RISK INFORMATION SERVICES FOR DISASTER RISK MANAGEMENT (DRM) IN THE CARIBBEAN

OPERATIONAL DOCUMENTATION

Authors:
Colm J Jordan, Stephen Grebby, Tom Dijkstra, Claire Dashwood and Francesca Cigna
(British Geological Survey, Natural Environment Research Council)

reference/*réference*	OR/15/001
issue/*édition*	1
revision/*révision*	2
date of issue/*date d'édition*	19/02/2015
status/*état*	Final
Document type/*type de documen*	Technical Note

TABLE OF CONTENTS

1 THE PURPOSE OF THE DOCUMENT 3

2 EXECUTIVE SUMMARY 4
- **2.1 The World Bank Project Context 4**
- **2.2 Requirements for Geo-Spatial Information 7**
- **2.3 Interpretation of the results 10**
  - **2.3.1 Service 1: Land use/land cover mapping** 11
  - **2.3.2 Service 2: Hazard mapping to support landslide risk assessment** 12
  - **2.3.3 Service 3: Digital Elevation Models of Belize** 17
- **2.4 Guidelines for use 18**

3 PRODUCTS DESCRIPTION 20
- **3.1 Products 20**
  - **3.1.1 Service 1: Land use/land cover mapping** 20
  - **3.1.2 Service 2: Hazard mapping to support landslide risk assessment** 25
  - **3.1.3 Service 3: Digital Elevation Models of Belize** 49
- **3.2 Metadata 51**

4 GUIDELINES FOR USE 53

5 VALIDATION RESULTS 56
- **5.1 Quality Checking 56**
  - **5.1.1 Service 1: Land use/land cover mapping** 56
  - **5.1.2 Service 2: Hazard mapping to support landslide risk assessment** 61
  - **5.1.3 Service 3: Digital Elevation Models of Belize** 63
- **5.2 Initial Validation 63**

6 NON-CONFORMANCE 64

7 REFERENCES 65

8 APPENDIXES 67
- **8.1 Appendix 1, Service Operation 67**
  - 8.1.1 EO Data Procurement 67
  - 8.1.2 Ancillary Data Procurement 68
- **8.2 Appendix 2, Acronyms and Abbreviations 69**

1 THE PURPOSE OF THE DOCUMENT

This document specifies the EO information products / services delivered to the World Bank (primarily via the ITC-led CHARIM project) in the framework of the European Space Agency (ESA) "eoworld 2" initiative. The products services were produced by the British Geological Survey (BGS) in the Caribbean using a combination of satellite EO data, ground validation exercises and pre-existing data.

This document includes:

- detailed description of the products included within each of the three services;
- description of how the services were produced;
- guidelines on how to use the products.

A note on copyright: there are a significant number of figures containing satellite images within this report. Rather than identify the copyright holder for each image in each figure, the satellite image has been identified and the copyright attribution appears here:

Copyright notices for the satellite imagery used in the project are as follows:

- Products derived from Pleiades satellite imagery – includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.
- Products derived from RapidEye satellite imagery – includes material © 2014 BlackBridge, all rights reserved.
- Products derived from ASTER satellite data – ASTER GDEM is a product of METI and NASA
- Products derived from SPOT satellite data – includes material © CNES 2014, Distribution Astrium Services / SPOT Image S.A., France, all rights reserved

2 EXECUTIVE SUMMARY

2.1 The World Bank Project Context

The primary objective of this ESA project is to raise awareness within the World Bank (WB) of the capabilities of Earth Observation (EO) data and specialist service providers to supply information customised to the specific needs of individual projects. This project was set up within the ESA/WB *eoworld* initiative to contribute to the WB Caribbean Risk Information Program that is operating under a grant from the ACP-EU Natural Risk Reduction Program.

The Caribbean is heavily affected by natural (and geo-) hazards with over 5 billion US$ in losses in the last 20 years (source: CRED database). Figure 1 illustrates the division of natural disaster by occurrence in the region over the last 30 years, providing an insight into the impact in the region over a significant time period. A specific example of the environmental, social, economic and political issues that the project is addressing is highlighted by the effects of Hurricane Tomas on St Lucia in October 2010. The hurricane resulted in seven deaths with 5952 people severely affected, while the cost of the damage was estimated at US$336.2 million, representing 43.4% of GDP (ECLAC, 2011). Understanding and mitigating these “geo-environmental disasters” (as they are termed in ECLAC, 2011) is a primary concern in the region.

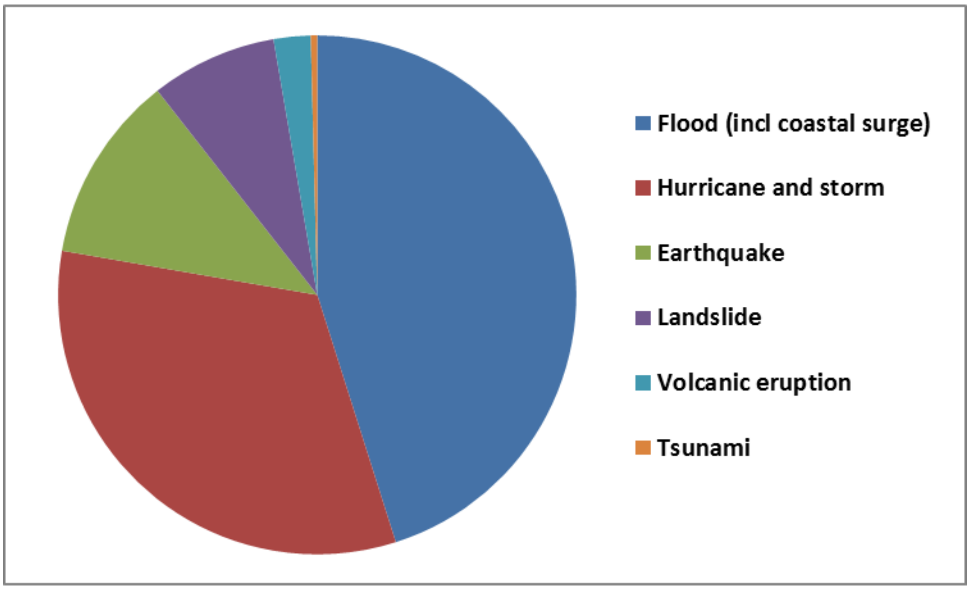


Figure 1 Natural disaster occurrences in the Caribbean region. Source: CRED database

The ITC-led Caribbean Handbook for Disaster Information Management (CHARIM) is operating in five Caribbean countries (Belize, Dominica, Saint Lucia, St Vincent & the Grenadines and Grenada). CHARIM has several objectives including developing a structure for landslide and flood hazard and risk assessment. This ESA project is focussed on “risk information services for disaster risk management in the Caribbean” a title that has been abbreviated to **EO-RISC** (Earth Observation for Risk Information Services in the Caribbean) internally by BGS. EO-RISC deliverables directly contribute to the CHARIM objectives e.g. by providing data and services that enable certain hazards such as landslides to be identified directly.

EO-RISC is addressing various issues in the Caribbean. In broad terms, the Latin America and Caribbean Regional Urban and Disaster Risk Management Unit (GPSURR) with funding from the ACP-EU Natural Disaster Risk Reduction Program, managed by the Global Facility for Disaster Reduction Recovery (GFDRR) has begun the “Caribbean Risk Information Programme to support the Integration of Disaster Risk Management Strategies in Critical Sectors” project. This has been initiated in order to strengthen the regional and national capacity to create and use hazard and risk information for planning and development processes, and consists of four components: (a) creation of a geospatial information basis, focusing on the collation, quality control and adequate storing, management and sharing of existing geospatial data in a spatial data infrastructure, (b) development of a methodological framework for the development of hazard and risk information for development and planning processes, (c) implementation of five national pilot hazard studies aimed at implementing the methodological framework in partnership with Caribbean countries, and (d) integrating institutional strengthening as a cross-cutting activity to all components. The Caribbean Risk Information Programme forms part of the Probabilistic Risk Assessment (CAPRA) Program whose objective is to enhance the capacity of targeted sectors in Latin America and the Caribbean region to develop and mainstream disaster risk information into development programs and policies by providing knowledge products and services. Counterpart agencies are the Ministries of Works and Physical Planning in the following countries: Belize, Dominica, Grenada St. Lucia and St. Vincent and the Grenadines. With a focus on national-level landslide and flood hazard assessments, country-wide baseline data and information are required. They span a broad range such as: Land Use/ Land Cover, updating of river and stream courses, extent of lakes, water bodies, and watersheds, basic road network, landslide inventory, Digital Elevation Models, geology including fault lines, geomorphology, soil maps, etc.

Table 1 lists the hazard characteristics of the four islands that EO-RISC is covering, and provides an overview of the issues and problems being encountered by agencies in the region. CHARIM introduced BGS to the local stakeholders in the region at the WB workshop in St Vincent in October 2014. Presentations by BGS introduced the EO data and the preliminary derivative services, and feedback was received from the stakeholders / potential users on the services and their formats.

Table 1 General disaster management and hazard characteristics for the four countries in EO-RISC (Source: CDEMA website, and modified from van Westen, 2014)

	Belize	**Saint Lucia**	**St. Vincent and the Grenadines**	**Grenada**
Area	22,806 km^2	606 km^2	389 km^2 (Saint Vincent 344 km^2) with 32 islands and cays	344 km^2
Coastline	386 km	158 km	84 km	121 km
Terrain	Flat, swampy coastal plain; low mountains in south. Max. elevation 1,160 m	Volcanic and mountainous with some broad, fertile valleys. Max. elevation: 950 m	Volcanic, mountainous. Max. elevation: 1,234 m	Volcanic in origin with central mountains. Max elevation: 840 m
Natural hazards	Frequent, devastating hurricanes (June to November) and coastal flooding (especially in the south)	Hurricanes and volcanic activity, landslides, debris flows, flashfloods	Hurricanes; Soufriere volcano on the island of Saint Vincent is a constant threat. Flashfloods and landslides	Lies on edge of hurricane belt; hurricane season lasts from June to November. Flashfloods and landslides.
Hazard characteristics	Hurricanes and tropical storms are the principal hazards, causing severe losses from wind damage and flooding due to storm surge and heavy rainfall. Hurricanes Keith (2000), and Iris (2001) caused some of the worst damage ever, reaching 45% (US$280 million) and 25% of GDP, respectively.	Saint Lucia's mountainous topography coupled with its volcanic geology means that it experiences landslides, particularly in the aftermath of heavy rains. Much of the island's housing is distributed along steep slopes and poorly engineered and constructed housing is particularly at risk. Additionally, the island periodically experiences earthquakes of generally lower magnitudes. Also storm surge and flash floods are among the other risks regularly faced by the island.	Landslides, particularly on the larger islands, are a significant hazard and the risk is increased during the seasonal rains. Coastal flooding is a major concern particularly relating to storm surge and high wave action. The Grenadines are more susceptible to drought. The active volcano La Soufriere, located on the north end of St. Vincent is another risk factor, posing threats from shallow earthquake and eruption events. Since 1900, St. Vincent has been hit by 8 named storms, the strongest being Hurricane Allen (Category 4), which passed between St. Lucia and St. Vincent in 1980. The 1939 eruption of the volcano Kick-'em-Jenny located some 100 km S of Grenada, generated a 2-meter high tsunami.	The country was heavily affected by Hurricane Ivan in 2004, and Hurricane Emily in 2005. There are two active volcanoes in Grenada, Mount St. Catherine in the center of the island and the submarine volcano Kick-'em-Jenny is located 8 km north of the island and has led to tsunami in the past. Flood risk in Grenada is largely associated with storm surge in low lying coastal areas. Flash flooding from mountain streams coupled with storm surge events are the primary causes of flood events and effects are generally limited to communities located in the coastal margins along stream passages. Landslides are a common event in Grenada, with much of the impact experienced along the roadway network.
Population	334,297 (2013)	174,000 (2010).	104,574 (2009)	110,000 (-)

Of the natural disasters listed above, BGS has been tasked with producing an inventory of landsides; over 1200 landslides were identified in St Lucia alone from the satellite imagery. The impact of this geohazard on the island was noted at first hand during the fieldwork when travel was curtailed e.g. roads were closed due to landslides (Figure 2).

Figure 2 Road closure due to landslides – the type of problem the project is addressing

Section 3 outlines the products that were delivered in response to the issues affecting the region.

2.2 Requirements for Geo-Spatial Information

The geospatial data listed in Table 2 are the primary ones identified by the users that are utilised by WB and local users through a variety of projects and initiatives. EO-RISC has been tasked with providing landslide inventories, DEMs and landcover maps for selected territories in order to contribute missing information, to update older information or to increase the (spatial / temporal) resolution of existing information.

In **Grenada** mapping and GIS capability is managed predominantly by the Ministry for Agriculture, but progress is limited. A school landslide vulnerability assessment has been completed (http://www.oas.org/CDMP/document/schools/vulnasst/gre.htm). No comprehensive multi-hazard map compilation has been prepared. The WB is implementing a Disaster Vulnerability Reduction Programme (DVRP). Component 2 (Disaster and Climate Risk Reduction) of the Disaster Vulnerability Reduction Project which would consist of new construction and rehabilitation of existing infrastructure in order to reduce their vulnerability to natural hazards and climate change. Included within the activities are consultancy services to undertake soil investigation mitigation measures for landslip sites in several sites.

In **St. Vincent and the Grenadines**, progress in preparation of hazard maps is limited. To date, risk mapping has been limited to volcanic risks and some coastal vulnerability analyses. Basic GIS-ready maps of roads, contours, rivers, coastlines, agricultural & urban land use have been prepared – primarily available through the Ministry of Planning and the National Emergency Managements Organisation (NEMO). The WB is implementing a Disaster Vulnerability Reduction Programme (DVRP). Components include identification and creation of required baseline data for hazard assessment; development of institutional systems for the collection, sharing and management of geospatial data among national agencies and with regional institutions; training and education in applications integrating geospatial data systems, hazard and risk assessment to support decision making within various sectors and mainstream the use of these tools as a standard practice in development planning.

In **Saint Lucia**, hazard maps have been produced for debris flows, but these may not reflect current conditions. Furthermore, NEMO is not equipped to support GIS data and there is no program to support additional hazard mapping. The WB is implementing a DVRP. Component 2 (Technical Assistance, Regional Collaboration Platforms for Hazard and Risk Evaluation, Geospatial Data Management, and Applications for Improved Decision-Making) would finance: a series of capacity-building, knowledge-building and technical assistance interventions at the national and regional levels to support disaster risk management and climate change adaptation. There are specific areas that have been identified and proposed as high priorities for intervention. At the national level, activities would include, inter alia: i) enhancement of national hydro-meteorological monitoring networks; ii) development of an integrated watershed management plan for flood mitigation; iii) technical assistance for the establishment of maintenance monitoring systems for bridges and public buildings that would integrate natural hazards and extreme events considerations; iv) establishment of geo-spatial data sharing and management platform and related training activities; and v) climate change adaptation public education and awareness campaigns. The GeoNode platform for Saint Lucia http://sling.gosl.gov.lc is accessible.

In **Belize**, no nationwide flood hazard maps have been made for the country based on hydrological modelling, and the source of the only flood map identified by van Westen (2014) was unclear. However, hazard mapping has been completed in several areas with GIS datasets covering landslide risk, volcanic hazard assessment and storm hazards amongst others. Belize is participating in the Central American Probabilistic Risk Assessment (CAPRA) platform but the initiative remains modest in Belize.

Table 2 Geospatial information sources currently used by WB teams and / or local users (derived and updated from van Westen, 2014). The EO-RISC services are highlighted in green.

Current geospatial information sources	Grenada	St Vincent and the Grenadines	Saint Lucia	Belize
DEM	10m raster DEM (source unknown) and partial LiDAR coverage	5m raster DEM (higher parts are not covered). There are LiDAR data of St.V but the format is incorrect so they cannot be analysed	50m raster maps and contours with 2.5m intervals	ASTER and SRTM. Higher resolution data are urgently required for flood risk modelling.
	30m DEM		**30m DEM**	**National DEM at 30m, 40% of territory at 20m and sub-area at 1m**
Landcover	USDA 30m raster map	Polygon map exists with 11 land use classes	1:50,000 raster maps. Vegetation information is in vector format	
	Landcover derived from 2m satellite data	**Landcover derived from 2m satellite data**	**Landcover derived from 2m satellite data**	
Landslide inventory and hazard map	1988: OAS study for selected towns. 2006: CBD/CDERA study – limited inventory of 40 landslides, but not available digitally	Landslide footprints are available, but there is no detail	2010 inventory map has been produced from satellite imagery	Not applicable
	Landslide inventory at 1:20,000		**Landslide inventory at 1:20,000 with key areas (no more than 50%) at 1:10,000**	
Elements-at-risk	Non-attributed building footprints	Not available	Available for the country, including building footprints – though occupancy and structural type is unavailable	Not available
	Building footprints may be derived from 2m satellite imagery, but this is not a priority for EO-RISC	**Building footprints may be derived from 2m satellite imagery, but this is not a priority for EO-RISC**	**Building footprints may be derived from 2m satellite imagery, but this is not a priority for EO-RISC**	
Geological map	A very general one is available, made by USGS	A very general one is available, made by USGS	Vector map is available	
Soil map	A 1959 soils report exists but ITC have not been able to obtain the 1959 map	General soil map from USAID from 1990	Vector map is available	General map has been scanned by ITC
Discharge data	Continuous stream flow data do not exist	None available	None available	None available
Geotechnical data	None available to date	None available	None available	
Rainfall data	Approx 50 rainfall stations. Data is not continuous. Data available from the Land Use Division, Ministry of Agriculture, Lands, Forestry and Fisheries	None obtained thusfar, but rainfall stations do exist	Hourly rainfall data for 24 stations	Missing
Socio-economic data	Missing	Missing	Missing	Missing

The fieldwork and discussions with local users has highlighted two main future geo-spatial information requirements:

1. The landslide inventory and land cover maps are vitally important to gain a full understanding of the events and the associated risk. However landslides are highly dynamic systems, and the land cover is also constantly changing so the requirement is to update these maps on an annual or bi-annual basis. The annual imagery used from 2010 to 2014 to create the landslide inventory highlighted patterns e.g. related to weather systems, however more data from inventories gathered in successive years would help to clarify potential thresholds for weather fronts and their impacts on the environment;
2. Those missing datasets (such as geotechnical data) or ones that are identified as 'general' (such as geology) are obligatory for the users to gain a true understanding of the geohazard processes. For example EO-RISC identified that there were far fewer landslides in Grenada than in St Lucia, despite similar topography and weather conditions on both islands. Therefore it is proposed that increased knowledge of geology, geomorphology, and soils coupled with geotechnical data are mandatory if the associated risks and the potential to provide forecasts for landslides is desired.

2.3 Interpretation of the results

The WB actively supports Disaster Risk Reduction in the Caribbean and has received a grant from the European Union for the Caribbean Risk Information Programme regarding the development and use of risk information in critical sectors. The primary Risk Information Programme objective is to strengthen the regional and national capacity of governments in the Caribbean region to develop or procure the development of landslide and flood hazard and risk information. EO-RISC is contributing to the WB requirements via the CHARIM project by providing them with the products, which are outlined in Chapter 3. Specifically, CHARIM is developing national hazard mapping studies in the five target countries (Belize, Dominica, St. Lucia, St. Vincent and the Grenadines and Grenada), one on Belize related to floods and two on each island for landslides and floods.

Contact with the Users was required to define the user requirements that were outlined in the Service Readiness Document (Jordan and Grebby, 2014) and subsequently to refine the services to ensure fitness-for-purpose. The sole face-to-face contact with users (to date) was via the CHARIM workshop in St Vincent (29 September – 3 October 2014) which was attended by users including Chief Engineers, Chief Planners and Geospatial Experts from each Caribbean country. Preliminary EO-RISC services / results were presented to the users assembled as an entire group (30th September) and subsequently to a focused meeting of the geospatial experts during a technical meeting (1st October). This enabled us to interpret how the results relate to the user requirements.

2.3.1 Service 1: Land use/land cover mapping

The objective of Service 1 is to generate land use/land cover maps for St. Lucia, Grenada, and St. Vincent & the Grenadines by exploiting recent high-resolution or very high-resolution optical satellite imagery. As well as land use/land cover, the objective was to utilise the imagery to produce a vector layer of water features (e.g. lakes, ponds, rivers) present in each of the areas of interest (AOI). With a preference on utilising imagery acquired using European and Canadian sensors, a set of recent images with acceptable levels of cloud cover was identified and obtained from the relevant archives for each of the three AOIs. The satellite data comprised Pleiades imagery (acquired between 2013-2014) and RapidEye imagery (acquired 2010-2014). These datasets have a spatial resolution (pixel size) of 2m and 5m, respectively, for the multispectral waveband images. Additionally, the Pleiades datasets includes a very high-resolution 0.5m panchromatic image.

Existing land use / land cover maps for the three AOIs were produced as part of The Nature Conservancy's Mesoamerica and Caribbean Region project (Helmer et al., 2007; 2008). These maps were derived at 30m resolution from satellite imagery with the aid of extensive field knowledge and observations. Accordingly, these maps represent useful baseline data to build upon for the land use/land cover mapping under this service.

To enable the most detailed information to be resolved, the Pleiades imagery was used as the primary dataset for generation of the new land use/land cover maps for the three AOIs; thus achieving a spatial resolution of 2m, which is equivalent to a mapping scale of 1:10,000. For each of the AOIs, land use/land cover was mapped using a combination of automated image classification, rule-based refinement and manual digitisation. The existing 30m maps were used to define the different land use/land cover types and identify representative areas in the imagery to help guide the initial automated classification and to subsequently validate the mapping. Water features and the basic road networks were manually digitised at 1:10,000-scale from Pleiades imagery that had been pan-sharpened to 0.5m resolution using the panchromatic image. Wherever available, existing vector layers were utilised as baseline information during mapping.

