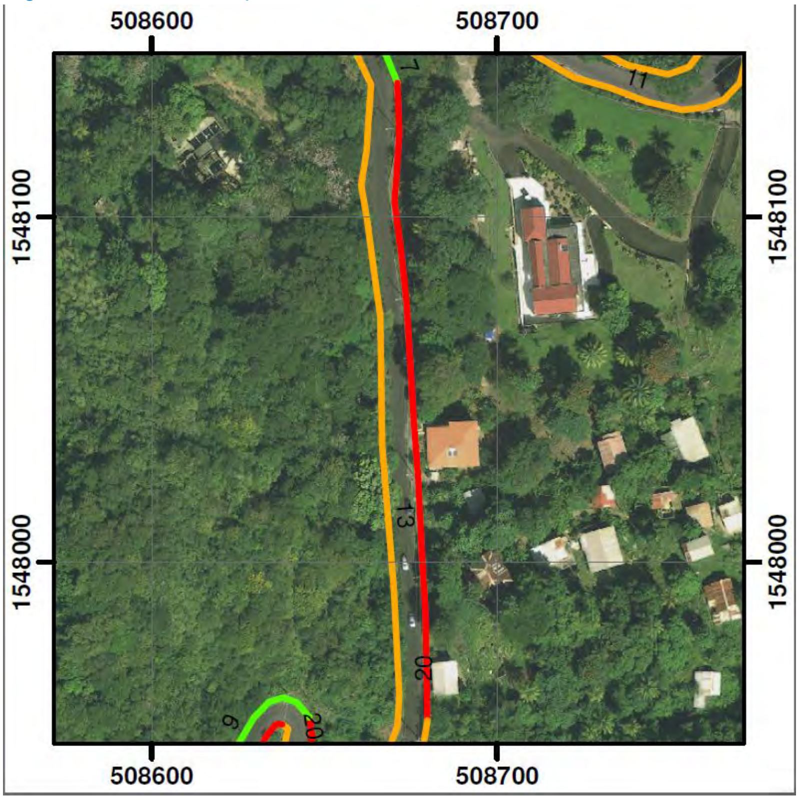
H.1 Bois Cachet straight

H.1.1 Location

Approximate chainage: BC 70 – 260m

Grid reference: 508,676mE; 1,548,047mN

Figure H.1: Location plan



Risk levels: 20 below road; 13 above road

H.1.2 Site description

One-way single lane roadway with extensive tension cracks and displacement parallel to the pavement. Drainage is mainly at the toe of the slope along the inner carriageway.

Figure H.2: Site photograph

Figure H.3: Site photograph

H.1.3 Slope movement

Tension cracks in pavement as a result of creep movement appeared more than 15 years ago. Landslide activity accelerated during Hurricane Tomas when sections of the outer carriageway collapsed and slope failures exposed the bedrock.

H.1.4 Ground conditions

Residual soils and Andesite rock outcrops exposed on slopes along the roadway observed from site walkover. No knowledge of subsurface investigations having been conducted at the site.

H.1.5 Investigations required

Detailed geomorphological/damage mapping of the area to define the type and extents of landslide

Following geomorphological mapping, further investigative work such as subsurface explorations and/or installation of monitoring instrumentation may be required.

H.1.6 Remedial/management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.1: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Shut down the road to vehicular traffic	May result in protest from local residents

Remedial / management option	Notes
	Road condition may worsen if neglected
Road maintenance	Seal tension cracks on road surface with bitumen Place asphaltic overlay on road surface Clear existing drains
Allow use of roadway to vehicular traffic and monitor ground movement during the rainy season.	Time consuming and will require special team Difficult to monitor during rainfall events High risk of slope failure during and post rainstorms
Control of surface run-off by constructing masonry drains.	Masonry drains required to control surface run-off at upper and lower slopes Stepped masonry drain structure required at hairpin from upper slope to lower slope Intercept run-off on upper slope below crest
Driven piles to bedrock for slope stabilisation	Equipment available locally Costly undertaking Ground vibrations from pile driving may affect slope stability Piling noise may result in protests from local residents Shut down of access road
Soil nailing for slope stabilisation	Technology to be imported Costly undertaking Construction noise may result in protests from local residents Shut down of access road

H.1.7 Immediate actions recommended

- Seal tension cracks on road surface;
- clear existing drains.

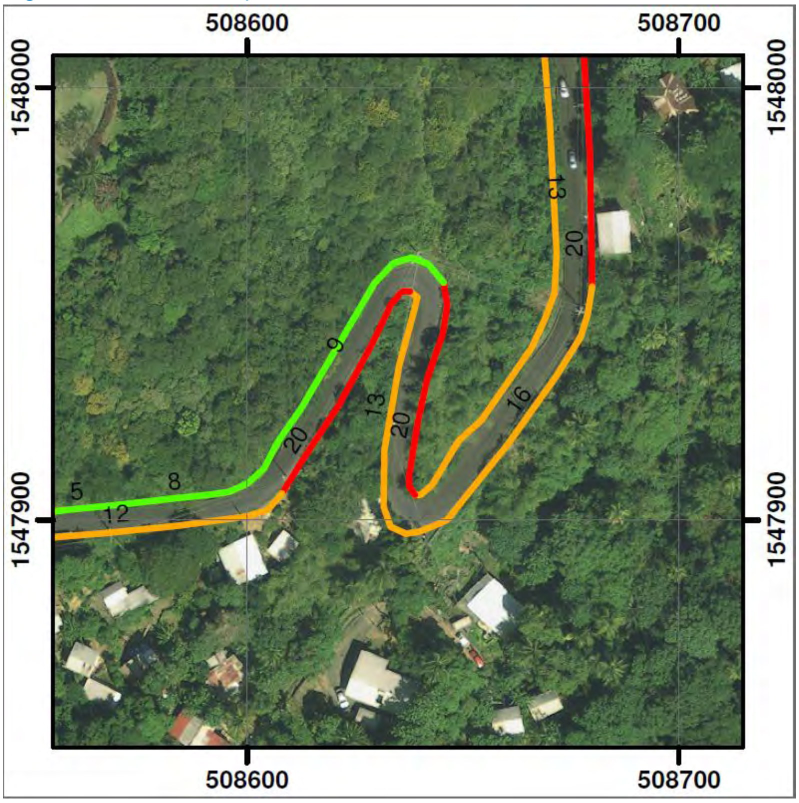
H.2 Bois Cachet hairpins

H.2.1 Location

Approximate chainage: BC 260 – 440m

Grid reference: 508,630mE; 1,547,930mN

Figure H.4: Location plan



Risk levels: 9 to 20

H.2.2 Site description

Steep and tight one-way single lane roadway with extensive tension cracks and displacement parallel to the pavement. Retaining walls below slope show evidence of movement. Drainage is mainly at the toe of the slope along the inner carriageway.

Figure H.5: Site photograph

Figure H.6: Site photograph

H.2.3 Slope movement

Tension cracks in pavement as a result of creep movement appeared more than 15 years ago. Movement accelerated during Hurricane Tomas. The area has been monitored for surface movement in the past however no records are available.

H.2.4 Ground conditions

Residual soils and Andesite rock outcrops exposed on slopes along the roadway observed from site walkover. No knowledge of subsurface investigations having been conducted at the site.

H.2.5 Investigations required

Detailed geomorphological/damage mapping of the area to define the type and extents of landslide.

Drainage survey to determine capacity and system requirements.

Following geomorphological mapping, further investigative work such as subsurface explorations and/or installation of monitoring instrumentation may be required.

