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AN EVALUATION OF SRTM, ASTER, AND CONTOUR BASED DEMS IN THE CARIBBEAN REGION

Abstract: There are numerous sources of digital elevation models (DEMs) available for geographic information system (GIS) applications and natural hazard studies. Each source of DEM data is subject to inaccuracies based on the data source, its resolution, and characteristics of the terrain. This study evaluates DEMs derived from the Shuttle Radar Topography Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, and topographic contours for the island of Grenada in the southeastern Caribbean. Statistical measures of accuracy, developed through a comparison to high-resolution control points, demonstrate the vertical accuracy of the three sources of DEMs for the study area. The effect of terrain and vegetation on the accuracy of SRTM, ASTER, and contour-based DEMs is further demonstrated through an analysis of elevation, slope, and surface curvature measurements. Finally, selection of appropriate DEM data for natural hazard mapping, landform studies, and GIS applications in the Caribbean region is discussed.

INTRODUCTION

Geospatial information describing the elevation of the land surface above a common datum plane is defined as a digital elevation model (DEM). In the literature, there are studies that distinguish between digital surface models (DSMs), which incorporate the heights of forest canopy or the tops of buildings and so-called “bare earth” digital terrain models (DTMs) which represent the elevation of the earth itself, devoid of manmade structures and vegetation effects (NDEP, 2004). DTMs and DSMs are stored in a number of different types of data structures that correspond to specific user requirements or applications. These structures include mass point elevations, triangular irregular networks (TIN), or raster grids. For the purpose of this study, the term DEM refers to a raster grid array of elevation values representing orthometric heights of the land surface.

Raster DEM data store one elevation value for a square pixel, or cell, of a given size. The elevation value stored in a pixel represents an average elevation for the actual elevations within that pixel area in the real world. The size of the pixel is generally described as the horizontal resolution of the DEM. For example, a DEM with a horizontal resolution of 30m is composed of pixels measuring 30m on each side and containing one elevation value for that entire area (Figure 1). Vertical resolution is the term that refers to how accurately the elevation values stored for each individual pixel in the DEM match the true elevation of the land surface. DEM horizontal and vertical resolution varies depending on the quality of the source data and the method used to develop the DEM.

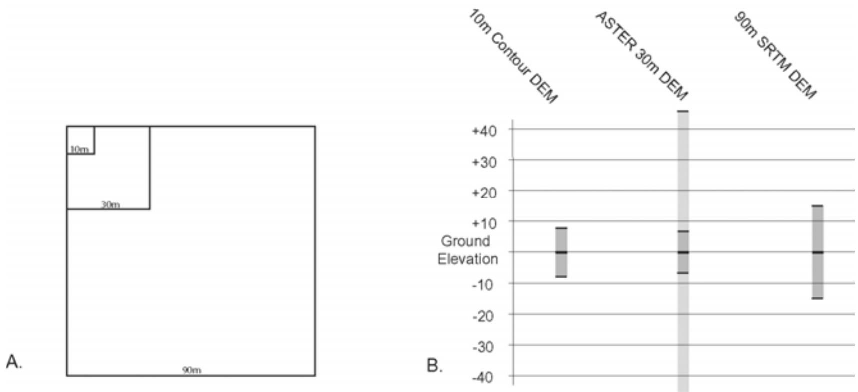

Figure 1. Comparison of (A) horizontal resolution of DEM data and (B) vertical resolution of elevation values within DEM.

DEMs are produced from a variety of source data but are most commonly produced from contours represented on topographic maps, derived from ground surveys, or triangulated from stereo aerial photographs. Stereo interpretation and auto-correlation from satellite image stereo-pairs such as with SPOT, IRS, and ASTER satellite imagery is also an effective means of producing DEM data. RADAR technology is also a reliable means from which elevation data is obtained. Referred to as InSAR or IfSAR, interferometric radar emits and receives radio waves from either a satellite or aircraft and calculates the distance (or elevation) from the returned signals. Light detection and ranging (LIDAR) employs a similar methodology to InSAR, except that the emitted and received signal is a pulsed laser and not radio waves. LIDAR is rapidly becoming the standard for developing high horizontal and vertical resolution DEMs. Processes to remove vegetation canopy and man-made structures from InSAR and LIDAR are also becoming standardized (Raber, et al., 2002). This filtering process allows these DEMs to be used both for DSM and DTM portrayal depending on the application.

