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

MAINSTREAMING OPPORTUNITIES

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1 INTRODUCTION

1.1 Scope of the document

This document describes the assessment of opportunities for mainstreaming the satellite Earth Observation (EO) information products / services delivered by the British Geological Survey (BGS) via the framework of the European Space Agency (ESA) *eoworld2* initiative. The products /services were delivered to the Caribbean region and the World Bank (WB) primarily via the 'Caribbean Handbook on Risk Information Management' project (CHARIM) which is financed by the EU-funded ACP-EU Natural Disaster Risk Reduction Program, managed by the Global Facility for Disaster Reduction and Recovery, led by the WB team, and implemented with the University of Twente, ITC and the local users from various Government Ministries in the Caribbean region. The prospect of increased exploitation and additional opportunities in further WB operations, programmes and initiatives is briefly addressed, as is an evaluation of further actions to be taken to further grow uptake of EO products / services across the WB in future.

1.2 Acronyms and abbreviations

AOI	Area of Interest
ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
BGS	British Geological Survey
CAPRA	Central American Probabilistic Risk Assessment
CHARIM	Caribbean Handbook on Risk Information Management
DEM	Digital Elevation Model
EO	Earth Observation
ESA	European Space Agency
EU	European Union
FP	Final Products
FR	Final Report
GIS	Geographic Information System
GMES	Global Monitoring of Environment & Security
GPS	Global Positioning System
KO	Project kick-off
LiDAR	Light Detection And Ranging
MDB	Multi-Lateral Development Bank
MMU	Minimum Mapping Unit
MO	Mainstreaming opportunities
NEMO	National Emergency Management Organisation
NERC	Natural Environment Research Council
OD	Operational Documentation
PM	Progress meeting
SOW	Statement of Work
SRD	Service Readiness Document
SRR	Service Readiness Review
SRTM	Shuttle Radar Topography Mission
SUR	Service Utility Review
SUD	Service Utility Document
TPM	Third Party Mission
TTL	Task Team Leader
VP	Validation Protocol
WB	World Bank

2 MAINTREAMING OPPORTUNITIES CONTEXT

2.1 EO Information Products Delivered

Numerous data layers were incorporated into eleven map-based EO information products that were delivered through the implementation of three Services for disaster risk management in the Caribbean region. These Services are summarised in Table 1. Services 1 and 2 deliver key information – including landslide inventories, land use/land cover maps, elevation data and information on rivers and streams – for input to landslide and flood hazard assessments undertaken within the WB-led CHARIM project (van Westen, 2014). Service 3 delivers elevation information for input to flood hazard assessments for Belize, also undertaken within the CHARIM project. More detailed descriptions of the Services and their associated EO information products are provided in the following sub-sections along with associated Service Readiness information published in Jordan & Grebby (2014) with Operational Documentation published in Jordan et al (2015) and a Service Utility review published in Grebby et al (2015).

Table 1 Summary of the Services.

Service Number	Service Description	Service Coverage
1	Land use/land cover mapping	St. Lucia Grenada St. Vincent and the Grenadines
2	Hazard mapping to support landslide risk assessment	St. Lucia Grenada
3	Digital Elevation Model	Belize

2.1.1 Service 1: Land use/land cover mapping

The objective of Service 1 was to generate land use/land cover maps (including water features and road basic networks) for St. Lucia, Grenada, and St. Vincent and the Grenadines by exploiting recent high-resolution or very high-resolution optical satellite imagery. The mapping was undertaken using a combination of Pleiades (spatial resolution of 0.5 m panchromatic and 2 m multispectral) and RapidEye (5 m) satellite imagery, acquired from the relevant providers through the ESA Third Party Mission (TPM) scheme.

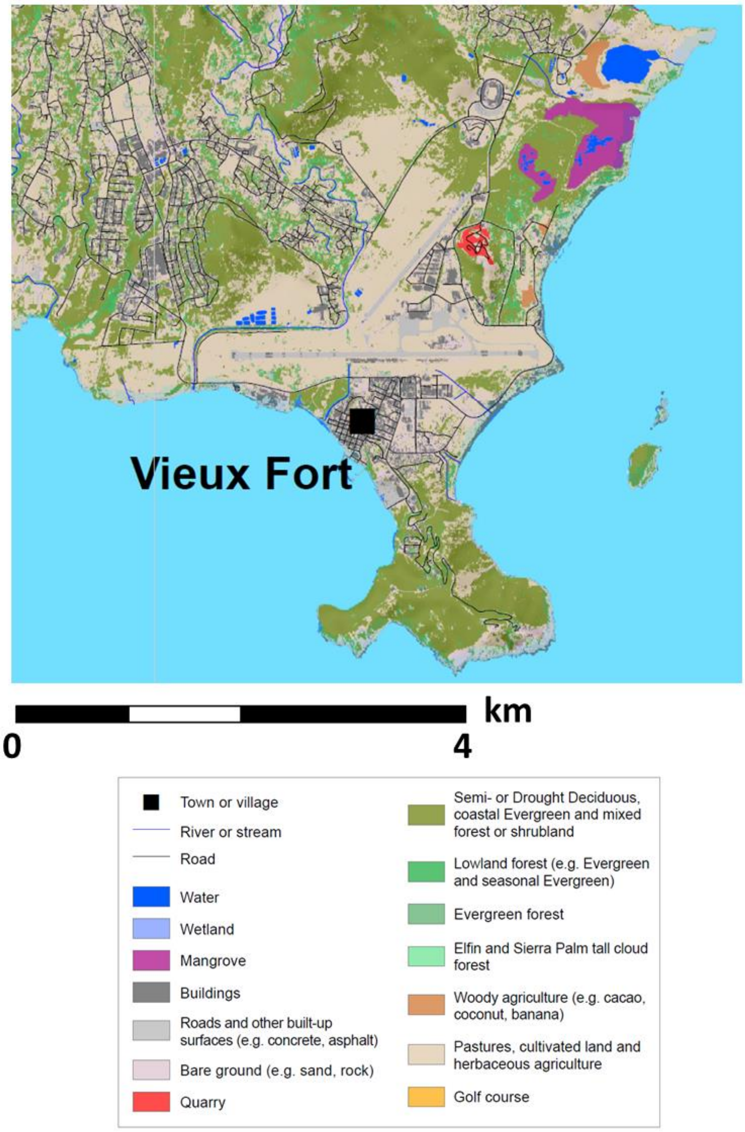
Service 1 demonstrates the ability to produce high-resolution land use/land cover maps remotely from EO data using a largely automated processing method. The primarily benefits of this approach are increased cost and time effectiveness in comparison to traditional field based mapping, and the ability to overcome terrain accessibility issues that commonly restrict field surveys in tropical environments and rugged terrain. The maps delivered by this Service provide a more contemporary snapshot of land cover/land use than the existing maps produced by The Nature Conservancy Mesoamerica and Caribbean Region project (Helmer et al., 2007; 2008), while also providing an order of magnitude increase in spatial resolution (2 m compared to 30 m). More detailed and recent land use/land cover information has been beneficial to the CHARIM project because it was used to better understand the factors controlling landslides and consequently improve the landslide susceptibility modelling. Beyond hazard risk, EO-derived land use/land cover information delivered by this Service has a wide spectrum of uses. For example, such information can be used for planning purposes, asset management and conservation. Given its semi-automated nature, the mapping approached implemented in this Service can be readily applied to monitor change over time.

Prior to delivery, the land use/land cover information products were quality checked and subject to an initial validation (Jordan *et al* 2015). Quality checking generally comprised evaluating whether the products satisfied the specified user requirements with regards to the minimum coverage of the areas of interest (AOIs) and thematic accuracy. The thematic accuracy of the land use/land cover maps was determined using the conventional remote sensing approach of deriving confusion matrices (Congalton, 1991). Specifically, the land use/land cover class identities of a sample of validation pixels in the map were compare with their ‘true’ land use/land cover class to compute the overall accuracy (i.e., the percentage of validation pixels correctly classified). The thematic accuracies were then further corroborated with the aid of observations made in the field during a 10-day visit to the region in October 2014. This involved visiting numerous randomly selected locations on the ground to cross-check the actual land use/land cover type with that on the map.

Ahead of delivery, the land use/land cover data was released to the CHARIM project partners at ITC for initial validation. This initial validation involved evaluating the suitability of the define land use/land cover classes for hazard assessment and checking for significant misclassifications or artefacts in the maps.

The EO information products delivered through Service 1 are described in Figures 1-3.

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td rowspan="2">Service 1: Land use/land cover mapping

Land use/land cover map for St. Lucia</td><td>Map showing the spatial extent of the main land use/land cover types, as well as water bodies and the basic road network</td></tr>
<tr><th>Example</th></tr>
<tr><th>Metadata</th><td rowspan="6">
</td></tr>
<tr><td>• Spatial resolution:
2 m land use/land cover
1:10,000 roads & rivers
• Coordinate system: WGS84 UTM Zone 20N
• Thematic accuracy: 84.9%
• Time period: 2013-2014</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
• Pleiades panchromatic (0.5 m)
• Pleiades multispectral (2 m)
• RapidEye multispectral (5 m)

Ancillary data
• SRTM DEM (90 m)
• ASTER GDEM (30m)
• The Nature Conservancy's Mesoamerica and Caribbean Region Project land cover/land use maps (30 m)
• In-situ field observations</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>• Automated image classification
• Visual image interpretation
• Rule-based post-processing refinement
• Map production
• Quality checking and validation</td></tr>
</table>

Figure 1 Land use/land cover map 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. ASTER GDEM is a product of METI and NASA).