H.2.6 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.2: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Shut down the road to vehicular traffic	May result in protest from local residents Road condition may worsen if neglected
Road maintenance	Seal tension cracks on road surface with bitumen Place asphaltic overlay on road surface Clear existing drains
Allow use of roadway to vehicular traffic and monitor ground movement during the rainy season.	Time consuming and will require special team Difficult to monitor during rainfall events High risk of slope failure during and post rainstorms
Control of surface run-off by constructing masonry drains.	Masonry drains required to control surface run-off at upper and lower slopes Stepped masonry drain structure required at hairpin from upper slope to lower slope Intercept run-off on upper slope below crest
Replace damaged/unstable retaining walls	Costly undertaking to construct new retaining walls Only sensible if combined with other works
Driven piles to bedrock for slope stabilisation	Equipment available locally Costly undertaking Ground vibrations from pile driving may affect slope stability Piling noise may result in protests from local residents Shut down of access road
Soil nailing for slope stabilisation	Technology to be imported Costly undertaking Construction noise may result in protests from local residents Shut down of access road

H.2.7 Immediate actions recommended

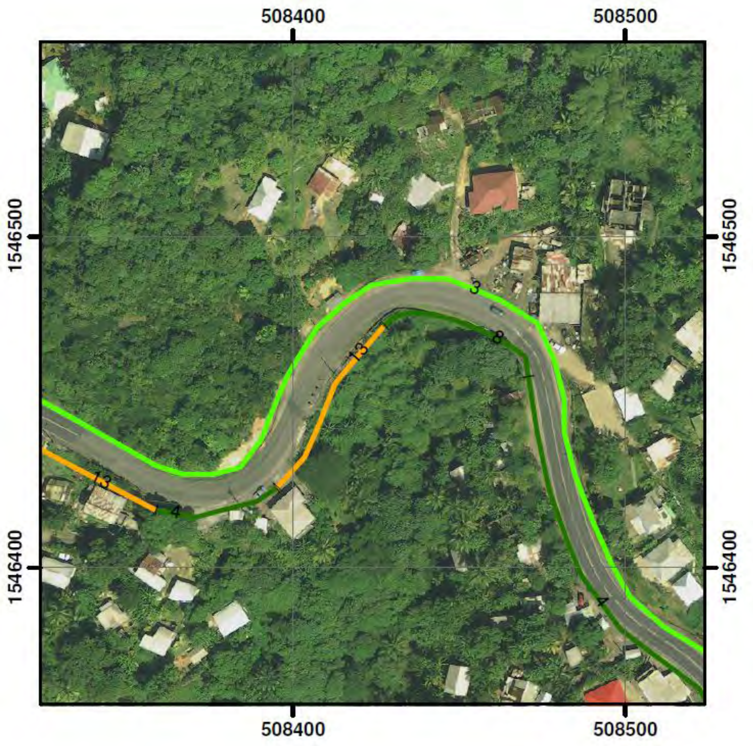
- Seal tension cracks on road surface and in time repave entire road;
- clear existing drains.

H.3 The Morne (near Eudovic Studios)

Approximate chainage: 17885 – 17945m

Grid reference: 508,410mE, 1,546,455mN

Figure H.7: Location plan



Risk levels: 13

H.3.1 Site description

Currently a two lane road, however the width of the road is reduced owing to historical movement. An existing wall below the road has moved and concrete bollards have been installed where settlement and cracking of the pavement has occurred. The slope below is steep and vegetated, leading to a gully. The slope above has had shallow failures depositing material on the road and blocking drainage.

Figure H.8: Site photograph

Figure H.9: Site photograph

H.3.2 Slope movement

At the time of writing, no record of the history of movement is available. It is understood the original movement occurred several years ago and minor pavement degradation has occurred since.

H.3.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site. The failed slope above the road has a backscarp of very weak cream and purple highly weathered rock, probably Andesite.

H.3.4 Investigations required

Site walkover. Topographical survey and possibly intrusive investigations to determine ground conditions is project budget allows.

H.3.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.3: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Road maintenance	Seal tension cracks on road surface with bitumen Place asphaltic overlay on road surface Clear existing drains
Replace damaged/unstable retaining walls	Costly undertaking to construct new retaining walls

Remedial / management option	Notes
	Only sensible if combined with other works
Cut into slope above road and widen away from failed area	Will require stabilisation measures of slope above road

H.3.6 Immediate actions recommended

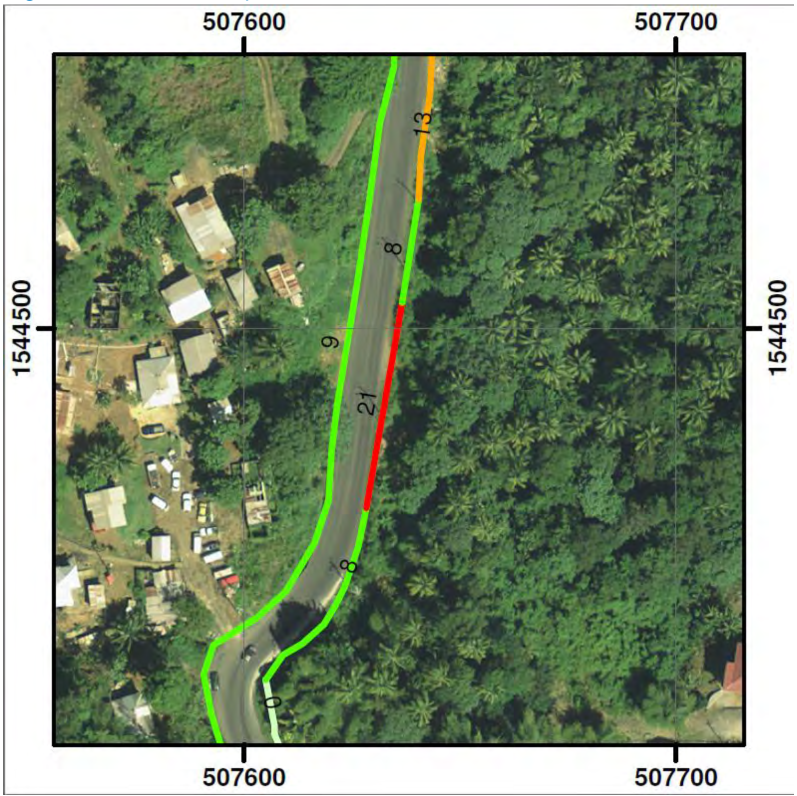
- None

H.4 Ticolon

Approximate chainage: 20320 – 20370 SB

Grid reference: 507,632mE; 1,544,482mN

Figure H.10: Location plan



Risk levels: 21

H.4.1 Site description

Roadway with arcuate cracking affecting half of the width of the road. Slope below is steep and highly vegetated. An existing gabion structure is present over part of the site but it is difficult to see the condition of the structure.

Figure H.11: Site photograph

H.4.2 Slope movement

No record of this history of movement is available. Road has settled approximately 50mm in places

H.4.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site.

H.4.4 Investigations required

Topographical survey of the site.

Two test pits in road side to define ground conditions in the slide area and outside. Shallow borehole to investigate ground conditions and allow installation of a piezometer to determine groundwater level. Disturbed and undisturbed sampling for shear strength testing and index properties

H.4.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.4: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Road maintenance	Seal tension cracks on road surface with bitumen Place asphaltic overlay on road surface

Remedial / management option	Notes
	Clear existing drains
Allow use of roadway to vehicular traffic and monitor ground movement during the rainy season.	Time consuming and will require special team Difficult to monitor during rainfall events High risk of slope failure during and post rainstorms
Control of surface run-off by constructing masonry drains.	Masonry drains required to control surface run-off at upper and lower slopes
Replace damaged/unstable gabion walls	May be expensive Have not been effective to date – reason for this needs to be determined before reconstruction/reuse is attempted.
Driven piles to bedrock for slope stabilisation	Equipment available locally Costly undertaking Ground vibrations from pile driving may affect slope stability Shut down of road may be required
Soil nailing for slope stabilisation	Technology to be imported Costly undertaking Shut down of road may be required