Cloud and associated shadow coverage in the Pleiades imagery was quite significant, typically varying in the region of 20-40% for the AOIs. Wherever the ground was obscured by cloud and shadow in the Pleiades imagery, the land use/land cover maps were patched using the RapidEye imagery and the existing land use/land cover maps in order to provide complete areal coverage of the AOIs. Unfortunately, it was generally not possible to map water features (particularly rivers and streams) and roads in the areas obscured by cloud and shadows in the Pleiades imagery because the alternative RapidEye imagery lacked the spatial resolution required to resolve such features.

The land use/land cover maps were validated using a standard remote sensing approach, which involves comparing the land use/land cover class identities of a sample of pixels in the map with their 'true' land use/land cover class. The 'true' land use/land cover classes of these pixels were determined using a combination of the pan-sharpened Pleiades imagery and existing maps. Consequently, the maps for St. Lucia, Grenada, and St. Vincent and the Grenadines were found to have accuracies of 84.9%, 84.8% and 80.8%, respectively; which are within the desired target accuracy of 80-90%. Additional validation of the maps for St. Lucia and Grenada was achieved using point-sampled field observations at a number of locations.

Compared to the existing maps, the new land use/land cover maps derived for this service represent an order of magnitude increase in terms of spatial resolution — increasing from 30m to 2m. As a result, the new maps provide much more detailed information on the distribution of the different land use/land cover types in the AOIs. Moreover, a number of significant errors (due to misclassification) in the existing maps have been corrected in the new maps. Nevertheless, a relatively minor degree of confusion between inherently similar land use/land cover types (particularly vegetation) does persist. Overall, the results demonstrate the potential to utilise high-resolution satellite imagery to produce detailed and accurate land use/land cover maps more efficiently than through an equivalent field-based survey.

2.3.2 Service 2: Hazard mapping to support landslide risk assessment

The objective of Service 2 is to generate ground-truthed landslide inventories and digital elevation models for both St. Lucia and Grenada from optical satellite imagery.

Landslide inventory mapping
The establishment of landslide inventories for St Lucia and Grenada is based on the interpretation of satellite images covering the period 2010-2014. For most of this period RapidEye images are available. Images from the Pleiades satellite are only available for 2014.

Landslide activity can result in the disturbance of vegetative cover and exposure of soils at the surface. This spectral signature is combined with an assessment of other information such as position in the landscape, slope morphology, vegetation cover, etc. to interpret the satellite images and create outlines of landslide events. The distribution of landslides for each image (year) was captured manually by skilled operators and the results stored in one event database. The attributes stored for each event are shown in Table 3. The interpretation of potential landslide sites was analysed throughout the complete image sequence. This enhanced confidence in the mapping process, particularly if polygons are visible in several images. This approach also helped to reduce the negative effects of cloud cover and occasional poor image quality (e.g. the SE quadrant of the 2013 RapidEye satellite image of St Lucia).

It is theoretically possible to capture a landslide spectral signature automatically, but our experience has shown that this leads to an over-representation of cultivated fields necessitating supervised re-classification of every polygon. It was therefore decided not to pursue this approach.

The RapidEye images are available at a resolution of 5 m while the Pleiades image was pan-sharpened to a resolution of 0.5m. Determination of landslide events at 5 m resolution is not very reliable and results therefore in rather low confidence mapping. However, when polygons persist into the 2014 Pleiades images, much more detailed interpretation can be achieved leading to greater confidence in the mapped product.

Table 3. Attributes stored for each landslide event in the multi-temporal cumulative inventory.

description	name	type	length	information
Landslide ID	LID	number	7	polygon identifier that can be related to landslide database entry point
Location District	DISTR	text	30	district name
Location Locale	LOCAL	text	30	locality name
Movement type	TYPE	code	2	.. (not entered), FL (flow), SR (rotational slide), SP (planar slide), SU (undifferentiated slide), FA (fall), TO (topple), SP (spread), UN (undefined)
Morphology	MORPH	code	1	L, S, T, A (Landslide undifferentiated, Scarp, Transport zone, Accumulation zone)
Confidence	CONF	code	1	H, M, L
2010	2010	code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2011	2011	code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2012	2012	code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2013	2013	code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2014	2014	code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
FIELD CHECK	FIELD	TEXT	50	free text

The project imposed scale limitations pre-determined that the landslide inventory should be established at a scale of 1:20,000 with key areas (no more than 50%) at 1:10,000 for St Lucia, and at 1:20,000 scale for Grenada. This scale limitation affects the mappable minimum size of landslides. Based on the experience of mapping landslide polygons in St Lucia using the

Pleiades high resolution images as guidance the following limitations apply. At a scale of 1:20,000 the minimum mappable size is approximately 30 by 30m or 900m^2. At 1:10,000 this enhances to mappable polygons of about 15m side lengths (225m^2). At a scale of 1:5,000 it is possible to map elements with effective minimum dimensions of about 10m (100m^2), depending on the terrain. Closely grouped small events were sometimes visible and these have been mapped as landslide clusters. The database therefore contains some polygons that contain several events (too small to map individually).

Considering the difficulties encountered in mapping landslide polygons at 1:20,000 scale this project adopted a pragmatic (though time-consuming) approach where the landscape was interpreted at 1:5,000 scale (or an even more detailed scale where features were uncertain). Outlines were then up-scaled (i.e. generalized) to be representative of polygons at 1:10,000-scale (this is a standard BGS approach). As a consequence of this practice it was possible delineate landslide events in the size range smaller than 1000 m^2 (approximately 100 events) and this has resulted in a more ‘complete’ landslide inventory.

The clarity and detail offered by the high resolution (0.5m) Pleiades has been used to carry out detailed investigations of a limited number of individual sites and events. In combination with other data (landuse, topography, etc.) it is possible to generate highly detailed geomorphological maps that not only show the spatial extent of an event, but also can be attributed with information on the likely nature of deformation and, in combination with other images, a timeline of event progression. This level of detailed interpretation falls outside the scope of work for this project but is discussed in case studies in Section 3 of this report to highlight the significant additional value of these new, high resolution products.

The opportunities to capture landslide event outlines is strongly linked with the time period between trigger and image capture. The use of a multi-temporal image stack therefore provides the best opportunity to achieve ‘completeness’ of the database. The database can then be used to evaluate how quickly a landscape recovers and what the consequences are of subsequent trigger events (Figure 3). For St Lucia, the time series captured two major landslide trigger events; the 2010 Hurricane Tomas event and the 2013 December Trough. This has led to important insights into changes in the annual inventories as the landscape firstly recovers and then gets disturbed at a later date.

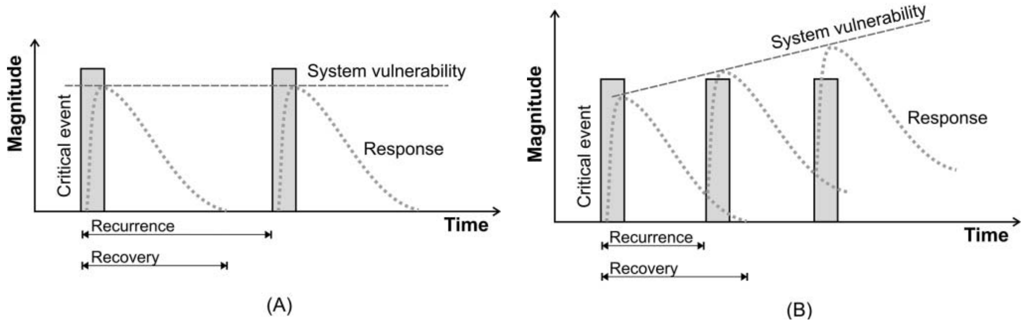


Figure 3. Landscape recovery versus trigger event recurrence. When recurrence exceeds recovery, relatively stable system vulnerability can be assumed (A), but when recovery exceeds recurrence, system vulnerability is likely to increase significantly. (From Dijkstra et al., 2014)

Two previous inventories were available for comparison with the present dataset. In 1995 some 712 events were identified, whilst an inventory created following 2010 Hurricane Tomas captured 1132 landslide events. The current multi-temporal inventory covered the years of 2010-2014 and contained 1233 landslide polygons that have been classed as active (fresh signs of landsliding) or inactive (no evidence of active movement, but still recognisable landslide features) at least once during this period. Generally, each polygon represents a single event. However, where clusters of very small events (dimensions smaller than about 5m) are encountered, a single polygon can represent more than one landslide. There are considerable benefits offered by a sequential analysis covering several years, including a reduction in the effects of cloud cover, a better insight into persistence of features and a more comprehensive capture of events. Any year looked at in isolation is likely to result in fewer events being recorded.

The 1995 landslide event database is largely based on field observations. This resulted in the capture of many events along roads and relatively few events in the forested areas where access is very limited. This database was checked against the multi-temporal inventory and relatively little overlap was encountered. Even taking into consideration the large time gap between the 1995 and 2010-14 inventories it is an indication that field capture and satellite image interpretation of events result in different populations and should be regarded as complementary activities.

The 2010 inventory captured the events generated by Hurricane Tomas and is based on satellite image interpretation. It appears that the use of ‘bare earth’ automated classification provided an important contribution to the establishment of the landslide inventory. As a consequence, the difference between this inventory and our multi-temporal inventory is considerably larger than the numerical difference between the two.

Field verification

During a 6-day field visit to St Lucia more than 650km were covered and as many landslides as feasible were visited. Many rural roads were still blocked as a consequence of landslides generated during Hurricane Tomas and the 2013 December Trough hampering access to landslides in the interior of the Island. Field verification in Grenada was limited to two days only, but during this brief period of time it became apparent that only one of the mapped polygons did in fact represent a landslide. The false positives were generally the result of newly cultivated fields on hillsides, many of which involved small banana plantations.

The field verification emphasised the importance of satellite image interpretation. Many of the mapped landslides are some distance away from roads. Gaining access to these sites in the field is very laborious and the road network does not reach very far inland. In addition, particularly in the case of St Lucia, many of the smaller rural roads in the interior were dramatically affected by landslide events triggered by Hurricane Tomas and the December 2013 Trough. It was therefore often impossible to reach landslide sites beyond those that cut off the roads.

In conclusion the following observations are drawn regarding the use of satellite images for landslide inventory establishment for St Lucia and Grenada:

- Landslide signatures in St Lucia are recognisable by skilled operators
- Observations are limited by clouds, not by road access, enabling much more comprehensive coverage
- The current database is constrained by scale (1:20,000 and 1:10,000) and identification of events at more detailed scales is possible, particularly with recent Pleiades images at the resolution of 0.5m
- Minimum landslide dimensions in the database are approximately 200 m^2 and many smaller events are known to have occurred
- Very small (<5 m) and obscured (in the shade, on steep slopes, below overhanging vegetation) landslides are difficult to capture
- Small events can still have a significant impact on lives and livelihoods and recording these through different means will complement the database
- Automatic classification is, at present, not conducive to establishing a reliable record
- Temporal proximity of trigger event and satellite image acquisition affects the number of events that can be captured
- Multi-temporal inventory establishment enhances the number of events captured and can be used to establish derived products such as landscape resilience and hazard assessments
- Landslides triggered by Hurricane Tomas (2010) were rapidly covered by vegetation indicating a rapid rate of recovery of the landscape, but many events were re-activated during the 2013 December Trough indicating a still heightened sensitivity of the landscape to disturbance
- Extending the multi-temporal record with ongoing acquisitions will create further insights into landscape response and this will be vital in establishing relevant hazard and risk assessments
- Landslides in Grenada are much more difficult to establish due to widespread cultivation practices resembling landslide signatures
- Field verification remains an essential tool to ascertain validity of image interpretations

Digital Elevation Models

The desired spatial resolution of the digital elevation models (DEMs) to be produced from optical satellite imagery for St. Lucia and Grenada was 30m or better. Originally, it was intended to utilise stereo Pleiades satellite imagery to derive DEMs with significantly higher resolution of ca. 1m. With no suitable imagery available in the appropriate archive, a request to have new stereo imagery acquired for the two AOIs was submitted in early August 2014. However, due to the timing of the request coinciding with the hurricane season in the Caribbean region, no suitable cloud-free stereo imagery for either AOI has yet been acquired.

As an alternatively, national 30m DEMs for both AOIs were produced using stereo imagery acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor. Specifically, the nadir and backward-looking ASTER band 3 stereo images can be used to extract DEMs through the application of standard photogrammetric processing techniques.

This approach was utilised by NASA and Japan’s Ministry of Economy, Trade and Industry (METI) in order to produce the ASTER Global DEM (ASTER GDEM); of which version 2 is the most recent (released in 2011).

For St. Lucia, the ASTER-derived elevation data were first vertically calibrated with a subset of contour height data using regression analysis. Next, the calibrated ASTER elevation dataset was merged with the contour height data to form a single file containing x-y-z coordinates of all points. These points were then interpolated to generate the 30m DEM. The vertical accuracy of the DEM was determined using 18 GPS control points provided by the Physical Planning Office, and found to have a root-mean-square (RMS) vertical accuracy of 1.4m.

Similarly, for Grenada, the ASTER-derived elevation data were vertically calibrated with a subset of airborne Light Detection And Ranging (LiDAR) data using regression analysis. Sizeable ‘pit’ artefacts in the DEM were subsequently rectified with the aid of elevation data acquired by the Shuttle Radar Topography Mission (SRTM). The vertical accuracy of the DEM was determined using an independent subset of 500 LiDAR data points and found to have an RMS vertical accuracy of 4.9m.

2.3.3 Service 3: Digital Elevation Models of Belize

The objective of Service 3 is to generate a national DEM of Belize and a precise DEM for a subset of Belize to support hazard/risk assessment.

National Digital Elevation Model

The desired spatial resolution of the national DEM to be produced from optical satellite imagery for Belize was 30m or better. A 20m DEM derived from high-resolution SPOT-5 stereo satellite imagery for 40% of Belize was also acquired from Airbus Defence & Space. This DEM is reported to have an RMS vertically accuracy of 7m.

With no other suitable imagery available, a 30m DEM covering the entirety of Belize was generated based on the ASTER-derived elevation data. Firstly, ASTER-derived elevation data were first vertically calibrated with a subset of elevation data from the 20m DEM using regression analysis. Next, a 3×3 pixel moving average filter was applied in order to reduce “noisy” data values and notable “spike” artefacts present in the calibrated DEM. In the absence of any GPS or other control data, the accuracy of the 30m DEM was determined using an independent subset of 32,000 points extracted from the 20m DEM. The national 30m DEM was found to have an RMS vertical accuracy of 9.8m.

Precise Digital Elevation Model

The second aspect of Service 3 was to generate an accurate 1m resolution DEM from very high-resolution optical satellite imagery for a subset of Belize encompassing an area to the north of Belize City. To meet these requirements, a request to have new tri-stereo (triplet) Pleiades imagery acquired was submitted in early August 2014. However, due to the timing of the request coinciding with the hurricane season in the Caribbean region, no suitable cloud-free tri-stereo imagery for has yet been acquired.

2.4 Guidelines for use

The land use/land cover maps produced under Service 1 provide detailed information in St. Lucia, Grenada, and St. Vincent & the Grenadines. The products are equivalent to a map scale of approximately 1:10,000. The accompanying vector layers of water bodies, rivers and streams and the basic road network were also mapped at 1:10,000 scale. Accordingly, the intended scale for use of these data is 1:10,000, and so may not be representative at finer scales. The land use/land cover maps provide 100% coverage of the AOIs, however the vector layers are fragmented due to cloud and shadow obscuring the ground in the Pleiades satellite imagery. Overall, the new land use/land cover maps represent a considerable improvement on the existing 30m maps.

The land use/land cover maps can be used to determine spatial correlations with landslide occurrences documented in Service 2. Such analysis is useful in establishing whether specific land use/land cover types are more prone to landslide events, and can thus be used as input, alongside the DEMs (also generated in Service 2) to derive landslide susceptibility maps for St. Lucia and Grenada. Additionally, the DEMs generated in Service 2 can also be used in conjunction with the water surface features mapped under Service 1 to model the flood risk in both St. Lucia and Grenada. Furthermore, the land use/land cover maps could be readily turned into impervious layers, which can also be incorporated in flood risk analysis. The 20m and 30m DEMs produced for Service 3 can also be used to model flood risk in Belize.

Beyond the scope of this project, the land use/land cover information can be used for a wide spectrum of uses. For example, the maps could be used for planning purposes, asset management and in developing forestry management strategies. The data can also be used to monitor change over time. Some broader applications of the DEMs could include forestry management, the planning of new transport infrastructure (i.e. roads and railways), and natural resource exploration.

Landslide inventories for St Lucia and Grenada contain polygons that represent the maximum extent of events mapped during the period 2010-2014. Each polygon is attributed with landslide type, morphology, confidence level of the mapped outline and a statement of activity for each of the five years in the sequence 2010-2014. Because of the prevalence of small events, the inventories were established on a scale of 1:10,000 (a pragmatic limit considering 5 m resolution of RapidEye images). However, high 0.5 m resolution Pleiades images will allow landslide inventory establishment at even more detailed scales.

The inventory provides a clear indication of landscape response to trigger events and this information can provide context to future studies of landslide hazard and landslide risk reduction.

Interpretation of satellite images requires well-trained operators with a good understanding of mass movement processes and local conditions.

It is also good practice to populate each polygon with additional information that can be stored in a relational database for further analysis. This was not within the remit of this project and requires further work, but will result in an invaluable tool for future landslide hazard and risk assessments. Examples of the additional information are included in Section 4.

The current multi-temporal sequence can be extended both using older images and through regular updates, at least annually and when major trigger events such as extreme rainfall or earthquakes occur.

3 PRODUCTS DESCRIPTION

3.1 Products

3.1.1 Service 1: Land use/land cover mapping

The objective of Service 1 is to generate land use/land cover maps and produce a vector layer of water features (e.g. lakes, ponds, rivers) for St. Lucia, Grenada, and St. Vincent & the Grenadines from high-resolution or very high-resolution optical satellite imagery. In keeping with the “eoworld” framework, suitable imagery for this service was preferentially sought from European and Canadian sensors. Consequently, archived Pleiades imagery (acquired 2013-2014) and RapidEye imagery (acquired 2010-2014) with reasonable levels of cloud (and associated shadow) were obtained through the ESA Third Party Mission scheme. The basic characteristics of the obtained datasets are shown in Table 4.

Table 4 Basic characteristics of the utilised satellite data.

Dataset	Wavebands	Spatial resolution (m)
Pleiades	Panchromatic (470-830nm) Blue (430-550nm) Green (500-620nm) Red (590-710nm) Near-infrared (740-940nm	0.5 2 2 2 2
RapidEye	Blue (440-510nm) Green (520-590nm) Red (630-685nm) Red Edge (690-730nm) Near-infrared (760-850nm)	5 5 5 5 5

Existing land use/land cover maps from 2001 were available for the three AOIs following their production by the various partners of The Nature Conservancy’s Mesoamerica and Caribbean Region project (Helmer et al., 2007; 2008). These maps were produced at a spatial resolution of 30m through a combination of automated imagery classification of Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery and manual delineation of IKONOS satellite imagery. The mapping was augmented with extensive field knowledge and observation. Accordingly, these maps provide excellent baseline data to build upon for the land use/land cover mapping under this service.

The Pleiades multispectral imagery was selected as the basis for the three new land use/land cover maps because its higher spatial resolution enables the most detail to be resolved. With a spatial resolution (pixel size) of 2m for the multispectral bands, mapping can theoretically be undertaken at a scale equivalent to 1:10,000. Given the areal extent of the AOIs, the spatial resolution and the resources available, it was decided that the most efficient mapping strategy was to utilise a largely automated approach with subsequent refinement and manual digitisation.

Before mapping, the land use/land cover classes for the three AOIs were first defined by considering those included on the existing 30m maps, which are based on the International Institute of Tropical Forestry classification scheme. Minor modifications to these classes were made where appropriate to reflect the anticipated discrimination capability of the satellite imagery (Table 5). For example, the “low density urban” and “Medium-high density urban” classes in the existing maps were modified to “Roads and other built-up surfaces” and “Buildings” given the ability to resolve these features in the high-resolution Pleiades imagery. Moreover, given their inherent similarities and the anticipated difficulty in discriminating between them, “Pastures”, “Cultivated land” and “Herbaceous agriculture” were merged to form a single class.

Table 5. Land use/land cover classes for the three AOIs.