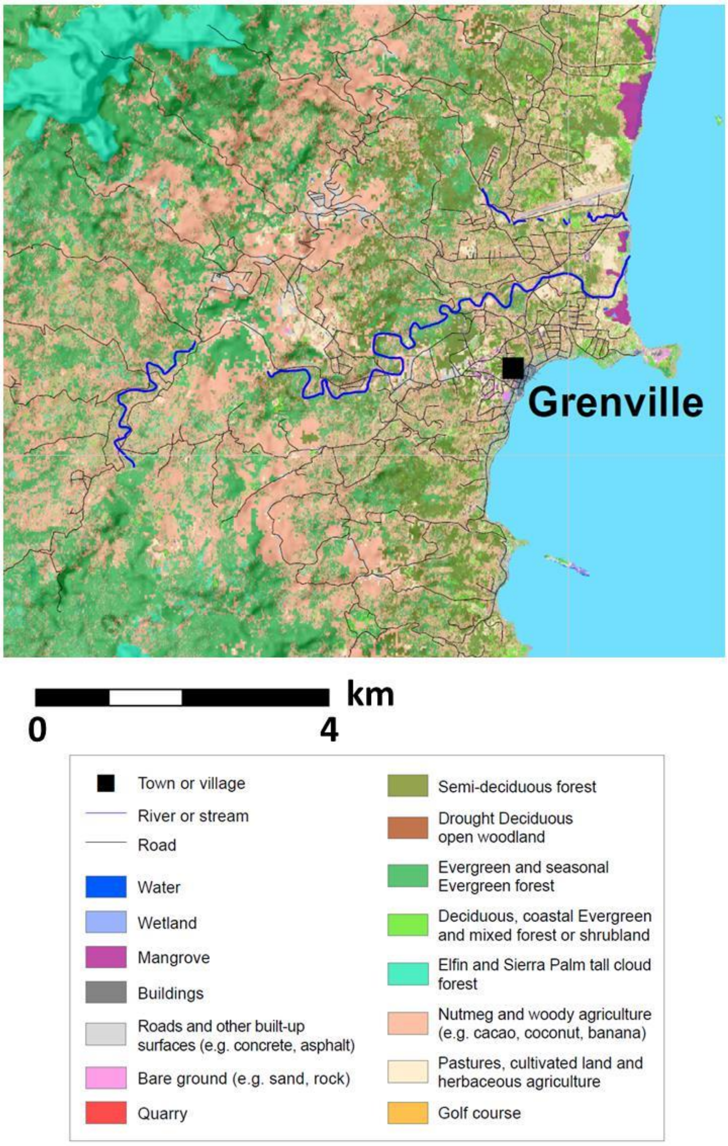
Service and Product	Description
Service 1: Land use/land cover mapping Land use/land cover map for Grenada	Map showing the spatial extent of the main land use/land cover types, as well as water bodies and the basic road network
	Example
Metadata	
• Spatial resolution: 2 m land use/land cover 1:10,000 roads & rivers • Coordinate system: WGS84 UTM Zone 20N • Thematic accuracy: 84.8% • Time period: 2011-2014	
Input data	
Satellite imagery • Pleiades panchromatic (0.5 m) • Pleiades multispectral (2 m) • RapidEye multispectral (5 m) **Ancillary data** • SRTM DEM (90 m) • ASTER GDEM (30m) • The Nature Conservancy's Mesoamerica and Caribbean Region Project land cover/land use maps (30 m) • In-situ field observations	
Methodology	
• Automated image classification • Visual image interpretation • Rule-based post-processing refinement • Map production • Quality checking and validation	

Figure 2 Land use/land cover map for Grenada (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved. ASTER GDEM is a product of METI and NASA).

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td rowspan="2">Service 1: Land use/land cover mapping

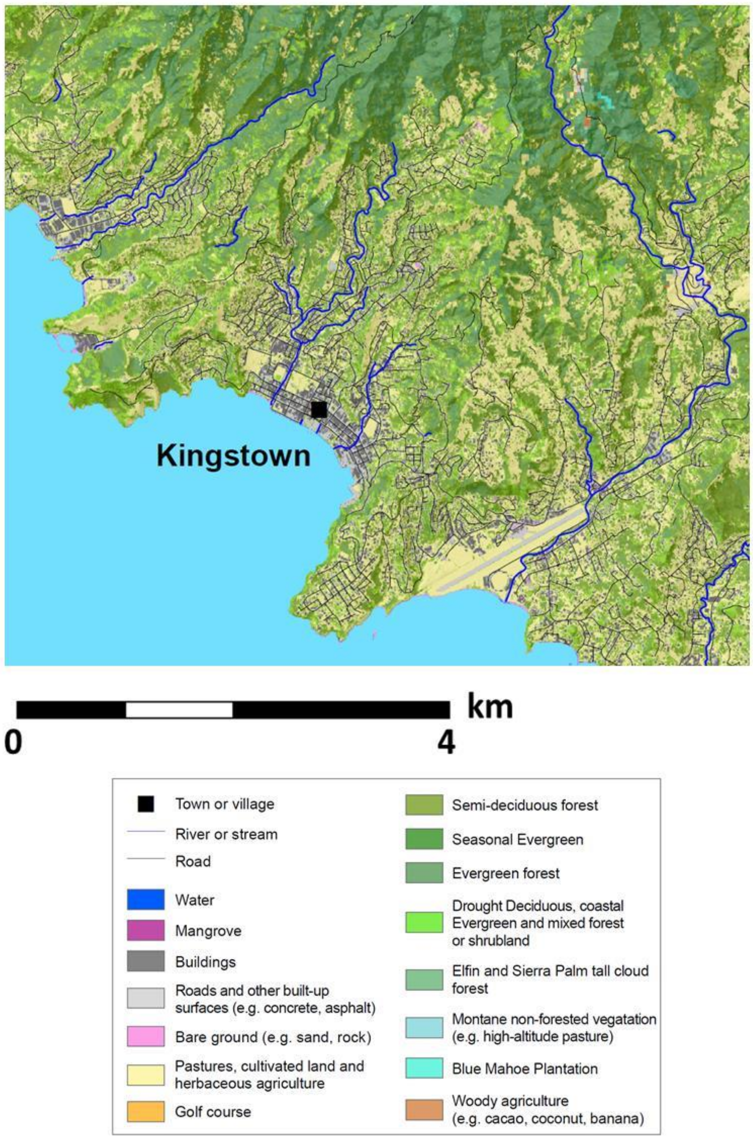
Land use/land cover map for St. Vincent and the Grenadines</td><td>Map showing the spatial extent of the main land use/land cover types, as well as water bodies and the basic road network</td></tr>
<tr><th>Example</th></tr>
<tr><th>Metadata</th><td rowspan="6">
</td></tr>
<tr><td>Spatial resolution:
2 m land use/land cover
1:10,000 roads & rivers
Coordinate system: WGS84 UTM Zone 20N
Thematic accuracy: 80.8%
Time period: 2012-2014</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
Pleiades panchromatic (0.5 m)
Pleiades multispectral (2 m)
Ancillary data
SRTM DEM (90 m)
ASTER GDEM (30m)
The Nature Conservancy’s Mesoamerica and Caribbean Region Project land cover/land use maps (30 m)
In-situ field observations</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>Automated image classification
Visual image interpretation
Rule-based post-processing refinement
Map production
Quality checking and validation</td></tr>
</table>

Figure 3 Land use/land cover map for St. Vincent and the Grenadines (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved. ASTER GDEM is a product of METI and NASA).

2.1.2 Service 2: Hazard mapping to support landslide risk assessment

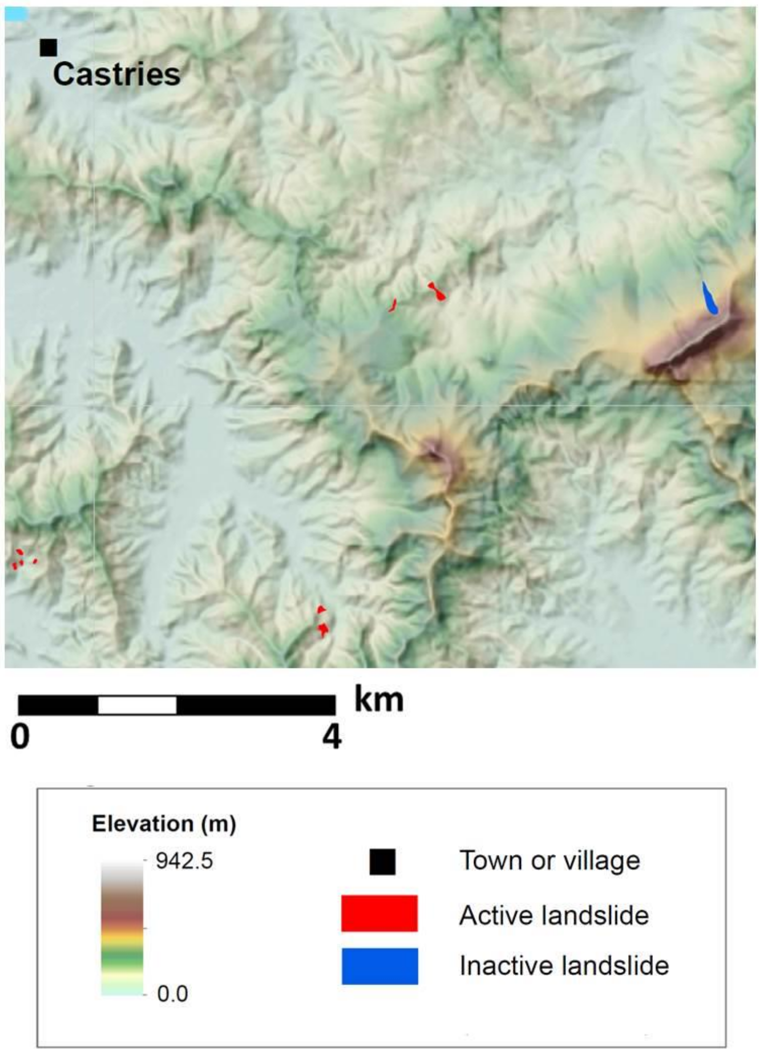
The objective of Service 2 was to generate ground-truthed landslide inventories and digital elevation models (DEMs) for St. Lucia and Grenada. The landslide mapping was undertaken using a combination of multi-temporal, pan-sharpened Pleiades (spatial resolution of 0.5 m) and RapidEye (5 m) satellite imagery, acquired from the relevant providers through the ESA TPM scheme. The DEMs were generated using ASTER stereo satellite imagery (30 m) in conjunction with ancillary elevation data (e.g., airborne LiDAR, contour heights, SRTM DEM).

