GeoSY Ltd

Dunoon • Dayrells Rd • Rockley • Barbados

Tel/Fax: +1 246 228-7876 • Mobile: +1 246 250-2481
Email: GeoSY@caribsurf.com

Phase I of BVI QRAP

Preparation of GIS-Ready Probabilistic Hazard Maps for Quantitative Risk Assessment for the British Virgin Islands

Final Report

Contract # CHAMP 1.5/01/09/2003

Dr Simon R Young

Prepared for:
Caribbean Disaster Emergency Response Agency
CHAMP Coordinator
Building #1, Manor Lodge Complex, Lodge Hill
St Michael, Barbados

Date: 12 January 2004

Geoscience and natural hazards
consultancy throughout the Caribbean

DISCLAIMER

The information provided in this report is advisory. It is offered, without prejudice, for the purpose of informing the party commissioning the study of the availability and nature of probabilistic hazard maps for the BVI and related issues, and has been prepared subject to constraints imposed on the performance of the work. While the author believes that he has acted honestly, reasonably, and in good faith, he accepts no responsibility or liability, jointly or severally, for any decisions or actions taken by the commissioning party or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can he accept any liability to any third party in any way whatsoever.

1. INTRODUCTION

Phase I of the Quantitative Risk Assessment Project (QRAP) for critical infrastructure in the British Virgin Islands (BVI) comprises collection and preparation of as full a suite as possible of probabilistic hazard maps for natural hazards affecting the BVI, for use as hazard layers in the QRAP.

This final report covers Work Assignment 4 of the Special Services Agreement (CHAMP 1.5/01/09/2003) between the contractor and the Caribbean Disaster Emergency Response Agency (CDERA):

4. Prepare a final report to include:

4.1 An outline of any deviation from the proposed methodology used to compile maps.
4.2 Description of criteria for data selection and documenting relevant accuracy/uncertainty of each hazard map.
4.3 Identification of prioritized area(s) of further work required for more accurate hazard assessment.
4.4 A hard copy of all maps produced.

Submitted along with this report, an accompanying CD-ROM includes the deliverables as required by Work Assignment 3:

3. Compile GIS-ready portfolio of best available probabilistic natural hazard maps for BVI using consistent methodologies at consistent scales and probability levels. These maps should be compatible with risk assessment methodologies such as HAZUS and can be fully integrated into the National GIS of BVI.

This final report should be read in conjunction with the Interim Report, which includes an introduction to the project and the methodology for hazard map preparation. This final report describes the derivation of the maps and other information in the atlas and the uncertainties attached to those maps. It also presents a series of hazardous event scenarios to further inform the risk assessment process. Chapter 4 presents recommendations for further work required to better constrain quantitative hazard maps or to undertake primary quantitative hazard mapping, and Chapter 5 presents a list of all data files included in the BVI Natural Hazards Atlas, which accompanies this report as a CD-ROM.

2 METHODOLOGY AND UNCERTAINTY ANALYSIS

This chapter presents a summary of the methods used to prepare the GIS map and data atlas. It includes discussion of variations from the methodology described in the interim report and also addresses issues raised in comments on the interim report. It also includes an assessment of the uncertainty of each data set.

Table 2.1 summarises the proposed contents of the hazards atlas as per an addendum to the interim report.

Hazard	*Semi-quantitative maps*	*Probabilistic maps*	*Hazard curves*	*Other (quantitative)*
Ground shaking		**X**	**X**	
Site effects				**X**
Ground failure	**X**			
Wind		**X**	**X**	
Wave		**X**	**X**	
Inland flood	**X**			
Landslide (rain)	**X**			
Landslide (eq)	**X**			
Coastal flood (TC)		**X**	**X**	
Coastal flood (eq)	**X**			
Coastal flood (tele-tsunami)	**X**			

Table 2.1 Proposed contents of BVI hazards atlas.

2.1 Ground shaking

Maps produced for Puerto Rico and the Virgin Islands by the US Geological Survey in 2003 were used as a basis for the probabilistic ground shaking maps. As discussed in the interim report, these maps are the best available for BVI based on a number of criteria.

The original USGS maps of peak ground acceleration at 10% probability of exceedance in 50 years (10PE50) and 2PE50 were digitised, geolocated and rasterised to produce a unique value of peak ground acceleration at each grid node (pixel). The USGS maps were extended to the northeast to include Anegada; extension of the PGA contours was done following the trend of contours in regional PGA maps from GSHAP/CDMP/SRU.

The USGS hazard curve for Charlotte Amalie (St Thomas, USVI) is used as a direct proxy for Road Town (in the absence of any other relevant information). Using this hazard curve (included in the atlas), the relationship between PGA at 10PE50 and 50PE50 was established, and this ratio used within a spatial analysis module of GIS to produce a raster map of PGA at 50PE50. For verification purposes, the same process was used to convert the 2PE50 map to 50PE50. PGA values at each grid node in the two resulting maps were always within 5% of one another, well within the general uncertainty bounds of the data and thus verifying the validity of this approach.