H.4.6 Immediate actions recommended

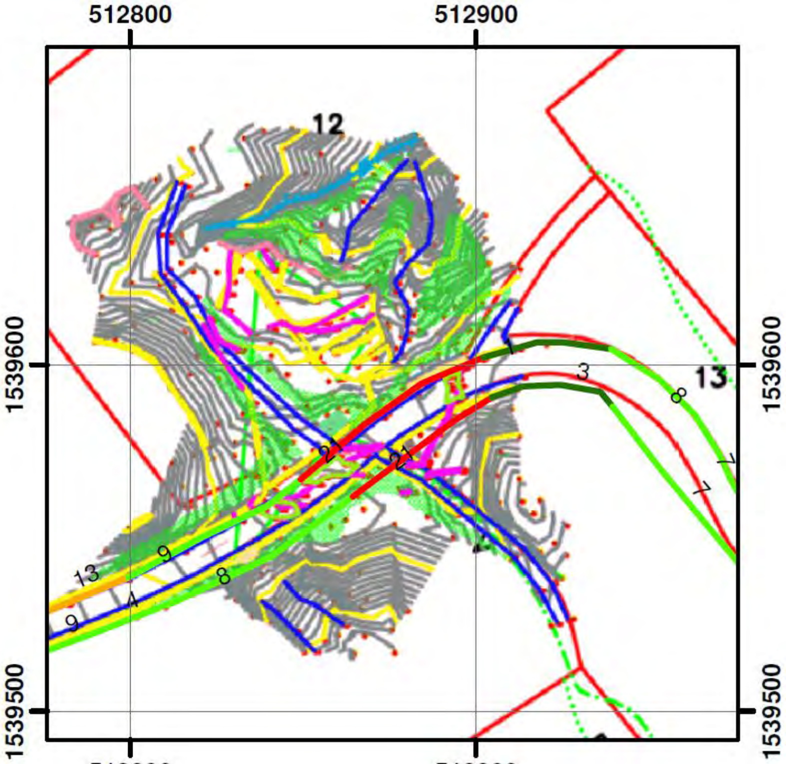
- Seal tension cracks on road surface and in time repave entire road;
- clear existing drains.

H.5 Barre de L'isle – site 1

Approximate chainage: 124905 - 124965

Grid reference: 502,880mE; 1,539,580mN

Figure H.12: Location plan



Source: LRTP map for the Barre D'Lisle.dwg' provided by the Ministry

Risk levels: 22

H.5.1 Site description

Agricultural development with bananas, oranges and vegetables

Figure H.13: Site photograph

H.5.2 Slope movement

Initial slope movement observed in July 2005 following a rainstorm. Other parts of the island experienced landslips including the Windjammer Landing Beach Resort which experienced a mean monthly rainfall of 199 mm for July 2005. Subsequent slope movements at occurred during October 2008 and during Hurricane Tomas.

H.5.3 Ground conditions

Residual soil slope with stratigraphy composed of inter-bedded layers of clayey silt and silty sand overlying highly weathered andesite bedrock. Initial groundwater table at 6.0m below existing ground surface near the crest of the slope.

Extensive geotechnical studies and instrumentation monitoring conducted to date to determine subsurface stratigraphy, ground deformation, geotechnical properties, rainfall, pore water pressures, groundwater conditions, infiltration rate and run-off. Slope stability and steady state and transient seepage analyses conducted and factors of safety determined.

H.5.4 Investigations required

Detailed geomorphological survey to define boundaries and improve understanding of landslide.

H.5.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.5: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Install slope indicators for long term monitoring of ground deformation	slope movement previously monitored long term monitoring recommended
Site dewatering with trench drains	design and install trench drains to intercept groundwater flow to the site design and install trench drains to reduce pore water pressures at the site
Site dewatering with horizontal drains	design and install horizontal drains at toe of slope to reduce pore water pressures technology to be imported costly undertaking
Driven piles to bedrock for slope stabilisation	equipment available locally costly undertaking ground borne vibrations may affect stability of the slope (liquefaction)
Soil nailing for slope stabilisation	technology to be imported costly undertaking some materials available locally (grout, rebar)

H.5.6 Immediate actions recommended

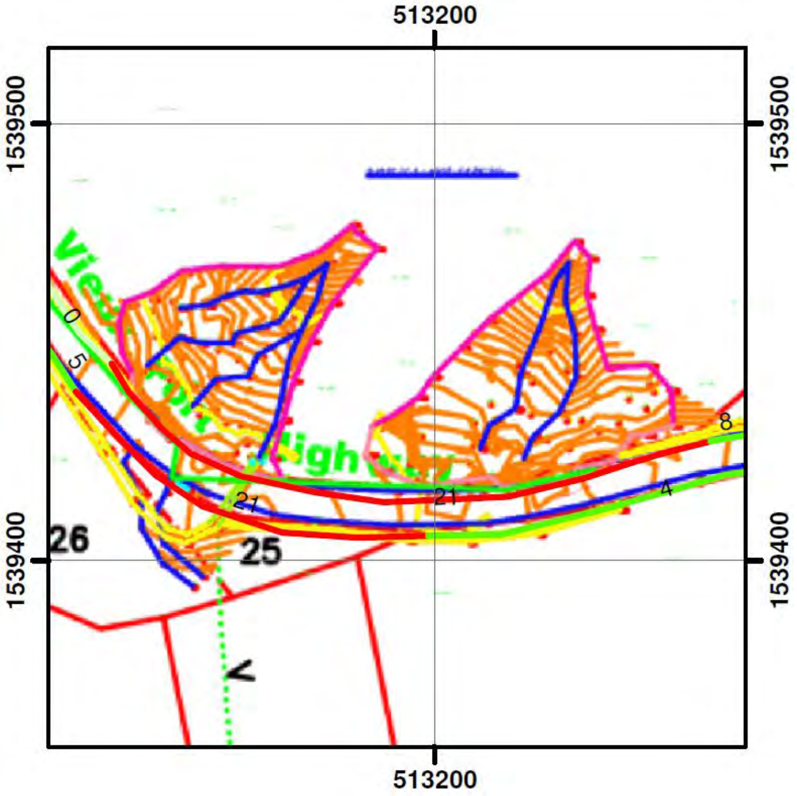
- None.

H.6 Barre de L'isle – sites 2 and 3

Approximate chainage: 124465 - 124620

Grid reference: 513,190mE; 1,539,413mN

Figure H.14: Location plan



Source: RTP map for the Barre D'Lisle.dwg' provided by the Ministry

Risk levels: 21

H.6.1 Site description

Two failures that are currently being remediated. Some features identified during site visits including geomorphology, location of drainage channels and possible backscarps suggest the slide may be deep seated. This is considered unlikely however the available ground investigation will be investigated to confirm that the failure is shallow and therefore the current remedial works are appropriate.

Figure H.15: Site photograph

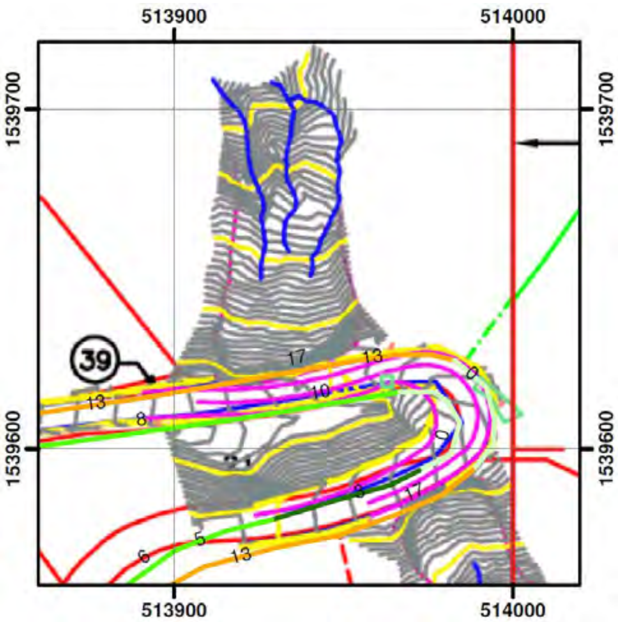
H.7 Barre de L'isle / Tomazo (sites 6, 7, 9 and 10)

Several of the high risk sites along the Barre de L'isle have previously been investigated and had remedial works designed for them by FDL Consult Inc. A summary of the information on sites 6, 7, 9 and 10 is presented below.