Service 2 demonstrates the ability to utilise very-high resolution, multi-temporal optical satellite imagery for landslide inventory mapping. Implementation of this Service has led to the delivery of annual landslide inventories for St. Lucia for the period 2010-2014 and a single inventory for Grenada (also covering the same period). Mapping landslides remotely from satellite imagery is again far more time and cost effective than traditional field-based mapping, and it provides a means of readily accessing the inhospitable terrain in which landslides typically occur. The very-high resolution Pleiades satellite imagery offers advantages over satellite imagery with a more moderate spatial resolution (e.g., Landsat) because it enables small landslides (<100 m^2) to be mapped in detail. Furthermore, the very-high resolution imagery provides sufficient detail to allow the generation of geomorphological maps that can be attributed with information such as the likely nature of deformation and a timeline of event progression. This Service also provides a practical means of monitoring landslide activity on an annual basis, which helps gain a better understanding of the landscape response to trigger events (e.g., hurricanes). Information on trigger event response, spatial distribution, magnitude-frequency, type of movement that can be obtained through this Service is very valuable for the development of landslide susceptibility maps and landslide risk assessments. Accordingly, the landslide inventories delivered in Service 2 comprised crucial information that was input to the landslide susceptibility modelling under the CHARIM project. Service 2 also delivered accurate national-scale 30 m DEMs generated from optical satellite imagery. This Service therefore demonstrates a cheaper, alternative approach to generating DEMs at this scale over large areas in comparison to ground-based GPS or airborne LiDAR surveys. The DEMs and derived information (e.g., slope, relief) are essential to both the landslide and flood risk assessments undertaken within the CHARIM project. The generation of 1 m DEMs was planned, but issues acquiring cloud-free Pleiades stereo satellite imagery during the Atlantic hurricane season meant that this could not be completed within the timeframe.

The landslide inventories were ground-truthed prior to delivery, by visiting the locations of potential landslides identified on the satellite imagery during a 10-day field trip to the region. Subsequently, the inventories were updated to remove any false positives that were confirmed during ground-truthing. The DEMs were validated by computing their vertical accuracies using GPS control points (St. Lucia) and high-resolution airborne LiDAR data (Grenada).

The EO information products delivered through Service 2 are described in Figures 4-9.

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td>Service 2: Hazard mapping to support landslide risk assessment

Landslide inventory (2010) and digital elevation model for St. Lucia</td><td>Landslide inventory for 2010 and a national-scale 30 m digital elevation model (DEM). A total of 29 landslides were identified using the satellite imagery.</td></tr>
<tr><th>Metadata</th><th>Example</th></tr>
<tr><td>• Spatial resolution:
30 m digital elevation model
1:20,000 landslide inventory
(50% at 1:10,000)
• Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
• DEM accuracy (RMS): 1.4 m
• Time period: 2010</td><td rowspan="5">
</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
• Pleiades panchromatic (0.5 m)
• Pleiades multispectral (2 m)
• RapidEye multispectral (5 m)
• ASTER stereo imagery (15 m)

Ancillary data
• ASTER GDEM (30 m)
• Elevation contours
• In-situ field observations
• GPS data</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>• Automated image classification of bare ground areas
• Visual image interpretation of landslides
• Photogrammetric processing of stereo imagery and calibration
• Map production
• Ground-truthing and validation</td></tr>
</table>

Figure 4 The 2010 landslide inventory and national-scale DEM 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. ASTER GDEM is a product of METI and NASA)..

Service and Product	Description
Service 2: Hazard mapping to support landslide risk assessment Landslide inventory (2011) and digital elevation model for St. Lucia	Landslide inventory for 2011 and a national-scale 30 m digital elevation model (DEM). A total of 1028 landslides were identified using the satellite imagery.

Metadata

- Spatial resolution:
  30 m digital elevation model
  1:20,000 landslide inventory
  (50% at 1:10,000)
- Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
- DEM accuracy (RMS): 1.4 m
- Time period: 2011

Input data

Satellite imagery
- Pleiades panchromatic (0.5 m)
- Pleiades multispectral (2 m)
- RapidEye multispectral (5 m)
- ASTER stereo imagery (15 m)

Ancillary data
- ASTER GDEM (30 m)
- Elevation contours
- In-situ field observations
- GPS data

Methodology

- Automated image classification of bare ground areas
- Visual image interpretation of landslides
- Photogrammetric processing of stereo imagery and calibration
- Map production
- Ground-truthing and validation

Example

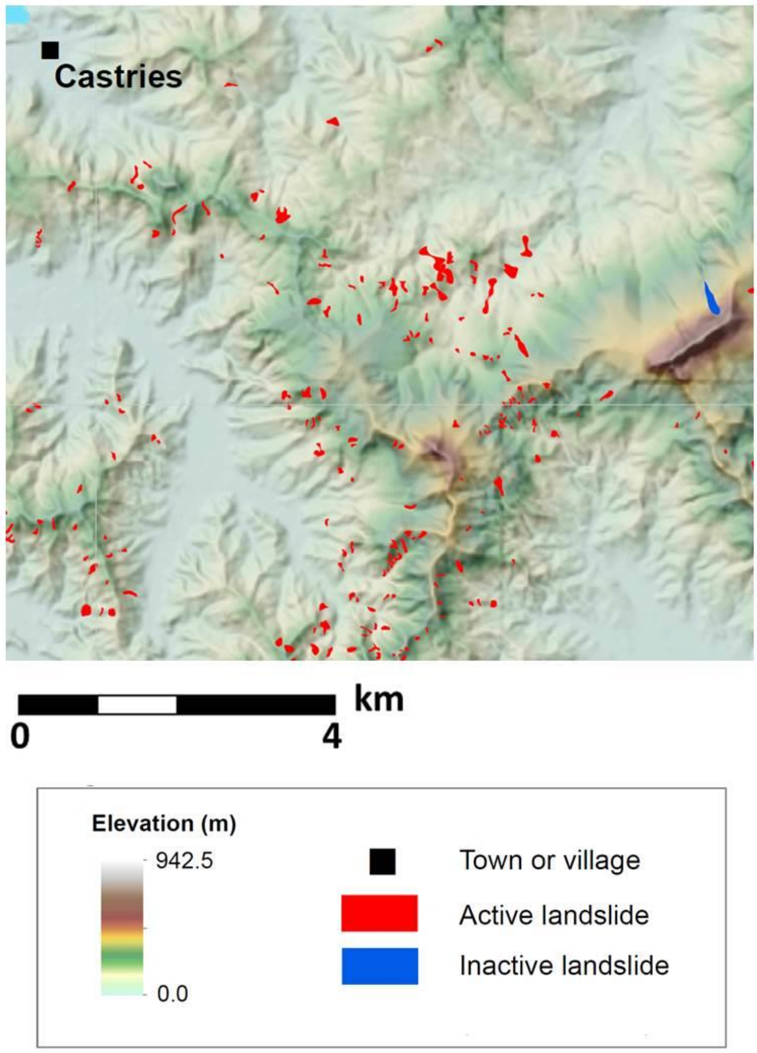
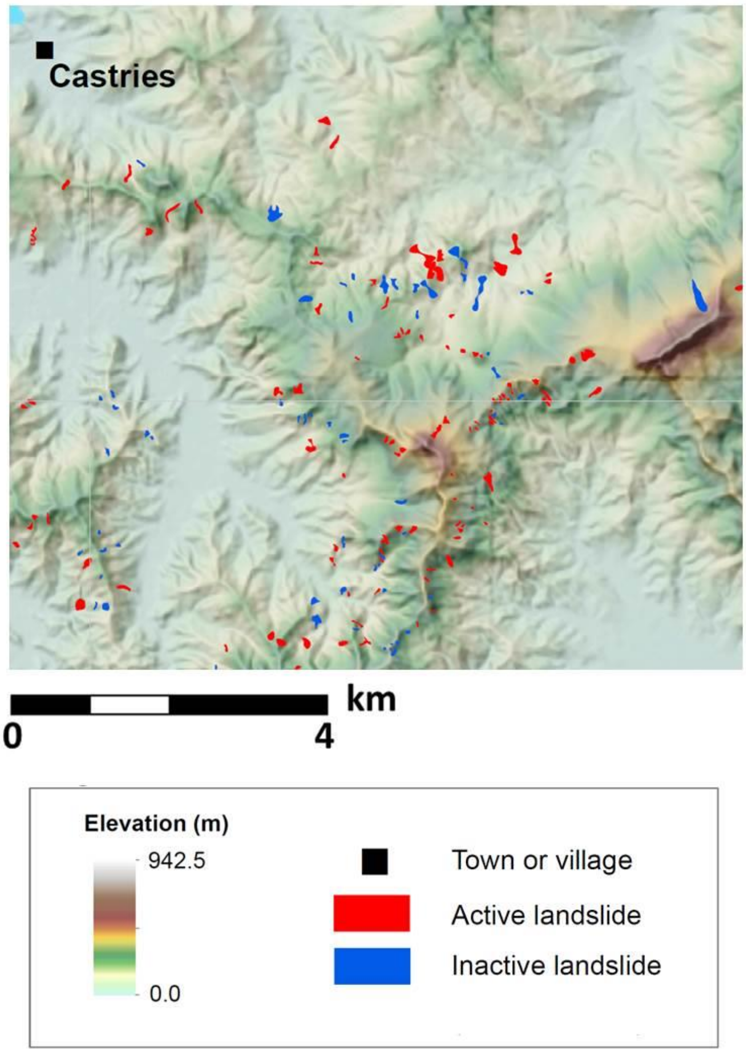


Figure 5 The 2011 landslide inventory and national-scale DEM for St. Lucia (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved. ASTER GDEM is a product of METI and NASA).