The USGS do not provide quantitative uncertainty information regarding their seismic hazard maps. Comparison between the USGS maps and regional maps from SRU and a local map produced as part of the BVI HRAP in 1997 was presented in the interim report. The SRU regional maps are based on a purely probabilistic methodology which is always thought to be less accurate than methods involving deterministic elements. The HRAP methodology was partly deterministic and, in many ways, similar to the USGS methodology; however, the new USGS study used a combination of 6 different attenuation functions (the greatest source of uncertainty in seismic hazard maps), none of which were available at the time of the HRAP study (which instead used a 1982 attenuation function).

Uncertainty analysis in the HRAP study actually shows that the significantly higher values of PGA found in the USGS study are within the range of uncertainty of the HRAP results (based on sensitivity analysis of the attenuation function). Sensitivity analysis in the USGS study, and comparison to a similar academic study, suggest PGA errors of up to 20% for the eastern part of the study area, and ±20% is used as the uncertainty range on the BVI-QRAP maps.

As stated in the interim report, a more precise evaluation of the uncertainty of the ground shaking maps requires strong motion accelerometer data, which is completely lacking for BVI and does not have a sufficiently long baseline in Puerto Rico to be able to assist in assessing the uncertainty in the seismic hazard models.

The ground shaking maps for 2, 10 and 50 PE50 (return periods of 2,475, 475 and 72 years respectively) are provided as raster images in GEOTIFF format, based on the BVI local grid and with value units in %g (1%g = 9.8gals).

2.2 Site effects

Ground acceleration can be significantly modified by ground conditions. Ground shaking maps are conventionally drawn for PGA in rock; areas of the land which are covered with less rigid sediments are subject to amplification of seismic waves, and thus relatively greater shaking intensity.

A site effects map is provided as part of the hazards atlas. This map is based on the new (2003) geology map of BVI, from which areas of potential site effects are taken, and attributed with a site amplification function. Two mapped units were identified as having potential for site amplification; alluvium and sand (which is only mapped on Anegada).

Generalised relationships between rock/soil type and amplification function are used where the engineering characteristics of a particular local ground condition are unknown. For BVI, the HRAP study included some work on site amplification in alluvium and reclaimed land in Road Town. Site amplification functions were thus assigned on the basis of generalised relations, but with consideration of the HRAP study results. Thus alluvium was assigned a function of 2 and sand a function of 1.5.

Uncertainties in these amplification functions are at least ±100%; the HRAP study reported estimated amplification functions of up to 7 for some areas in Road Town, while the standard function for alluvium is 1.5. Reduction of these uncertainties is required to levels more compatible with the uncertainties in the ground shaking maps, otherwise the maps of modified ground shaking will be of little value in the QRA process.

Collection of specific ground condition information by geophysical means for alluvium and reclaimed land in BVI, and subsequent revision of the site effects map is recommended prior to the risk assessment being undertaken.

The site effects map is presented as an ArcView shapefile with local BVI grid coordinates and with the amplification function as the data value attribution. This function is dimensionless. At the current level of knowledge, site amplification function does not vary with ground shaking intensity, so only one map is required. However, research in California suggests that amplification functions can vary with ground acceleration and, depending on the results of BVI-focused studies, different site amplification maps may be required at different return periods (keyed to the ground acceleration at each return period).

In addition to the ground shaking and site amplification maps, a suite of maps of modified ground shaking, scaled in Modified Mercalli Index (MMI) are also provided as a demonstration of the final product of seismic hazard mapping. These raster maps are in GEOTIFF format, with local BVI grid coordinates and attributed in half-MMI units.

2.3 Ground failure

As stated in the interim report, only liquefaction is important in BVI. The only study which has considered potential liquefaction in BVI is HRAP. That study is not particularly detailed and deals only with one area of reclaimed land. Evidence from around the Caribbean suggests that, in addition to all of the reclaimed land in BVI, the alluvial deposits may also be susceptible to liquefaction under certain circumstances.

A liquefaction potential map within the BVI-CRIS National GIS is used as the basis for the liquefaction potential map in the hazards atlas. It is an incomplete map of reclaimed land around Road Town Bay. The HRAP study suggests that liquefaction is possible in some areas of reclaimed land for ground accelerations as low as 17%g and for many areas of reclaimed land above 20%g. Such ground accelerations have return periods of around 150-200 years in BVI.

Representation of liquefaction potential in the hazards atlas is preliminary and subject to modification. At present, a single liquefaction potential map has been included, delineating areas with high potential for liquefaction. This map is valid at 475 and 2,475 year return periods (i.e. 10PE50 and 2PE50 PGA maps) but not with the 50PE50 PGA map (at which level there is no liquefaction potential).

The level of uncertainties in the liquefaction map are significant and considerable work is required to collect better data to inform that map. The study already recommended for site amplification should also cover mapping and characterisation of areas with potential for liquefaction. That study should provide better aerial coverage of liquefaction potential (at present the map only covers a small area in Road Town) and also may enable some quantification of liquefaction potential at different return periods.

The liquefaction potential map is provided as an ArcView shapefile with local BVI grid coordinates.