Regardless of data quality or production method, all DEMs are subject to both systematic and random error. Systematic error is defined as being error occurring in some fixed pattern and introduced by data collection procedures and systems (NDEP, 2004). Random errors are deviations that occur within the DEM but cannot be corrected by the use of a standard adjustment. In theory, if errors in a DEM were all systematic they could be corrected prior to testing and use.

This goal of this study is to quantify random DEM error through the comparison of three sources of DEM data to a set of high-resolution checkpoints from GPS and topographic benchmark measurements for the island of Grenada.

STUDY AREA

Grenada is located in the southeastern Caribbean at 12º 02’ N and 61º 15’ W and is part of the Windward island chain. Grenada represents one of many islands in the Caribbean region with typical high central mountain topography and underlying geology structure of a volcanic origin. The highest point in Grenada is Mount Catharine which lies at 2757ft (840m). While other Caribbean islands maintain higher central mountain ranges, Grenada was chosen as a study area for its size and topographic diversity, which includes narrow ravines and steep ridges, but also exhibits coastal plain topography along its eastern coast (Figure 2). In addition, Grenada is subject to tropical storms and rains lasting from June to November. As a result, coastal flooding, soil erosion, and slope stability are issues for Grenada and many other Caribbean nations.

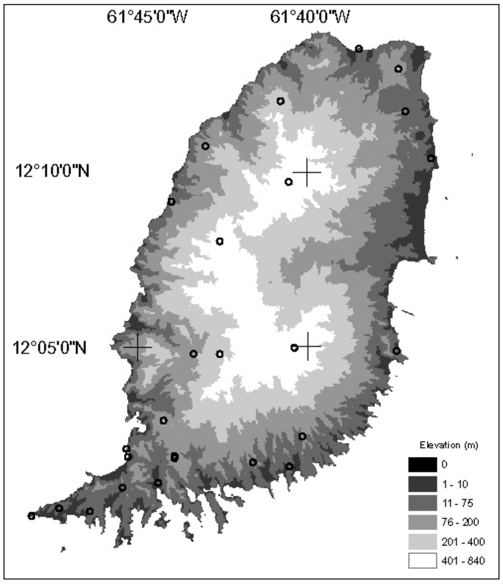

Figure 2. Map showing general topographic relief of Grenada and checkpoint benchmarks.

METHODOLOGY

This study evaluates DEMs derived from the Shuttle Radar Topography Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, and topographic contours for the island of Grenada in the southeastern Caribbean.
To compare DEMs from different sources, elevation models were acquired or produced from each source for the study area. Elevation control checkpoints were developed from the Grenada Ministry of Lands and Survey benchmarks, many of which were recently verified by the U.S. National Geodetic Survey (NGS) using high resolution global positioning system (GPS) measurements.

Datum adjustment calculations were performed on the DEM data to adjust all source data to elevations based on the WGS84 EGM96 geoid in order to make comparisons between data that was collected in different vertical datums. An estimated conversion was developed to convert Grenada local tidal datum elevation to the Carib97 geoid model; then Carib97 elevations were adjusted to EGM96. These calculations were based on NGS calculations for the Carib97 geoid model development in the Caribbean region (Smith and Small, 1999). Grenada local tidal elevations +67 cm is approximately equal to WGS84 EGM96 elevations. This calculation is based on average values throughout the Caribbean and may contain marginal errors but was necessary is the absence of a directly measured Grenada local tidal elevation conversion.

Once elevation values for each DEM are compared to this set of high resolution checkpoints a series of root mean squared (RMSE) values are calculated for the elevation value (RMSEz) to quantify the vertical accuracy of DEMs from each source. In addition to overall RMSEz values, values were compiled based on topographic elevations above and below 75m. 75 meters in elevation is a value designed to replicate the change in contour interval in the original topographic contour data for Grenada. This elevation value also serves as a topographic comparison of lower and generally flat elevations as compared to steeper topographic relief.