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td>Service 2: Hazard mapping to support landslide risk assessment

Landslide inventory (2012) and digital elevation model for St. Lucia</td><td>Landslide inventory for 2012 and a national-scale 30 m digital elevation model (DEM). A total of 793 landslides were identified using the satellite imagery.</td></tr>
<tr><th>Metadata</th><th>Example</th></tr>
<tr><td>• Spatial resolution:
30 m digital elevation model
1:20,000 landslide inventory
(50% at 1:10,000)
• Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
• DEM accuracy (RMS): 1.4 m
• Time period: 2012</td><td rowspan="6">
</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
• Pleiades panchromatic (0.5 m)
• Pleiades multispectral (2 m)
• RapidEye multispectral (5 m)
• ASTER stereo imagery (15 m)

Ancillary data
• ASTER GDEM (30 m)
• Elevation contours
• In-situ field observations
• GPS data</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>• Automated image classification of bare ground areas
• Visual image interpretation of landslides
• Photogrammetric processing of stereo imagery and calibration
• Map production
• Ground-truthing and validation</td></tr>
</table>

Figure 6 The 2012 landslide inventory and national-scale DEM 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. ASTER GDEM is a product of METI and NASA).

Service and Product

Service 2: Hazard mapping to support landslide risk assessment

Landslide inventory (2013) and digital elevation model for St. Lucia

Description

Landslide inventory for 2013 and a national-scale 30 m digital elevation model (DEM). A total of 371 landslides were identified using the satellite imagery.

Metadata

- Spatial resolution:
  30 m digital elevation model
  1:20,000 landslide inventory
  (50% at 1:10,000)
- Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
- DEM accuracy (RMS): 1.4 m
- Time period: 2013

Input data

Satellite imagery
- Pleiades panchromatic (0.5 m)
- Pleiades multispectral (2 m)
- RapidEye multispectral (5 m)
- ASTER stereo imagery (15 m)

Ancillary data
- ASTER GDEM (30 m)
- Elevation contours
- In-situ field observations
- GPS data

Methodology

- Automated image classification of bare ground areas
- Visual image interpretation of landslides
- Photogrammetric processing of stereo imagery and calibration
- Map production
- Ground-truthing and validation

Example

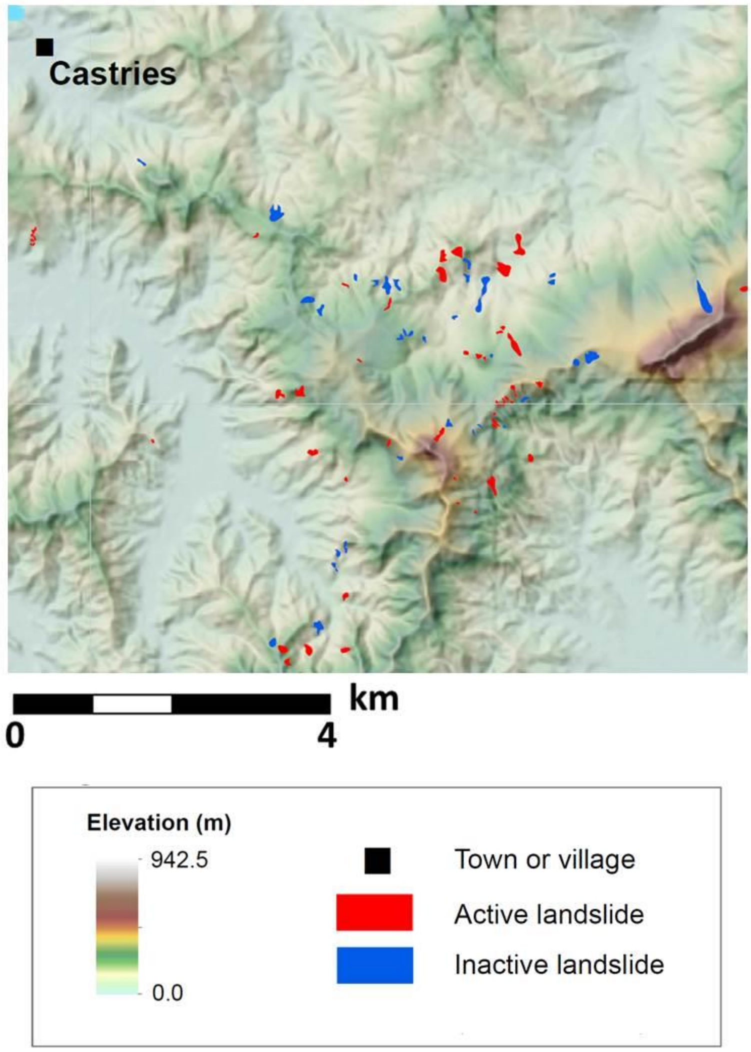


Figure 7 The 2013 landslide inventory and national-scale DEM for St. Lucia (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved. ASTER GDEM is a product of METI and NASA).

Service and Product	Description
Service 2: Hazard mapping to support landslide risk assessment Landslide inventory (2014) and digital elevation model for St. Lucia	Landslide inventory for 2014 and a national-scale 30 m digital elevation model (DEM). A total of 770 landslides were identified using the satellite imagery.

Metadata

- Spatial resolution:
  - 30 m digital elevation model
  - 1:20,000 landslide inventory (50% at 1:10,000)
- Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
- DEM accuracy (RMS): 1.4 m
- Time period: 2014

Input data

Satellite imagery
- Pleiades panchromatic (0.5 m)
- Pleiades multispectral (2 m)
- RapidEye multispectral (5 m)
- ASTER stereo imagery (15 m)

Ancillary data
- ASTER GDEM (30 m)
- Elevation contours
- In-situ field observations
- GPS data

Methodology

- Automated image classification of bare ground areas
- Visual image interpretation of landslides
- Photogrammetric processing of stereo imagery and calibration
- Map production
- Ground-truthing and validation

Example

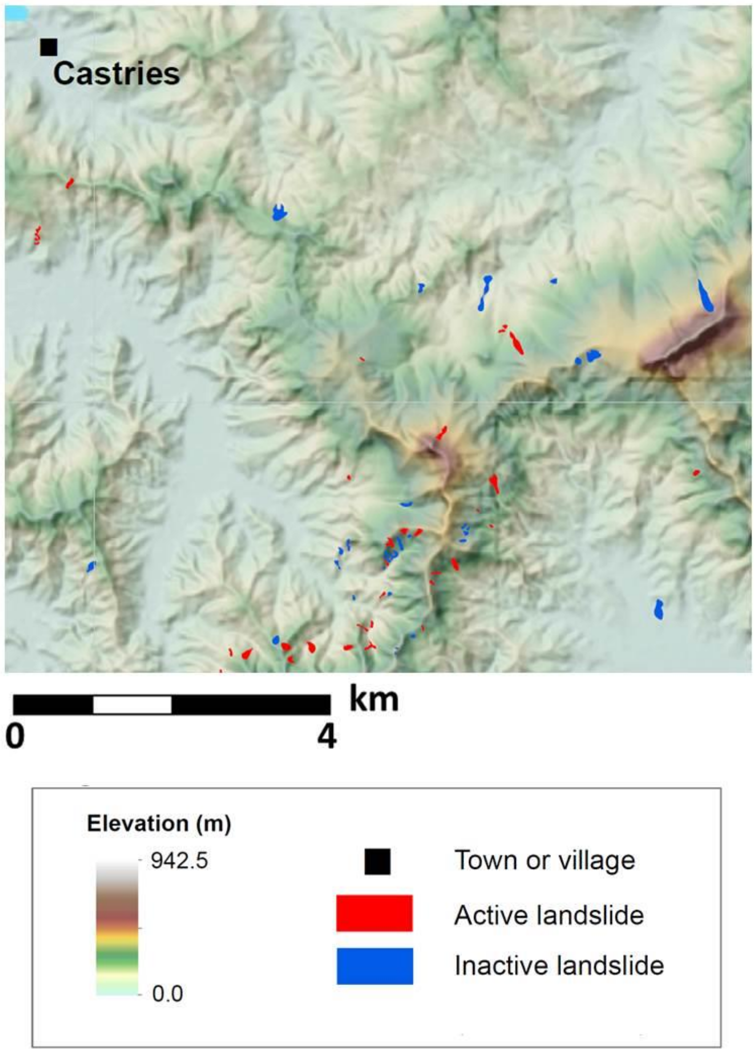


Figure 8. The 2014 landslide inventory and national-scale DEM for St. Lucia (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved. ASTER GDEM is a product of METI and NASA).

Service and Product	Description
Service 2: Hazard mapping to support landslide risk assessment Landslide inventory and digital elevation model for Grenada	Landslide inventory covering the period 2011-2014 and a national-scale 30 m digital elevation model (DEM). Only 1 inactive landslide was identified using the satellite imagery for this period.

Metadata

- Spatial resolution:
  30 m digital elevation model
  1:20,000 landslide inventory
- Coordinate system: WGS84 UTM Zone 20N (EGM96 geoid)
- DEM accuracy (RMS): 4.9 m
- Time period: 2011-2014

Input data

Satellite imagery
- Pleiades panchromatic (0.5 m)
- Pleiades multispectral (2 m)
- RapidEye multispectral (5 m)
- ASTER stereo imagery (15 m)

Ancillary data
- ASTER GDEM (30 m)
- SRTM DEM (90 m)
- Airborne LiDAR DEM (5 m)
- In-situ field observations

Methodology

- Automated image classification of bare ground areas
- Visual image interpretation of landslides
- Photogrammetric processing of stereo imagery and calibration
- Map production
- Ground-truthing and validation