2.4 Wind

The wind hazard maps for BVI have been derived from analyses undertaken using the TAOS system (described more fully in the interim report). Two sources of TAOS output were identified in the interim report and a methodology proposed to combine those two data sources. After discussion with Chuck Watson (author of the TAOS software), it was decided that the CDCM web-based outputs from TAOS were sufficient on their own to produce maps at the required return periods, without the need for combination with CDMP-TAOS maps.

Discussions with Mark Johnson of Central Florida University, who wrote the statistical packages in TAOS, clarified some matters concerning the comparison between exceedance probabilities and return periods in conventional seismic hazard assessment and in the TAOS system. The CDCM-TAOS web-based mapping tool allows maps to be drawn at different levels of statistical confidence, which can be equated to different 'return periods' in the sense used in seismic hazard analysis.

For BVI, three maps were required for full aerial coverage of BVI (due to the display limitations of the web-based TAOS output), and for each of these, three statistical confidence levels were used: 50 year MLE (which equates to 50PE50), 50 year 90% limit (which equates to 10PE50) and 100 year 95% limit (which equates to a return period of ~1,950 years).

The 50 year MLE and 90% maps were combined graphically and geolocated within the GIS to produce BVI-wide GEOTIFFs at 50PE50 and 90PE50 attributed for 1-minute sustained peak windspeed in m/sec. The attributed value in the GEOTIFF was taken as the centre of the range of values given in the CDCM-TAOS output.

Hazard curves were also derived from the CDCM-TAOS web interface. Numerical output was generated for each of the 4 confidence levels (MLE, 75%, 90% and 95%) at each time interval (10, 25, 50 and 100 years) to produce 16 different peak windspeed estimates for each of three sites (Road Town, Spanish Town (Virgin Gorda) and The Settlement (Anegada)). Each peak windspeed value was associated with its pseudo return period, and thus the hazard curve could be drawn.

Once the hazard curve was drawn, the 2PE50 map could be derived within the GIS from the 100 year 95% map and a function derived from the hazard curves quantifying the difference between the wind hazard values at 1,950 and 2,475 year return periods. In effect, the difference between values for these two return periods is negligible. This is because there is a physical limit to the peak windspeed which can be generated, and this limit is approached at return periods of a few hundred years, and increases in peak windspeed with return period thereafter are very small.

There are two main limitations in the TAOS system which define the uncertainties in the output maps. First, the Atlantic Basin storm catalogue and the windfield equations used in any storm mapping system are subject to uncertainties. Statistical techniques are used within TAOS to smooth out these uncertainties, but they still remain as immovable limitations on the data (essentially, these are aleatory uncertainties). The second set of limitations is instilled during the process of modifying the windspeed by topographic and land cover information. In TAOS, the information used for modification of the wind field has been gathered at a resolution of 1km and from purely remotely-sensed data. This second set of uncertainties is essentially epistemic – the uncertainties can be reduced by higher resolution mapping of these characteristics, especially the topography.

In absolute terms, the immovable uncertainties are greater than those which could be reduced, so that modifying topography and land cover to higher resolution would not improve the accuracy of the wind hazard maps (*i.e.* how closely the values on the map relate to the actual 'correct' value on the ground). However, given the scale of topographic variation in BVI, rerunning the model with topography at higher resolution could significantly improve the wind hazard map in relative terms. For example, at 1km resolution, narrow ridge lines and funnelling valleys are not resolved whereas at 90m resolution (available from the Shuttle Radar Topography Mission), such features would be resolved and would impact on the level of wind hazard.

The absolute uncertainty in the wind hazard maps is of the order of ±20%. Should the opportunity arise, TAOS should be rerun with 90m or better topography for better relative resolution of wind hazards; however, this is not a priority for the QRAP as the absolute values of the wind hazard would not be significantly improved.

The wind hazard maps for 2, 10 and 50 PE50 (return periods of 2,475, 475 and 72 years respectively) are provided as raster images in GEOTIFF format, based on the BVI local grid and with value units in m/sec for 1-minute sustained winds.

2.5 *Waves*

Wave hazard maps were derived in exactly the same way as the wind hazard maps described above, and the discussions there are entirely valid for the wave hazard maps also. The main difference is that the modification of wave height is by bathymetry and sea floor character (rather than topography and land cover).

Although they will not be used in QRAP, wave hazard maps and curves are included in the atlas. Maps at 2, 10 and 50 PE50 are provided as raster images in GEOTIFF format, based on the BVI local grid and with value units of peak wave height in metres, and hazard curves are provided for Road Town Bay, and areas immediately offshore of Spanish Town and The Settlement.

2.6 *Inland flooding*

Inland flooding was the primary focus of comments on the interim report, and is of particular interest in BVI in the wake of the November 2003 rain event and resulting flooding. Considerable work was done during a visit to BVI in December 2003 with regard to collection of rainfall and flooding data, and a detailed assessment of the flood hazard study reported as part of HRAP was undertaken.

From this work, it is clear that quantification of flooding hazards for BVI represents a significant challenge, especially at the relatively modest scale which occurred in November 2003. For the purposes of the hazards atlas, a single flood hazard map has been derived from the output of HRAP, showing maximum extent of flooding with a 50% probability of exceedance in 50 years (72-year return period) for the three main ghuts draining into Road Town.