Figure H.16: Site locations

	Site 6	Site 7	Site 9	Site 10
Grid reference	513,937mE; 1,539,623mN	513,978mE; 1,539,586mN	514,240mE; 1,539,610mN	514,500mE; 1,539,900mN
Risk level	17	17	22	22

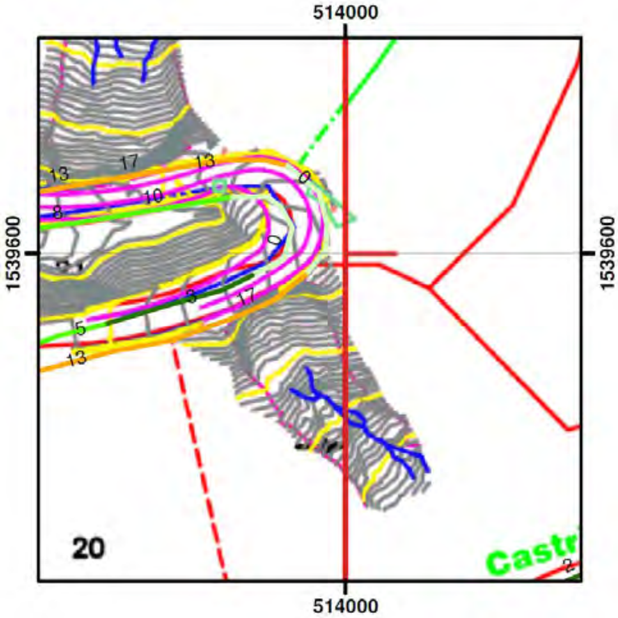
Figure H.17: Location plan – site 6



Source: LRTP map for the Barre D'Lisle.dwg' provided by the Ministry

Figure H.18: Site photograph – site 6

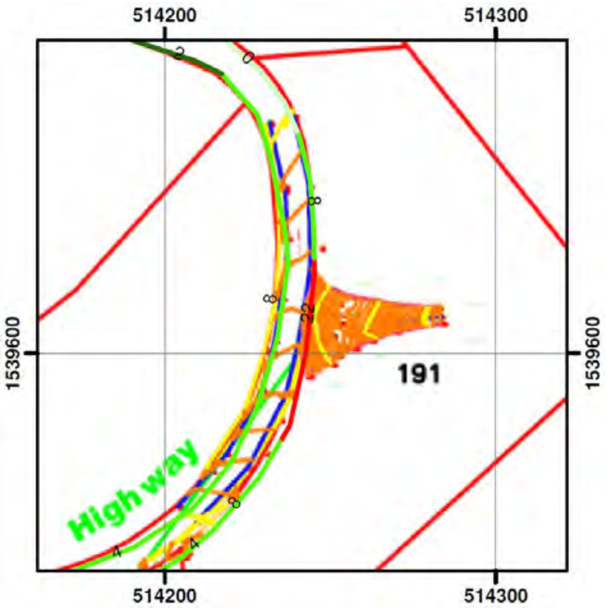
Figure H.19: Location plan – site 7



Source: LRTP map for the Barre D'Lisle.dwg' provided by the Ministry

Figure H.20: Site photograph – site 7

Figure H.21: Location plan – site 9



Source: LRTP map for the Barre D'Lisle.dwg' provided by the Ministry

Figure H.22: Site photograph – site 9

Figure H.23: Location plan – site 10

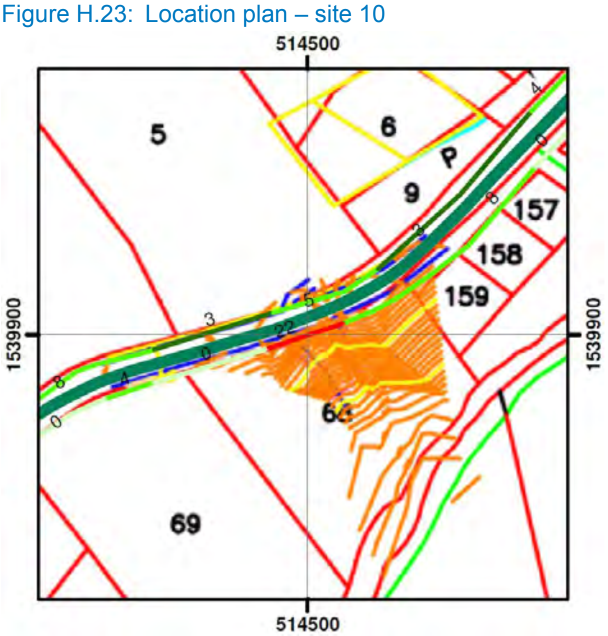


Figure H.24: Site photograph

Source: 'LRTP map for the Barre D'Lisle.dwg' provided by the Ministry

FDL Consult Inc. were commissioned under the Hurricane Tomas Rehabilitation Programme to evaluate the causes of land movement at sites along the Barre de L'isle numbered 1 – 10 from west to east. Sites 6, 7, 9 and 10 have been investigated by FDL and information summarised in their Draft Design Report dated February 2012. The appendices of the report have not been made available.

The FDL report discusses the failure mechanism at each of the sites. FDL consider prolonged rainfall during Hurricane Tomas lead to a reduction in the shear strength of the soil such that it became fluidised and easily eroded. Runoff became focused at locations it could flow over the edge of the road on to the down slope causing erosion and concentrated infiltration.

The FDL report contains photographs of the sites that indicate a structure has failed in each location:

- At site 6 a collapse retaining wall is shown. This may have been a crest wall with limited retaining function.
- At site 7 no structure is visible on the photographs but the report notes the presence of a retaining structure prior to Hurricane Tomas.
- At site 9 a collapsed gabion wall is shown.
- At site 10 a collapsed dry stone wall, probably a crest wall is shown.

It is noted that the masonry walls were not constructed with large bases and their primary function was to limit soil displacement caused by lateral earth pressure and vehicular loading.

FDL describe the physical characteristics of each site. The four sites have steep sections immediately below the road, decreasing towards the toe of the slides. FDL consider the plane of weakness to be coincidental with the post failure ground surface.

The design report states that two hand dug test pits have been excavated at each site, to a maximum of 2m depth. The pits were located on the down slope approximately 3m vertically below the crest of the landslide. The pits are reported to have encountered a layer of topsoil 0.5m thick, underlain by residual clay to the base of the pits. Weathered rock was not proven in the pits.

The FDL draft design report includes a qualitative assessment of the potential slope stabilisation design options, including dismissing the 'do nothing' approach because of the likelihood of further damage to the roadway. Several other possible remediation measures were also dismissed, including piled walls, soil nailing/anchors and anchored shear keys, based on the Caribbean Development Bank's mandate of the least cost option capable of meeting the design objectives, and the probable requirement for closure of the entire road during construction of these options. The optioned mentioned are seldom used in Saint Lucia and would require foreign contractors, leading to high costs. Reinforced concrete cantilever retaining walls were dismissed based on preliminary analysis suggesting founding level at significant depths and width of wall required leading to an unfavourable surcharge at the top of the slopes adversely affecting global factors of safety. Design life and cost of these solutions was also investigated and it was determined that the additional design life of some of the more expensive structures did not offset their additional cost.

Shortlisted options for sites 6, 7, 9 and 10 were:
- construction of gabion walls;
- construction of rock fill embankments;
- road reinstatement;
- drain rehabilitation and/or construction; and
- planting of vetiver grass for slope erosion protection.

Three design options, road re-alignment, gabion wall and rock fill embankment, were compared using a qualitative and semi-quantitative analysis. A gabion wall solution, with associated drainage and vegetation, was selected as the preferred design option at all sites.

Slope stability analysis was completed at each site based on the existing site geometry and the construction of remediation works.

The pre remediation factor of safety of the current slopes in unsaturated dry conditions was calculated as varying between 1.1 and 1.3. FDL note this is likely to be conservative (i.e. low) because it assumes completely dry conditions, whereas the actual partially saturated conditions are likely to mean suction provides some apparent cohesion and small increase in shear strength. The factor of safety of the current slope in wet conditions, assuming the phreatic surface (groundwater level) to be at ground level and the soils fully saturated, was calculated as between 0.4 and 0.8, i.e. the slopes at each site would fail in these conditions. This condition may occur with high antecedent rainfall with intense rainfall events.