Example

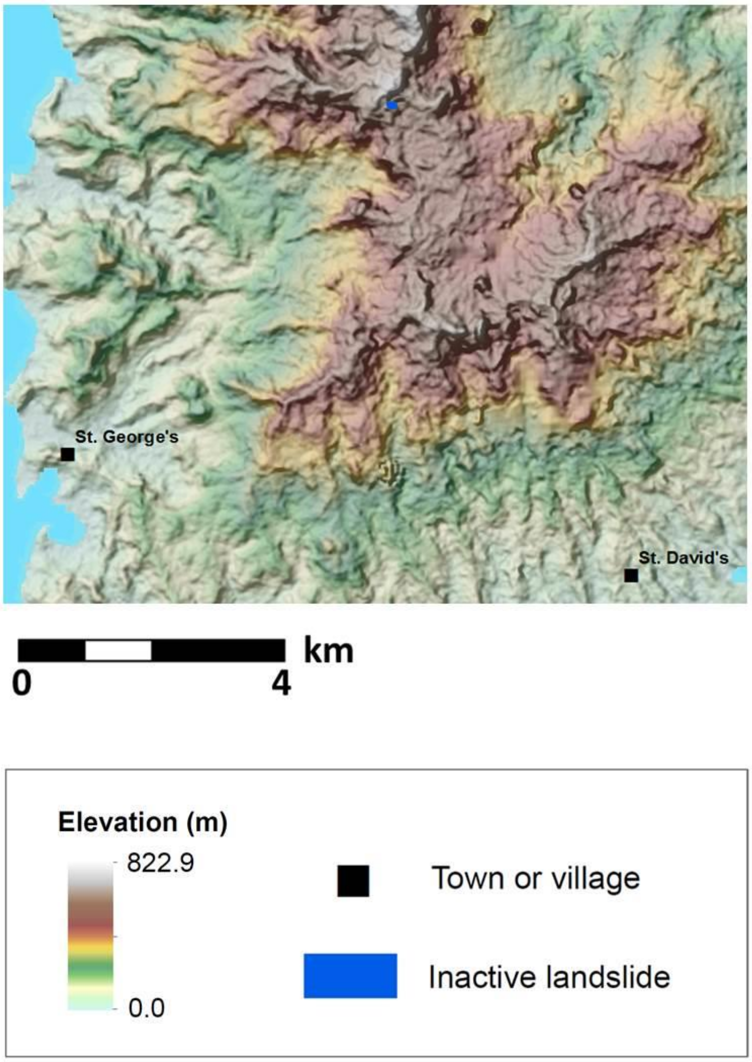


Figure 9 Landslide inventory (2011-2014) and national-scale DEM for Grenada (includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved and material © 2014 BlackBridge, all rights reserved. ASTER GDEM is a product of METI and NASA).

2.1.3 Service 3: Digital Elevation Model

The objective of Service 3 was to deliver a national-scale DEM for Belize and as a demonstration, a high-precision DEM (for an area 100 km^2) to support risk/hazard mapping. The national-scale 30 m DEM was generated using ASTER stereo imagery, while a higher resolution 20 m DEM covering 40% of the country was derived using SPOT-5 stereo satellite imagery. Pleaides tri-stereo (also refer to as triplet) satellite imagery, obtained through the ESA TPM scheme, was used to generate the high-precision 1 m DEM demonstration product.

This Service demonstrates the ability to generate both national and local-scale DEMs from optical satellite imagery with different spatial resolutions. In the absence of any other suitable elevation data, the 20 m and 30 m DEMs can be used as the basis for modelling flood risk at national-scale across Belize as part of the CHARIM project. Moreover, the precise DEM demonstration product derived from the very-high resolution Pleiades tri-stereo imagery can be used to more accurately model flood risk on a local-scale. With the ability to generate contemporary elevation data with a similar quality to airborne LiDAR, this approach represents a viable alternative to DEM production when airborne surveys are too costly or logistically challenging. Beyond flood risk modelling, high resolution DEMs such as this are important for infrastructure planning and resource management.

The DEMs delivered by this Service were quality checked for data gaps and artefacts, and rectified where necessary. In the absence of ancillary GPS or other control data, the national-scale 30 m DEM was validated using the higher resolution 20 m SPOT-derived DEM acquired from Airbus Defence & Space. The DEM was validated by computing the vertical accuracy using a subset of 32,000 randomly chosen elevation values from the 20 m DEM.

Due to issues acquiring cloud-free Pleiades tri-stereo satellite imagery during the Atlantic hurricane season, it was not possible to generate the 100 km^2 high precision DEM until relatively recently. For this reason – in addition to the lack of any suitable GPS or other control data – it has only been possible to undertake a preliminary validation of the high precision DEM to date. As for the national-scale DEM, this involved computing the vertical accuracy using 32,000 randomly chosen elevation values from the 20 m DEM.

The EO information products delivered through Service 2 are described in Figures 10-12.

Service and Product	Description
Service 3: Digital elevation model National-scale digital elevation model for Belize	A 30 m digital elevation model generated for Belize using ASTER optical satellite imagery.

Metadata

- Spatial resolution: 30 m
- Coordinate system: WGS84 UTM Zone 16N (EGM96 geoid)
- DEM accuracy (RMS): 9.8 m
- Time period: 2000-2011

Input data

Satellite imagery
- ASTER stereo imagery (15 m)

Ancillary data
- ASTER GDEM (30 m)
- SPOT DEM (20 m)

Methodology

- Photogrammetric processing of stereo imagery
- Vertical calibration with SPOT DEM
- Map production
- Quality checking and validation

Example

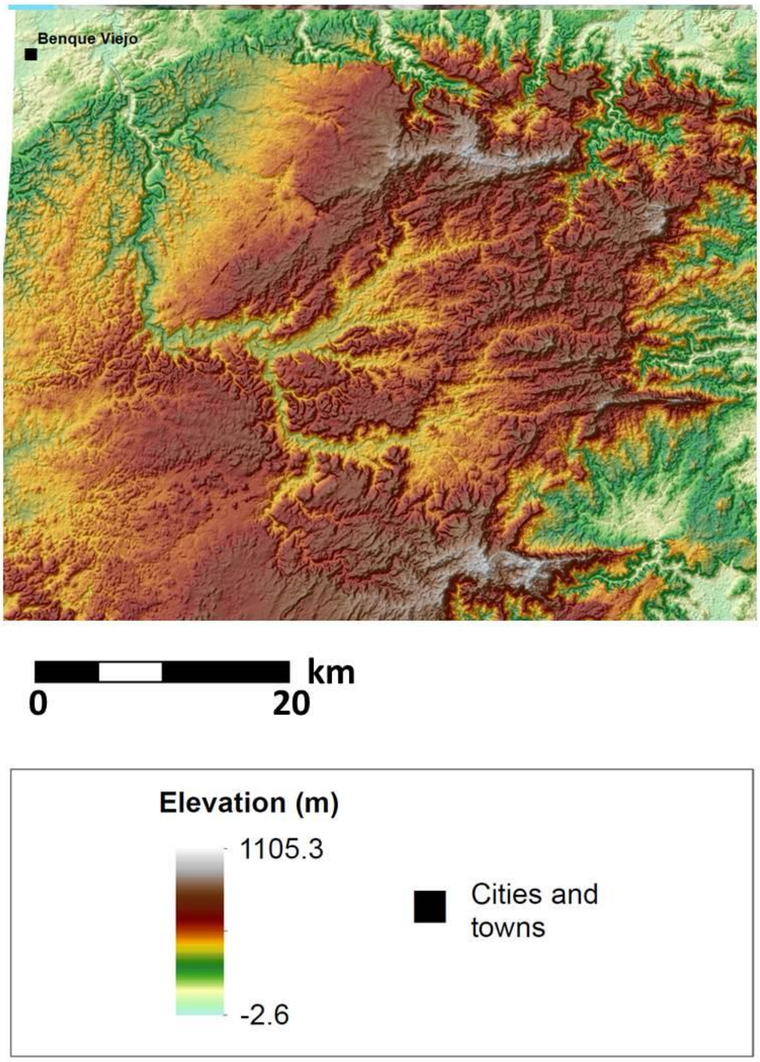


Figure 10 National-scale 30 m DEM for Belize (includes material © CNES 2014, Distribution Astrium Services / Spot Image S.A., France, all rights reserved. ASTER GDEM is a product of METI and NASA).

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td>Service 3: Digital elevation model

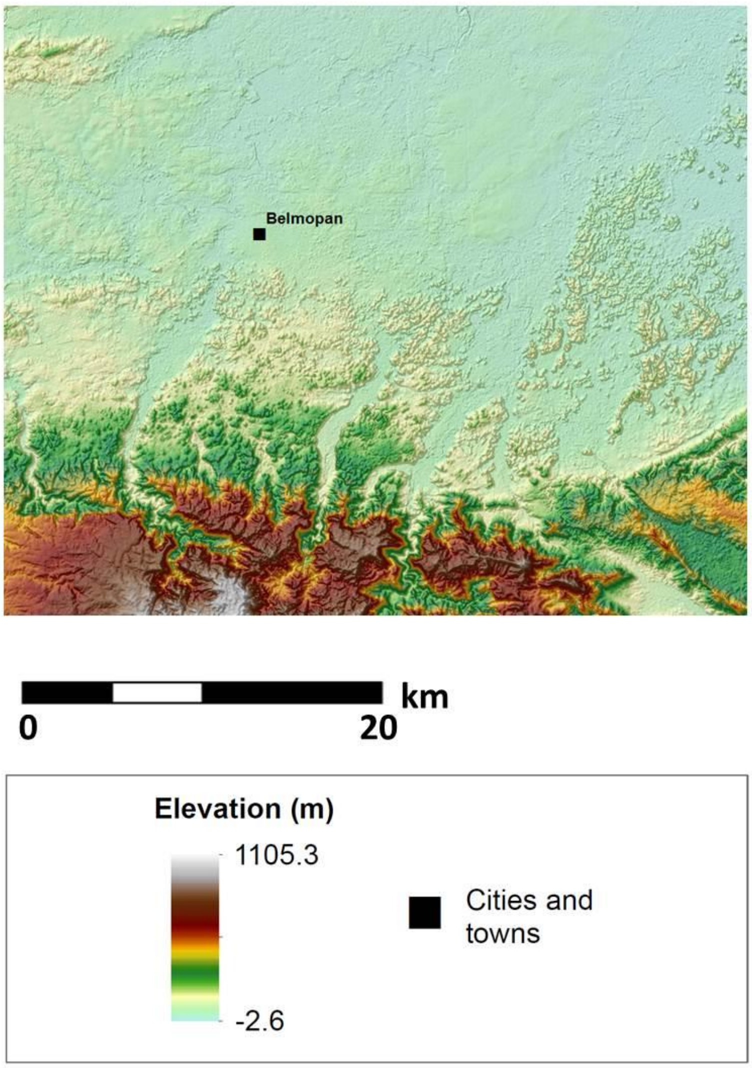
Digital elevation model for Belize</td><td>A 20 m digital elevation model (DEM) generated for Belize using SPOT-5 optical satellite imagery. This DEM provides approximately 40% coverage of Belize.</td></tr>
<tr><th>Metadata</th><th>Example</th></tr>
<tr><td>• Spatial resolution: 20 m
• Coordinate system: WGS84 UTM Zone 16N (EGM96 geoid)
• DEM accuracy (RMS): 7 m
• Time period: 2003-2006</td><td rowspan="5">
</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
• SPOT-5 stereo imagery (5 m)</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>• Photogrammetric processing of stereo imagery
• Map production
• Quality checking and validation</td></tr>
</table>

Figure 11 The 20 m SPOT-derived DEM for a subset of Belize (includes material © CNES 2014, Distribution Astrium Services / Spot Image S.A., France, all rights reserved).