	St. Lucia	**Grenada**	**St. Vincent & the Grenadines**
Land use/land cover classes	Water	Water	Water
	Wetland	Wetland	Mangrove
	Mangrove	Mangrove	Buildings
	Buildings	Buildings	Roads and other built-up surfaces (e.g. concrete, asphalt)
	Roads and other built-up surfaces (e.g. concrete, asphalt)	Roads and other built-up surfaces (e.g. concrete, asphalt)	Bare ground (e.g. sand, rock)
	Bare ground (e.g. sand, rock)	Bare ground (e.g. sand, rock)	Semi-deciduous forest
	Quarry	Quarry	Seasonal Evergreen forest
	Semi- or Drought Deciduous, coastal Evergreen and mixed forest or shrubland	Semi-deciduous forest	Evergreen forest
	Lowland forest (e.g. Evergreen and seasonal Evergreen)	Drought Deciduous open woodland	Drought Deciduous, coastal Evergreen and mixed forest or shrubland
	Evergreen forest	Evergreen and seasonal Evergreen forest	Elfin and Sierra Palm tall cloud forest
	Elfin and Sierra Palm tall cloud forest	Deciduous, coastal Evergreen and mixed forest or shrubland	Montane non-forested vegetation (e.g. high-altitude pastures)
	Woody agriculture (e.g. cacao, coconut, banana)	Elfin and Sierra Palm tall cloud forest	Blue Mahoe plantation
	Pastures, cultivated land and herbaceous agriculture	Nutmeg and mixed woody agriculture (e.g. cacao, coconut, banana)	Woody agriculture (e.g. cacao, coconut, banana)
	Golf course	Pastures, cultivated land and herbaceous agriculture	Pasture, cultivated land and herbaceous agriculture
		Golf course	Golf course

The basis for each land use/land cover map was the result of supervised per-pixel classification of the imagery according to the land use/land cover classes outlined in Table 5. Due to their inherent similarities, it was anticipated that some of the classes — in particular some forest types, and “Bare ground”, “Roads and other built-up surfaces”, “Pastures, cultivated land and herbaceous agriculture” — could be particularly difficult to discriminate using the limited spectral information contained in only the blue, green, red and near-infrared bands of the Pleiades imagery. Therefore, textural information was also incorporated in the form of the Grey-Level Co-occurrence Matrix (GLCM) parameters of entropy, dissimilarity, second moment and homogeneity (Haralick et al., 1973 and Herold et al., 2003). These parameters were derived from the Pleiades green band in the ENVI 4.8 software package (Research Systems, Inc.) for a 3 × 3 pixel (i.e. 6m × 6m) window and a co-occurrence window shift of 4 pixels (i.e. 8 m) in both the x- and y-direction. These 4 textural bands were merged with the 4 Pleiades multispectral bands to create an 8-band spectral-textural dataset for each AOI for input to the classification.

Classification of the datasets was performed using a supervised neural network (NN) classification algorithm. The NN used in this case was a Multi-Layered Perceptron NN with a back-propagation learning algorithm for supervised learning (Richards and Jia, 2006). Using a three-layered NN (i.e., input, output and one hidden layer), land use/land cover classifications were performed in ENVI 4.8 with the default training parameters. Each classification was supervised with the aid of a set of training pixels that were carefully selected to represent the spectral and textural characteristics of each of the land use/land cover classes. These training pixels were identified in Pleiades imagery by using the existing maps as a guide.

The classified images did not initially provide full areal coverage of the AOIs owing to the obscuring effects of cloud cover and associated shadowing in the imagery. Accordingly, areas with missing land use/land cover information in the classified image were first patched using the results of RapidEye image classifications achieved using the same approach as outline above. Any remaining unclassified areas were then patched using the existing land use/land cover information (Figure 4). The St. Vincent & the Grenadines classification was patched entirely using the existing land use/land cover maps due to the poor quality of the RapidEye imagery.

Next, the preliminary land use/land cover maps were augmented using a combination of rule-based refinement and manual delineation. Rule-based refinement comprised reclassifying the classes of some pixels according to a set of rules or criteria. For instance, in all 3 cases rule-based refinement was used to reclassify forested pixels as “Elfin and Sierra Palm tall cloud forest” if they occurred above a specific elevation. Similarly, for St. Lucia, rule-based refinement was used to distinguish between “Lowland forest” and “Evergreen forest” according to the elevation at which the transition occurs. Land use/land cover classes that were difficult to discriminate using a combination image classification and rule-based refinement were manually delineated. This involved visually identifying and mapping (at 1:10,000-scale) classes such as “Mangrove” and “golf course” from the Pleiades imagery, which was pan-sharpened to a spatial resolution of 0.5m using the panchromatic band.

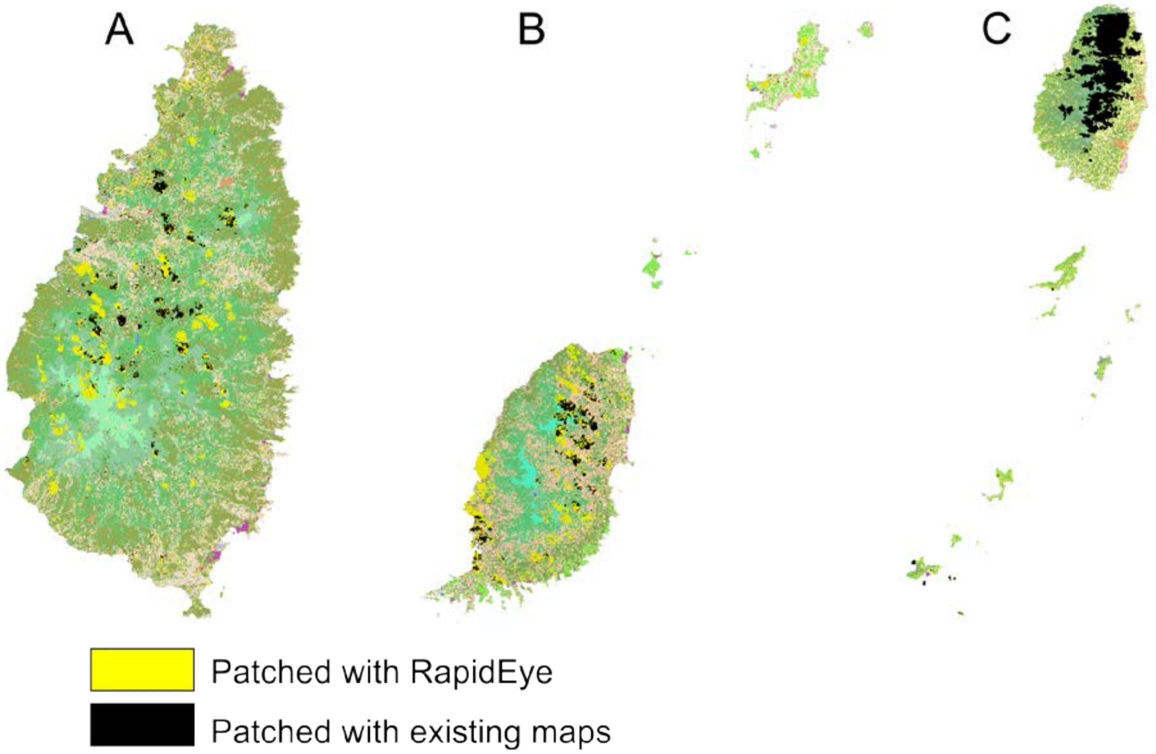


Figure 4. Data used to patch the land use/land cover maps for (A) St. Lucia, (B) Grenada and (C) St. Vincent and the Grenadines.

The final land use/land cover maps are raster images with a spatial resolution of 2m, and thus provide an order of magnitude increase in the amount of detail they contain in comparison to the existing maps (Figure 5). Each 2m pixel in the raster is attributed with its associated land use/land cover class.

Figure 5. Comparison of the level of detail provided in the new 2m land use/land cover maps (middle) and the existing 30m maps (right, © Nature Conservancy Mesomerica and Caribbean Region). Pleiades imagery is shown on the left (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A., France, all rights reserved)

In addition to land use/land cover, vector layers (shapefiles) documenting water features (e.g. lakes, ponds, rivers, streams) and the basic road network were also created for all 3 AOIs. These features were manually digitised at 1:10,000-scale from the pan-sharpened Pleiades imagery. Where available, existing vectors layer provided by various sources (e.g. local Physical Planning Offices, OpenStreetMap) were utilised as baseline information during mapping. These layers were edited to add, remove and shift features, or re-digitised at a finer scale, as necessary. Cloud cover, associated shadowing and dense vegetation made it difficult to delineate linear features such as rivers, streams and roads in the imagery (Figure 6). With such features generally only resolvable at the resolution of the Pleiades imagery, complete coverage of the AOIs was not possible.

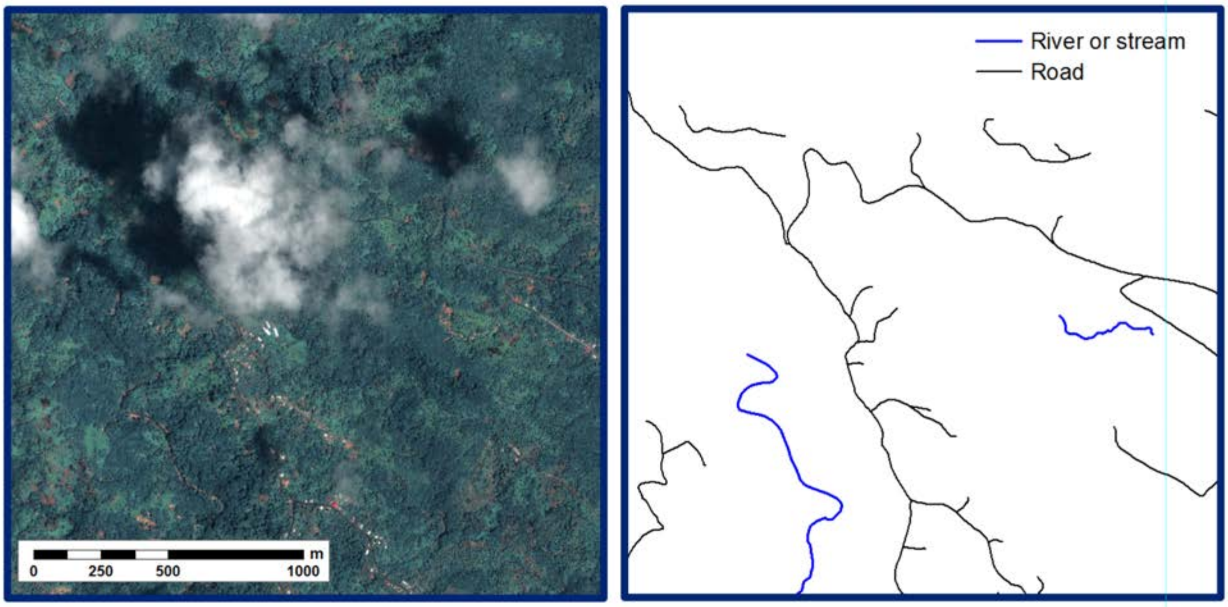
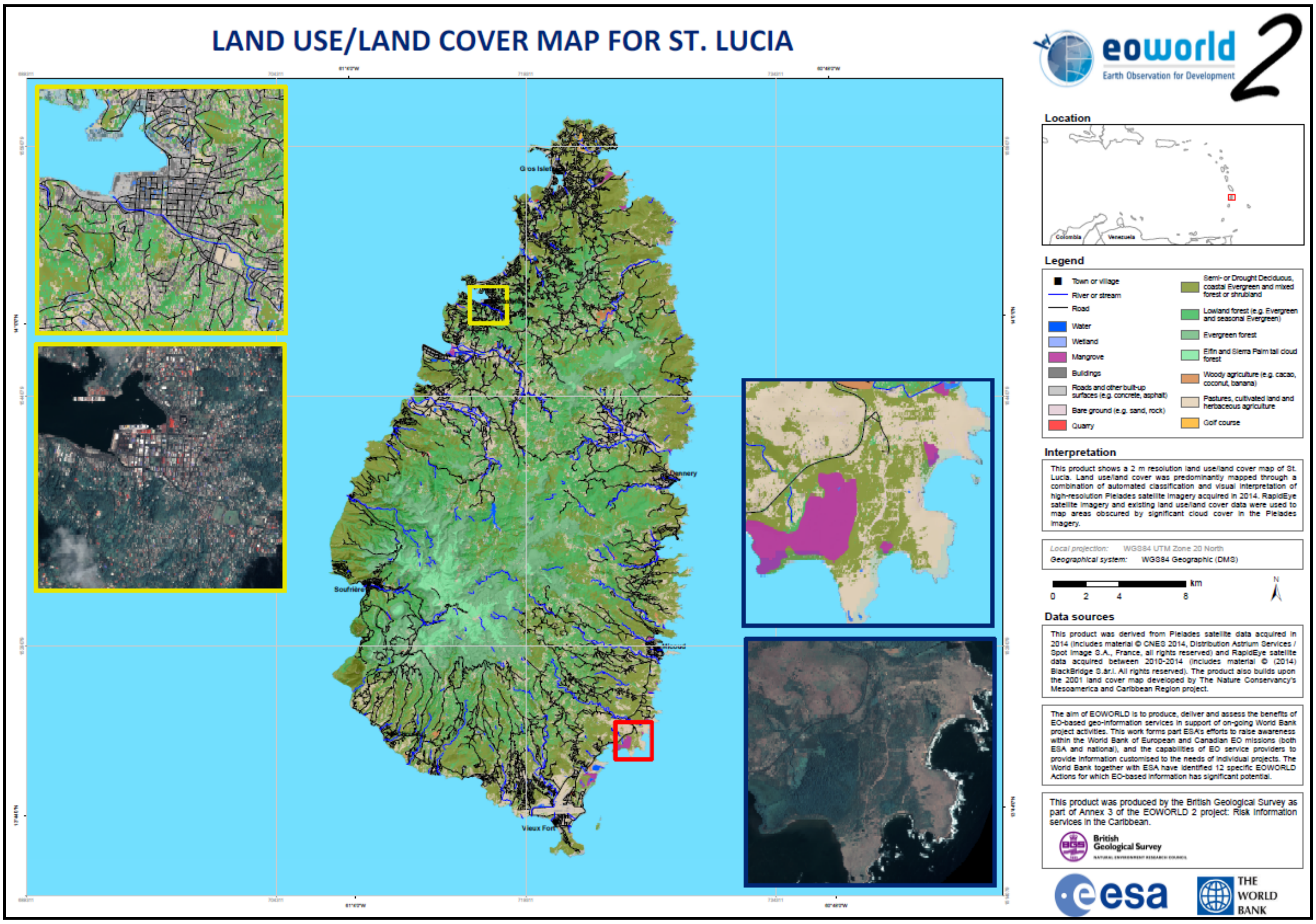


Figure 6 Delineation of rivers, streams and roads from pan-sharpened Pleiades imagery.

The land use / land cover raster and vector datasets for each country were also compiled into map format. An example (for St Lucia) is illustrated in Figure 7. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.



This product shows a 2 m resolution land use/land cover map of St. Lucia. Land use/land cover was predominantly mapped through a combination of automated classification and visual interpretation of high-resolution Pielades satellite imagery acquired in 2014. RapidEye satellite imagery and existing land use/land cover data were used to map areas obscured by significant cloud cover in the Pielades imagery.

This product was derived from Pielades satellite data acquired in 2014 (includes material © CNES 2014, Distribution Astrium Services / Spot Image S.A., France, all rights reserved) and RapidEye satellite data acquired between 2010-2014 (includes material © (2014) BlackBridge S.àr.l. All rights reserved). The product also builds upon the 2001 land cover map developed by The Nature Conservancy's Mesoamerica and Caribbean Region project.

The aim of EOWORLD is to produce, deliver and assess the benefits of EO-based geo-information services in support of on-going World Bank project activities. This work forms part ESA's efforts to raise awareness within the World Bank of European and Canadian EO missions (both ESA and national), and the capabilities of EO service providers to provide information customised to the needs of individual projects. The World Bank together with ESA have identified 12 specific EOWORLD Actions for which EO-based information has significant potential.

This product was produced by the British Geological Survey as part of Annex 3 of the EOWORLD 2 project: Risk information services in the Caribbean.

Figure 7 Land use / land cover map of St Lucia

3.1.2 Service 2: Hazard mapping to support landslide risk assessment

Landslide inventory mapping

RapidEye and Pleiades images were available for interpretation and landslide inventory establishment. The RapidEye images are available at resolution of 5m while the Pleiades imagery was pan-sharpened to a resolution of just 0.5m. The project imposed scale limitations pre-determined that the landslide inventory should be established at a scale of 1:20,000 with key areas (no more than 50%) at 1:10,000 for St Lucia, and at 1:20,000-scale for Grenada. This scale limitation affects the mappable minimum size of landslides. Based on the experience of mapping landslide polygons in St Lucia using the Pleiades high resolution images as guidance the following limitations apply. At a scale of 1:20,000 the minimum mappable size is approximately 30 by 30m or 900m^2. At 1:10,000 this enhances to mappable polygons of about 15m side lengths (225m^2). At a scale of 1:5,000 it is possible to map elements with effective minimum dimensions of about 10m (100m^2), depending on the terrain. In many areas landslides were observed that were smaller than the mappable size and these were captured as landslide clusters. Visibility of a feature is also dependent upon terrain slope. On very steep slopes the plan dimensions of an event may be much larger than the minimum dimensions discussed above, but the intersection with a near-perpendicular view may become so small that detection is not feasible. Dimensions of the polygons are taken from a ‘flat’ map and are not adjusted for slope. These simplifications affect the cumulative frequency-area distribution (see section 5 of this report).

Landslide activity can result in the disturbance of vegetative cover and exposure of soils at the surface. Many of the landslides in the inventory were triggered by Hurricane Tomas (30/31 October 2010; P_{max} ~ 400-600mm). This hurricane was of an intensity comparable to a 1:180 year event, but as it was preceded by drought conditions it is estimated that the combined likelihood ‘drought/rain’ exceeds 1:1000 years (ECLAC 2011). As a consequence, the resultant disturbance of the landscape was much more severe than could be expected on the basis of the severity of the hurricane alone. ‘Landslide’ is a generic descriptor for slope movements including rotational slide, planar slide, debris flow, mud flow, debris avalanche. Generally these take place in deeply weathered materials, where for dry soil conditions a rapid infiltration can lead to a sudden loss of strength, the initiation of slope deformation and a rapid transition from sliding to flow.

To map a particular landform as a landslide requires a landslide scar and/or landslide deposits to be visible on the satellite image. Mapping of landslide events is in the first instance on the basis of simple spectral/colour signatures. In the case of the relatively low resolution RapidEye images this is not very reliable and results therefore in rather low confidence mapping. The better resolution offered by the Pleiades image enables much more detailed interpretation leading to much higher confidence in the final mapped product. As this exercise involved the establishment of a multi-temporal landslide inventory, the detailed Pleiades image could therefore be used to enhance the overall confidence of the final product.

As the differences between exposed soils and vegetated surface are quite distinct the use of automatic classification of ‘bare earth’ sites was tested in a part of St Lucia to aid the landslide identification process, using the 2011 RapidEye image as a pilot study. However, it was found that this approach leads to a large over-estimation of the areas affected by landsliding. Many cultivated fields are included in this automatic classification. The additional effort involved in fine-tuning the classification outweighed the benefits for image interpretation and therefore it was not pursued for other images.

General practice of mapping landslides is to investigate at a more detailed scale and then upscale to the desired level of detail. This enhances the confidence that the features are mapped correctly. The practical approach to this project therefore involved mapping the whole Island at a scale of 1:10,000 or at an even more detailed scale where features were uncertain. Outlines were established on the basis of representation at 1:10,000-scale. As a consequence of this practice it was possible outline landslide events in the size range smaller than 1000 m^2 (approximately 100 events) and this has resulted in a more ‘complete’ landslide inventory. However, with its high resolution of 0.5m the Pleiades images offer interpretation of the landscape at much greater detail and there are therefore opportunities to enhance the capture of landslide polygons, both in detail of feature outlines and in number of small events (covering less than about 100 m^2). The Pleiades images also offer detailed investigations of individual sites and events. In combination with other data (land use, topography, etc.) it is possible to generate highly detailed geomorphological maps that not only show the spatial extent of an event, but can be attributed with information on the likely nature of deformation and, in combination with other images, a timeline of event progression. This level of detailed interpretation falls outside the scope of work for this project but is discussed in a case study in Section 3 of this report to highlight the tremendous additional value of these new, high resolution products.

Landslide inventory establishment - St Lucia

RapidEye images from 2010, 2011, 2012 2013 and 2014 and one Pleiades image from 2014 were available for interpretation and landslide inventory establishment for St Lucia (Table 6; Figure 8, Figure 9, Figure 10, Figure 11). The satellite images are affected by variable cloud cover, particularly the 2010 and 2014 RapidEye for St Lucia. The SE quadrant of the 2013 RapidEye image for St Lucia was of particularly poor quality and this affected determination of small landslide events.