The gabion wall structure was designed to resist sliding, overturning and bearing capacity failure. The post remediation factor of safety of the overall slope, after installation of a gabion wall founded on a rockfill base and assuming free draining of the structure, was calculated. The critical slip surface was calculated to be in the slope below the structure. Therefore vetiver grass was included within the analysis below slope to prevent the critical slip surface from forming. The overall slope factor of safety for the retained slope in wet conditions with vetiver grass was calculated to be 1.1 in all cases. This is very close to unity. The overall slope stability is reliant on the propagation and continual presence of deep roots. Therefore, on-going monitoring of land use will be required to ensure the land is not cleared for cultivation, destroying the slope stabilising properties of the vegetation.

The analysis does not take an increase in strength of material with depth or the possible presence of bedrock into account. Therefore, FDL consider the analysis to be conservative. This may be the case. However, given the weathering profile of materials in this area, weaker layers at depth may also be present and so it is possible the analysis is not conservative.

On-going maintenance of drainage and vegetation will be required.

Following, submission of FDL's draft design report, the Ministry commissioned Trintoplan Consultants Limited to complete intrusive investigations at the sites. Trintoplan completed boreholes at each of the sites and determined a ground profile that comprised clay or clayey silt overlying sand, with weathered rock at depth. This differed from the homogeneous clay profile assumed by FDL.

Pre remediation factor of safety of the current slopes in unsaturated dry conditions was calculated by Trintoplan as varying between 1.0 and 1.6. The factor of safety of the current slope in wet conditions, assuming the phreatic surface (groundwater level) to be at ground level and the soils fully saturated, was calculated by Trintoplan as between 0.6 and 1.0.

Trintoplan discuss potential remediation measures and recommend drainage improvements and a structural solution at each site. The structural solution recommended at sites 9 and 10 is a retaining wall founded on a deep augered pile foundation. A range of options is suggested for sites 6 and 7, including a proposed reinforced earth structure.

Both Trintoplan and FDL emphasise the importance of drainage in the control of slope stability in the Barre De L'isle area.

H.7.1 Recommendations

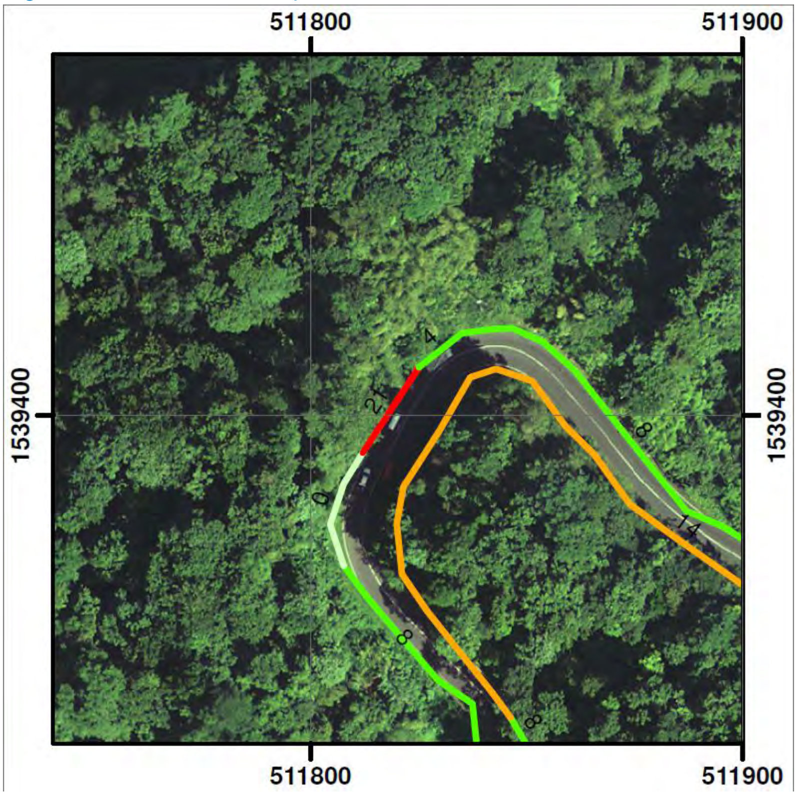
It is considered the final FDL design report should be sought, which should take into account the investigations by Trintoplan. The final design report should include a comparison of the design options to determine the most economically advantageous and feasible solution.

H.8 Ravine Cribiche

Approximate chainage: 126540 - 126565

Grid reference: 511,819mE; 1,539,401mN

Figure H.25: Location plan



Risk level: 21

H.8.1 Site description

Steep slope below road. Existing masonry retaining wall damaged above ground and possibly damaged below ground but difficult to see. Northern end has 3-4m of collapsed wall which is being undermined. Drainage is currently partly channelled towards the failure and drains are not lined on this side of the road.

Figure H.26: Site photograph

H.8.2 Slope movement

Understood to have occurred during Hurricane Tomas.

H.8.3 Ground conditions

No ground investigation completed. Considered likely to be residual soil.

H.8.4 Investigations required

Topographical survey.

A condition survey of retaining wall on the north of the slide is recommended but is not considered within the scope of this project.

H.8.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.6: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Improve drainage	Prevent surface water from discharging directly on to the slope and infiltrating behind remaining retaining wall Relatively low cost

Remedial / management option	Notes
Reinstate masonry retaining wall	Relatively expensive Needs to be combined with improving drainage
End tip material off slope to provide some temporary support	Temporary fix Quick and cheap Requires drainage to be improved May damage land below road

H.8.6 Immediate actions recommended

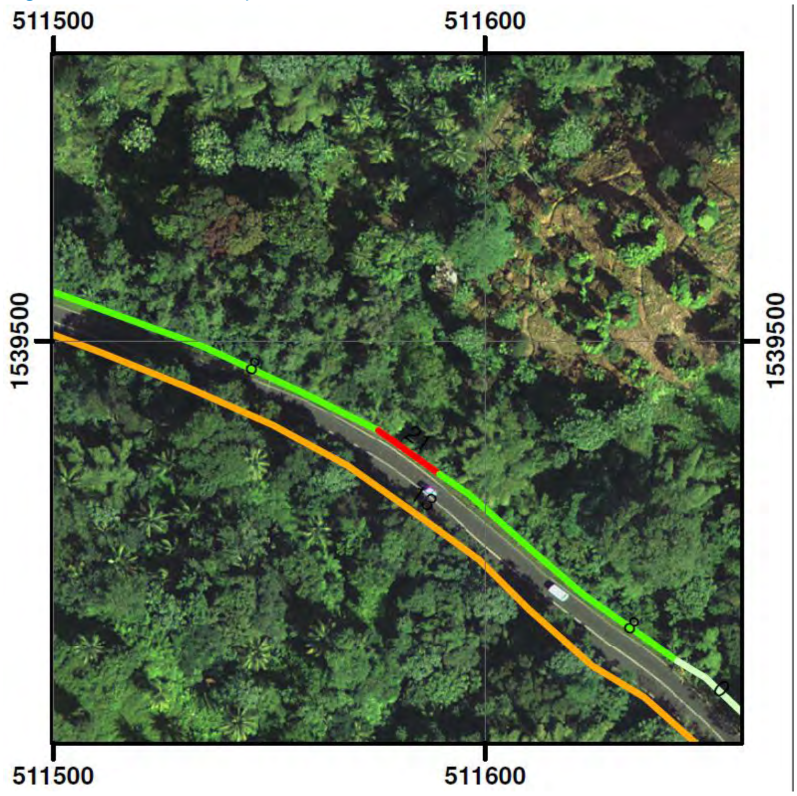
- Improve drainage to prevent infiltration behind the remaining retaining wall and prevent surface flow off the slope beneath the retaining wall and in failed area.

H.9 Ravine Poisson

Approximate chainage: 127040 – 127055 EB

Grid reference: 511,582mE; 1,539,474mN

Figure H.27: Location plan



Risk level: 21

H.9.1 Site description

Small stretch of road with small failed area at edge of retaining wall encroaching on the road. The failed area is associated with a failed section of retaining wall. Steep slope below. Water being directed onto the failure by current drainage layout.

Figure H.28: Site photograph

H.9.2 Slope movement

Not known.

H.9.3 Ground conditions

No ground investigation completed. Considered likely to be residual soil.