<table>
<tr><th>Service and Product</th><th>Description</th></tr>
<tr><td>Service 3: Digital elevation model

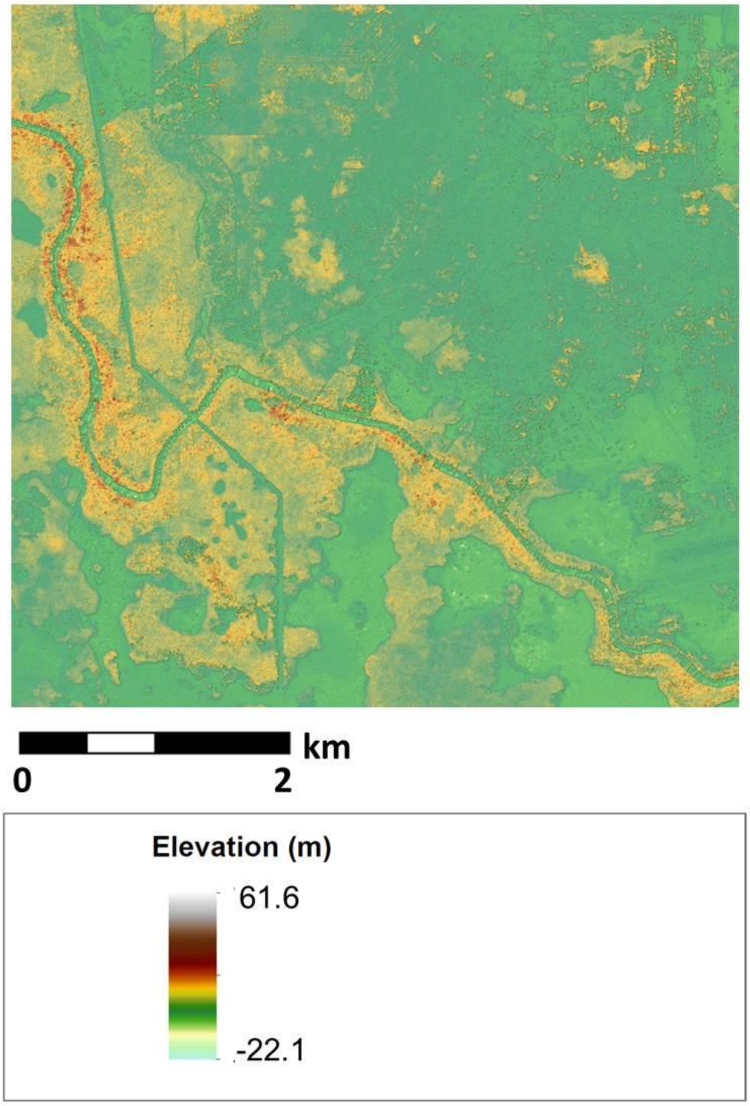
Precise digital elevation model for Belize</td><td>A precise 1 m digital elevation model (DEM) generated using Pleiades tri-stereo optical satellite imagery. This DEM covers an area of 100 km^2 of Belize.</td></tr>
<tr><th>Metadata</th><th rowspan="1">Example</th></tr>
<tr><td>• Spatial resolution: 1 m
• Coordinate system: WGS84 UTM Zone 16N (EGM96 geoid)
• DEM accuracy (RMS): 4.1 m (preliminary estimate; true accuracy expected to be significantly better)
• Time period: 2014</td><td rowspan="5">
</td></tr>
<tr><th>Input data</th></tr>
<tr><td>Satellite imagery
• Pleiades tri-stereo satellite imagery (0.5 m)</td></tr>
<tr><th>Methodology</th></tr>
<tr><td>• Tasking of fresh tri-stereo imagery
• Photogrammetric processing of tri-stereo imagery
• Map production
• Quality checking and initial validation</td></tr>
</table>

Figure 12 The precise (1 m) DEM demonstration product for an area of Belize(includes material © CNES 2014, Distribution Airbus DS / SPOT Image S.A. France, all rights reserved).

2.2 Current User Requirements

The EO products and Services delivered by this project address the issue of disaster risk management in the Caribbean region. Specifically, the Services deliver data products that are fundamental in helping to improve understanding of the risk posed by natural (geo-) hazards that frequently affect each country (Jordan *et al*, 2015) (Table 2).

Table 2 Hazard characteristics for the four countries (source: CDEMA, and Jordan et al 2015, modified from van Westen, 2014).

	Belize	Saint Lucia	St. Vincent and the Grenadines	Grenada
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 south).	Hurricanes and volcanic activity, debris flows, flash floods.	Hurricanes; Soufriere volcano on the island of Saint Vincent is a constant threat. Flash floods and landslides	Lies on edge of hurricane belt; hurricane season lasts from June to November. Flash floods 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 reports South 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 centre 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.

The user requirements were determined by WB and the WB CHARIM project, and then used to define the Services in the SOW. In some cases, these initial requirements were refined slightly following subsequent discussions with the WB team (i.e., the WB TTL and CHARIM project) and BGS-stakeholder discussions in workshops held in the Caribbean and in the Netherlands (Jordan *et al* 2015). Overall, the Services are designed to support flood/landslide hazard mapping by providing essential data that is currently missing or inadequate due to limitations with the current practices. Specifically, the primary requirement is information on land cover/land use, water bodies (e.g., streams, rivers, lakes), landslides and elevation (i.e., DEMs). Acceptance of the Services by the users is therefore dependent on successfully demonstrating the capability to deliver EO products that provide information on these elements that is currently missing, or new information that represents a significant improvement over what already exists (e.g., in terms of accuracy, detail, time period). Further acceptance by the local users could also be dependent on them recognising the benefit of the EO products in applications beyond disaster risk management.

Service 1 provides comprehensive information on the main land use/land cover types, surface water bodies, basic road network and building footprints for St. Lucia, Grenada and St. Vincent and the Grenadines. Overall, the delivered EO products meet the requirements outlined in the SOW, and provide enhanced information that is considerably more detailed and up-to-date than already exists (Table 3). Although this can be implemented as an entirely stand-alone Service for land use/land cover mapping from optical satellite imagery, some aspects were augmented using ancillary baseline information (e.g., existing land use/land cover maps) in order to produce more accurate and consistent data for input to the risk assessment undertaken within the CHARIM project.

Service 2 delivered detailed landslides inventories and national-scale DEMs for St. Lucia and Grenada. The EO products fully meet the requirements, additionally providing yearly landslide inventories for St. Lucia. Although existing landslide inventories are available (see Table 3), the inventories delivered by Service 2 better capture the state of recent activity. Similarly, elevation data also exists, but is outdated, has a low spatial resolution or provides only partial coverage of the countries. Service 2 addresses this by generating DEMs with full coverage and the desired spatial resolution. The landslide inventory mapping aspect of this Service is stand-alone, as it was undertaken using information derived from the optical satellite imagery. However, as defined in the SOW, the mapping was ground-truthed using in-situ field observations. The generation of DEMs from optical satellite imagery can be implemented as a stand-alone process, but in this case was augmented with the existing elevation data to maximise the accuracy of the data for use in subsequent risk assessments.

Service 3 provides a national-scale DEM for Belize, in addition to a higher resolution regional DEM and a local-scale high-precision DEM. In contrast to Service 2, this Service is implemented as a stand-alone service for generating DEMs solely from optical satellite imagery. The resulting DEMs provide more accurate and higher resolution elevation information than currently available, therefore permitting enhanced flood risk modelling at national- and local-scale.

The EO information products delivered by the three Services are fundamental in assessing the flood and/or landslide risk in the four countries. However, these products must be used in conjunction with additional information (e.g., geology, soils, rainfall data) in order to robustly assess risk. Although beyond the scope of this project, optical satellite imagery and other types of EO data (e.g., radar) can be used to provide much of this additional information.

2.3 Current Practices

There is a range of skills and experience amongst the local users, ranging from little or no use of geospatial data, to complex use and understanding (e.g., the University of West Indies). Table 3 lists the geospatial information currently being utilised by WB and local users through a variety of risk/hazard-related projects and initiatives in the Caribbean region. In general, flood and landslide hazard assessments to date have relied upon making the best use of any existing relevant geospatial data. However, much of this data is incomplete, generalised or somewhat outdated – with the historical data likely to have been produced through conventional means such as field surveys. Table 3 also highlights how the current project has utilised EO satellite data to help overcome limitations associated with the current practices and the availability of essential information.

In Grenada, risk mapping and GIS capability is managed predominantly by the Ministry for Agriculture, but progress is limited and digital data is relatively scarce. A vulnerability assessment of school buildings as shelters in the event of natural hazards has been completed (http://www.oas.org/CDMP/document/schools/vulnasst/gre.htm), but this did not consider landslides. Nonetheless, flooding due to torrential rain was considered, with the vulnerability assessment based on very generalised topographical and land use/land cover information gained through local field surveys. To date, a comprehensive multi-hazard map has not been prepared. The WB is implementing a Disaster Vulnerability Reduction Programme. 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 2006, a landslide hazard map was produced by the Caribbean Development Bank/Caribbean Disaster Emergency Response Agency. This involved producing a landslide inventory based on limited field work confined locations accessible from the road network. This inventory was used in conjunction with a DEM-derivatives derived from a contour map and low quality (i.e., outdated and generalised) soil and geology maps (see Table 3) to model landslide susceptibility. Recently, an enhanced airborne LiDAR DEM has become available, but this does not provide full national coverage. A national flood hazard assessment was also undertaken by the Caribbean Development Bank in 2006, but this did not involve rigorous hydrologic/hydraulic analysis and its reliability will be hindered by the use of outdated and generalised input data (e.g., land use/land cover, soil map) that was likely mapped through field surveys.