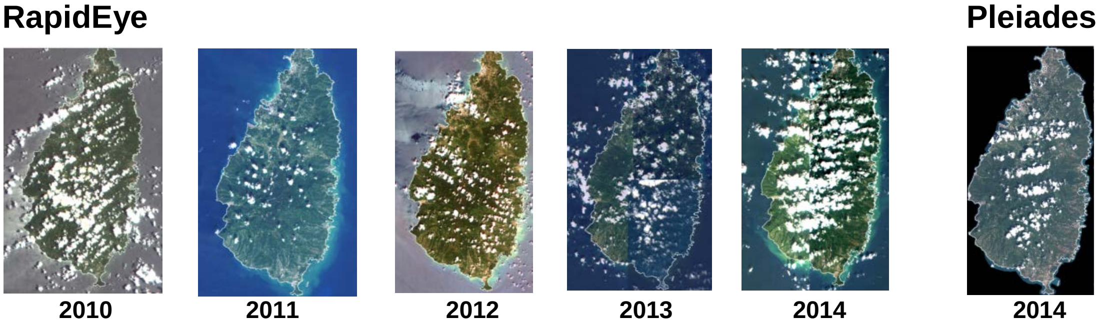


Figure 8. Satellite images used for landslide event identification for St Lucia. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved

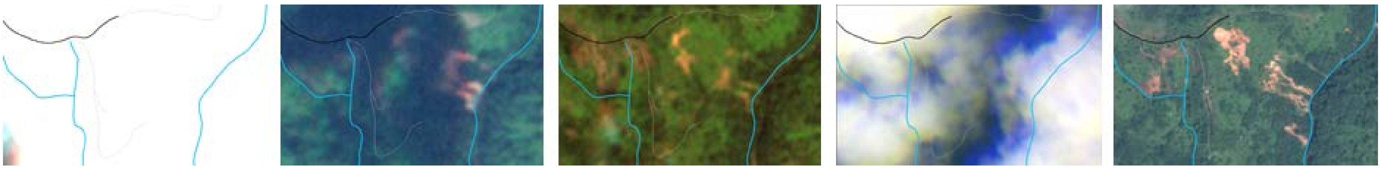
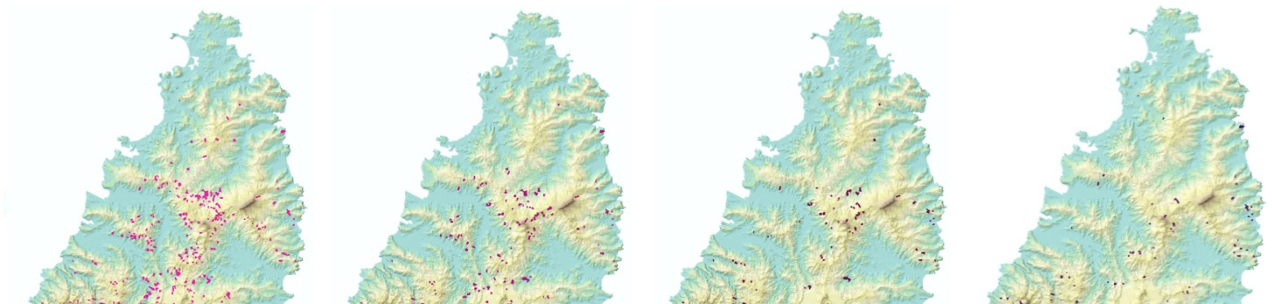


Figure 9. Capture of a small scene in St Lucia (Chateau Belair, image width about 400 m) illustrating the variations in quality of the images (from left to right) RapidEye 2010, 2011, 2012, 2013 and Pleiades 2014. Streams (blue lines) and a rural path (black lines) are added to aid cross-referencing. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved.

Table 6 Summary of landslides identified for each year of the multi-temporal image stack from 2010-2014 in St Lucia.

Year, image, date	Landslides	notes
2010 RapidEye 18/8/2010	27 active, 2 inactive	The image captures the state of the Island before Hurricane Tomas. Some 40% of the land surface was affected by cloud cover (and associated shadow and could-fringe effects). The small number of landslides that were captured where the land surface is visible is likely the result of much vegetation regrowth masking previous events. Many inactive sites, susceptible to re-activation, are therefore not included. Absence of older images (closer in time to major disturbing events such as hurricanes and troughs) limits opportunities of extend the size of this initial dataset.
2011 RapidEye 03/1/2011	1025 active, 3 inactive	This image captures all events generated by Hurricane Tomas (October 30-31, 2010). Thick cloud covers approximately 2% of the Island. For a further 5% the view is obscured by cloud fringe effects. Approximately 10% of the land surface is affected by cloud shadows, but this did not obstruct interpretation significantly.
2012 RapidEye 29/9/2012	489 active, 304 inactive	Only 14 new events were identified (these polygons were not recognised as active in the 2011 inventory). An additional 30 events are identified as active, but initiation of slope instability is uncertain; twenty events were identified in areas where cloud cover was encountered in the images of 2010 and 2011; ten events did not exist in the 2010 inventory and were obscured by clouds in the 2011 inventory. Some 16% of the land surface is not visible due to clouds with a further 2% obscured as a consequence of cloud shadow effects.
2013 RapidEye 14/22013	198(238)* active, 173 inactive	*SE quadrant of the Island is not included in first value; the second value represents a larger total where persistence of landslide activity is plausible (i.e. all these polygons are active in the inventories of 2011, 2012 and 2014). Approximately 35% of the land surface is not visible due to cloud cover, with a further 17% obscured as a consequence of shadows and poor image quality.
2014 Pleiades 25/2/2014	459 active, 311 inactive	Some 129 landslides were new events not included in the 2011 inventory. Approximately 5% of the land surface is not visible due to cloud cover, with a further 25% slightly affected by a thin clouds and shadows that only slightly affect image interpretation.
All images	1233	Total number of polygons in the multi-temporal inventory (including 2 polygons mapped as inactive throughout the period 2010-2014). 50% of the landslides were mapped as active in one year only. 27% were observed in two years, 16% in three years and 6% in four years. Less than 0.5% was observed in all five years of the period 2010-14.

Figure 10 . Pie diagrams of the number of polygons classified as active, inactive, not a landslide and those where identification was not possible due to cloud cover or, in 2013, due to poor image quality in the SE section of the Island.



2011 2012 2013 2104

Figure 11. Landslide inventory maps of St Lucia showing the distribution of active landslides (NB identification is affected by cloud cover and a poor quality SE quadrant for 2013; see Table 3).

Field checking involved a six-day field investigation in the first week of October 2014. The identification of routes and areas to concentrate on was facilitated by the ECLAC (2011) report. This report provided excellent guidance in terms of the impact of Hurricane Tomas in 2010.

While in the field, the team was able to access all available digital information on a GPS-enabled laptop. The routes taken are shown in the figure below. The aim was to see as many potential landslide sites as possible in this short period of time with a focus on the following landslides sites (Figure 12):

- The area in the vicinity of the Roseau Dam
- The valleys and hillslopes of Fond St Jacques and Migny
- Road-side landslides in the Colombette
- The Micoud/Thomazo/Barre de L'Isle road
- Landslide clusters in the Ti Rocher, Trois Pitons
- Landslide events in Marc
- Rockfalls off the Pitons
- Detailed interpretation of a landslide at Chateau Belair

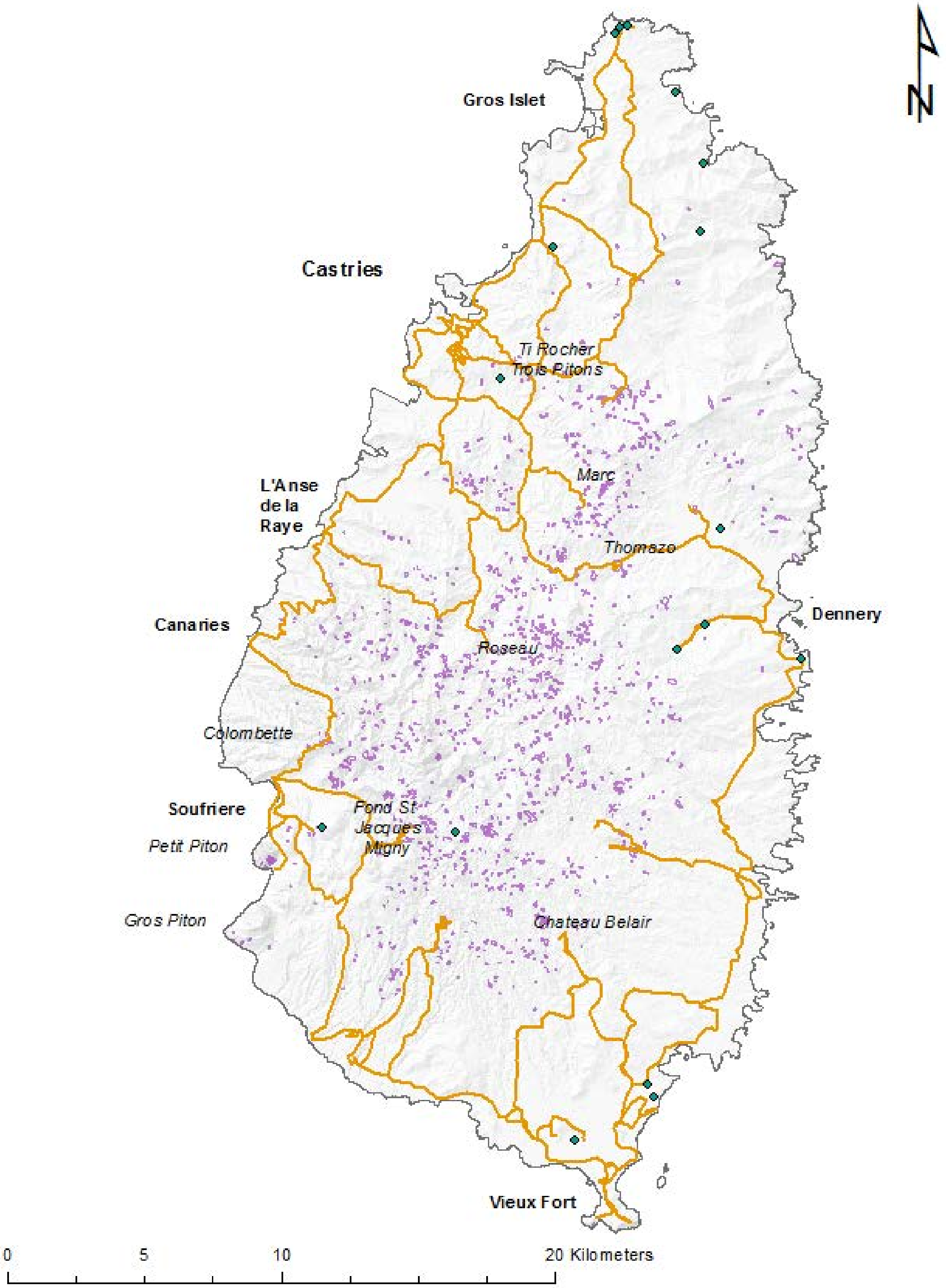


Figure 12. Map of St Lucia with landslide events in purple outline, identified from RapidEye (acquired in 2010-2013) and Pleiades (2014) satellite imagery. Field checking routes taken are shown in brown. Green dots represent land-use classification field check spots.

At **the Roseau Dam** many landslides were observed from the 2011 image and the road provided good access to the interior. Along the way it was possible to field check many sites mapped as landslides, with those generated in 2010 close to the dam still clearly recognisable (Figure 13). The road was in many places affected by recent landslides, including on the stretch from the Roseau Dam to L'Anse la Raye (Figure 2).

The **Fond St Jacques** area was heavily affected by flowslides triggered by Hurricane Tomas. Many events originated in deforested, cultivated fields in the upper slopes (ECLAC 2011). The Migny road was severely affected and remains out of service. This area was used to evaluate the potential of a 'bare earth' classification for landslide identification (Figure 14).

The **Colombette** landslide was initiated in the upper parts of the flanks of Mount Tabac, north of Soufriere. The deeply weathered pyroclastic bedrock and lightly cemented ash soils rapidly disintegrated to form a debris slide stripping the lower slopes of vegetation, soil and roadway structure (ECLAC 2011). Satellite images clearly show the outlines of the landslide in 2011 through to 2013. However, the 2014 image, albeit providing greater detail, is partly obscured by clouds. If earlier images had not been available, it is unlikely that this landslide would be detected on the basis of the 2014 image alone (Figure 15).

The **Micoud/Thomazo/Barre de L'Isle** road traverses the steep terrain of the centre of the Island and forms an essential transport link between Vieux Fort and Castries. Along this road many landslides are known to occur and these are subject to substantial stabilisation works (Figure 16).

A debris flow in the **Ti Rocher, Trois Pitons** area was identified on the satellite image of 2011. The translational slide/debris flow has a length of some 300 m. The highest point is at approximately 230m above sea level and its runout drops by more than 110 m. It originated in weathered bedrock comprising andesite, basalt and some agglomerates. Local soils belong to the Bocage Stony clay. On the satellite image of 2012 a substantial part of the lower part of the event was overgrown, making identification very difficult. It shows that, unless captured close to the event occurrence, recognition of landslides is very difficult in an environment where recolonization of affected slopes by vegetation occurs in a very short period of time (Figure 17).

The **area around Marc** was identified in the ECLAC (2011) report as being particularly affected by landslides. Many of these were small translational or rotational events in deeply weathered bedrock and lightly cemented, mainly granular soils. The landslides occurred on slopes steeper than approximately 25 degrees and rapidly disintegrated to form flows. The events seriously affected communities where the houses were constructed on the hill-slopes (Figure 18). Identification of individual events is difficult in this area because of the patchwork of colours from housing, infrastructure and variations in vegetation on steep slopes and the relatively poor resolution of the 2011 RapidEye image (5 m). In order to map these very small events with some degree of confidence at a 1:10,000 scale the higher resolution of the 2014 Pleiades image is required. However, by the time this image was taken, many of these smaller events were re-vegetated and their signatures difficult to establish. It is not impossible to map these small events using the images available, but it requires interrogation of the data at scales that are much more detailed than stipulated for this exercise.

The Pitons form arguably the most charismatic images representing St Lucia. These steep rock slopes are generating rock falls and several trails were mapped following Hurricane Tomas. Since then the interpretation was downgraded to ‘inactive’. However, during the field visit a loud rockfall was heard and the scars of recent events were observed. Local narratives report regular rockfalls from the Petit Piton. It is evident that this area remains one of continued activity and could benefit from careful observation and monitoring (Figure 19 and Figure 20).

The **Chateau Belair** site (approximate location 719400/1527030) has been used to evaluate opportunities that exist for detailed interpretation of satellite images. Comparison of the area of interest at three different scales (1:20k, 1:10k, 1:5k and 1:1k) shows how polygons drawn around landslide signatures range from very course outlines around possible multiple events (this affects the size frequency distribution by over-emphasising larger events) to very detailed metre-scale outlines of surface features. At scales of 1:5k to 1:1k it is possible to create detailed outlines of areas where evidently planar slides disintegrate into flows and where small slides rapidly transfer into debris flows down steep gradients. This is particularly facilitated by the high-resolution of the Pleiades image (see Figure 21). Comparison of the interpretation performed using this image with the stack of RapidEye images of previous years enables determination of the time at which small landslide scars are initiated.

The satellite image interpretation initially leads to identification of surface features, but further investigation using a digital elevation model shows that landslide activity at this site is affected by a topography determined by a much larger ancient (and potentially relict) rotational landslide. Combining all information enables the establishment of a detailed geomorphological sketch map that can provide useful information on the changes in activity of deformation at a remote site (Figure 22 & Figure 23) and considerable detail of morphological features of individual events (Figure 24). These interpretations require substantial field verification and the Chateau Belair site was therefore visited in October 2014. Field observations corroborated the satellite based interpretation, and this provided further confidence in the approach taken.

Access to remote sites can be difficult and time consuming. In the case of Chateau Belair, access was particularly problematic as many roads leading into the centre of the Island were compromised by the landslides of Hurricane Tomas in 2010 and the December Trough in 2013. Chateau Belair is situated at the head of a valley with only a small, unpaved road leading up to an adjacent hill where it is possible to obtain an overview of the site. To find suitable locations where a good overview of a site can be achieved on the ground is not an easy task in an environment blessed with exuberant vegetation (Figure 23). There is therefore much merit in the use of satellite images to enable interpretation of features at remote locations.

Figure 13 . Landslides near the Roseau Dam. Multiple events in 2010 seriously affected the water quality of the reservoir and a large landslide occurred to the east of the dam (see inset photo from ECLAC 2011). The remains of this landslide are still clearly visible. The direction of the photo is indicated by a red arrow on the satellite image of 2014. Compared with the 2011 image it is evident how much more detail can be observed. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved.

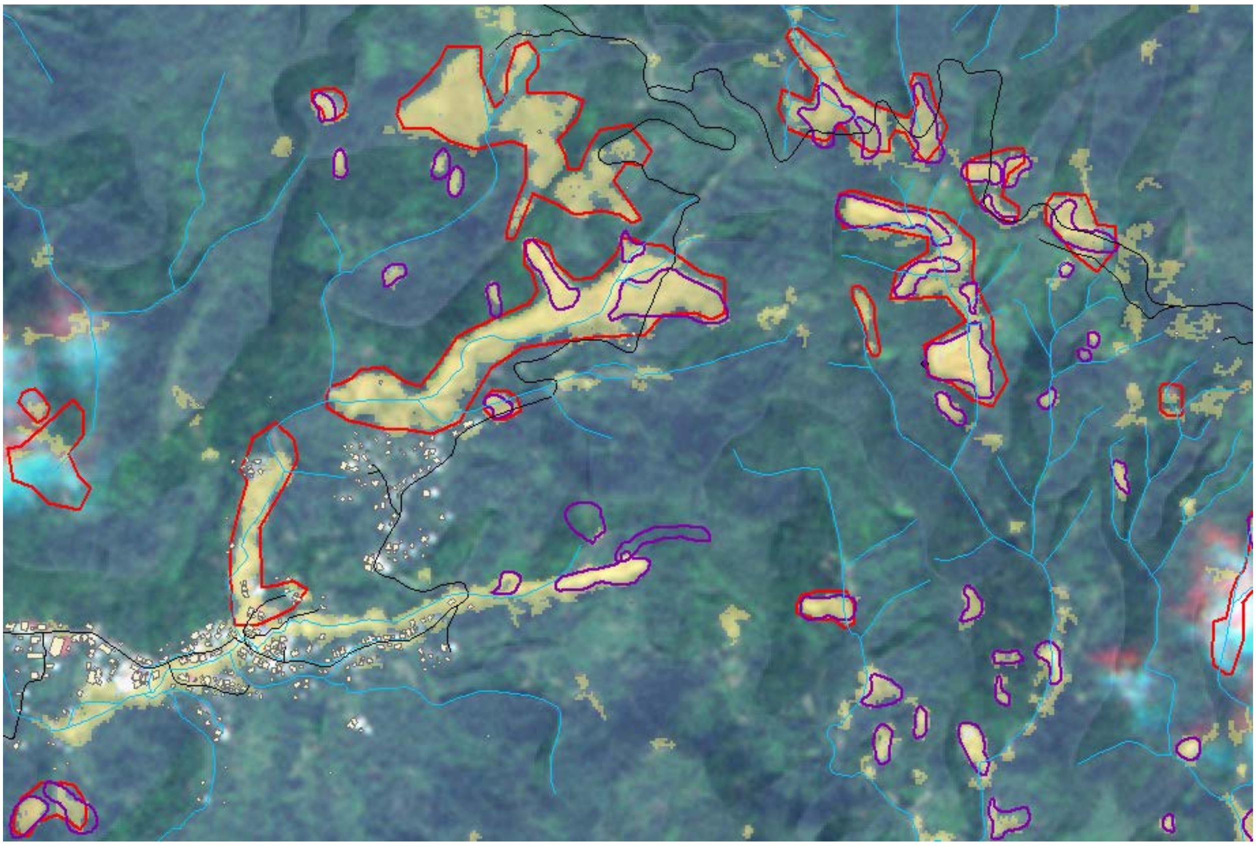


Figure 14 . The Fond St Jacques/Migny area on the 2011 RapidEye image. The light coloured pixels indicate the result of a 'bare earth' classification (areas larger than 300 m^2). The red polygons represent the 2010 landslide inventory and the purple polygons the multi-temporal inventory where bare earth signatures in valleys and fields have not been included. The two landslide polygons in the centre were generated in 2014. Includes material © 2014 BlackBridge, all rights reserved.

Figure 15. Colombette Landslide. Top left is the state of the upper part of the landslide in October 2014 and top right shows the landslide in 2011. The lower images represent scenes from RapidEye (2011 and 2013) and Pleiades (2014). Despite the greater resolution of the Pleiades image, the landslide is barely visible. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 16 Landslide stabilisation works along the Vieux Fort-Castries road at Thomazo.

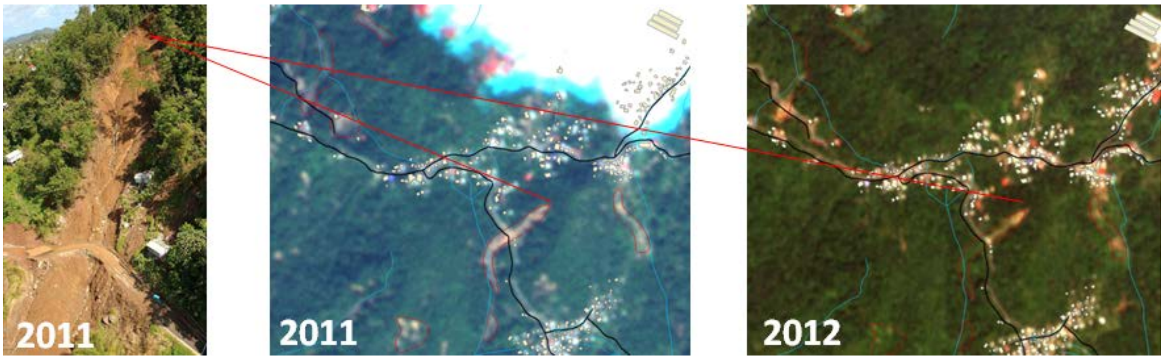


Figure 17. The landslide/debris flow event of Ti Rocher. To the left an oblique of the event is shown (source ECLAC 2011). The event is clearly visible on the 2011 RapidEye image, while only a year later all landslide deposits below the road are covered by vegetation. Includes material © 2014 BlackBridge, all rights reserved.

Figure 18. Landsliding near Marc. The oblique photo on the left (source ECLAC 2011) shows the extent of the area affected. The blue outlines in the 2011 image follow the outline of the valley. In the 2014 Pleiades image the landslide complex is barely recognisable. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved.