Contour Derived DEM

Contours for Grenada were digitized from Directorate of Overseas Surveys (DOS) 1:25,000 scale maps (DOS, 1979; DOS, 1988). The maps were produced from aerial photographs taken in 1951 and updated with additional aerial photography in 1978. The topographic maps of Grenada have a contour interval of 7.62m (25 ft) below 76.20m (250 ft) elevation and a 15.24m (50 ft) contour interval above 76.20m (250 ft) elevation. Based on U.S. National Map Accuracy Standards (NMAS) that 90% of true elevation values are within one-half of the contour interval, the vertical accuracy for a DEM developed from these contours is estimated to be ±3.81m to ±7.62m. A DEM with a 10m horizontal resolution was created using the TOPOGRID command in ArcGIS (Hutchinson, 1993). Subsequently, the 10m DEM (10m Contour DEM) was resampled to 30m (30m Contour DEM) and 90m (90m Contour DEM) resolution for comparison to the ASTER and SRTM DEMs.

ASTER

The ASTER sensor is one of three instruments carried onboard NASA's Terra satellite platform in a near-polar orbit at 705km altitude. The ASTER pushbroom sensor samples 14 bans from the visible and near infrared (VNIR), the shortwave infrared (SWIR), and the thermal infrared (TIR) portions of the electromagnetic spectrum. The VNIR bands, numbered 1, 2 and 3, are recorded at 15m resolution, the SWIR bands, numbered 4 through 9, are recorded at 30 m resolution and the TIR bands, numbered 10 through 14, are recorded at 90m resolution. Band 3, which samples from the 0.78 to 0.86μm range, is the only band to record through both a nadir (3N) and a back-looking (3B) telescope at 27.6º creating along track stereo scenes at 15m resolution. Each ASTER scene covers an area approximately 60km x 60km. The accuracy of along-track stereo auto-correlation is improved because the time difference between band 3N collection and band 3B collection is approximately 1 minute which ensures nearly identical environmental conditions during stereo imaging (Figure 3). ASTER is on a 16-day repeat cycle but does have a cross-track pointing capability of ±24º allowing for more frequent imaging of ground targets. The base-to-height ratio of the stereo images acquired by ASTER is 0.6, which is nearly ideal for generating DEMs in a variety of types of terrain (Hirano et al., 2003). Original ASTER mission specifications called for DEMs to have a vertical resolution within the ±7m - ±50m RMSEz range depending on the number and quality of ground control points (GCPs) and tie points (Lang and Welch, 1999).

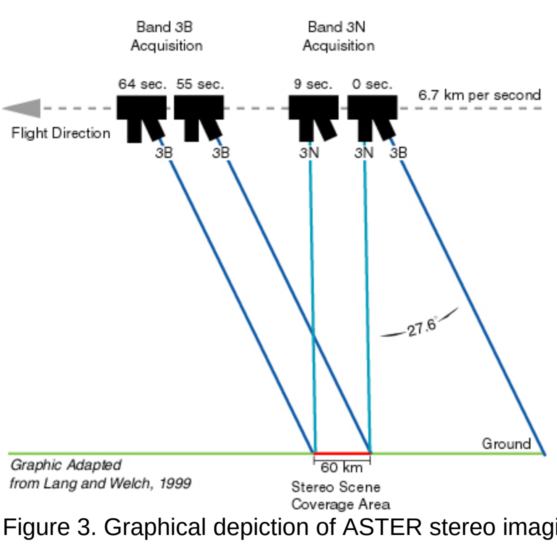

Figure 3. Graphical depiction of ASTER stereo imaging capability. Adapted from Lang and Welch, 1999.

To generate DEMs from ASTER, a single level 1A scene is required. Level 1A scenes are essentially raw image frames which have the radiometric and geometric coefficients included but not applied to the image. The level 1A images are required to produce the best stereo-autocorrelation. The ASTER scene acquired for Grenada was collected on August 28, 2002 and has a significant amount of clouds covering the central part of the island (Figure 4). Band 3N and band 3B were individually imported into PCI Geomatica's Orthoengine® software (ver. 9.1.4) where 20 ground tie points and 16 ground control points (GCPs) were identified in each image frame. GCPs were collected directly from geographically referenced raster graphics of the DOS topographical map sheets and included an elevation value, which was converted from feet into meters. In general, major road intersections and other visible targets in the imagery were used for ground control point selection. Cloud cover throughout the central highlands prevented GCP collection and DEM production for the central part of the island.