This map was derived by digitising the 100- and 50-yr flood limits for the two drainage basins analysed in HRAP (Huntums/Long Bush and Johnson) and taking a median line between these two as the 72-yr flood limit. This digitised data was then georeferenced, and the two maps combined and extrapolated to the coastline. The resulting single polygon shows the flood hazard area at 50PE50.

A rainfall hazard curve was also produced from rainfall return period relations documented in HRAP.

The limitations on the flood data set are immense. First, the aerial coverage is limited to three of 36 drainage basins identified in HRAP. Second, only one of the three selected return periods is represented. Use of the rainfall hazard curve to extrapolate rainfall rates and thus flood limits at longer return periods (as had been suggested in the interim report) proved invalid given the limitations on the rainfall and other input data. Third, the flood limit maps are highly idealised and do not account for local drainage basin characteristics and potential blockages. Fourth, the flood limit maps do not provide likely depth of flooding.

It is clear that a significant effort is required to better quantify the inland flood hazards for BVI prior to undertaking the quantitative risk assessment. A two-part project is recommended; one part concentrating on quantifying rainfall events and return periods for BVI and quantifying the impacts of the November 2003 event (also see Chapter 3 on scenario events); and a second part concentrating on extending the aerial coverage of flood maps. Of note is that the US National Weather Service is nearing completion of a thorough update of rainfall rate data at all return periods for Puerto Rico and the USVI; this information will be valid for BVI and should be available in the middle of 2004.

HRAP produced approximate discharge rates at different return periods (up to 100 years) for all 36 of the identified drainages on the three main islands in BVI, based on the rainfall hazard curves presented in the hazards atlas and on USVI-based infiltration rates and other data. The tests run in HRAP on the discharge model for the USVI storm of April 1983 showed good accuracy and, adjusted for an improved rainfall hazard curve, discharge rates for BVI drainages are probably accurate to ±10%. These can then be used to estimate flood depth maps for 72- and 475-yr return periods.

The flood inundation map at 50PE50 is provided as an ArcView shapefile with local BVI grid coordinates. It comprises a single polygon showing the area of inundation for the area of Road Town for which the data exists.

2.7 *Shallow landslide*

The lack of any data relevant to shallow landslide hazard for BVI was identified in the interim report and was again highlighted in received comments on that report. It was hoped that semi-quantitative landslide hazard maps could be drawn from a simple correlation of known landslide zones (derived from fieldwork and BVI-DDM and PWD data collection) with geological units identified in the 2003 geological mapping project. However, the events of November 2003 and discussions with Dr James Joyce of UPRM (who undertook a rapid post-event assessment of the landslides) have demonstrated that the 2003 geological map does not contain sufficient information to make any estimates about landslide susceptibility.

It is thus recommended that a specific two-part landslide hazard study be completed. First, geological units need to be characterised and subdivided by engineering geology criteria. (A project to undertake this has already been recommended separately to DDM). Second, the engineering geology map, in combination with GIS-derived slope information and other relevant data, should be used to derive semi-quantitative landslide hazard maps for both earthquake and rainfall triggering mechanisms. Work elsewhere in the Caribbean can usefully inform such a project.

2.8 *Coastal inundation*

Coastal inundation occurs through three different hazardous phenomena; storm surge during tropical cyclones, and local/regional and tele tsunami.

For storm surge hazard, TAOS-CDCM maps have been utilised in a manner identical to that already described for wind and wave hazards; instead of wind speed, the unit mapped is storm surge height in metres. Open-water storm surge height calculated from the Atlantic Basin tropical cyclone record is modified by bathymetry and seabed character. Both of these are mapped at 1km resolution in the TAOS-CDCM maps and, in the case of bathymetry, this coarse resolution provides the greatest source of error in the storm surge hazard maps. This error is especially acute for BVI, where modification of surge height by the bathymetry is significant. It is also notable that at 1km resolution, the TAOS output shows major, abrupt changes in surge height across pixel boundaries. This has a major negative impact on inundation maps drawn using this data.

In the course of discussions at the University of Puerto Rico, Mayaguez regarding regional tsunami hazard mapping, it was discovered that much higher resolution bathymetry data are available for BVI than the 1km resolution used in TAOS. It is thus recommended that TAOS storm surge models are run again using higher resolution bathymetry, and also, for comparison, the NOAA SLOSH model is also run for BVI. This NOAA model was developed in part by Prof Mercado at UPRM, who has also led the tsunami modelling efforts in the region.

For surge inundation mapping, small scale accurate coastal topography is also required. For BVI, the current level of topographic data in CRIS is variable. Contour intervals for different islands are different, and the contour interval within a single island is also irregular. Digital remapping of topography using newly flown aerial photography is currently being undertaken in the Lands and Surveys Department in BVI, and it is hoped that a new, accurate DEM will be available during 2004 for more accurate inundation modelling. The near-coast topography is particularly important for BVI, where small surge heights and flat coastal areas exaggerate the dem and surge map resolution issues.