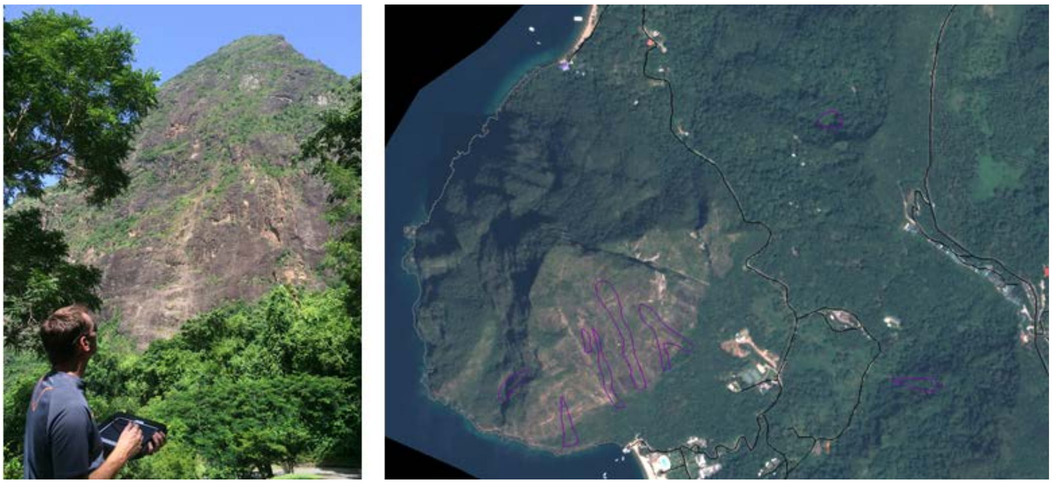


Figure 19. The Petit Piton with fresh trails of rockfalls and the 2011 rockfall trails superimposed on the 2014 Pleiades image. In the SE corner of the image landslide trails were observed in the field (Figure 17) but these could not be identified on the satellite images. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 20 . An example of landslide scars along the main ridge connecting the two Pitons. These events were generated during Hurricane Tomas but could not be picked up in the satellite images because of size, terrain steepness, shadow effects and overhanging vegetation.

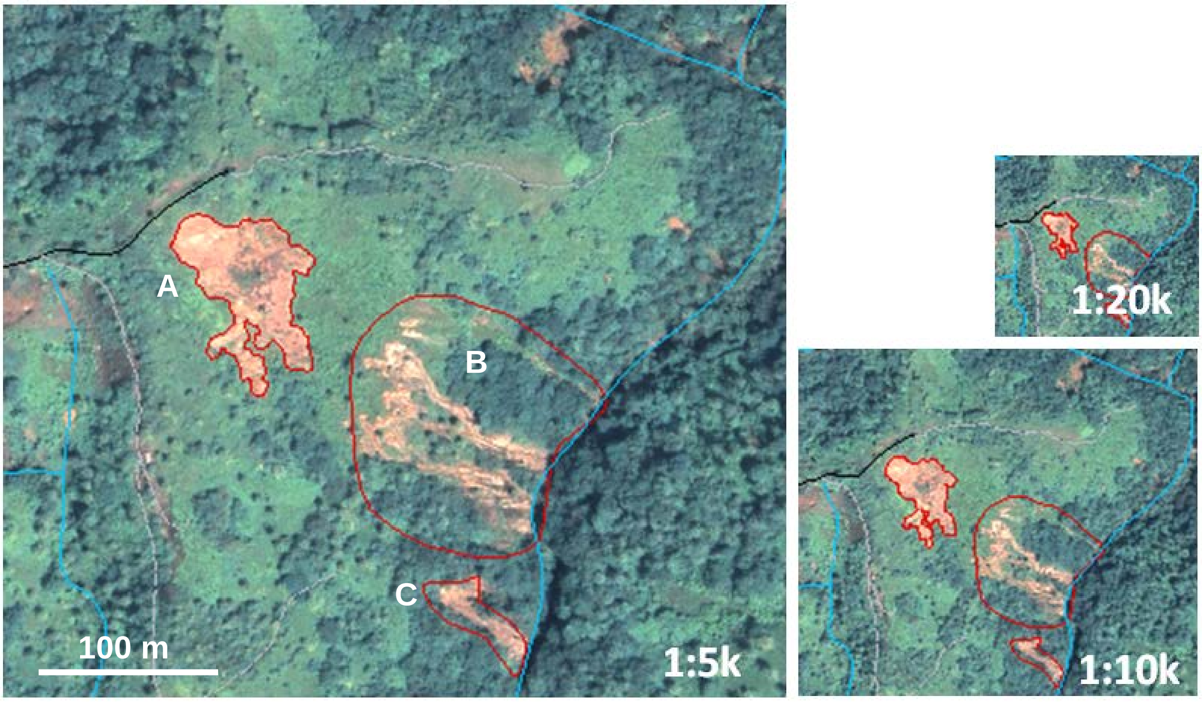


Figure 21. An example of mapping at different scales at Chateau Belair using the 2014 Pleiades satellite image as an example (see also Figure xx for an indication of image variability across the multi-temporal image stack). At 1:5,000 scale it is possible to create a detailed outline of freshly exposed soils of a landslide (A), at 1:10k it is possible to roughly outline a small event (C) while at 1:20,000 scale a small cluster of linked events is grouped together (B). Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

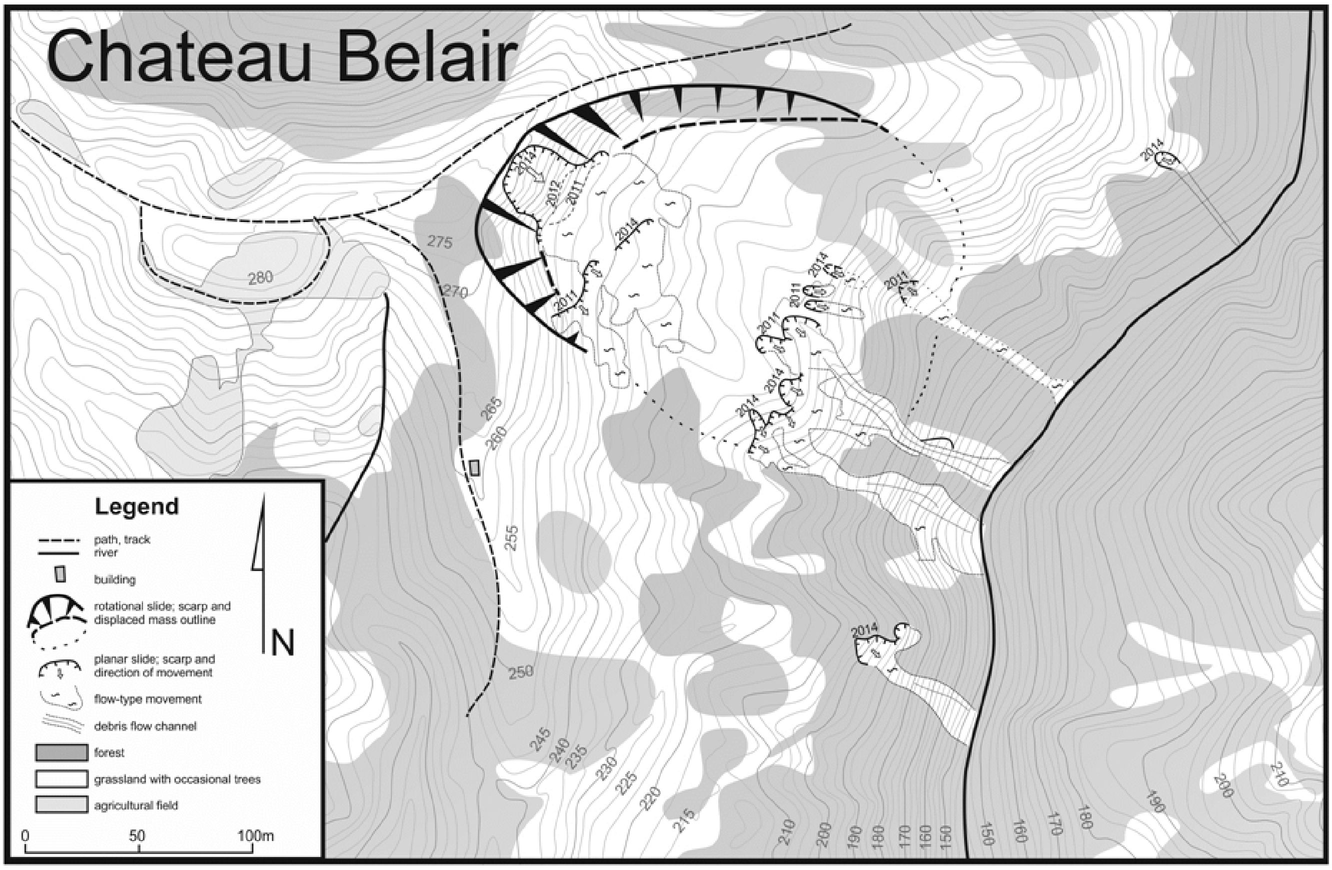


Figure 22 .A geomorphological sketch map produced using Pleiades and a surface model. This illustrates the opportunities that are on offer given time to interrogate these information sources at their maximum level of detail.

Figure 23. The Chateau Belair landslide as seen from a vantage point during field verification.

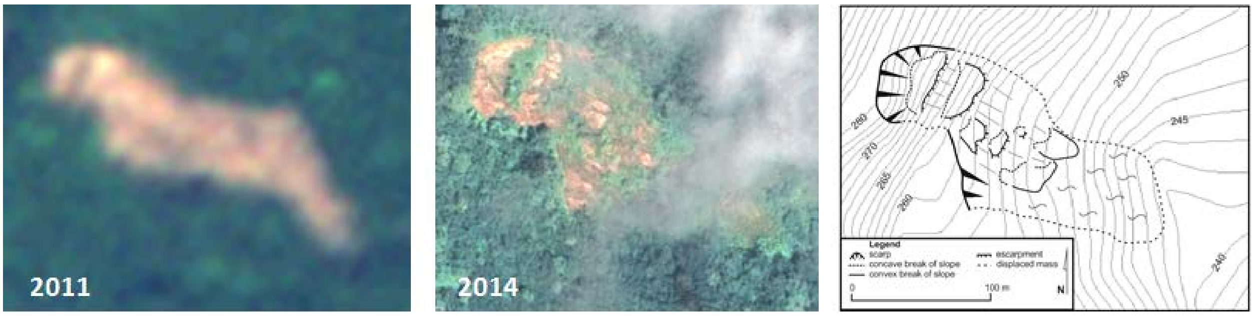
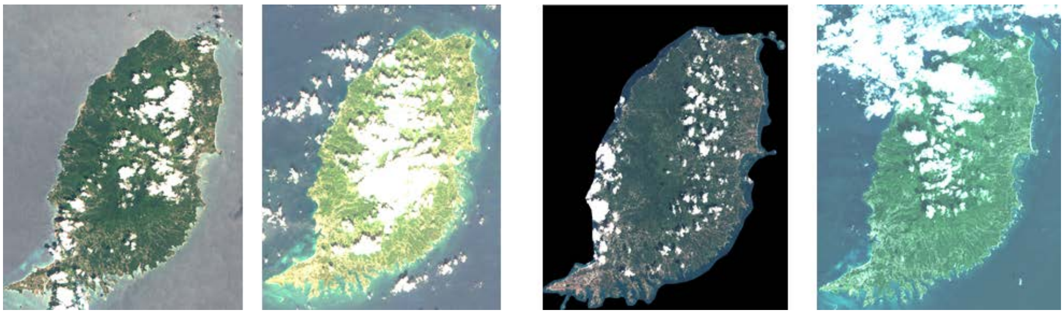


Figure 24. The 2011 image of a landslide enables establishment of just an outline of a landslide feature near the Roseau Dam. However, the 2014 Pleiades image can be used to draw a tentative morphological map of a landslide complex. Field checks are required to ensure these interpretations are realistic. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved.

Landslide inventory establishment - Grenada

For the creation of a landslide inventory in Grenada RapidEye images from 2011 and 2012, a Pleiades image from 2013 and a Landsat TM from 2014 were used (Figure 25). The 2012 RapidEye image is particularly affected by significant cloud cover.



RapidEye 2011 **RapidEye 2012** **Pleiades 2013** **Landsat TM 2014**

Figure 25 . Satellite images used for landslide event identification for Grenada. Includes material © 2014 BlackBridge, all rights reserved.

Satellite image interpretation and landslide inventory establishment for Grenada followed the same process as used for St Lucia. However, it was found that the terrain in Grenada is substantially more complex and that landslide signatures are not as clear. The satellite interpretation resulted in identification of 109 sites potential landslides. However, confidence in all 109 mapped landslide polygons was extremely low.

The interpretation of the satellite images was made more difficult as agricultural landuse created a dense patchwork of cultivated fields, such as small banana plantations, that take on multi-temporal signatures resembling unstable terrain with a gradually re-establishing a vegetation cover. Even in forested areas of the upland regions of the Island there are patches of disturbed vegetation that could be interpreted (on the basis of experience gained at St Lucia) as old landslide scars.

Field checking involved a two-day field investigation on Saturday 27th and Sunday 28th September 2014. The routes taken are shown in the figure below. The aim of the fieldwork was to see as many potential landslide sites as possible and the focus was on the following clusters of potential landslides (Figure 26);

- La Fortune and Levera region
- The uplands of St Patrick between Union, Castle Hill and Tricolet
- The hills around Mt Qua Qua and the Grand Etang
- The valley from Marigot leading up to Concord Falls
- The road between Gouyave and Grenville

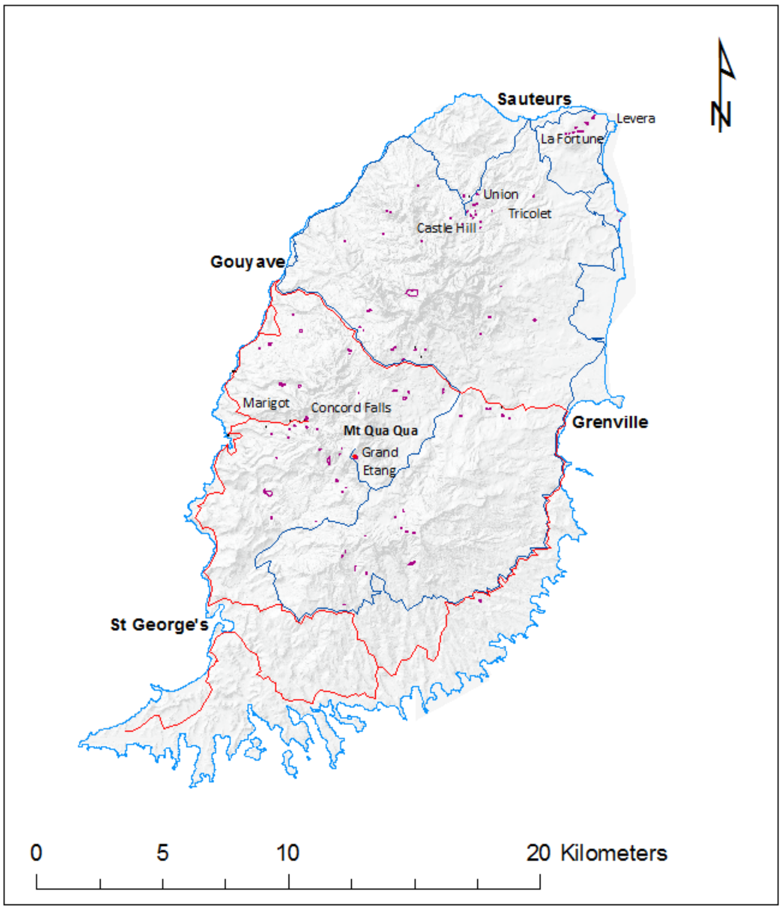


Figure 26 . Potential landslides (in purple outline) identified from RapidEye (acquired in 2011-2012) and Pleiades (2013-2014) satellite imagery. Following field checking (routes taken are outlined in dark blue and red) of the mapped polygons, only one landslide polygon remained - a red polygon near Grand Etang representing an old, inactive landslide.

La Fortune and Levera region. In the NE of the Island several coastal landslides were identified (tentatively) from satellite images on the basis of morphology and exposed soils. Field checking of these sites near Antoine Point indicated that the dominant processes involve surface erosion and that there was a lack of vegetation development along the coastal cliff (Figure 27). A cluster of potential landslides associated with an unpaved road system were identified (again tentatively) on the satellite images. Their features were quite persistent and some morphologies suggested rather substantial movement, on relatively gentle terrain (Figure 28). Instead it turned out that road construction near Levera point has resulted in extensive erosion in soft bedrock (tuffs) with overlying fractured basalts (members of the Levera volcanics) flowing down into erosion gullies. Topography and exposed soils observed in the vicinity of Lake Antoine could lead to classification as a potential landslide, but field inspection concluded that this site was not affected by landsliding (Figure 29).

The uplands of St Patrick between Union, Castle Hill and Tricolet. During the brief fieldwork phase this area was investigated at, but none of the sites offered sufficient evidence to warrant a landslide classification. Instead, the patterns observed in the satellite images from 2011, 12 and 13 are most likely the result of cultivation of these slopes. Many of the discounted landslides represented small banana plantations. It was checked whether these were coincident with old landslides (as was observed at a small number of sites in St Lucia), but this did not appear to be the case (Figure 30, Figure 31).

The hills around Mt Qua Qua and the Grand Etang comprise steep slopes in the Mount Granby Volcanics (Miocene-Pliocene). The vegetation cover is still re-establishing itself following the devastation caused by Hurricane Ivan of September 7, 2004. The relatively young vegetation enabled some views across the hills from the footpaths along the Grand Etang and leading up to Mt Qua Qua. It is apparent that the morphology of these steep slopes has involved slope deformation processes, but during the field visit it was not possible to determine positive indications of landsliding in this landscape, with the exception of one event on the southern slopes of Mt Qua Qua. The landslide represents the only polygon on the Island where there is confidence in the mapped product. Further interrogation of the satellite images following the field survey resulted in discounting all the other (tentatively) mapped polygons (Figure 32).

The valley from Marigot leading up to Concord Falls and the road between Gouyave and Grenville. Discussions with people at Concord Falls (two contractors working on the road and two people from the Visitor Centre) revealed that landslides are not recognized as posing a threat. The 1991 rock fall killing 14 people is still seen as an exceptional event. The only other event that was recounted involved a small rockfall in July/August ago that caused an accident, but details were very vague. There were no recollections of any significant landslides in the area, either along the road or on the higher slopes. Several small landslide events were observed during the field investigations. These include landslides along steeply incised river channels along the road to Concorde Falls (Figure 33, Figure 34). These shallow translational failures are generated following undercutting by a small stream. Often, the valley floor deposits in which these small failures develop are capable of sustaining near-vertical slopes and comprise angular blocks in a coarse matrix. This provides substantial interlocking, frictional resistance and drainage. Some degree of cementation may also assist the preservation of these steep slopes.

Slope failures in weathered bedrock can contain a greater fines content which is likely to affect slope drainage negatively and will result in a quite different post-failure behaviour and morphologies (For example as observed on the slopes of Mt Qua Qua, Figure 32). Upon further investigation, none of the small failures that were observed along the roads could be identified on the satellite images and therefore these were not included in the final product (Figure 30).

Additional observations. A large landslide complex near Palmiste Bay has led to the closure of the coastal road and a lengthy diversion inland (the Mount Nesbit Detour; Figure 35). This complex was not picked up during the satellite investigation. Upon inspection of the closed road there were few visible signs of landsliding along this road. Some sections were not paved, probably because of recurring deformation, but at the time no cracks or other signs of landslide activity were observed. Further investigation of satellite images did not enable the drawing of a clear outline of this mass movement complex. Palmiste Clays are well known to generate landslides and the 2006 landslide inventory and hazard mapping exercise highlighted this geological material as scoring particularly in the hazard index (CDB and CDERA, 2006).

Signs of small rockfalls are observed along many of the Island’s rock cliffs. Immediately opposite the arrivals/departures pick up area at the airport a clear sign of this potential risk is clearly indicated (Figure 36, Figure 37). This cliff in pyroclastic deposits is a clear example of the kind of cliff faces that are prevalent throughout the country. Widely spaced persistent and intersecting joints often provide for a fragmented rock face where blocks can get dislodged during or following adverse weather conditions. These events pose a significant hazard, but are too small and ephemeral to be identified through satellite image interpretation.

The ground-truthing thus resulted in the observation that none of the 109 mapped landslide polygons were landslides, with just one exception - a large inactive rotational slide on the upper slopes of Mt Qua Qua. The EO interpretation and associated field investigation exercise has shown that unless there are very clear signs of displacement, most landslide event signatures (that in St Lucia could be interpreted with some confidence as being landslide related) are in fact associated with cultivation of these slopes.

Figure 27 . Southern cliffs of the headland at Antoine Bay and landslide polygons mapped using the Pleiades 2013 image. Vegetation alignment indicates strong coastal effects reducing vegetation growth potential near the edge of the cliffs and wind and water erosion of local soils leading to exposure of the underlying bedrock. The small landslide to the north of the headland was also dismissed from the landslide record. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 28. Levera Point. Initially mapped as landslides, ground truthing indicated that these are predominantly surface erosion features. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 29. Landscape looking north from the tufaceous explosive crater rim of Lake Antoine in NE Grenada.

Figure 30. Typical landscapes in St Patricks (Union/Castle Hill) showing a patchwork of cultivated fields where several potential landslides had been mapped (see inset map with landslide polygons in purple outlines and the route taken in blue). Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 31. A field in the St Patricks area. This was initially mapped as a landslide because of the position in the landscape and a bare earth signature that gradually re-vegetated.

Figure 32. View looking north of the upper slopes of Mt Qua Qua and the outlines of the only positive identification of a landslide. The steep slopes that make up this ridged landscape are characterised by morphologies that are indicative of phases of landsliding and surface erosion. However, during the current mapping exercise, no evidence of active mass movements was found.

Figure 33. Shallow translational and rotational landslides generated by undercutting along the road to Concorde Falls and, right, a small roadside failure NE of Constantine. These small failures were generated in 2014 but are not visible on the latest satellite image available for this study as these would have occurred since the images were taken. However, given the dimensions of these events, it is highly improbable that these will be picked up by an EO survey.