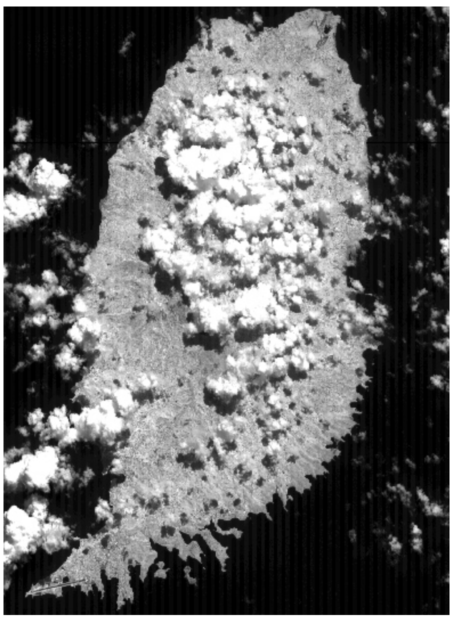

Figure 4. ASTER imagery showing amount and distribution of cloud cover.

After GCP collection, epipolar images are generated. Epipolar image generation reprojects the images to maintain the stereo image parallax at the time of collection (Hurtado, 2002). Epipolar image generation aids in pixel-to-pixel matching during the stereo autocorrelation phase. An ASTER DEM was created with a 30m horizontal resolution during the automated DEM extraction phase. Areas that failed to correlate were attributed with a value of -150, and background values of -100 were generated in portions of the image covered by water. Clouds, haze, and large amounts of atmospheric moisture decrease the correlation index for ASTER DEM production and can also cause erroneous elevation values, which is discussed further in the results section.

Shuttle Radar Topography Mission (SRTM)

For 11 days in February of 2000, NASA, the National Geospatial-Intelligence Agency (NGA), the German Aerospace Center (DLR), and the Italian Space Agency (ASI) flew X-band and C-band radar interferometry onboard the Endeavor Space Shuttle. The mission covered the Earth between 60ºN and 57ºS and will provide DEMs of approximately 80% of the Earth's land mass when processing is complete. In addition to interferometric digital elevation models, the mission also provided radar image products recorded by the onboard antenna (Rabus et al., 2003). The radar-pointing angle was approximately 55º at scene center. Ascending and descending orbital passes generated multiple interferometric data scenes for nearly all areas. Up to eight passes of data were merged to form the final processed SRTM DEMs. The effect of merging scenes averages elevation values recorded in coincident scenes and reduces but does not completely eliminate the amount of area with layover and terrain shadow effects. DEMs are processed to 1 and 3 Arc Seconds, which corresponds to approximately 30m and 90m resolution respectively. Currently, 30m SRTM DEM data are controlled by the NGA and use is restricted to certain government agencies under agreements with NGA. 90m SRTM data are publicly available and are distributed by the USGS from the EROS Data Center.

The vertical resolution of the 30m SRTM DEMs is stated as being ±16m for 90% of the data, while the remaining 10% may be greater than ±16m (Rabus et al., 2003). The Vertical datum reference for the SRTM data is mean sea level calculated by the WGS84 Earth Gravitational Model (EGM96) geoid (GLCF, 2004).

RESULTS

Table 1 documents the elevation values for the checkpoints as compared to extracted values from the different DEMs for the study area. A total of 26 checkpoints were compared to each DEM, except for the ASTER DEM which was compared to a subset of 6 checkpoints. Cloud cover in the ASTER image prevented DEM extraction for the entire study area; therefore, points were compared to only those areas where DEM extraction from the ASTER imagery was successful.