Using the current TAOS-CDCM surge maps and the best topography available, inundation depth maps have been produced within a GIS for each of the three return periods of interest for storm surge. These maps are in GEOTIFF format based on the BVI local grid. Attribution is depth of inundation in metres. Note that these maps only cover Tortola, Beef Island and Virgin Gorda, the only islands for which reasonable DEMs could be constructed.

As indicated in the interim report, very little information is available for quantitative tsunami hazard mapping. Discussions at UPRM proved valuable and, although no relevant information is currently available, an idea of what might be achieved was gained.

A project is thus recommended to undertake tsunami hazard mapping. There is insufficient information available regarding tsunami in the northeastern Caribbean to undertake full probabilistic hazard mapping, so a scenario-based approach must be used for tsunami inundation. Scenario tsunami events are further discussed in Chapter 3.

As an interim approach, a map of maximum recorded tsunami run-up height (which probably equates to a return period of a few hundred years) is provided. The maximum tsunami run-up recorded in Road Town is 1.5m; this is similar to the storm surge height for the 72-year return period, so that storm surge map is used as a basis for the tsunami inundation map. This map is provided in GEOTIFF format based on the BVI local grid. Attribution is depth of inundation in metres.

It should be noted that tsunami and storm surge run-up are not the same; the run-up height (and thus inundation zone) for a 3m (open water) storm surge is not the same as the inundation zone for a 3m tsunami wave. This means that separate models need to be used for tsunami and storm surge inundation mapping.

3 SCENARIO EVENTS

Quantitative risk assessment generally takes two forms; the first looks at averaging losses over long time periods, and requires hazard maps at a variety of return periods, while the second models the impact of particular 'scenario' events. This section outlines the physical parameters describing scenario earthquake, storm and tsunamogenic events for BVI. As discussed in the interim report, three scenario events are described for each natural hazard event type: one with a return period of several centuries (therefore equating to the largest historical event for which reasonable information is available), one corresponding to the maximum possible scale of event (limited by the physical process generating the hazard) for which the return period will be different for each event type, and the third corresponding to an unusual but potentially relatively frequent event which creates particular problems in terms of impact on BVI.

The historical event scenario is particularly important, as information regarding the impact of the particular hazard can be used to verify modelled results of both the hazardous phenomena and the vulnerability assumptions made in the QRA.

3.1 Earthquake

3.1.1 Historical event

Two earthquakes have been identified as potential candidates; an earthquake reported in 1785 to have caused severe damage in Tortola and an earthquake and accompanying tsunami which devastated St Thomas in 1867.

The 1785 earthquake is very poorly documented and has periodically been called into question as a valid event. Even the date is ill-defined; both 11 and 19 July are quoted. Apart from the one account from Tortola, other islands reportedly affected in the Tortola account (St Kitts and Antigua) have no records pertaining to the event. Report of surface rupture on Tortola ("In Tortola, the earthquake made great clefts in the rocks, and separated completely a part of the island, forming a new island"; Mallet, 1852) indicate a shallow event beneath Tortola which, if also felt as far away as Antigua, would have completely devastated Tortola and probably St John and St Thomas also. Interestingly, there was a major hurricane through the Virgin Islands during 1785 (probably 25 August, possibly 25 September), and such modifications as formation of new islands in shallow waters such as surround Tortola is much more likely the result of a hurricane than an earthquake.

Given the lack of credible evidence regarding this event, it is not possible to use it as a scenario event.

Thus the selected scenario event is that of 18 November 1867. According to the Port of Spain (Trinidad) Gazette of 11 December 1867, "Most awful series of earthquakes ever felt in the Virgin Islands; islands are in complete ruin; tidal wave." In a more scientific report by Deville

(1867), the following was written: “In St. Thomas, a violent earthquake; several shops collapsed, nearly all houses were severely damaged; fifteen minutes after the first shock, a tidal wave invaded shops in the lower part of the town to a depth of several feet; aftershocks were felt approximately every five minutes for the first 24 hours.”

This earthquake, which produced effects in Tortola consistent with MMI VII, has been assigned an approximate magnitude of M_s 7.75 by McCann & Sykes (1984) and was probably associated with the Anegada Trough extensional zone. This magnitude estimate is revised downwards slightly in more recent publications (M~7.3; LaForge & McCann, 2004).

This event also produced a major tsunami, with an estimated run-up height of 1.5m in Road Town Bay and on Peter Island.

Parameters for this scenario event are given below; both ground shaking and tsunami hazards from this event should be modeled.

Location:	18.00 N, 65.50 W
Depth	33 km
M_s	7.5

3.1.2 Worst case scenario

Worst-case scenario earthquakes are usually estimated from the physical limit of the length of fault rupture possible on the particular fault likely to source the most damaging earthquake for the area in question. For BVI, the subduction zone to the north of Anegada represents both the source of most seismicity and the source of the potentially most devastating earthquake.

Puerto Rico’s worst historical earthquake (in the more than 450 years of recorded history there) occurred on 2 May 1787, and caused widespread destruction throughout the island except in the southwest. A magnitude of M_s 8-8.25 was assigned to this event by McCann (1985) and McCann & Sykes (1984), and it is thought to have been caused by rupture of a shallow part of the subduction zone at the northern margin of the Puerto Rico Platform north of San Juan. The rupture zone is estimated to have extended towards Anegada.