H.9.4 Investigations required

Topographical survey.

H.9.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.7: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Improve drainage	Prevent surface water from discharging directly on to the slope and infiltrating behind remaining retaining wall Relatively low cost
Reinstate masonry retaining wall	Relatively expensive Needs to be combined with improving drainage

Remedial / management option	Notes
End tip material off slope to provide some temporary support	Temporary fix Quick and cheap Requires drainage to be improved May damage land below road

H.9.6 Immediate actions recommended

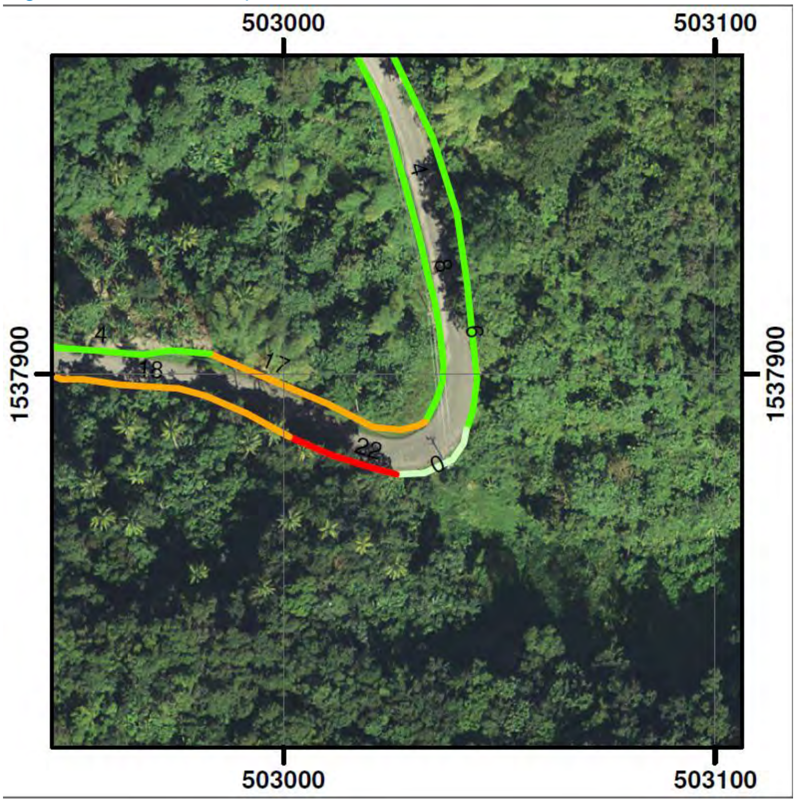
- Redirect drainage to prevent discharge directly onto failed area.

H.10 Ravine Joseph

Approximate chainage: 35910 – 35940 SB

Grid reference: 503,014mE; 1,537,881mN

Figure H.29: Location plan



Risk levels: 22

H.10.1 Site description

The slope is located on the south side of the sharp corner that crosses near the head of Ravine Joseph, north of Anse La Verdure.

The failure is on a corner which has a relatively large flat area on the outside of the road. The failure has a steep (>50°) backscarp 2-3m high, above a lower angled slope of backscarp and failed material at around 40°. The slope above the failure is around 35° on average and rises more than 80m vertically above the failed mass. It is this slope and material above the recent failure that is considered to pose the greatest risk to the road network. A similar slope extends west along the road.

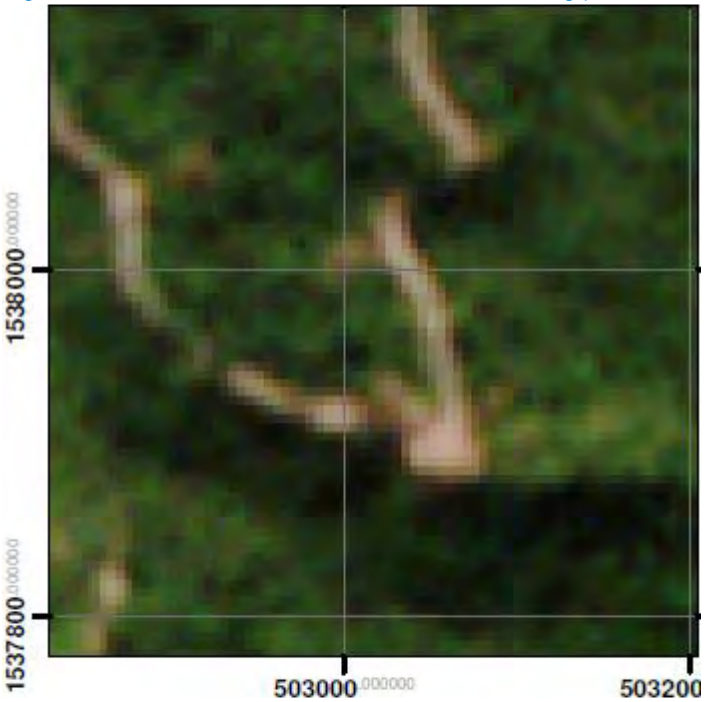
The failure is approximately 25m across at the base, and the top of the failure is estimated to be around 15m above road level. The depth/thickness of the failure appears to be less than 2m.

Figure H.30: Site photograph

H.10.2 Slope movement

The failure is above the road and the site is understood to have failed during Hurricane Tomas and completely blocked the road as shown in Figure H.31. DeGraff (1985) records a failure just west of the location.

Figure H.31: Location after Hurricane Tomas showing probable debris covering the road



H.10.3 Ground conditions

The published geological map indicates the site is within volcanic 'andesite agglomerate, mud flow' rocks of the Central Series. Further up slope from the slide, a change in geology to sedimentary 'agglomerate tuffs, tuffs' of the Northern Series is shown on the published map. The material currently exposed appears to be colluvium, with some areas of highly weathered rock.

No knowledge of subsurface investigations having been conducted at the site.

H.10.4 Investigations required

Topographical survey of the site.

H.10.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.8: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Accept the risk	Provide public warnings of the risk Develop warning systems that can close road when area is likely to be subject to failures Respond to events
Vegetate slope	Reduces surface erosion and infiltration
Put a barrier at the base of the slope to reduce material reaching road	In this particular location, a barrier which could take the form of deep rooted trees, may be possible to reduce the impact of a failure on the road
Soil nailing for slope stabilisation	Technology to be imported Costly undertaking Shut down of road may be required

H.10.6 Immediate actions recommended

- None recommended.

H.11 Colombette

H.11.1 Location

Approximate chainage: 48435 – 48575 (entire area)

Grid reference: 503,360E; 1,533,110mN

Figure H.32: Location plan (prior to Hurricane Tomas)

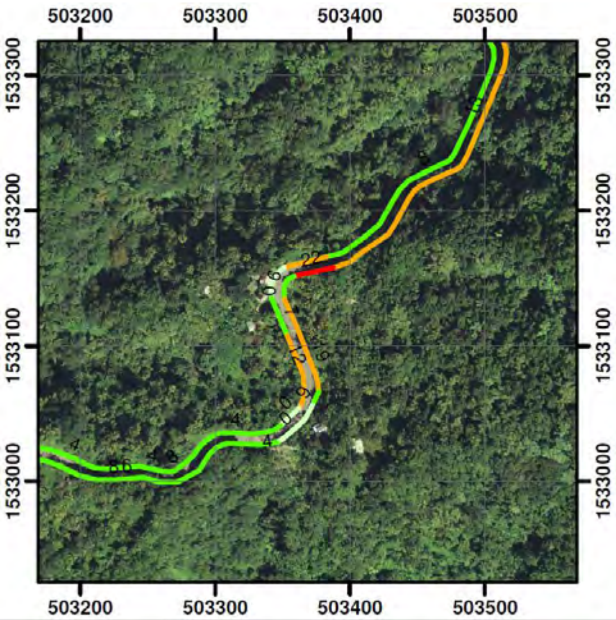
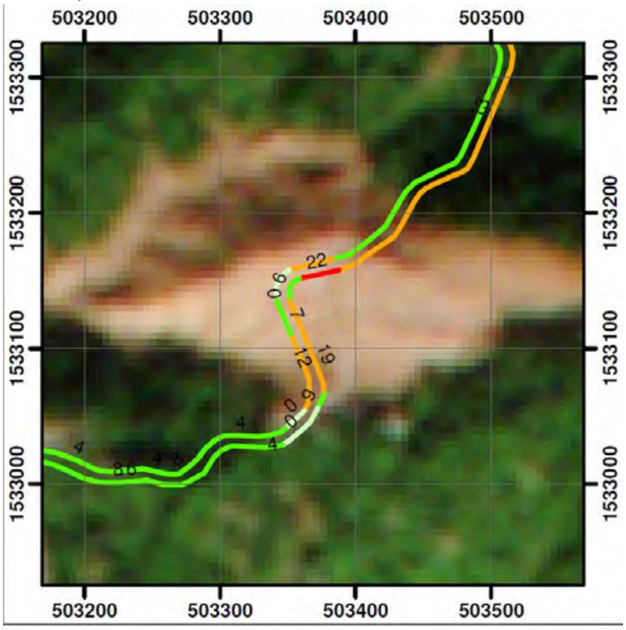