Figure 34. A field along the Concord falls road. This field is typical of many in this area that have been picked up during the satellite image interpretation as potentially being a landslide. The identification as potential landslide or cultivated field are affected by slope, shadows and overhanging, patchy vegetation.

Figure 35. Road closure at Palmiste Lane, south of Gouyave. This closure sign is positioned at the red dot on the coastal road, as indicated in the image scene on the right. A lengthy detour (the Mt Nesbit Detour) reconnects with the coast road, just south of Cuthbert Peters Park. Unfortunately, satellite interpretation alone is not sufficient to draw a boundary around a region of unstable slopes with confidence. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Figure 36. The potential for rockfall is apparent at many sites across the island. A large cliff face near Molinere Point provides an example of many steep cliff faces found throughout the Island from where it is not inconceivable that the occasional rock fall can be generated. Differences in coloration of the cliff faces provide an indication of the dynamic nature of these cliffs. However, dense vegetation along the base of these cliffs will reduce the magnitude of the zone away from the cliff where the effects of rockfalls will be felt. In the absence of vegetation, e.g. near the airport (centre) and along roads (e.g. at Levera, right) rockfalls can pose a hazard with a more direct impact pathway.

Figure 37. Some of the coastal road stretches, e.g. between Grand Roy and Dothan, are constructed along the base of old coastal cliffs. Even though wave action is no longer providing an input into the cliff dynamics, occasional rockfalls still occur.

Digital Elevation Models

Digital elevation models (DEMs) of St. Lucia and Grenada were also required to support landslide risk assessments for these two AOIs. The SOW stated that the DEMs were to be generated from stereo optical satellite imagery with a spatial resolution of 30m or better. Again, in keeping with the “eoworld” framework, the preferred source of imagery from which to produce the DEMs was a European or Canada sensor. With no suitable archived imagery available, a tasking request was submitted to Airbus Defence & Space in early August 2014 in order to have fresh stereo Pleiades imagery acquired for both St. Lucia and Grenada. However, the timing of this request coincides with the hurricane season in the Caribbean. As a result, all attempted acquisitions to date have been affected by considerable cloud and haze cover (Figure 38), thus rendering them inadequate for the generation of DEMs.

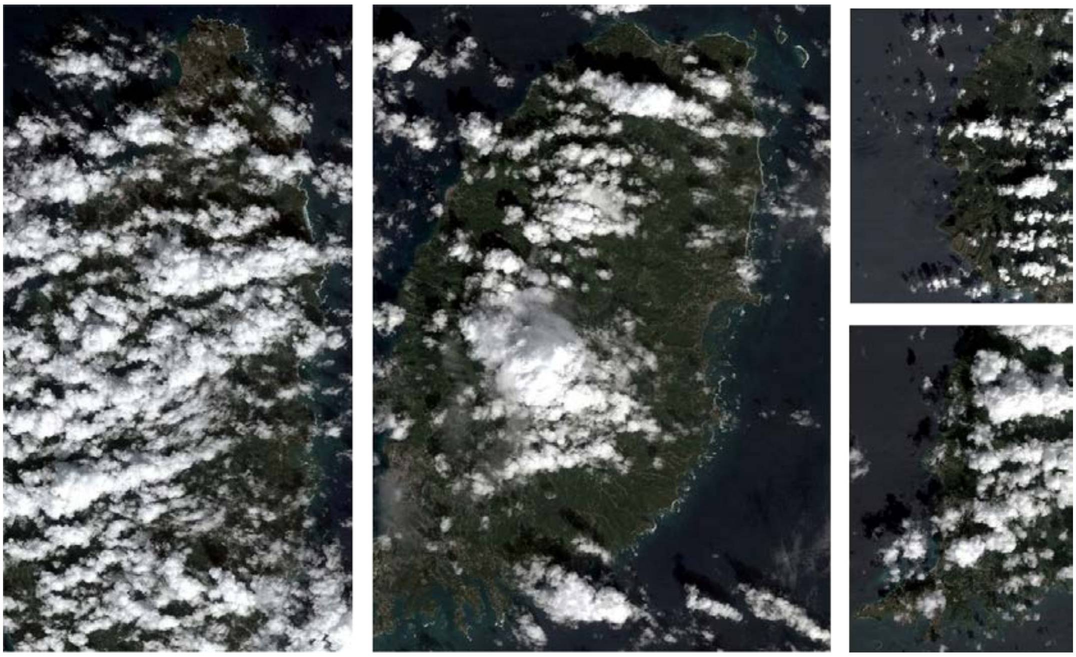


Figure 38. Select attempts to acquire fresh Pleiades stereo imagery for St. Lucia and Grenada. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved

In the absence of any other alternative stereo imagery, the DEMs for the AOIs were generated based on imagery acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor. The ASTER sensor has a stereo camera that acquires nadir and backward-looking images for band 3, which can be processed using a photogrammetric approach to extract DEMs. Using an optimised approach, NASA and Japan’s Ministry of Economy, Trade and Industry (METI) have already processed an extensive archive of ASTER stereo imagery for the purpose of producing the 30m ASTER Global DEM (ASTER GDEM); released in 2011. With a view to augmenting this ASTER-derived elevation data, different strategies were developed and implemented based on the ancillary data available for the two AOIs.

For St. Lucia, ancillary elevation data derived from contour maps was made available by the Physical Planning Office and University of the West Indies. In an attempt to increase the accuracy of the ASTER-derived elevation data, a vertical calibration approach utilising the contour data was implemented. To achieve this, 32,000 corresponding ASTER- and contour-derived elevation points were extracted and modelled (R^2=0.97) using regression analysis (Figure 39). All ASTER-derived elevation values were subsequently vertically calibrated using:

$$H_{cal} = (-9\times10^{-5})\, x^2 + 1.01x - 6.475 \,, \tag{1}$$

where H_{cal} are the vertically calibrated ASTER elevation values and x are the original ASTER elevation values. Next, the calibrated ASTER-derived elevation point data were merged with the contour heights to create a single x-y-z dataset. These data points were then gridded using a Triangular Irregular Network with linear interpolation algorithm to generate a 30m DEM.

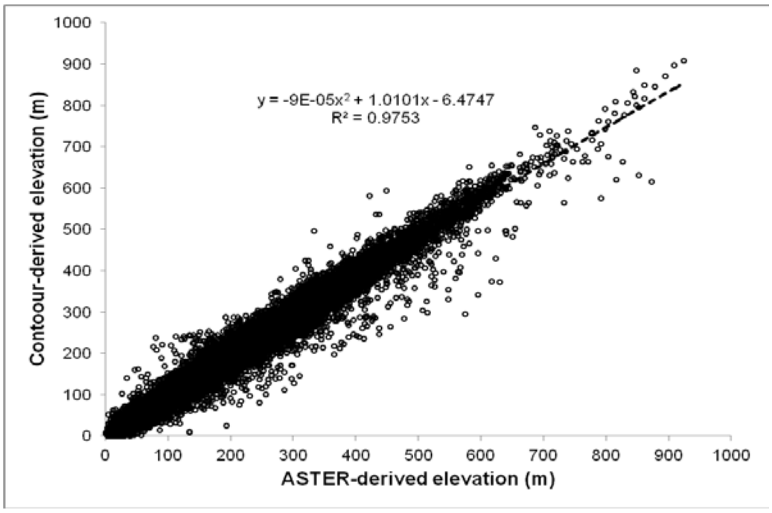


Figure 39. Vertical calibration of the ASTER-derived elevation data using regression analysis.

For Grenada, ancillary elevation data was available in the form of a 5m digital terrain model (DTM) generated from airborne Light Detection And Ranging (LiDAR) data. The ASTER-derived elevation data was vertically calibrated using this LiDAR data. To achieve this, 500 corresponding ASTER and LiDAR elevation points were extracted and modelled using regression analysis (R^2=0.99). To avoid introducing errors by comparing data from a digital surface model and a DTM, care was taken to ensure that only points corresponding to bare ground were selected. All ASTER-derived elevation values were subsequently vertically calibrated using:

$$H_{cal} = 1.018x - 1.016, \qquad (2)$$

where H_{cal} are the vertically calibrated ASTER elevation values and x are the original ASTER elevation values. The quality of the resulting DEM was further enhanced by replacing elevation values relating to a sizeable “pit” artefact using elevation values from a Shuttle Radar Topography Mission (SRTM) DEM.

The resulting enhanced DEMs for St. Lucia and Grenada are shown in Figure 40.

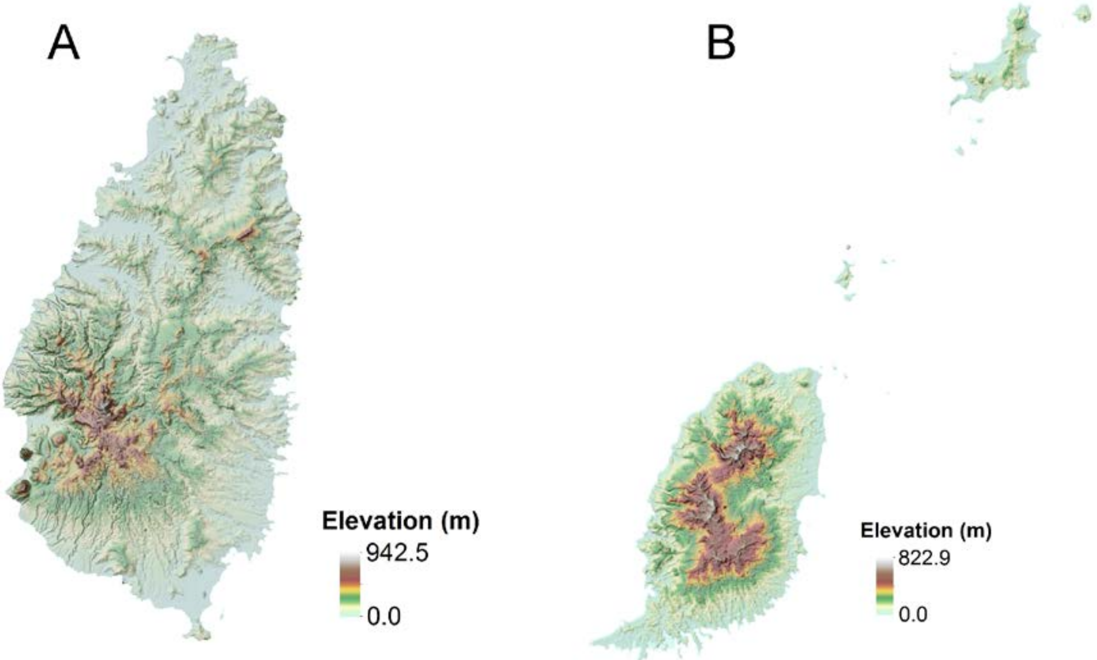
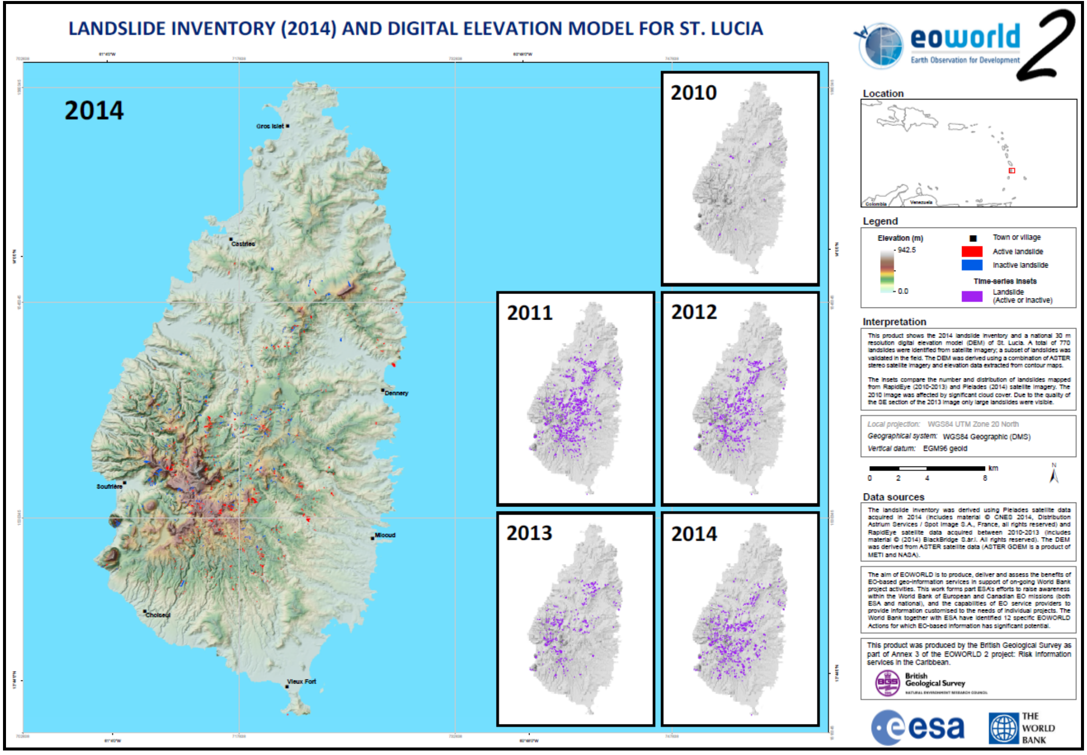


Figure 40. The 30m DEMs generated for (A) St. Lucia and (B) Grenada.

The landslide inventory polygon datasets for Grenada and St Lucia were also compiled into map format. An example (for St Lucia) is illustrated in Figure 41.



Interpretation

This product shows the 2014 landslide inventory and a national 30 m resolution digital elevation model (DEM) of St. Lucia. A total of 770 landslides were identified from satellite imagery; a subset of landslides was validated in the field. The DEM was derived using a combination of ASTER stereo satellite imagery and elevation data extracted from contour maps.

The insets compare the number and distribution of landslides mapped from RapidEye (2010-2013) and Pleiades (2014) satellite imagery. The 2010 image was affected by significant cloud cover. Due to the quality of the SE section of the 2013 image only large landslides were visible.

Data sources

The landslide inventory was derived using Pleiades satellite data acquired in 2014 (includes material © CNES 2014, Distribution Astrium Services / Spot Image S.A., France, all rights reserved) and RapidEye satellite data acquired between 2010-2013 (includes material © (2014) BlackBridge S.àr.l. All rights reserved). The DEM was derived from ASTER satellite data (ASTER GDEM is a product of METI and NASA).

The aim of EOWORLD is to produce, deliver and assess the benefits of EO-based geo-information services in support of on-going World Bank project activities. This work forms part ESA's efforts to raise awareness within the World Bank of European and Canadian EO missions (both ESA and national), and the capabilities of EO service providers to provide information customised to the needs of individual projects. The World Bank together with ESA have identified 12 specific EOWORLD Actions for which EO-based information has significant potential.

This product was produced by the British Geological Survey as part of Annex 3 of the EOWORLD 2 project: Risk information services in the Caribbean.

Figure 41 Map showing the landslide inventory (2014) and digital elevation model of St Lucia.

3.1.3 Service 3: Digital Elevation Models of Belize

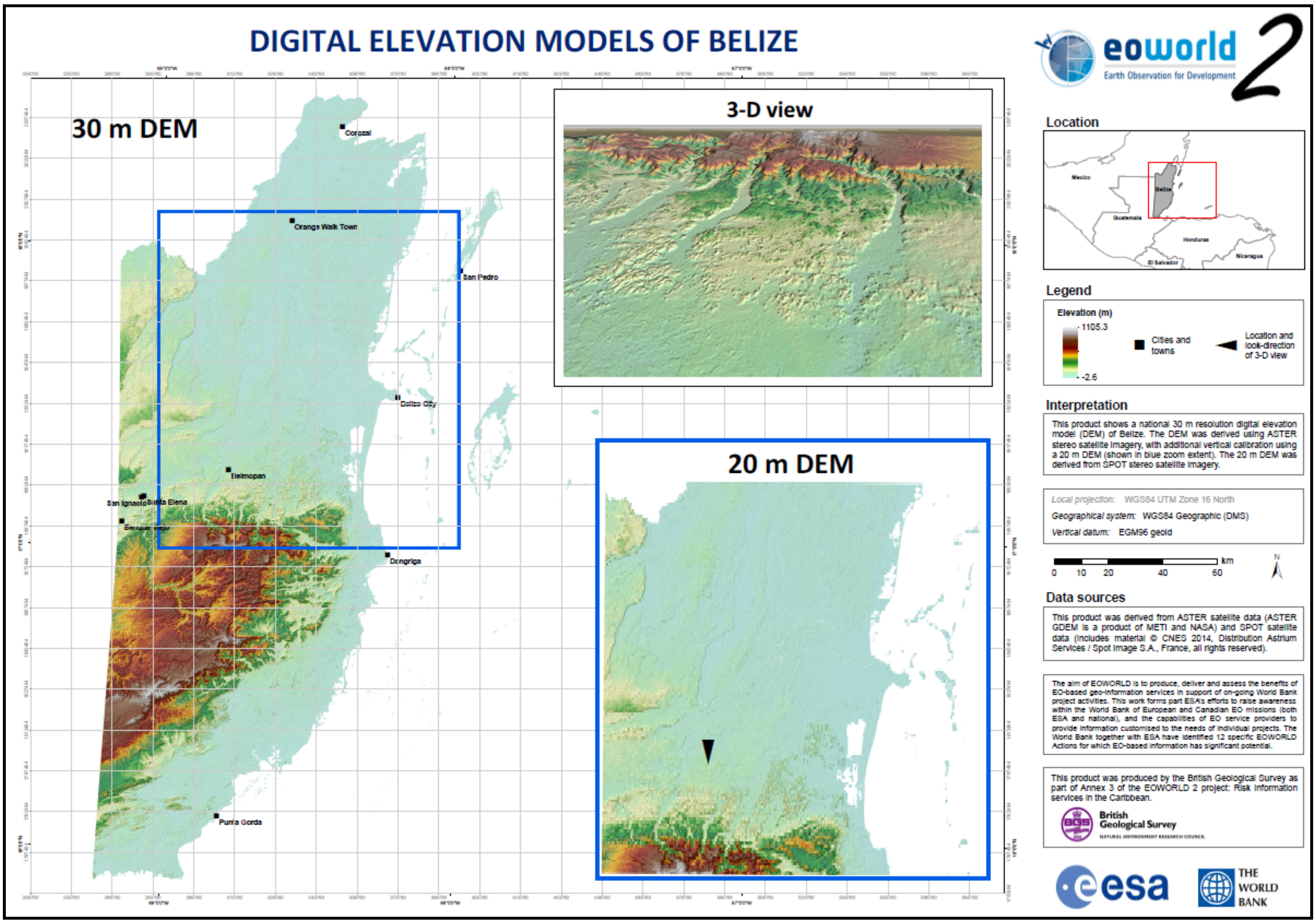
The objective of Service 3 is to generate a national DEM of Belize and a precise DEM for a subset of Belize to support hazard/risk assessment.

National Digital Elevation Model
The SOW stated that the national DEM of Belize should be generated from stereo optical satellite imagery with a spatial resolution of 30m or better. Again, in keeping with the “eoworld” framework, the preferred source of imagery was a European or Canada sensor. Accordingly, a 20m DEM produced from SPOT-5 stereo satellite imagery was identified and acquired from Airbus Defence & Space. However, this DEM provided only 40% coverage of the total Belize AOI.

Additionally, a 30m DEM covering the entirety of Belize was generated based on existing ASTER-derived elevation data. The accuracy of the ASTER-derived elevation data was enhanced by vertically calibrating it with the higher-resolution 20m DEM. To achieve this, 32,000 corresponding ASTER- and SPOT-derived elevation points were extracted and modelled using regression analysis (R^2=0.99). All ASTER-derived elevation values were subsequently vertically calibrated using:

$$H_{cal} = 0.989x - 2.610 \, , \tag{3}$$

where H_{cal} are the vertically calibrated ASTER elevation values and x are the original ASTER elevation values. The quality of the calibrated DEM was further enhanced by applying a 3×3 pixel moving average filter. This filter helped to reduce “noisy” data values as well as notable “spike” artefacts in the DEM. The 20m and 30m DEMs generated for Belize are shown in Figure 42 in the form of a map also produced as part of the project.



This product shows a national 30 m resolution digital elevation model (DEM) of Belize. The DEM was derived using ASTER stereo satellite imagery, with additional vertical calibration using a 20 m DEM (shown in blue zoom extent). The 20 m DEM was derived from SPOT stereo satellite imagery.

This product was derived from ASTER satellite data (ASTER GDEM is a product of METI and NASA) and SPOT satellite data (includes material © CNES 2014, Distribution Astrium Services / Spot Image S.A., France, all rights reserved).

The aim of EOWORLD is to produce, deliver and assess the benefits of EO-based geo-information services in support of on-going World Bank project activities. This work forms part ESA's efforts to raise awareness within the World Bank of European and Canadian EO missions (both ESA and national), and the capabilities of EO service providers to provide information customised to the needs of individual projects. The World Bank together with ESA have identified 12 specific EOWORLD Actions for which EO-based information has significant potential.

This product was produced by the British Geological Survey as part of Annex 3 of the EOWORLD 2 project: Risk information services in the Caribbean.

Figure 42. The national 30m DEM and 20m DEM (in blue window) of Belize.