Check Point	Check Elevation (m)	10m Contour DEM	30m Contour DEM	30m ASTER DEM	90m Contour DEM	90m SRTM
GRAN	10.66	18.58	17.38		7.52	6.07
GS 15	229.66	216.91	217.43	202.00	209.68	206.45
GT 140	81.86	74.73	74.73		73.76	79.49
GT 161	31.56	29.31	27.38		21.05	14.00
TGPY A	26.16	15.46	15.39		15.39	26.81
TGPY B	12.76	13.17	12.87	10.00	23.92	19.16
G22	838.66	827.98	823.17		827.42	817.11
G25	379.31	366.70	364.96		336.16	345.95
G24	258.63	246.18	246.45		219.52	219.83
G23	32.16	30.73	29.79		5.08	23.38
G16	82.15	77.84	76.87		75.25	60.87
G13	141.88	138.31	138.12		137.33	119.26
GT20	73.76	61.25	65.59	62.00	34.40	65.64
GT22	82.89	78.03	77.44		72.28	60.37
GS9	178.77	169.53	169.74		145.47	175.55
GS14	172.98	163.61	163.50		137.14	173.99
G2	17.22	15.29	15.36		13.12	29.59
GT4	1.07	0.17	0.17		0.66	10.18
GT5	0.76	3.04	3.24		3.24	6.90
GT29	56.85	54.37	51.51	35.00	44.42	20.02
GT10	204.07	200.13	200.13		200.92	186.72
GT28	437.86	441.23	441.88		409.08	412.20
G15	715.84	700.93	701.15		667.64	685.26
G21	682.92	668.88	670.17		651.91	604.18
GS5	134.58	123.99	123.68	113.00	111.41	94.63
G26	197.24	188.02	188.02	163.00	188.20	194.82

Table 1.Check point elevations compared to corresponding DEM elevations.

Table 2 lists the RMSEz values calculated from the checkpoint comparison. Also shown are the expected RMSEz values, and the RMSEz values for elevations below and above 75m.

Source	Total Number of Check Points	Expected RMSEz	RMSEz Below 75m	RMSEz Above 75m	Study Area RMSEz
10m Contour DEM	26	±3.81 - ±7.62	±5.97	±9.73	±8.48
30m Contour DEM	26	±3.81 - ±7.64	±5.38	±10.16	±8.64
30m ASTER DEM	6*	±7 - ±50	±14.41	±28.30	±22.46
90m Contour DEM	26	±3.81 - ±7.64	±16.80	±25.57	±23.30
90m SRTM	26	±16	±14.64	±30.42	±25.53

Table 2. Table showing expected RMSEz values comparison for study area DEM data.

The values indicate that the RMSEz for the 10m Contour DEM is slightly higher than expected overall but falls within the expected RMSEz value for areas lying below 75m. Similarly, values for 30m Contour DEM are slightly higher than expected overall but within expected for areas below 75m. The 30m Contour DEM values are somewhat more accurate than those for the 10m Contour DEM, and this may be a result of smoothing of the 10m Contour DEM during resampling.

An overall value of ±22.46m for the 30m ASTER DEM is within the expected range of RMSEz values (±7m - ±50m), but the RMSEz value for areas below 75m is ±8m better than overall. Areas at lower elevations were not obstructed by cloud cover, and better correlation accounts for much lower RMSEz values.

The overall RMSEz values for both the 90m Contour DEM and the 90m SRTM DEM are above the expected values, and only the SRTM data is within the ±16m RMSEz for areas below 75m.

DISCUSSION

Some of the factors that contribute to DEM accuracy are the quality of the input data, the resolution of the DEM, the methodology of data collection, and the effects of terrain and vegetation.

Horizontal resolution affects the vertical accuracy of DEM data. As pixel size increases, a single DEM pixel value reflects more land area by averaging values within the pixel. For example, the 90m resolution SRTM and Contour DEM data have a single DEM elevation value for an area that is modeled by 9 elevation values in the ASTER and 30m Contour DEM and 81 values in the 10m Contour DEM (Figure 5). The effects of averaging elevation values for larger resolution models make them inherently less able to accurately model smaller variations found within the terrain. Thus, overall RMSEz values increase with resolution from ±8.48m for the 10m Contour DEM to ±25.53m for the 90m SRTM DEM.

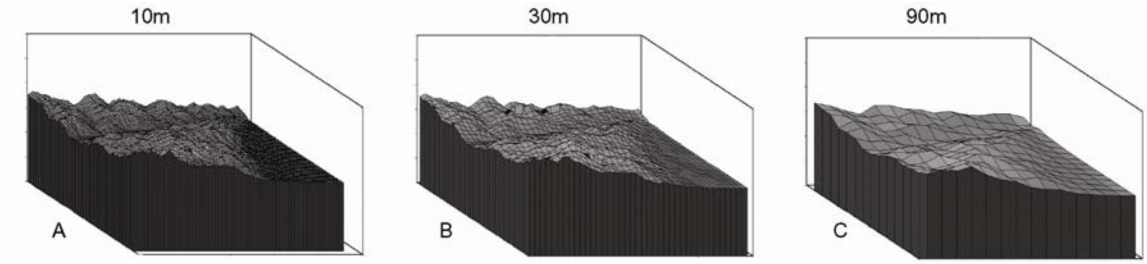

Figure 5. Extracted elevation surfaces showing (A) 10m Contour DEM, (B)30m ASTER DEM and (C) 90m SRTM DEM for 1km square area on the northeastern coast.