Figure H.33: Location plan (shortly after Hurricane Tomas)



Source: Ste-Lucia_rapideye_5m_20110103_BWIgrid.tifThe image georeferencing is not as accurate as the air photographs

Risk levels: 0 to 22

H.11.2 Site description

The Colombette slide itself is relatively shallow above the road up to the backscarp. The area is vegetated with some grass and scrub. Below the road the site is also vegetated with scrub vegetation, and is relatively shallow. Drainage channels are present on the slide mass but were not flowing during site visits to the area.

Around the site and in this location prior to the slide, the area is densely forested relatively steep slopes above and below the road.

Figure H.34: Site photograph

Figure H.35: Site photograph

H.11.3 Slope movement

Very rapid debris avalanche triggered by intensive rainfall and increased pore water pressures in the subsoils. The moving soil mass flowed over the main roadway without undermining any section of the road. The debris flow caused loss of life and property. Exposed upper backscarp slope expected to collapse onto lower slopes with time but not expected to reach the primary road

H.11.4 Ground conditions

Difficult to access upper section of the slope. Colluvial material from slide accumulated on lower portion of upper slope. The exposed soil on the slope is colluvial formed from andesite agglomerate consisting of boulders, cobbles, gravel, sand, silt and clay. Thin seams of volcanic ash are exposed on the in situ ground at some locations along the primary road.

H.11.5 Investigations required

Topographical survey of the area followed by detailed geomorphological mapping to define the type and extents of landslide, location of bedrock, thickness of deposits, material in the backscarp, surface water drainage and on-going morphological processes.

Series of test pits to be completed on slope above road to determine thickness of colluvial material to allow stability of mass to be confirmed and options for high risk area on the north side of the slide to be investigated.

A condition survey of retaining wall and drainage on the north of the slide is recommended but is not considered within the scope of this project.

H.11.6 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.1 presents some of the remedial / management options likely to be appropriate.

Table H.9: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Install surface and subsurface drains	install surface masonry drainage system to control run-off install subsurface drains to control pore water pressures
Instrumentation & Monitoring	difficult access to upper slope install standpipe piezometers to monitor pore water pressures install survey points to monitor ground deformation
Bench slope for stabilisation	design benched slope with acceptable factor of safety equipment available locally
Plant trees with deep root system	selected plant species with deep root system to be selected by forestry department for slope stabilisation control of pore water pressures by root absorption and transpiration increased shear strength of subsoils plant leaves reduce impact of raindrops onto the ground and reduce soil erosion
Construct a safety berm to prevent debris on the road	may prevent material that fails from reaching the road equipment available locally
Driven piles for slope stabilisation	equipment available locally costly undertaking

H.11.7 Immediate actions recommended

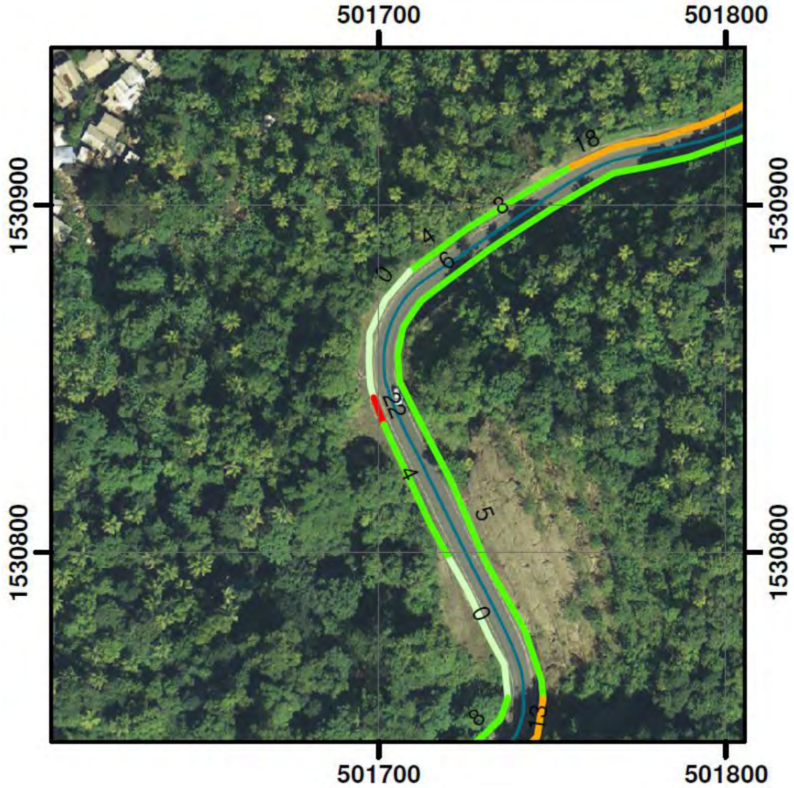
- Condition survey of retaining wall and drainage on the north side of the slide.

H.12 Calvaire

Approximate chainage: 53800 - 53805 NB

Grid reference: 501,700mE; 1,530,841mN

Figure H.36: Location plan



Risk levels: 22

H.12.1 Site description

A failure approximately 5m wide below the road. Failed slope is steep and drainage is being directed onto the slope.

Figure H.37: Site photograph

H.12.2 Slope movement

The slope is understood to have failed during Hurricane Tomas.

H.12.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site. The material in the back of the failure looks like residual soil and highly weathered rock.

H.12.4 Investigations required

Topographical survey of the site.

H.12.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.10 presents some of the remedial / management options likely to be appropriate.

Table H.10: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Improve drainage	Masonry/concrete drains in area to control infiltration and suitably direct surface run-off.

Remedial / management option	Notes
Gabion basket retaining wall	Stabilise slope below road and prevent further encroachment onto road. Local experience
Masonry/concrete retaining wall	Stabilise slope below road and prevent further encroachment onto road. Potentially expensive

H.12.6 Immediate actions recommended

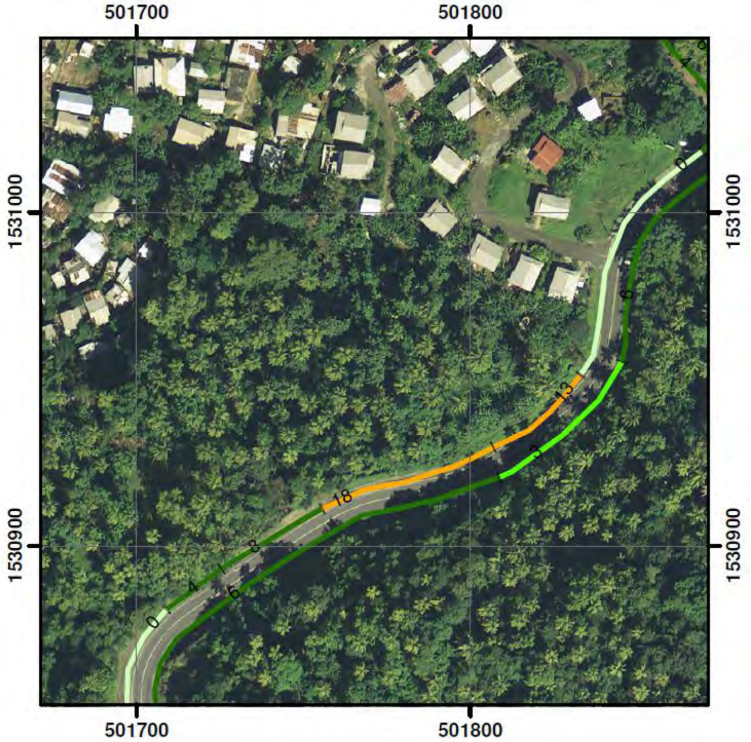
- Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.