Available evidence suggests that a worst-case scenario earthquake for BVI would involve rupture of the segment of subduction zone fault to the east of that which ruptured in 1787. Parameters for such an event are provided below:

Location:	19.00 N, 64.50 W
Depth	33 km
M_s	8.5

Such an event is potentially tsunamogenic, and the modeling of a tsunami from such an event should form part of the further work in the area of quantification of tsunami hazards for BVI.

3.1.3 Unusual event

Random shallow crustal events not associated with known faults or seismically active zones occur globally, and recent work in the northeastern Caribbean put an upper bound of M=7.0 for such events in the region. For events with magnitude 6.5-7.0, recurrence period estimated from the instrumental record are in the range 400-10,000 years (for 95% confidence limits, LaForge & McCann, 2004).

Given the HRAP findings of potential liquefaction at M=6.0-6.5, a 'random' earthquake at shallow depth beneath Tortola, with a return period of several hundred years, could cause significant damage. Such events have not occurred in the past few hundred years (unless the 1785 earthquake really happened), but could occur in the future. Parameters for such an event are provided below:

Location:	18.25 N, 64.50 W
Depth	10 km
M_s	6.0

3.2 *Tropical cyclone/rain event*

3.2.1 Historical event

A number of hurricanes have severely affected BVI in the last several hundred years, but relatively little useful information is available for these historical storms. In recent times, when storm parameters have been better measured and impacts more formally recorded, Hurricane Hugo in September 1989 stands out as the most severe to affect the Territory. Hugo's track and character are available from the NOAA 'best track' database; the relevant data for its passage through BVI are provided below.

Date (Sep 89)	Hour (UTC)	Latitude (N)	Longitude (W)	Wind (knots)	Pressure (mb)
17	0	16.1	60.4	120	941
17	6	16.4	61.5	120	943
17	12	16.6	62.5	125	949
17	18	16.9	63.5	125	945
18	0	17.2	64.1	130	934
18	6	17.7	64.8	120	940
18	12	18.2	65.5	110	945
18	18	19.1	66.4	105	958
19	0	19.7	66.8	100	959
19	6	20.7	67.3	90	962
19	12	21.6	68	90	964
19	18	22.6	68.6	90	966

Contemporary reports from BVI suggest peak sustained winds of 120 mph (gusts to 145 mph), with storm surge of 3-4ft and wave heights of 9-12ft. No information for rainfall is available from BVI, but upward of 5 inches fell in the USVI, so 5 inches (126 mm) is a reasonable estimate of peak rainfall for BVI.

3.2.2 Worst case scenario

A worst case scenario cyclonic event is somewhat less nebulous than that for an earthquake, especially in the northeastern Caribbean, where major earthquake damage has not been encountered in recent history. With upward of 10 cyclones per year affecting some part of the Caribbean Sea region, there are abundant examples of storms which, had they taken a different track, could have produced massive impact in BVI. It is important to note also that, unlike earthquakes and tsunami, the track of a tropical cyclone (and thus its impact footprint) is not confined by fixed physical conditions on a sub-regional scale. The only fixed constraint on impact is the minimum pressure (which relates directly to windspeed) of the system which, theoretically for the Atlantic Basin, bottoms out at a little less than the 26.22 inches of mercury recorded in the centre of Hurricane Gilbert in 1988 (the lowest sea level pressure ever recorded in the Western Hemisphere). This equates to wind speeds in excess of 165 mph (1-minute sustained).

For Atlantic storms, the worst sector of an east-west moving storm is the northeast sector (or, looking in the movement direction, the right rear sector). This is where the peak winds will occur (usually in the eye wall), and this is also the area where maximum storm surge height will be encountered. There is no systematic distribution of rainfall in a cyclone; however, a relatively slow-moving storm will dump more rain on a particular location than a fast moving one.

Thus a worst case scenario can be constructed of a slow moving Category 5 hurricane moving east to west, having crossed the Atlantic and with the northern eyewall passing over Tortola (meaning the centre would pass 0.1 degrees of latitude south of Road Town.)

The actual impacts of such a scenario event on BVI can be modelled accurately in TAOS – however, sustained winds of 160 to 170 mph for over 3 hours, rainfall of 15 inches in 24 hours and storm surge in Road Town of 3-4 metres could be anticipated.

3.2.3 Unusual event

For cyclone/rain events, forecasting provides a major mitigating factor, especially in terms of human safety. Although not accounted for systematically in a quantitative risk assessment, warning as a mitigation measure is important in disaster management planning for scenario events. Thus it is useful for the 'unusual' scenario event to have an element of surprise (which is no longer the case for all but a few Atlantic cyclones.) Two events over the past 5 years in the northeastern Caribbean have had this element of surprise; Hurricane ('wrong-way) Lenny in November 1999 and the recent November 2003 rainstorm in BVI. For the former, cyclone tracking models (with the exception of the UK Met Office Model) were wrong, and the official NHC forecast was also wrong. For the latter, the fact that the system causing the rain event was only a tropical wave meant that the usual cyclone warning system did not come into effect.