The collection date of the source data is also a factor that affects vertical accuracy. Topographic changes over time, either due to physical factors or man-made changes in the environment, can render a DEM inaccurate. This is particularly true for data in proximity to volcanoes, coastal zones, glaciers, areas subject to landslides, and urban areas that may change rapidly. Therefore, the date the original source data was collected is important in understanding and assessing overall accuracy. For example, the original topographic contour data was interpreted from photography flown in 1951 and 1978, but little more information is known about the scale, resolution, and type of photography that was used for contour generation. In reality the DEM developed from this source data is as current as 1978. Similarly, SRTM data was collected in February of 2000, and as dynamic topographic environments evolve, the SRTM data becomes out-of-date. Sources such as ASTER provide the ability to develop DEMs from images collected over time, but because of the vertical accuracy ranges (±7 - ±50m), changes in topographic relief within this range may not be reliably assessed. It is also important to note that, even though ASTERs along-track stereo imaging capability should ensure nearly identical environmental conditions in each image, clouds over Grenada posed a significant challenge to DEM production. Large clouds and their shadows obscure large portions of the central highlands and resulted in no elevation extraction. In addition, areas with low-lying clouds were correlated and erroneous elevations were extracted from tops of clouds.

RMSEz values for topography above 75m were nearly twice those for topography below 75m for all DEMs, with the exception of the 90m Contour DEM. This demonstrates that in areas of higher elevation the magnitude of error increases. Partially, this may be explained by inaccuracies due to horizontal resolution, but may also indicate that lower flatter topography is more simply modeled while higher elevation topography becomes more complex. Another factor may be related to land cover in lower elevation areas, versus land cover in higher elevations.

In Grenada, the topography with the highest relief is dominated by forest vegetation, while areas with moderate slopes are generally under cultivation or are mixed use regions (Ternan et al., 1989). Estimates indicate that 5% of the land area in Grenada is forested, while 53% is covered by shrublands, savannas, and grasslands, and 26% by mixed cropland (Earth Trends, 2003). Generating elevation measurements in areas of heavy vegetation and cloud cover is more difficult for photgrammetry as the interpreter must interpolate contour generation where the ground is not visible in the imagery. InSAR technology using C-band Radar, such as SRTM, penetrates clouds and is able to penetrate up to a few meters into vegetation cover. Chirico (2004) demonstrates that in areas of forested land cover and slopes greater than 25º the C-band Radar penetrates only partially through the canopy before returns are recorded, thereby demonstrating that elevation values in forested areas on steep terrain may more accurately refer to DSM elevations rather than DTM elevations.

DEMs derived from ASTER data are similarly biased toward reporting elevation values, which are averages of tree canopy and manmade structures. Because the ASTER imagery is an optical sensor, pixel values in the imagery encompass all land cover within the pixel. As elevations are extracted from these images the, elevations themselves reflect feature mixing and are likely to incorporate more features than simply the bare earth.

In coastal areas and around lakes, ponds, and marshes, the SRTM data either drops elevation values or erroneous elevation values are reported from irregular surface reflections on top of the water. Areas of wetlands, coastal areas, and around large bodies of water are often dropped out by the SRTM data because RADAR is absorbed and not returned to the sensor (Figure 6). Similarly, ASTER DEMs have problems resolving the coastlines, as water areas do not correlate well. Consequently, with both ASTER and SRTM data, coastal areas and water features need to be masked or filtered to ensure proper elevation values.