H.13 Calvaire 2

Approximate chainage: 53650 - 53710 SB

Grid reference: 501,780mE; 1,530,920mN

Figure H.38: Location plan



Risk levels: 18

H.13.1 Site description

Failures occurring on slope below road, undermining drainage.

Figure H.39: Site photograph

H.13.2 Slope movement

The slope is understood to have failed during Hurricane Tomas and has regular shallow movements associated with rainfall events.

H.13.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site. The material in the back of the failure looks like residual soil and highly weathered rock.

H.13.4 Investigations required

Topographical survey of the site.

H.13.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.11 presents some of the remedial / management options likely to be appropriate.

Table H.11: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Improve drainage	Concrete drains in area to control infiltration and suitably direct surface run-off.
Gabion basket retaining wall	Stabilise slope below road and prevent further encroachment onto road. Local experience
Masonry/concrete retaining wall	Stabilise slope below road and prevent further encroachment onto road. Potentially expensive

H.13.6 Immediate actions recommended

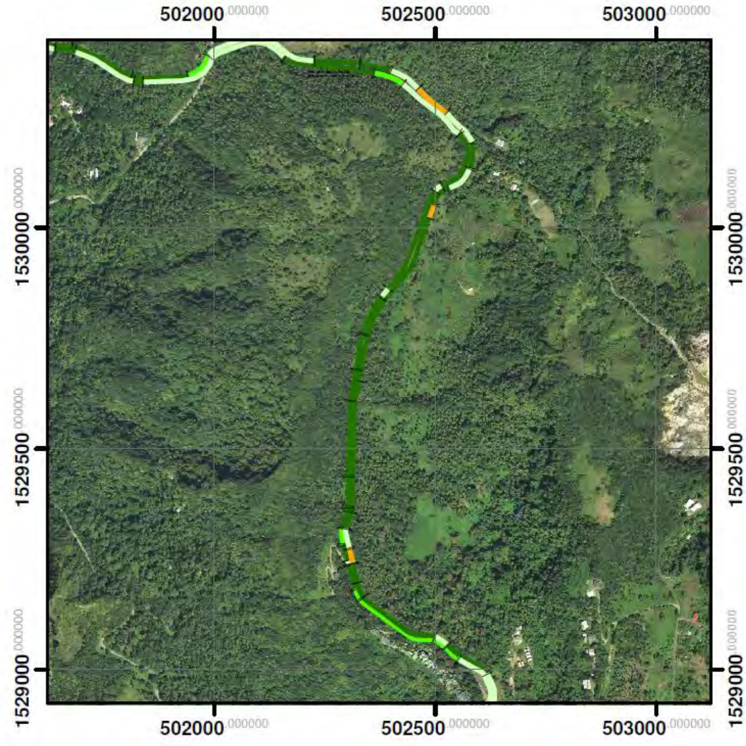
- Improve drainage to prevent water infiltration to the slope and prevent water being directed onto the slope causing erosion.

H.14 Road past the turn off to Sulphur Springs

Approximate chainage: 55750 - 56550

Grid reference: 502,330mE; 1,529,755mN

Figure H.40: Location plan



Risk levels: 4 – 9

H.14.1 Site description

Stretch of road approximately 1km long. Slope above the road is relatively steep and maximum elevation is approximately 100m above the road elevation.

H.14.2 Slope movement

Sections of the slope failed during Hurricane Tomas and were benched during/shortly after the clean-up operation to reduce likelihood of failure and debris reaching the road. It is understood from the Ministry that each year this area is a problem with debris reaching the road requiring clearance.

H.14.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site.

H.14.4 Investigations required

None specified.

H.14.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.12 presents some of the remedial / management options likely to be appropriate.

Table H.12: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Maintain benched areas	Clear benches where failure material is accumulating, Repair minor failures in benches. Improve drainage of benches.
Realign road	Could align road further in valley but would require significant earthworks to prevent flooding of road.
Debris fence / barrier	Reduce amount of material reaching the road side. Would require clearing and work best in combination with other measures.
Vegetate / bioremediation	May assist in improving stability. Would work best in combination with other measures.

H.14.6 Immediate actions recommended

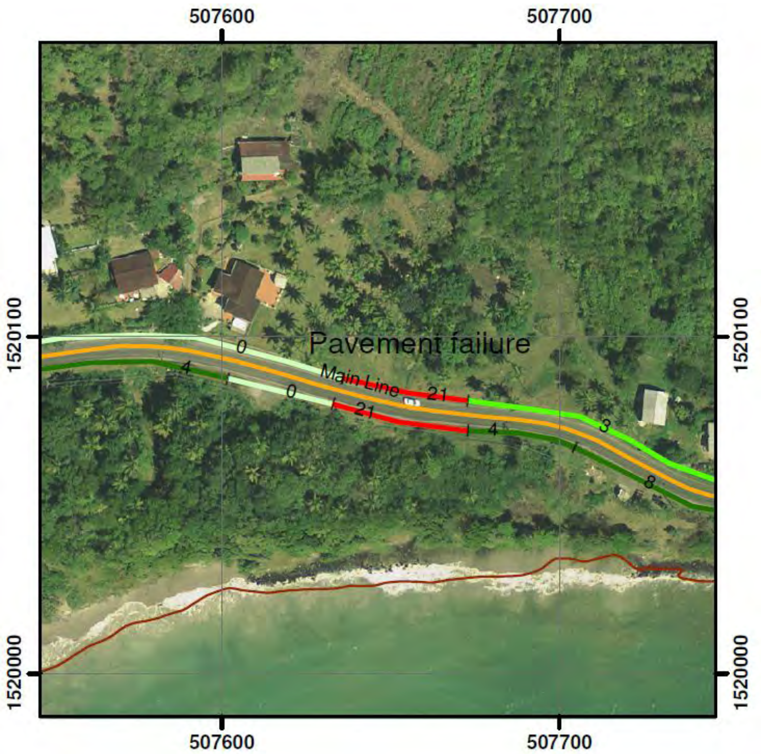
- None.

H.15 Laborie

Approximate chainage: 75755 – 75800

Grid reference: 507,650mE; 1,520,080mN

Figure H.41: Location plan



Risk levels: 21

H.15.1 Site description

Relatively shallow, vegetated slope above road and vegetated toe of slide extending to sea shore. Zone approximately 40m wide where pavement settles small amounts. Some rock (toe protection) appears to have been placed along the shoreline.

Figure H.42: Site photograph

Figure H.43: Site photograph

H.15.2 Slope movement

Pavement settles over a section approximately 40m wide. History of movement not known.

H.15.3 Ground conditions

No knowledge of subsurface investigations having been conducted at the site.

H.15.4 Investigations required

Topographical survey of the site.

Test pits to be completed on settlement areas to determine ground conditions and try to identify failure plane.

H.15.5 Remedial / management options

The remedial/management options will be further defined following investigations and any necessary seepage and slope stability analyses. Table H.13 presents some of the remedial / management options likely to be appropriate.

Table H.13: Summary of remedial/management options likely to be appropriate

Remedial / management option	Notes
Site dewatering with trench drains	design and install trench drains to intercept groundwater flow to the site design and install trench drains to reduce pore water pressures at the site

Remedial / management option	Notes
Improve toe protection	More formal design of toe protection to reduce erosion and unloading of slide, therefore slowing movement.
Repave when serviceability decreases	Relatively quick and cheap. Need to determine how often this is required before other measures become attractive.

H.15.6 Immediate actions recommended

- None.