Although another Lenny is becoming increasingly unlikely to be so poorly forecast again and rain events are becoming better quantified from satellite information, there is certainly still the possibility of a short, severe rain event affecting BVI with little or no warning. An event in April 1983 in St Thomas and St John is a good example of what could happen; 15 inches of rain fell in about 18 hours, causing major flooding and landslides throughout the two islands. Although modelling the impact of such an event in BVI would be difficult, the events of November 2003 would provide a good starting point for a detailed analysis of such a scenario event and the serious implications for BVI.

3.3 *Tsunami*

3.2.1 Historical event

The selected historical earthquake event includes generation of a tsunami, so that the historical tsunami event selected is the 1755 tele-tsunami which was caused by a massive earthquake close to Lisbon, Portugal. Modelling for the Atlantic-crossing waves for this event is well developed, and extending that modelling to run-up in BVI would be a useful contribution to understanding tsunami hazards in BVI and would also provide a basis for a scenario inundation map.

3.3.2 Worst case scenario

Work over the past decade on instability of volcanic edifices has highlighted the high frequency with which volcanoes collapse catastrophically. For island volcanoes, this provides the opportunity for generation of major tsunami, even without an actual eruption. For the entire North Atlantic Basin, a worst-case scenario tsunami wave would be generated by a collapse of Cumbre Vieja volcano on the Canary island of La Palma. Modelling work has shown potential open water wave heights of up to 50m off the Florida coast (Ward & Day, 2001), and the run-up of such waves onto BVI would be catastrophic. As with the historical tsunami event, run-up modelling of the known open-water tsunami wave set would be very useful in characterising the impacts of this worst-case scenario.

3.3.3 Unusual event

Both the historical and worst-case scenario events would (hopefully) be accompanied by some element of warning for the Caribbean as a whole. Although development of a regional tsunami warning system is advancing only very slowly, it is likely that there would, even today, be some warning of an approaching tsunami wave issued (probably by NOAA) if the wave was crossing the Atlantic. An unusual event should be one without warning, but not one already covered by the earthquake scenarios. A major eruption of the underwater Kick 'Em Jenny volcano north of Grenada provides such a scenario. Although not likely to generate a major tsunami, the BVI lies in a vulnerable position to any tsunami generated at KEJ due to its location at the northern end of the Grenada Trough, which would channel any waves northwards. Modelling of wave generation by such an event at KEJ is already available (Smith & Shepherd, 1996), and again, run-up modelling for BVI would be very useful to inform run-up inundation maps which in turn could inform risk assessment.

4 RECOMMENDATIONS FOR FURTHER WORK

Below is a brief summary of recommendations for further work aimed at quantifying, or better quantifying, the various natural hazards which affect BVI with a view to better constraining the proposed quantitative risk assessment. The recommendations are in priority order; the first five are necessary pre-requisites for a valid QRA; the remainder would add important, but not critical, validity to the QRA. It should be noted that the actual risk analysis process is relatively quick to perform, so that the QRA can be easily updated as new, improved hazard and vulnerability information becomes available.

4.1 Characterisation of site conditions for alluvium and reclaimed land

Project should include mapping and classification of reclaimed land and seismo-engineering characterisation of liquefaction potential and site amplification function for both reclaimed land and alluvium at a series of representative sites.

4.2 Quantification of landslide and flood impacts from November 2003 event and re-analysis of rainfall return periods

Project should collect and collate all information pertaining to flood depths, landslide occurrence, timing of events and meteorological conditions for the November 2003 event, and also re-evaluate the recurrence period of such rainfall events.

4.3 Construction of landslide susceptibility and semi-quantitative hazard maps

Project should include more detailed subdivision of geological units in terms of engineering character, characterisation of landslide susceptibility (in terms of rock type, slope angle and any other relevant factors) and mapping of landslide potential for both rain and (if possible) earthquake triggering. Mapped landslide susceptibility can be tied to return periods of triggering phenomenon for semi-quantitative landslide hazard maps.

4.4 Extension of flood hazard mapping to all BVI

Re-evaluate HRAP-evaluated discharge rates with revised rainfall return periods (from 4.2) and extend flood inundation maps (including depth of inundation) throughout BVI. Simplified approach to inundation mapping should be pursued in the first instance; this can be made more rigorous (leading to better accuracy) at a later date.

4.5 *Detailed study of tsunami wave run-ups for BVI and modelling of scenario events*

Project should concentrate on modelling of run-up and mapping of inundation for historical tsunamis including 1867 St Thomas and 1755 tele-tsunami, as well as potential tsunami from eruption of KEJ and collapse of Cumbre Vieja volcano (La Palma, Canaries).

4.6 *Re-mapping of storm surge height and inundation depth using more accurate bathymetry and topography*

Project should include re-running of TAOS for storm surge using better bathymetry, running of SLOSH model for storm surge, and re-mapping of inundation from both storm surge models using revised BVI DEM.

4.7 *Re-mapping of wind hazards using more accurate topography*

Project should include re-running of TAOS for wind speed using better topography (either SRTM 90m resolution DEM or new BVI DEM) and possibly higher resolution land cover data.