Table 3 Geospatial information sources currently used by WB teams and local users. The EO information delivered by the Services are highlighed in green (Jordan *et al* 2015).

Geospatial information	Grenada	St Vincent and the Grenadines	Saint Lucia	Belize
DEM	10m raster DEM (source unknown) and partial LiDAR coverage **30m DEM, full coverage**	5m raster DEM (higher parts are not covered). There are LiDAR data, but the format is incorrect so they cannot be analysed	50m raster maps and contours with 2.5m intervals **30m DEM, full coverage**	ASTER (30m) and SRTM (90m). Higher resolution DEM urgently required for flood risk modelling. **National DEM at 30m, 40% of territory at 20m and 100km^2 at 1m**
Land use/land cover	USDA 30m raster map from Landsat data from ca. 2000. **Derived from 2m satellite data**	Polygon map exists with 11 land use classes (ca. 2000) **Derived from 2m satellite data**	1:50,000 raster maps. Vegetation information is in vector format **Derived from 2m satellite data**	Not applicable
Landslide inventory and hazard map	1988: OAS study for selected towns. 2006: CDB/CDERA limited landslide inventory, not available digitally **Landslide inventory at 1:20,000**	Landslide footprints are available from 1987, but there is no detailed information.	Inventory for 1987 (USDA) and 2006 (CDB/CDERA). 2010 inventory produced from satellite imagery **Landslide inventory at 1:20,000 with key areas (< 50%) at 1:10,000**	Not applicable
Elements-at-risk	Non-attributed building footprints **Building footprints captured on 2m land use/land cover map**	Not available **Building footprints captured on 2m land use/land cover map**	Building footprints available for country - occupancy/ structural type unavailable **Building footprints captured on 2m land use/land cover map**	Not available
Geological map	A very general one is available, made by USGS	A very general one is available, made by USGS	Vector map is available	Not applicable
Soil map	A 1959 soils report exists, but map not available	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	Not applicable
Rainfall data	50 stations, non-continuous data available from Land Use Division, Ministry of Agriculture, Lands, Forestry & Fisheries	None obtained thus far, but rainfall stations do exist	Hourly rainfall data for 24 stations	Missing
Socio-economic data	Missing	Missing	Missing	Missing

In Saint Vincent and the Grenadines, progress in preparation of hazard maps is also limited. To date, risk mapping has largely focussed on volcanic risks and some coastal vulnerability analyses. A landslide inventory and susceptibility map exists (produced in 1987), but this was based on generalised and somewhat outdated input data (e.g., geology, elevation, land use/land cover) and therefore will not accurately reflect the current state. Similarly, past flood hazard assessments have been hindered by coarse DEMs derived from contour maps. In recent years higher resolution elevation data (e.g., airborne LiDAR) has become available from an unknown source, although the data is currently in a format that is usable. 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 Management Organisation (NEMO). The WB is implementing a Regional Disaster Vulnerability Reduction Programme. 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, landslide inventories were produced in 1987 and 2006 through field reconnaissance. However, fieldwork was confined to areas accessible from the roadside and so the inventories do not provide an accurate reflection of the spatial distribution of landslide activity. Subsequently, the Caribbean Development Bank/Caribbean Disaster Emergency Response Agency produced a landslide susceptibility map from the 2006 inventory, but this was again based on low quality (i.e., outdated and generalised) soil and geology maps and elevation data. A 2010 landslide inventory is available, although this appears to have been generated through automated classification of bare ground on satellite imagery. Accordingly, the inventory contains many false-positive landslides owing to a lack of expert knowledge and interpretation. A landslide hazard map was produced in 2012, but this predominantly relates to debris flows and there is also some concern about the source and integrity of much of the input data. A national flood hazard assessment was also undertaken by the Caribbean Development Bank in 2006, but this did not involve rigorous hydrologic/hydraulic analysis and its accuracy will be hampered by outdated and generalised input data. The WB is implementing a Disaster Vulnerability Reduction Programme. 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 is accessible here: http://sling.gosl.gov.lc.

In Belize, a multi-hazard risk study was undertaken in 1999 for several districts as part of a support activity for NEMO. This study focusses on landslides, volcanic and storm hazards amongst others. This assessment appears to have been based largely on historical data, local reports of the occurrence of such events and basic GIS data. Although a nationwide flood hazard map based on hydrological modelling does not appear to exist, several local- or regional studies have focussed on the susceptibility of the road network flood and coastal flooding. Nevertheless, flood hazard mapping in Belize is hindered by the absence of a detailed and accurate DEM. Previous studies have restricted to using a coarse DEM generated from a 1:50,000-scale contour map with 20 m contour intervals. Belize is participating in the Central American Probabilistic Risk Assessment (CAPRA) platform, but the initiative remains modest in Belize.

3 INCREASED EXPLOITATION AND ADDITIONAL OPPORTUNITIES

The Service Utility Document (Grebby et al, 2015) outlined the assessment of the services / products supplied via the *eoworld2* initiative. One of the primary outcomes from that document is a review of the areas where the stakeholders / users believed that the EO products could provide additional exploitation and opportunities. The EO products provided opportunities in terms of:

3.1 Improved information:

- *"The new land use/land cover maps are more precise and accurate where the old one is general" – Grenada.*
- *"The map quality is an improvement to the previous one (higher resolution)…more classes of land cover identified" – St. Vincent and the Grenadines.*
- *"Generally seems to be good and properly represented…there is no new information, but it shows an updated land cover map" – St. Lucia.*
- *"The landslide inventory map for Saint Lucia is a very important dataset for us, and it will certainly contribute a lot to improving the quality of the landslide map for the island" – CHARIM project team.*
    - *"The 20m elevation model is better than we currently have, which is a 30m. The maps are useful, especially the 1m, this is really what we need" – Belize.*

3.2 Timely delivery of results and updates

Over and above the additional information that could be provided with inputs from EO data, the stakeholders / users also identified that the integration of EO data could enable them to undertake new work that was not previously possible based on current practices and information:

- *"The land cover maps for Grenada, Saint Lucia and Saint Vincent are very important datasets for us, and they will certainly contribute a lot to improving the quality of the landslide and flood maps for these islands" – CHARIM project team.*

- *"This will result in on time delivery of maps which can assist in decision making and planning. When a map is done using other methods it sometimes takes too long to materialise and sometimes the land cover may have changed before even producing a map" – St. Lucia.*

- *"Can help with development decision making and help in preserving of watersheds" – Grenada.*

- *"The map can be useful in monitoring changes in forest cover…gives a good idea as to where development is taking place" – St. Vincent and the Grenadines.*

- *"I believe that the land cover maps generated through satellite takes so little time as doing it on site. This will result in on-time delivery of maps which can assist in decision making and planning" – St. Lucia.*

- *"Images on a 2-year interval from 2000 to future years would be appreciated" – St. Lucia."*

- *"We have been asking for LiDAR, but for some projects these maps that you produce can substitute for the accuracy needed" – Belize.*

The existing land use/land cover maps for the countries were produced from freely-available Landsat satellite imagery acquired ca. 2000. Although free, the data have only a moderate spatial resolution of 30 m. In contrast, the new land cover maps were predominantly generated from very-high resolution Pleiades satellite imagery, which provides an order of magnitude increase in the spatial resolution (2 m) of the resulting maps. Access to the Pleiades satellite imagery was provided through the ESA TPM scheme, but commercially such imagery typically costs upwards of €17 per km^2. Taking into account the overwhelmingly positive feedback from users, it is apparent that the enhanced information content, quality and subsequent benefits of the new maps do fully justify the costs. Moreover, land use/land cover mapping using EO data is generally more time and cost efficient than conventional field-based mapping. This was recognised by one local user:

- *"EO products will enable me to reduce the overall expenditure of data collection" – Grenada.*

The national-scale DEMs for St. Lucia and Grenada were generated using ASTER stereo satellite imagery with a spatial resolution of 30 m and vertical accuracies (RMS) better than 5 m. Although elevation data with a higher spatial resolution and accuracy can be acquired through traditional ground-based GPS surveys, this approach is extremely inefficient when covering large areas. Airborne LiDAR can provide accurate and high resolution elevation data, although surveys have to be commissioned and can therefore be very costly. At a cost of approximately $60US for a scene covering 3600 km^2, ASTER satellite imagery proves a cost effective means of generating a DEM for applications such as national-scale landslide and flood hazard mapping. If temporal coverage of the DEM is not an issue, then the 30 m ASTER Global DEM, generated using imagery acquired in 2000–2011, is available free of charge. As was initially planned for this project, optical stereo imagery acquired by the Pleiades satellites can be used to generate DEMs with a much higher spatial resolution (ca. 1 m) and vertical accuracy. Such imagery can be acquired for a cost in the region of €29 per km^2, and would enable the landslide and flood risk to be mapped more accurately.

Although offering a slightly enhanced spatial resolution and vertical accuracy over the 30 m ASTER-derived DEM for Belize, the 20 m DEM generated from SPOT satellite imagery is more expensive at a cost in the region of €2 per km^2. Accordingly, in the absence of a DEM produced through traditional means, the use of stereo satellite imagery is the most cost effective method of producing a DEM of Belize for national-scale flood risk mapping purposes.

The precise 1 m DEM for 100 km^2 of Belize provides a demonstration of the full potential in using optical satellite to generate accurate and high-resolution DEMs. In this case, the DEM was generated using state-of-the-art Pleiades tri-stereo satellite imagery. Again, the imagery was acquired free of charge through the ESA TPM scheme. Commercially, this type of imagery costs in the region of €50 per km^2. Whilst this is quite costly, the feedback from the users suggested that a DEM of this quality and accuracy is urgently required for accurate flood risk mapping in Belize because it far exceeds that of the existing DEM. Based on this alone, the cost associated with this Service appears fully justified with respect to the potential benefits and opportunities it can bring. The 1 m DEM delivered by the Service is comparable to the resolution and accuracy achievable using airborne LiDAR. In generally, the generation of DEMs from tri-stereo optical imagery is probably more cost effective than airborne LiDAR for mapping areas up to 200 km^2.