Precise Digital Elevation Model

The second aspect of Service 3 was to generate a high precision 1m resolution DEM from very high-resolution optical satellite imagery for a subset of Belize encompassing an area to the north of Belize City. To satisfy these requirements, a tasking request was submitted to Airbus Defence & Space in early August 2014 in order to have fresh Pleiades tri-stereo (triplet) imagery acquired for an area of 100km^2 situated to the north of Belize City, encompassing the town of Ladyville. However, the timing of this request coincides with the hurricane season in the Caribbean region. As a result, all attempted acquisitions to date have been affected by considerable cloud and haze cover (Figure 43), thus rendering them inadequate for the generation of a precise 1m DEM. Acquisition attempts for this area of Belize are still ongoing, and it is intended to generate the precise DEM upon acquisition of suitable tri-stereo imagery.

Figure 43. Selected attempts to acquire fresh Pleiades tri-stereo imagery for an area of Belize. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

3.2 Metadata

The primary metadata for all of the products generated for the three services is summarised in Table 7. More information on the products can be found in the relevant sections of this document.

Metadata are included with the digital services, where appropriate. For example, the landslide inventory includes an attribute table of information relating to each polygon of the inventory.

Table 7 Summary of the metadata for the products.

	Area of interest	Product	Data description	Geographical coordinate system	Spatial resolution/ scale	Thematic accuracy
Service 1	St. Lucia	Land use/land cover map	Attributed raster detailing distribution of 14 land use/land cover classes	WGS84 UTM Zone 20N	2m	84.9%
	St. Lucia	Water bodies	Shapefile (polygons) of lakes and ponds	WGS84 UTM Zone 20N	1:10,000	N/A
	St. Lucia	Rivers and streams	Shapefile (polylines) of rivers and streams	WGS84 UTM Zone 20N	1:10,000	N/A
	Grenada	Land use/land cover map	Attributed raster detailing distribution of 15 land use/land cover classes	WGS84 UTM Zone 20N	2m	84.8%
	Grenada	Water bodies	Shapefile (polygons) of lakes and ponds	WGS84 UTM Zone 20N	1:10,000	N/A
	Grenada	Rivers and streams	Shapefile (polylines) of rivers and streams	WGS84 UTM Zone 20N	1:10,000	N/A
	St. Vincent and the Grenadines	Land use/land cover map	Attributed raster detailing distribution of 15 land use/land cover classes	WGS84 UTM Zone 20N	2m	80.8%
	St. Vincent and the Grenadines	Water bodies	Shapefile (polygons) of lakes and ponds	WGS84 UTM Zone 20N	1:10,000	N/A
	St. Vincent and the Grenadines	Rivers and streams	Shapefile (polylines) of rivers and streams	WGS84 UTM Zone 20N	1:10,000	N/A
Service 2	St. Lucia	Landslide inventory	Shapefile (polygon) attributed with landslide activity status in 2010-2014	WGS84 UTM Zone 20N	1:20,000 (50% at 1:10,000)	N/A
	St. Lucia	DEM	Digital elevation model derived using combination of ASTER satellite imagery and height contours	*Horizontal datum*: WGS84 UTM Zone 20N *Vertical datum*: EGM96 geoid	30m	1.4m (RMS)
	Grenada	Landslide inventory	Shapefile (polygon) attributed with landslide activity status in 2011-2013	WGS84 UTM Zone 20N	1:20,000	N/A
	Grenada	DEM	Digital elevation model derived using combination of ASTER satellite imagery and airborne LiDAR data	*Horizontal datum*: WGS84 UTM Zone 20N *Vertical datum*: EGM96 geoid	30m	4.9m (RMS)
Service 3	Belize	DEM	Digital elevation model derived using SPOT satellite imagery	*Horizontal datum*: WGS84 UTM Zone 16N *Vertical datum*: EGM96 geoid	20m	7m (RMS)
	Belize	National DEM	Digital elevation model derived using combination of ASTER and SPOT satellite imagery	*Horizontal datum*: WGS84 UTM Zone 16N *Vertical datum*: EGM96 geoid	30m	9.8m (RMS)

4 GUIDELINES FOR USE

The land use/land cover maps produced under Service 1 provide detailed information on the spatial distribution of 14-15 different classes in St. Lucia, Grenada, and St. Vincent and the Grenadines. With a spatial resolution of 2m, these maps are equivalent to a map scale of 1:10,000. The accompanying vector layers of water bodies, rivers and streams and the basic road network were also mapped at 1:10,000-scale. Accordingly, the intended scale for use of these data is 1:10,000, and so may not be representative at finer scales. While the land use/land cover maps provide 100% coverage of the AOIs, some of the vector layers may appear somewhat fragmented due to cloud and shadow obscuring the ground in the Pleiades satellite imagery. It is also worth noting that although the land use/land cover maps have high overall accuracies, some confusion still persists between classes that are inherently similar. The predominant source of this confusion is due to overlap and/or similarity in the types of trees present in different types of forest. Enhanced discrimination between these types of forest could be achieved with the aid of satellite imagery acquired at periods reflecting different conditions (i.e. leaf-on and leaf off). Overall, the new land use/land cover maps represent a considerable improvement on the existing 30m maps.

Within the context of this project, the land use/land cover maps produced here can be used to determine whether there is a spatial correlation with landslide occurrences documented in Service 2. Such analysis is useful in establishing whether specific land use/land cover types are more prone to landslide events, and can thus be used as input, alongside the DEMs (also generated in Service 2) to derive landslide susceptibility maps for St. Lucia and Grenada. Additionally, the DEMs generated in Service 2 can also be used in conjunction with the water surface features mapped under Service 1 to model the flood risk in both St. Lucia and Grenada. Furthermore, the land use/land cover maps could be readily turned into impervious layers, which can also be incorporated in flood risk analysis. The 20m and 30m DEMs produced for Service 3 can also be used to model flood risk in Belize. However, prior to use in flood risk modelling, it is advised that the DEMs generated here are checked to ensure they are hydrologically correct.

Beyond the scope of this project, the land use/land cover information can be used for a wide spectrum of uses. For example, the maps could be used for planning purposes, asset management and in developing forestry management strategies. The data can also be used to monitor change over time. Some broader applications of the DEMs could include forestry management, the planning of new transport infrastructure (i.e. roads and railways), and natural resource exploration.

Landslide inventories for St Lucia and Grenada contain polygons that represent the maximum extent of events mapped during the period 2010-2014. Each polygon is attributed with landslide type, morphology, confidence level of the mapped outline and a statement of activity for each of the five years in the sequence 2010-2014. The inventory thus provides a clear indication of landscape response to trigger events. Interpretation of satellite images requires well-trained operators with a good understanding of mass movement processes and local conditions.

Information on trigger event response, spatial distribution, magnitude-frequency, type of movement, etc. can be very valuable for the development of derived products such as landslide susceptibility maps and landslide risk assessments. It is therefore envisaged that this product will provide context to future studies of landslide hazard (such as e.g. CDB and CDERA 2006, ECLAC 2011) and landslide risk reduction (e.g. CHARIM - van Westen, 2014; MoSSaiC - Holcombe and Anderson, 2010; Anderson and Holcombe, 2013).

The morphology of the landscape constrains the dimensions of landslides that are encountered with many events occurring on short, steep slopes. A substantial number of landslides have dimensions smaller than 1000 m^2 (the effective minimum size for an event that can be mapped on a 1:20,000 scale) and therefore the inventories were established on a scale of 1:10,000.

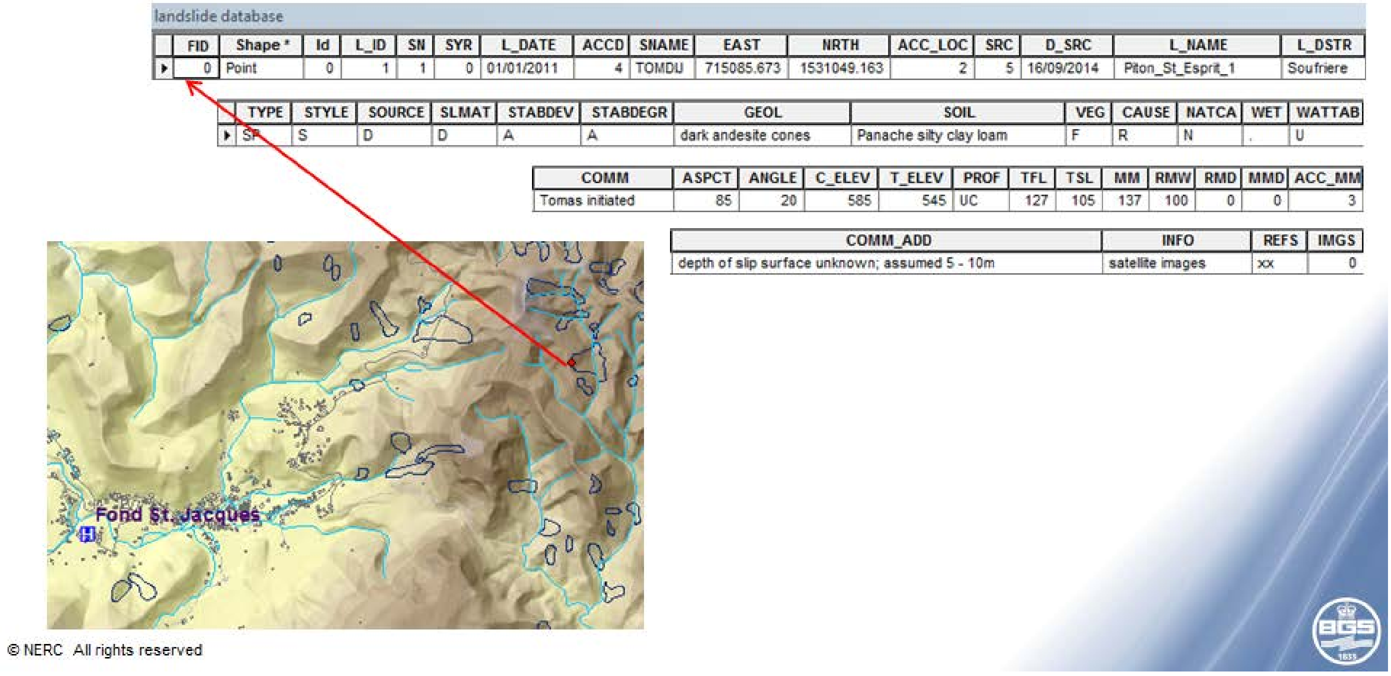
The latest satellite images provide substantial improvements in resolution that enable very detailed interpretations of the landscape to take place. There is therefore scope to map events smaller than the minimum size captured by the current inventory. It is also good practice to populate each polygon with additional information that can be stored in a relational database for further analysis (i.e. through connecting landslide polygons to landslide point data; see Gibson et al. 2013; Figure 44, and listed in http://nora.nerc.ac.uk/18890/). This will require substantial further work, but will result in an invaluable tool for future landslide hazard and risk assessments.

The current multi-temporal sequence can be extended backwards by incorporating older satellite images thus providing incremental quality enhancements of the database. Regular updates of the inventory (at least annually, but inventory establishment immediately following a trigger event should be a priority) will also provide important value. As the database updates continue, this can be of great value to evaluate the vulnerability of the landscape and estimate the potential consequences of a trigger event (see e.g. Foster et al. 2012; Gibson et al. 2013; Pennington et al. 2014).

The susceptibility of the terrain to generate landslides is not static and therefore trigger magnitudes capable of generating widespread disruption are also variable. For example, in periods shortly following a major disrupting event, much material is still in a critical condition and a relatively small trigger can result in large (re-)mobilisation of hillslope materials. If the landscape has had some time to regenerate a vegetation cover and re-establish a degree of stability fewer events will be active and visible on satellite images. Event capture using satellite images is therefore dependent upon the time difference between a trigger event and the capture of its aftermath by a satellite image. Using a multi-temporal image stack enhances the likelihood that events are being captured and a cumulative inventory will increasingly represent the distribution of unstable terrain.

The landslide inventory database can be interrogated in terms of the annual distribution of active and inactive (but still recognisable) events and this is of great potential value for subsequent analysis, for example in terms of event-response signatures, trigger threshold magnitudes and non-static hazard mapping. There is great value in maintaining and updating a multi-temporal landslide event database at least annually.

The cumulative inventory represents the outlines and associated metadata (Table 3) of landslide polygons for the period 2010-2014. Within the constraints of this project only a simple attribution of landslide type and morphology (undifferentiated) was possible, but enhancement of polygon outlines and further distinctions (for example reflecting better spatial constraints of areas of activity as a landslide becomes increasingly less active) are feasible if more time is available for interpretation of the imagery. The additional information could be maintained in a (relational) database with polygons representing the development of the landslide over time and tables identifying the attributes of the landslide at each point in time. Most features are recognised by bare earth and represent the remains of translational or flow type movements. Few polygons contain features of deep-seated rotational movement where it is theoretically possible to max scar, slide body, etc (Figure 20).



landslide database

FID	Shape *	Id	L_ID	SN	SYR	L_DATE	ACCD	SNAME	EAST	NRTH	ACC_LOC	SRC	D_SRC	L_NAME	L_DSTR
0	Point	0	1	1	0	01/01/2011	4	TOMDU	715085.673	1531049.163	2	5	16/09/2014	Piton_St_Esprit_1	Soufriere

TYPE	STYLE	SOURCE	SLMAT	STABDEV	STABDEGR	GEOL	SOIL	VEG	CAUSE	NATCA	WET	WATTAB
SP	S	D	D	A	A	dark andesite cones	Panache silty clay loam	F	R	N	.	U

COMM	ASPCT	ANGLE	C_ELEV	T_ELEV	PROF	TFL	TSL	MM	RMW	RMD	MMD	ACC_MM
Tomas initiated	85	20	585	545	UC	127	105	137	100	0	0	3

COMM_ADD	INFO	REFS	IMGS
depth of slip surface unknown; assumed 5 - 10m	satellite images	xx	0

© NERC All rights reserved

Figure 44. An example of additional point data that can be linked to each landslide polygon to build up a landslide database that can be used for further analysis (see Foster et al. 2012).

5 VALIDATION RESULTS

5.1 Quality Checking

5.1.1 Service 1: Land use/land cover mapping

Initial quality checks comprised evaluating whether the land use/land cover products satisfied the minimum requirements outlined in the SOW. Regarding spatial coverage, the minimum coverage of 80% of the AOIs was achieved by using the RapidEye imagery and existing land use/land cover maps to infill areas significantly obscured by cloud and shadowing in the Pleiades imagery. As a result, the land use/land cover maps cover 100% of the AOI.

Water features (e.g. lakes, ponds, rivers, streams) and the basic road network could only be delineated on the pan-sharpened Pleiades imagery. Therefore, the completeness of the water features and road vector layers was dependent on cloud and shadow in the Pleiades imagery, as well as the areal coverage of any existing relevant information. Although mapping of such features was hindered by cloud and shadow — resulting in a somewhat fragmented dataset in some areas — the vector layers satisfy the minimum coverage requirements 80%. The satellite imagery used for mapping in this service was required in the last 3 years.

The thematic accuracy of the land use/land cover maps was determined using the conventional remote sensing approach of deriving confusion matrices (Congalton, 1991). Confusion matrices summarise the overall, user’s and producer’s accuracies and Kappa coefficient (K). The overall accuracy is the percentage of all validation pixels correctly classified, whereas the user’s and producer’s accuracies provide information regarding the commission and omission errors associated with the individual classes, respectively. These accuracies were computed by comparing the land use/land cover class identities of a sample of pixels in the map with their ‘true’ land use/land cover class. To do this, an independent set of validation pixels was randomly sampled from regions of interests that were identified to represent each land use/land cover class based on a combination of the pan-sharpened Pleiades imagery and existing maps.

The confusion matrices for the three AOIs are shown in Tables 8-10. In all cases, the overall accuracies of the maps achieve the target accuracy of 80-90%, with accuracies for St. Lucia, Grenada, and St. Vincent and the Grenadines of 84.9%, 84.8% and 80.8%, respectively. These accuracies were further confirmed through point-location field observations made in St. Lucia and Grenada during validation of the landslide inventories produced in Service 2.

The confusion matrices provide a useful insight into the confusion between classes that affect the land use/land cover maps. From Tables 8-10, it is clear that most of the confusion occurs between different types of vegetation, particularly forests. This can be expected because many of the classes are inherently similar. In St. Lucia, for example, “Lowland forest” and “Evergreen forest” both contain Evergreen trees, thus accounting for the observed confusion. Likewise, in Grenada, similarities and overlap between results in some degree of confusion between classes such as “Semi-deciduous forest”, “Drought Deciduous open woodland”, “Deciduous, coastal

Evergreen and mixed forest or shrubland” and “Evergreen and seasonal Evergreen forest”. Enhanced discrimination between these classes would largely depend on acquiring satellite imagery to capture seasonal variations (i.e. leaf-on and leaf-off conditions). To a lesser degree, confusion between “Bare ground”, “buildings” and “Roads and other built-up surfaces” exists in all three maps. Again, this is not entirely unexpected because of colour similarities between these land use/land cover types. For example, bare rock or soil is a similar colour to buildings with reddish roofs, in the imagery, whereas grey buildings appear similar to surfaces made of concrete or asphalt roads. Similarly, some non-metalled or dusty roads also appear similar to bare rock or soil. Enhanced discrimination of these land use/land cover types would require more spectral information than that captured by the 4 multispectral bands of the Pleiades sensor. Nevertheless, observations both in the field and imagery confirm that this type of confusion has been reduced considerably in the new land use/land cover maps in comparison to the existing maps (Figure 45). However, it is worth noting that a relatively minor degree of confusion does still persist around the coastline, marking the transition from land to the sea. This is most likely the result of the colour similarities between roads, light grey buildings and a sub-pixel mixing of sand/rock and the wake caused by breaking waves on the coast.

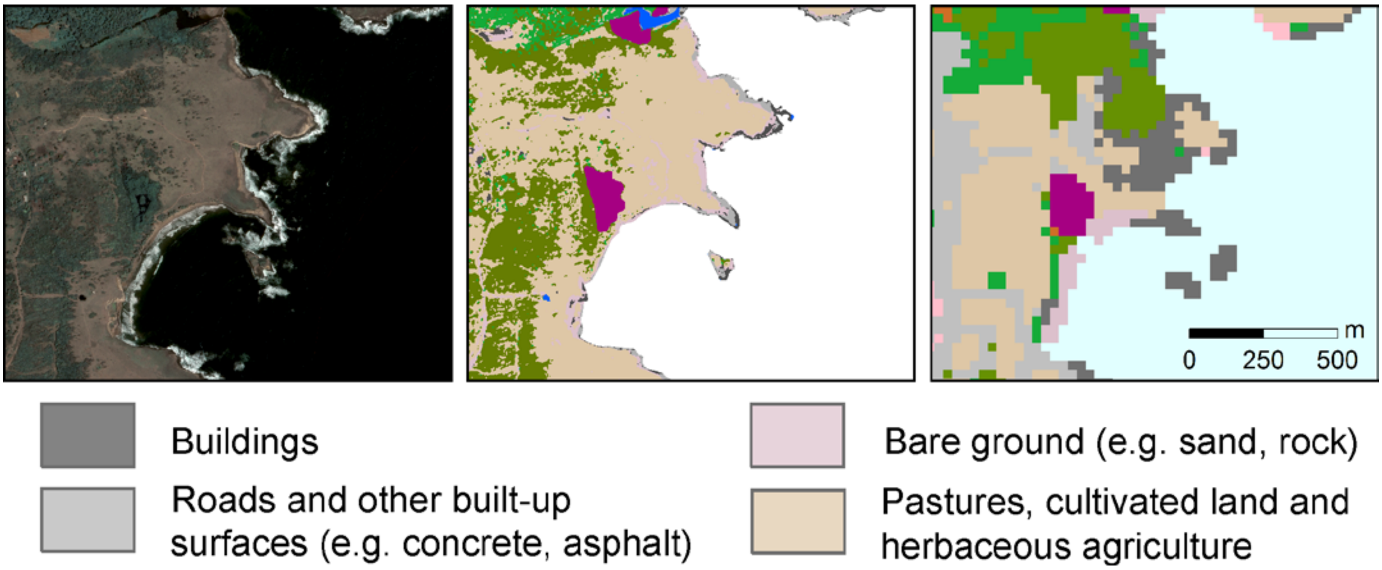


Figure 45. Confusion between buildings, roads and bare ground. Left image is Pleiades satellite data, middle is the EO-RISC land cover map, right image is the 2001 land cover map. Includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.

Table 8 Confusion matrix for the St. Lucia land use/land cover map. See Table 4 for full class names.

	Validation data															User's accuracy (%)
Mapped as	Water	Pasture	Semi-decid	Lowland	Buildings	Roads	Bare ground	Elfin	Evergreen forest	Golf course	Mangrove	Wetland	Quarry	Woody agric		
Water	1249	0	0	0	19	83	0	0	8	0	0	0	0	0		91.9
Pasture	0	3740	96	149	25	6	69	444	81	0	0	0	0	77		79.8
Semi-decid	0	120	6003	942	0	0	0	0	79	0	138	0	0	527		76.9
Lowland	0	0	112	3886	0	9	2	0	353	0	25	0	0	570		78.4
Buildings	0	110	0	1	845	74	45	0	0	0	0	0	0	0		78.6
Roads	0	0	0	0	180	1501	151	0	0	0	0	0	0	0		81.9
Bare ground	0	64	0	0	96	17	292	0	0	0	0	0	0	0		62.3
Elfin	0	0	0	0	0	0	0	1703	179	0	0	0	0	0		90.5
Evergreen	0	0	0	0	0	0	0	232	2901	0	0	0	0	0		92.6
Golf	0	0	0	0	0	0	0	0	0	1048	0	0	0	0		100.0
Mangrove	0	0	0	0	0	0	0	0	0	0	2712	0	0	0		100.0
Wetland	0	0	0	0	0	0	0	0	0	0	0	590	0	0		100.0
Quarry	0	0	0	0	0	0	0	0	0	0	0	0	619	0		100.0
Woody agric	0	0	0	0	0	0	0	0	0	0	0	0	0	1583		100.0
Producer's accuracy (%)	100.0	92.7	96.6	78.1	72.5	88.8	52.2	71.6	80.6	100.0	94.3	100.0	100.0	57.4		
Overall accuracy (%)	84.9% (K = 0.83)															

Table 9 Confusion matrix for the Grenada land use/land cover map. See Table 4 for full class names.