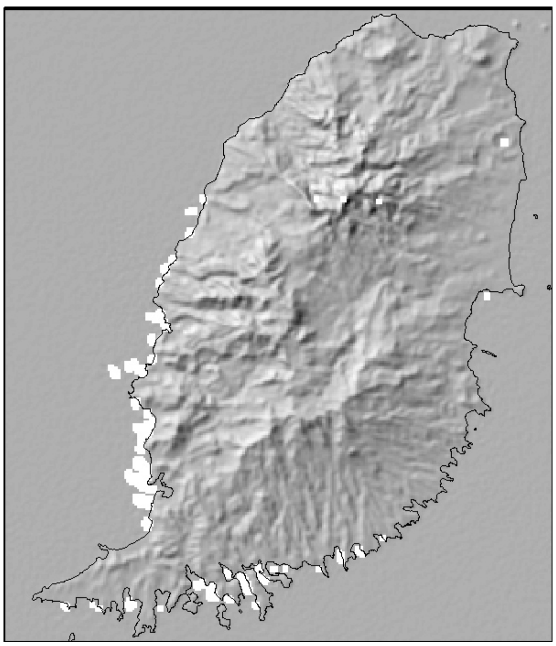

Figure 6. SRTM DEM hillshade showing data gaps in white on south and southwestern coastal areas.

Slope calculations, and other DEM derivative measures, are used in various types of GIS and natural hazards models. Figure 7 shows slope calculations for a small area in western Grenada from three sources of DEM data. The 10m Contour DEM depicts slopes from 10º to areas of greater than 50º. The 30m ASTER DEM's highest slope, in this example, is greater than 30º, while the 90m SRTM DEM shows slopes of no more than 20º. This example illustrates that with increasing resolution slope values are decreased. GIS models relying on accurate slope calculations would yield very different results using the three sources shown in this example.

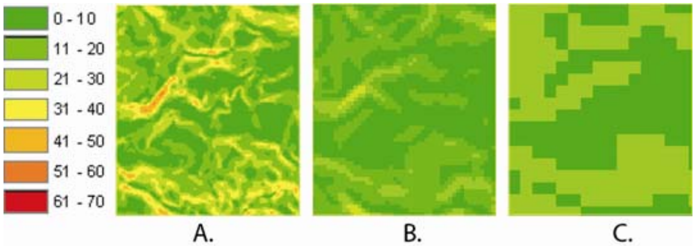

Figure 7. Example of slope calculations (in degrees) from (A) 10m Contour DEM, (B) 30m ASTER DEM, and (C) 90m SRTM DEM.

CONCLUSIONS

One of the most important data inputs for natural hazards mapping is an accurate digital elevation model. DEM data provide risk managers and GIS practitioners with information about the slope and aspect of the terrain and are used heavily in models for landslides, floods, soil erosion, and watershed catchment area studies. Because of the many sources of elevation data available for GIS modeling, care must be taken in selecting the most appropriate data set for the desired application.

Horizontal and vertical data resolution is a critical component to terrain modeling and represents the most important consideration in DEM source selection. Lower resolution data may not provide enough detail to model the necessary processes or may give low resolution results, when, in fact, a higher resolution result is needed. Higher resolution data can be developed from contour-based sources but may be out-of-date or costly to produce for very large areas.

The type of elevation model needed for a particular application is also an important component in selecting DEM data for GIS modeling. DSMs may be more appropriate for terrain correcting imagery, air navigation routing, and wireless communication network modeling because elevations that include man-made structures and vegetation are better suited for these types of applications. For this purpose, both SRTM and ASTER may be appropriate as both types of DEMs yield results which are closer to DSM measurements and both sources also offer a lower cost solution to gathering DEM data over large areas. DTMs are more appropriate for modeling erosion, hydrologic flow and for use in landslide models. Contour-based DTMs and provide better vertical and horizontal resolution for this purpose and topographic source maps are widely available. Some disadvantages to contour-based DTMs are that they may be costly to produce, take more time to process, and may be out-of-date.

Clouds, dense vegetation, and coastal features are important considerations for terrain modeling in the Caribbean. DEMs developed from optical sources such as ASTER and aerial photography may be negatively impacted by the frequency of cloud cover. In contrast, SRTM data penetrates clouds but does not fully penetrate dense vegetation. Therefore, DEMs produced from SRTM may not depict actual land surface elevations. In addition, SRTM data has significant voids in coastal areas which must be masked or filtered to produce a viable DEM.

New technologies such as airborne InSAR and LIDAR are rapidly becoming the choice for GIS practitioners and land managers interested in very-high resolution DEMs. These technologies have matured to become more than experimental and future studies should be conducted to assess these systems for terrain modeling in the Caribbean region.

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