The ability to generate DEMs from the optical imagery was perceived to be one of the major strength of the Services. This was particularly true for the precise 1 m DEM for Belize, with one local user adamantly stating that data of that quality was what they urgently required to enable accurate flood risk mapping.

A major limitation of the EO Services was the dependency on cloud free imagery. Many users commented on the incompleteness of the rivers and roads layers owing to clouds and associated shadows in the imagery. Cloud cover is arguably one of the main restrictions on the use of EO data in tropical environments such as the Caribbean region, largely because of the Atlantic hurricane season. The probability of acquiring useable cloud-free imagery can be maximised by increasing the time duration of the acquisition window or to avoid tasking during known climatic events.

Although information on the validation of the EO products using conventional procedures was provided, it is apparent that some local users preferred the opportunity to undertake their own field validation. This may be partly due to the relative unfamiliarity of these users with EO-based products and conventional validation procedures. Although not possible in this project, more interaction with the local users prior to and during the assessment phase would have helped to improve the level of confidence these user have in the reliability of the EO products. Despite this, all users were able to recognise the substantial benefits provided by the use of EO data in their activities.

4 WORLD BANK OPERATIONS

4.1 Relevance to Wider Bank Operations

ESA and the WB have invested in the increased utilisation of EO data through the eoworld and eoworld2 partnerships. Between 2008 and 2012 ESA and the WB jointly implemented fifteen dedicated technical assistance activities aimed at delivering high-impact EO-based data and knowledge products (EO for Sustainable Development, 2013). The demonstration projects began in the area of adaptation to climate change, progressing to activities focussed on the sectors of disaster risk management, urban development, forestry, agriculture, water resources management, coastal zones and marine environment management. In many cases the results revealed ground-breaking information. This was followed up with sixteen projects within this eoworld2 phase.

This project demonstrates the ability to utilise EO data to provide risk information services for disaster risk management. Specifically, the Services have provided fundamental geospatial information directly for input to the landslide and flood risk mapping that has been undertaken for the Caribbean region by the WB CHARIM project. Nevertheless, the type of EO-derived land cover/land use maps, landslide inventories and DEMs delivered by Services 1, 2 and 3 are also relevant for other WB disaster risk-related projects, such the sub-Saharan African landslide risk project that has recently commenced, and the WB Regional Disaster Vulnerability Reduction project. In fact, information on land use/land cover and DEMs could be considered a mandatory requirement of any hazard mapping project, whether that be related to the disaster risk or the risk posed by climate change. The generation of landslide inventory maps using EO data, as demonstrated in Service 2, is especially useful in rugged or mountainous terrain as this approach helps to overcome accessibility issues that limit traditional field surveys. Recently, BGS has employed this approach for mapping co-seismic and monsoon-induced landslides in Nepal following the 25 April 2015 earthquake (e.g. http://www.bgs.ac.uk/research/earthHazards/epom/Nepalearthquakeresponse.html).

Service 1 has the capability to generate temporal land use/land cover information which would be of considerable benefit to other WB Urban Development, Forestry, and Coastal/Ocean monitoring projects being undertaken as part of the eoworld2 initiative. Specifically, the approach used in Service 1 could be used to support ongoing WB forestry, biodiversity and conservation projects in South America, Africa and Indonesia. Moreover, the combination of land use/land cover, river/stream information and DEMs would be applicable to watershed management projects in areas such as Nigeria and India, and sustainable land and water management projects in Ghana and Mauritania. The EO data and techniques utilised in Service 1 can also be modified to contribute information in support of projects concerning food security. For example, such approaches can be used to provide information on agricultural productivity in areas with harsher climatic conditions, in particular Africa and the Middle East.

Service 3 demonstrates the ability to generate accurate and high-resolution DEMs from very high resolution optical satellite imagery. Accordingly, such an approach provides a valuable cost-effective alternative for acquiring elevation data in parts of the world where airborne LiDAR surveys are not feasible due to financial or political constraints. However, if terrain elevation information is required, then airborne LiDAR is perhaps more suitable in areas with dense forest, such as the Caribbean, South America, Indonesia and forested regions of Africa.

Since the inception of this project the World Bank has shown increasing confidence in the efficacy of EO data such as:

- Assessment of urbanization trends via the Global Urban Growth Data initiative;
- Collaborations in international water basins (Zambezi River basin, Lake Chad);
- Green Wall initiative for the Sahel and Sahara to address land degradation;
- Dedicated GEF-financed project to support forest data development (satellite monitoring for forest planning and management);
- WB gained from ESA's experience from the TIGER project (http://www.tiger.esa.int/) dedicated to African national water authorities.

Furthermore, in 2015 WB GFDRR released a call for projects relating to the "Development of national disaster risk profiles for sub-Saharan Africa" relating to landslide susceptibility and risk. The call included a note that inputs may include 'satellite-based landslide occurrence observations'. This simple statement significantly encourages the inclusion of appropriate EO techniques and is an ideal example of an action that the WB can take to further grow uptake of EO products / services in future.

From BGS experience in high profile situations such as the immediate and longer-term response to the Nepal earthquakes and subsequent landslides (2015) it is clear that there is significant interest in WBG regarding the utility of EO data e.g. regarding identification/mapping of damage distribution. Nevertheless there appears to be a degree of uncertainty regarding what can realistically be achieved, and which organisations or individuals should be involved.

4.2 Further actions to increase uptake of EO Products

This "Risk information services for DRM in the Caribbean" project focussed on in-country dissemination of results via a range of methods including meetings directly with technical staff in government departments, interaction with landowners and the public during the fieldwork components, and workshops that included a range of stakeholders from WB staff to international agencies. The project Scope of Work included two meetings at the WB offices in Washington DC i.e. the Service Readiness Review and the Service Utility Review meetings. However, it was agreed with the ESA coordinator and the WB TTL that these meeting would in fact take place in the Caribbean as part of the wider CHARIM workshops. Whilst this had the positive effect of increasing the project interaction with stakeholders in the Caribbean, it did result in reduced interaction with a wider group of WB staff had the meetings taken place in Washington DC, as originally planned. We are very grateful to the WB TTL (Dr Melanie Kappes) for reviewing the project reports and Services and for disseminating these within the WB, however to further promote the EO capabilities we would recommend the action to hold a workshop at the WB offices in Washington to present the methodology and results as this could lead to increased awareness and therefore increased exploitation and additional opportunities in further WB operations, programmes and initiatives.

It is evident that there are joint WB and ESA reviews of EO e.g. Earth Observation for Sustainable Development (2013) which have the potential to raise awareness in the WB and increase exploitation of the technology. BGS would welcome the opportunity to contribute to any future joint reports, if deemed appropriate. The input would include the perspectives gained during this eoworld2 project but also those acquired during other current WB projects such as "Development of National Disaster Risk Profiles for Sub-Saharan Africa; landslide susceptibility and risk".

The WB has also initiated their own reviews of EO, e.g. in 2015 a tender was released to review the "State of Play on Satellite Services". The ToR included:

1. A review of relevant previous documentation and recent projects
2. Research and summarize current providers and data characteristics
3. Overall assessment of the market dynamics in the coming 15 years.

BGS cannot comment on the motives that the WB had for releasing the call for this review, nor have we seen the results, however we support the strategy that the WB wishes to learn more about the services possible with satellite technology and the prospects for the roles it may play in future markets.

Without doubt, wider dissemination of what EO can offer the WB is one of the primary methods to increasing its uptake within the group (for applicable projects). BGS made the results of this DRM project available via several pathways including conference presentations and portals (e.g. the ESA Geohazard Exploitation Platform). The conference presentations include the ESA Living Planet Symposium, Prague (May 2016) and RSPSoc 2016, UK (September 2016) highlighting that we are endeavouring to make the results available beyond the timeline of the project funding. The action is on ESA and the WB to ensure long term endorsement of appropriate EO products and services beyond the time frame of eoworld2.

5 CONCLUSIONS

This project successfully demonstrates how information derived from EO data can contribute directly to flood and landslide disaster risk management in the Caribbean by providing fundamental geospatial information on land use/land cover, landslides and DEMs. The users appreciated the ability to produce this information from EO data with a higher degree of detail and accuracy than already available, in a more time- and cost-effective manner. Another major strength of the EO approach is the ability to produce consistent information, both historical and in the future (as soon as imagery is acquired). This provides users with the means to undertake various monitoring activities that are not possible or viable using current practices. The main limitations of the EO approaches in the Services were perceived to be the cloud cover and the validation of the EO products. Cloud cover and associated shadows in the imagery made it challenging to achieve complete coverage of the areas of interest during the hurricane season. Although unavoidable here, this issue can be mitigated in the future by either extending the tasking window or planning the acquisition of new imagery around the hurricane season. All the EO products delivered by the Services were validated using conventional practices where possible. However, some users felt that it was necessary to further validate the products through their own additional ground-truthing. This may be partly due to the relative unfamiliarity of these users to EO based products and conventional validation procedures. Accordingly, in future additional interaction with the local users may be required to increase their level of confidence in the reliability of the EO products. Nonetheless, in summary, all users expressed acceptance of the Services, with the delivered EO products appearing to either meet or exceed their expectations.

This project focussed on interaction with stakeholders in the Caribbean, possibly to the detriment of interaction with a wider group of staff (beyond the WB TTL) in the WBG in Washington DC. A list of suggested actions to potentially increase exploitation and additional opportunities in further WB operations, programmes and initiatives were proposed:

1. Hold an EO workshop at the WB offices in Washington DC to promote appropriate use of EO-derived products and services to the widest range of WB staff possible;

2. Invite organisations such as BGS to contribute to future ESA/WB reviews of EO;

3. Promote long term and wider dissemination of the results of initiatives such as eoworld2 and other appropriate ESA and/or WB projects that utilized EO data. This should include projects where EO was used successfully, as well as a review of projects where EO may not have been successful.

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