	Validation data																**User's accuracy (%)**
Mapped as	Nutmeg	Pasture	Drought	Decid	Semi-decid	Evergreen	Elfin	Bare ground	Buildings	Roads	Golf course	Wetland	Mangrove	Quarry	Water		
Nutmeg	2047	393	13	168	163	262	0	1	28	0	0	0	21	1	0		66.1
Pasture	52	2126	0	224	14	0	0	120	52	3	0	0	2	0	0		82.0
Drought	0	0	622	7	3	0	0	0	0	0	0	0	13	0	0		96.4
Decid	95	365	175	5013	395	4	0	6	25	1	0	0	44	1	0		82.0
Semi-decid	381	41	4	72	1733	185	0	0	1	0	0	0	4	0	0		71.6
Evergreen	471	69	13	235	212	5283	0	0	0	0	0	0	12	0	0		83.9
Elfin	101	54	0	0	0	73	3910	0	0	0	0	0	0	0	0		94.5
Bare ground	0	1	0	9	0	0	0	1073	9	35	0	0	0	0	0		95.2
Buildings	0	0	0	11	0	1	0	168	1103	56	0	0	0	0	0		83.1
Roads	0	0	0	0	0	0	0	99	133	1123	0	0	0	0	0		82.1
Golf course	0	0	0	0	0	0	0	0	0	0	296	0	0	0	0		100.0
Wetland	0	0	0	0	0	0	0	0	0	0	0	860	0	0	0		100.0
Mangrove	0	0	0	0	0	0	0	0	0	0	0	0	1699	0	0		100.0
Quarry	0	0	0	0	0	0	0	0	0	0	0	0	0	437	0		100.0
Water	0	0	0	0	0	0	0	0	7	3	0	0	9	0	1305		98.6
Producer's accuracy (%)	65.0	69.7	75.2	87.3	68.8	91.0	100.0	73.1	81.2	92.0	100.0	100.0	94.2	99.5	100.0		
Overall accuracy (%)	84.8% (K = 0.83)																

Table 10 Confusion matrix for the St. Vincent and the Grenadines land use/land cover map, See Table 4 for full class names.

	Validation data															User's accuracy (%)
Mapped as	Evergreen	Seasonal	Semi-decid	Pasture	Bare ground	Roads	Buildings	Drought	Water	Elfin	Woody agric	Montane	Blue Maho	Golf course	Mangrove		
Evergreen	2882	1088	1419	5	2	9	15	86	0	283	0	0	0	0	0		49.8
Seasonal	11	867	37	0	0	0	0	3	0	2	0	0	0	0	0		94.2
Semi-decid	928	273	2764	315	0	0	0	1239	0	25	0	0	0	0	0		49.9
Pasture	29	0	25	7023	866	26	85	482	0	1271	259	0	0	0	0		69.8
Bare ground	0	0	1	5	3450	8	15	4	0	0	0	14	0	0	0		98.7
Roads	0	0	0	2	258	1501	169	0	0	0	0	0	0	0	0		77.8
Buildings	0	0	0	12	52	64	1693	0	0	0	0	0	0	0	0		93.0
Drought	42	82	436	85	99	10	12	10954	0	540	0	0	0	0	0		89.3
Water	0	0	0	21	1	0	0	0	2131	0	0	0	0	0	0		99.0
Elfin	0	0	0	4	0	0	0	0	0	4992	0	234	9	0	0		95.3
Woody agric	0	0	226	0	0	0	0	0	0	0	4351	0	0	0	0		95.1
Montane	0	0	0	0	0	0	0	0	0	40	0	506	0	0	0		92.7
Blue Maho	0	0	0	0	0	0	0	0	0	0	0	0	484	0	0		100.0
Golf course	0	0	0	0	0	0	0	0	0	0	0	0	0	463	0		100.0
Mangrove	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3224		100.0
Producer's accuracy (%)	74.0	37.5	56.3	94.0	73.0	92.8	85.1	85.8	100.0	69.8	94.4	67.1	98.2	100.0	100.0		
Overall accuracy (%)	80.8% (K = 0.78)																

5.1.2 Service 2: Hazard mapping to support landslide risk assessment

Landslide inventories

The identification of landslide polygons was quality checked by two operators independently mapping two test areas in St Lucia. The results were compared and this led to fine-tuning of interpretation of indicators and establishment of observational guidance (landuse, bare soil signatures, use of elevation models, minimum landslide size, and use of landslide clusters). The final products were again cross-checked by two engineering geologists. Following the establishment of the multi-temporal inventory the results were evaluated against the 2010 landslide inventory. It was observed that there were some differences between the multi-temporal inventory and the 2010 inventory and these were all carefully evaluated. Generally, these differences were the result of an over-emphasis on ‘bare-earth’ mapping in the 2010 inventory. Additional differences were observed with the more conservative outlines of landslide areas in the multi-temporal inventory as long runouts were not mapped.

The completeness of landslide inventory is a function of the capability of the mode of recording of all the events over a period of time. Clearly, there are several issues therefore that influence completeness. In the case of this project these include, aspects of image resolution, of scale, and of the length of time over which observations are made. Visibility (absence of cloud cover, canopy overhangs, shadow effects, etc.) further influences the completeness of the landslide inventory.

To achieve an insight into the completeness of the landslide inventory of St Lucia, the complete multi-temporal dataset has been analysed. The extent of an individual landslide throughout the multi-temporal dataset is not constant. Deviations from this extent will occur in different years. This can occur through, for example, re-establishment of a vegetation cover leading to increasingly smaller areas remaining ‘active’. But it is also possible that slides extent, either downslope as a consequence of continuing displacement of a landslide mass, or upslope and laterally through retrogressive failure involving increasing large amounts of slope. For this exercise, landslide polygons offer an outline representing the maximum extent of an event throughout the time series. It is therefore unrealistic to construct area frequency diagrams for each year.

The analysis of the full dataset (incorporating the dataset mapped at 1:10k) resulted in a cumulative frequency-area distribution shown in Figure 46, following an approach outlined by Guzzetti 2005 and Malamud et al 2004 (see also Hurst et al. 2014). It is interesting that spill-overs (i.e where the largest number of events are found of a particular size) depend on the nature of the survey. For quick reconnaissance surveys this spill-over lies at a characteristic size of about 10^4 to 10^5 m^2 (i.e. landslide dimensions of approximately 100x100 m to 300x300 m). For more detailed geomorphological surveys greater detail can be captured and this results in a trend with a spill-over at about 10^3 m^2 (indicative dimensions of about 30x30 m) which is similar to what was found in our survey.

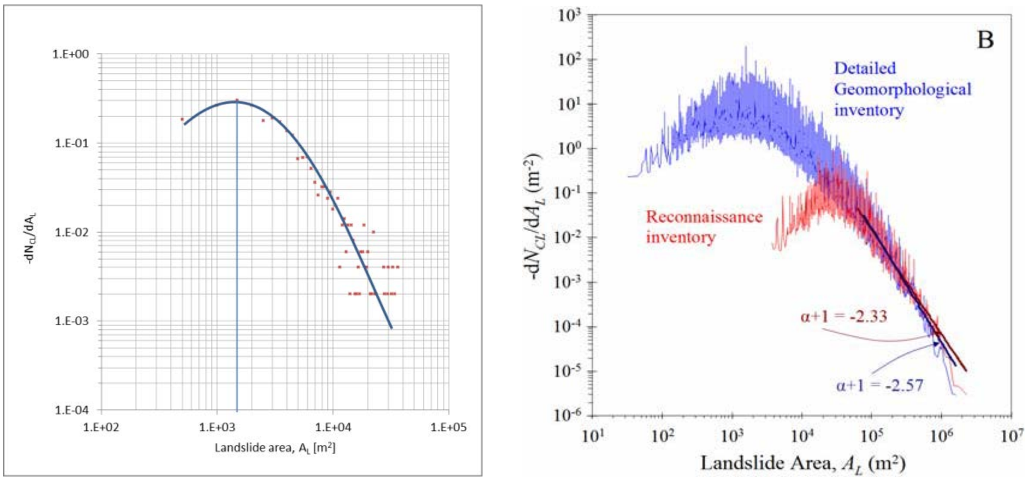


Figure 46. a) Cumulative frequency-area distribution for landslide events in St Luci for the period 2010-2014 and b) an example of the different cumulative frequency-area distributions for reconnaissance and for detailed geomorphological surveys (Guzzetti 2005).

Even though from the above it appears that the established inventory provides a degree of confidence that it forms a fair representation of events there are known omissions from the database.

Minimum dimensions in the database are approximately 200 m^2 and many smaller events are known to have occurred. Very small (<5 m) and obscured (in the shade, on steep slopes, below overhanging vegetation) landslides are difficult to capture but are known to exist in substantial numbers. These small events have a significant impact on lives and livelihoods and recording these through different means will be important to add to the database. It is possible to interrogate the recent Pleiades images (at resolution of 0.5m) at a greater level of detail and it is therefore advantageous to carry out future assessments at scales of 1:5,000 or better. The case study of Chateau Belair (discussed in section 2) highlights the restrictions in using satellite images for interpretation. Subtle changes in topography can be interpreted by skilled operators as signatures of landslides in a complex terrain. At high resolutions (1:10k and better) this can lead to very detailed maps showing geomorphology and engineering geology features relevant to slope instability.

It will remain very difficult to identify **very large, relic and inactive landslides**. This exercise has shown that very large, and mostly relic, landslides are often difficult to identify and interpret in the context of Caribbean Islands where a substantial vegetation cover masks topographic features. This will require much detailed additional geological and geomorphological investigations that falls beyond the current scope of the project.

Digital Elevation Models
The accuracy of the 30 DEMs was derived by comparing the elevation values in the DEMs to the most accurate ancillary elevation data available for that AOI using. For St. Lucia, the ancillary elevation data comprised 18 GPS control points. For Grenada, ancillary elevation data comprised a random sample of 500 LiDAR data points selected independently of those used in the vertical

calibration. Accordingly, the vertical accuracy of the DEMs was computed as the root-mean-square (RMS) error:

$$RMS = \sqrt{\frac{\sum \left(Z_{DEM} - Z_{ref}\right)^2}{n}} \, , \qquad (3)$$

where Z_{DEM} and Z_{ref} are the corresponding DEM and ancillary elevations, respectively, and n is the number of elevation values.

Subsequently, the vertical accuracy of the DEM for St. Lucia was found to be 1.4m, whereas the vertical accuracy for the Grenada DEM was computed as 4.9m. The accuracies of these DEMs therefore exceed the target accuracy of 5-10m.

5.1.3 Service 3: Digital Elevation Models of Belize

National Digital Elevation Model
The 20m DEM provides 40% coverage, and the 30m DEM provides 100% coverage of the Belize DEM; thus exceeding the minimum requirement of 80%. The vertical accuracy (RMS) of the 20m DEM is reported to be in the region of 7m by the data providers. With no other ancillary elevation data available, the 20m DEM was used compute the vertical accuracy of the 30m DEM as in Eq. 3 above. As a result, the 30m DEM was found to have a vertical accuracy (RMS) of 9.8m, which is within the target accuracy of 5-10m.

Precise Digital Elevation Model
As discussed above, the precise 1m DEM for a 100km^2 subset of Belize has not yet been produced due to a lack of suitable tri-stereo Pleiades imagery.

5.2 Initial Validation

Preliminary data have only recently been released to the ITC project therefore we do not have validation data from the users yet. A workshop / training exercise with the users is planned for end February to early March 2015 and BGS expects to gain more complete feedback from the users at that workshop / exercise.

6 NON-CONFORMANCE

The results of the quality checking confirm that the all products generated as part of this project meet the minimum requirements outlined in the SOW. However, as discussed above the precise DEM for Belize (Service 3) has yet to be produced due to the factors beyond our control. Specifically, the generation of this DEM was dependent upon the acquisition of fresh Pleiades tri-stereo imagery over Belize. Unfortunately, the time-scale of this project meant that the image acquisition had to take place during the hurricane season in the Caribbean region. Despite multiple acquisition attempts by Airbus Defence & Space, considerable cloud and haze has critically hindered the acquisition of suitable imagery. Nevertheless, attempts to acquire imagery are ongoing, and it is intended to generate the 1m DEM as and when suitable tri-stereo imagery is acquired.

7 REFERENCES

Anderson, M., & Holcombe, E. (2013). Community-Based Landslide Risk Reduction: Managing Disasters in Small Steps. The World Bank, Washington DC, 447p.

CDB & CDERA (2006). Final Project Report: Development of landslide hazard maps for St Lucia and Grenada. The Caribbean Development Bank (CDB) and the Caribbean Emergency Response Agency (CDERA). February 2006, 53p

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37, 35-46.

Dijkstra, T., Dixon, N., Crosby, C., Frost, M., Gunn, D., Fleming, P., & Wilks, J. (2014). Forecasting infrastructure resilience to climate change. Proceedings of the ICE-Transport, 167(5), 269-280.

ECLAC Report (2011). Saint Lucia: Macro socio-economic and environmental assessment of the damage and losses caused by Hurricane Tomas: a geo-environmental disaster. Towards Resilience. Economic Commission for Latin America and the Caribbean. 183pp.

Foster, C., Pennington, C. V. L., Culshaw, M. G., & Lawrie, K. (2012). The national landslide database of Great Britain: development, evolution and applications. *Environmental Earth Sciences*, 66(3), 941-953.

Gibson, A. D., Culshaw, M. G., Dashwood, C., & Pennington, C. V. L. (2013). Landslide management in the UK—the problem of managing hazards in a 'low-risk' environment. *Landslides*, *10*(5), 599-610.

Guzzetti, F. (2005). Landslide hazard and risk assessment. Concepts, methods and tools for the detection and mapping of landslides, for landslide susceptibility zonation and hazard assessment, and for landslide risk evaluation (Doctoral dissertation, PhD Thesis, Bonn).

Haralick, R. M., Shanmugan, K., & Dinstein, I. (1973). Textural features for image classification. *IEEE Transactions on Systems, Man, and Cybernetics*, 3, 610-621.

Helmer, E. H., Schill, S., Pedreror, D. H., Kennaway, T., Cushing, W. M., Coan, M. J., Wood, E. C., Ruzycki, T.,& Tieszen, L. L. (2007). Forest formation and land cover map series-Caribbean Islands. U.S. Geological Survey/Earth Resources Observation and Science (EROS), Land Cover Applications and Global Change, International Land Cover and Biodiversity, Caribbean Land Cover Analyses.

Helmer E. H., Kennaway T. A., Pedreros, D. H., Clark, M. L., Marcano-Vega, H., Tieszen, L. L., Ruzycki, T. R., Schill, S. R. & Carrington, C. M. (2008). Land cover and forest formation distribution for St. Kitts, Nevis, St. Eustatius, Grenada and Barbados from Decision Trees classification of cloud-cleared satellite imagery. *Caribbean Journal of Science*, 44, 175-189.

Herold, M., Liu, X., Clarke, K. C. (2003). Spatial metrics and image texture for mapping urban land use. *Photogrammetric Engineering & Remote Sensing*, 69, 991-1001.

Holcombe, E. & Anderson, M. (2010). Tackling landslide risk: Helping land use policy to reflect unplanned housing realities in the Eastern Caribbean. *Land Use Policy*, 27, 798 – 800.

Hurst, M. D., Ellis, M. A., Royse, K. R., Lee, K. A., & Freeborough, K. (2013). Controls on the magnitude-frequency scaling of an inventory of secular landslides. *Earth Surface Dynamics*, 1, 67-78.

Jordan, C. J. & Grebby, S. (2014) Risk Information Services for Disaster Risk management (DRM) in the Caribbean: Service Readiness Document. British Geological Survey Open Report) OR/14/064 and ESA Technical Report.

Malamud, B. D., Turcotte, D. L., Guzzetti, F., & Reichenbach, P. (2004). Landslide inventories and their statistical properties. *Earth Surface Processes and Landforms*, 29(6), 687-711.

Pennington, C., Dijkstra, T., Lark, M., Dashwood, C., Harrison, A., & Freeborough, K. (2014). Antecedent Precipitation as a Potential Proxy for Landslide Incidence in South West United Kingdom. In Landslide Science for a Safer Geoenvironment (pp. 253-259). Springer International Publishing.

Richards, J. A., & Jia, X. (2006). Remote Sensing Digital Image Analysis, Fourth edition, Springer-Verlag, Berlin, pp. 232-242.

Van Westen C J (2014). Preliminary Assessment Report: CHARIM Caribbean Handbook on Risk Information management. ITC, University of Twente.

8 APPENDIXES

8.1 Appendix 1, Service Operation

8.1.1 EO DATA PROCUREMENT

Table 11 Lists the EO data procured or tasked for the project.

Table 11 EO data procured for the project

Satellite	Sensor/product/Mode	Date	# of image	Service/event	ESA/ TPM?
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	25/02/2014	2	Service 1 - LCM (AOI-A)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	06/08/2013	2	Service 1 - LCM (AOI-B)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	11/04/2014	1	Service 1 - LCM (AOI-B)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	18/04/2014	1	Service 1 - LCM (AOI-B)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	15/08/2013	1	Service 1 - LCM (AOI-C)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	28/01/2014	2	Service 1 - LCM (AOI-C)	Yes
Pléiades	Pléiades-HR Bundle (0.5m Pan + 2m MS)	23/02/2014	1	Service 1 - LCM (AOI-C)	Yes
RapidEye	MS 5m L3A	12/02/2014	4	Service 1 - LCM (AOI-C)	Yes
RapidEye	MS 5m L3A	27/12/2014	1	Service 1 - LCM (AOI-C)	Yes
RapidEye	MS 5m L3A	15/01/2013	2	Service 1 - LCM (AOI-C)	Yes
RapidEye	MS 5m L3A	03/01/2014	1	Service 1 - LCM (AOI-C)	Yes
Landsat-8	OLI/TIRS	01/02/2014	1	Service 1 - LCM (AOI-A)	Yes
Landsat-8	OLI/TIRS	16/01/2014	1	Service 1 - LCM (AOI-B)	Yes
Landsat-8	OLI/TIRS	05/03/2014	1	Service 1 - LCM (AOI-C)	Yes
SRTM	SRTM DEM	2000	5	Service 1 - LCM (AOI-A,B,C)	**NO**
RapidEye	MS 5m L3A	18/08/2010	4	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	03/01/2011	4	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	29/09/2012	4	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	15/01/2013	3	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	14/02/2013	1	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	03/01/2014	2	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	19/02/2014	2	Service 2 - LSM (AOI-A)	Yes
RapidEye	MS 5m L3A	10/03/2011	6	Service 2 - LSM (AOI-B)	Yes
RapidEye	MS 5m L3A	12/02/2012	6	Service 2 - LSM (AOI-B)	Yes
RapidEye	MS 5m L3A	03/01/2014	1	Service 2 - LSM (AOI-B)	Yes
Pléiades	Pléiades-HR (new acquisition of stereo imagery)	06/07/1905	2	Service 2 - DEM (AOI-A)	Yes
ASTER	VNIR stereo	19/11/2009	1	Service 2 - DEM (AOI-A)	NO
ASTER	VNIR stereo	29/09/2011	1	Service 2 - DEM (AOI-A)	NO
Pléiades	Pléiades-HR (new acquisition of stereo imagery)	06/07/1905	2	Service 2 - DEM (AOI-B)	Yes
ASTER	VNIR stereo	29/01/2010	1	Service 2 - DEM (AOI-B)	NO
ASTER	VNIR stereo	31/12/2010	1	Service 2 - DEM (AOI-B)	NO
SPOT DEM	Elevation30	-	1	Service 3 - National DEM (AOI-D)	NO
Pléiades	Pléiades-HR (new acquisition of tri-stereo imagery)	06/07/1905	3	Service 3 - Precise DEM (AOI-D)	Yes

Copyright notices for the satellite imagery used in the project are as follows:

- Products derived from Pleiades satellite imagery – includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved.
- Products derived from RapidEye satellite imagery – includes material © 2014 BlackBridge, all rights reserved.
- Products derived from ASTER satellite data – ASTER GDEM is a product of METI and NASA
- Products derived from SPOT satellite data – includes material © CNES 2014, Distribution Astrium Services / SPOT Image S.A., France, all rights reserved

8.1.2 ANCILLARY DATA PROCUREMENT

The landcover / land use products build upon the 2001 land cover maps developed by The Nature Conservancy's Mesoamerica and Caribbean Project.

OpenStreetMap sources were used, where appropriate as baseline information for land use map production.

We would also like to gratefully acknowledge the support, assistance and data provided by local Physical Planning Offices.

8.2 Appendix 2, Acronyms and Abbreviations

BGS	British Geological Survey
EO	Earth Observation
EO-RISC	Earth Observation – Risk Information Services in the Caribbean
EU	European Union
FP	Final Products
FR	Final Report
GMES	Global Monitoring of Environment & Security
KO	Project kick-off
MDB	Multi-Lateral Development Bank
MMU	Minimum Mapping Unit
OD	Operational Documentation
PM	Progress meeting
SOW	Statement of Work
SRD	Service Readiness Document
SRR	Service Readiness Review
SUR	Service Utility Review
SUD	Service Utility Document
TTL	Task Team Leader
VP	Validation Protocol
WB	World Bank