4.8 *Initiation of a sustainable natural hazards monitoring network for BVI*

All hazards mapping depends on modelling of the impact of known phenomena. Modelling is subject to many uncertainties, and the only way to verify models is by comparison between known and model impacts of historical events. Unfortunately, documentation of impacts from previous hazardous events in BVI is very poor. Baseline data needs to be collected routinely, starting as soon as possible, and should include monitoring of ground motion, rainfall, wind speed, storm surge and wave height.

5 DATA INVENTORY

The quantitative natural hazards atlas for BVI contains digital files in two main formats:

Vector files in ESRI shapefile format (extension .shp). All shapefiles have an associated pair of files with the same root filename (extensions .dbf, .shx).

Raster files in GEOTIFF format (extension .tif). All geotiffs have an associated geolocation file (extension .tfw).

Although ESRI ArcView software works mainly in vector format, raster format is more suitable for the spatial analysis required for quantitative hazard mapping and QRA. Interchange between these two formats is relatively straightforward.

Both shapefiles and GEOTIFFs are geolocated to the BVI National Grid. The first 5 or 6 characters of the filename refer to the probability level of the map; 2pe50 is 2% probability of exceedance in 50 years and so on.

The table below lists the root filenames for all of the maps in the atlas.

Filename	File type and attribution units	Description
50pe50surge	Raster, metres	Peak offshore surge height (TAOS)
50pe50inun	Raster, metres	Onshore surge inundation depth (mod TAOS)
50pe50pga	Raster, %g	Peak ground acceleration (USGS)
50pe50modmmi	Raster, MMI	Modified peak ground shaking intensity (mod USGS)
50pe50wind	Raster, m/sec	Peak wind speed (TAOS)
50pe50wave	Raster, metres	Peak offshore wave height (TAOS)
50pe50fd	Vector, none	Flood inundation polygon for Roadtown
10pe50surge	Raster, metres	Peak offshore surge height (TAOS)
10pe50inun	Raster, metres	Onshore surge inundation depth (mod TAOS)
10pe50pga	Raster, %g	Peak ground acceleration (USGS)
10pe50modmmi	Raster, MMI	Modified peak ground shaking intensity (mod USGS)
10pe50wind	Raster, m/sec	Peak wind speed (TAOS)
10pe50wave	Raster, metres	Peak offshore wave height (TAOS)
2pe50surge	Raster, metres	Peak offshore surge height (TAOS)
2pe50inun	Raster, metres	Onshore surge inundation depth (mod TAOS)
2pe50pga	Raster, %g	Peak ground acceleration (USGS)
2pe50modmmi	Raster, MMI	Modified peak ground shaking intensity (mod USGS)
2pe50wind	Raster, m/sec	Peak wind speed (TAOS)
2pe50wave	Raster, metres	Peak offshore wave height (TAOS)
Tsuninun	Raster, metres	Onshore inundation depth for 1867 tsunami
Liquef	Vector, none	High liquefac potential at 10 & 2pe50 polygon
Site Amplification	Vector, d'less	Site amplification factor polygons

In addition to maps, five hazard curve diagrams are provided in .jpg image format for:

Offshore surge height (curves for Road Town Bay, offshore SE Anegada and offshore Spanish Town)
Peak wind (curves for Road Town, The Settlement and Spanish Town)
Peak wave height (curves for Road Town Bay, offshore SE Anegada and offshore Spanish Town)
Peak ground acceleration (curve nominally for Road Town)
Rainfall (curve nominally for Road Town)

Image versions (in .jpg format) are provided of all the maps in the atlas on the accompanying CD-ROM, and hard-copy versions of these maps and the hazard curves are provided as an Appendix to this report.

6 REFERENCES

Deville, C.S-C. 1867. Sur le tremblement de terre du 18 Novembre 1867 aux Antilles. *Comptes Rendus de l'Academie de Sciences de Paris*, v. 65, pp. 1110.

LaForge, R and McCann, W R. 2004. A seismic source model for Puerto Rico for use in probabilistic ground motion hazard analysis. *Geological Society of America Bulletin*, in press.

Mallet, R. 1852. *Catalogue of recorded earthquakes*. Third Report on the facts of earthquake phenomena. London, U.K.

McCann, W R. 1985. On the earthquake hazards of Puerto Rico and the Virgin Islands. *Bulletin of the Seismological Society of America*, v. 75, pp. 251-262.

McCann, W R and Sykes, L R. 1984. Subduction of aseismic ridges beneath the Caribbean plate: implications for the tectonics and seismic potential of the northeastern Caribbean. *Journal of Geophysical Research*, v. 89, pp. 4493-4519.

Smith, M S and Shepherd, J B. 1996. Tsunami waves generated by volcanic landslides: an assessment of the hazards posed by Kick 'em Jenny volcano. In W. McGuire, A.P. Jones and J. Neuberg (eds) *Volcanic instability on the Earth and other planets*. Geol. Soc. London Special Pub. 115-123

Ward, S N and Day, S J. 2001. Cumbre Vieja - Potential collapse and tsunami at La Palma, Canary Islands. *Geophysical Research Letters*, v. 28, pp. 3397-3400.