Practical use of SRTM data in the tropics – Comparisons with digital elevation models generated from cartographic data

***Andy Jarvis**, **Jorge Rubiano**, **Andy Nelson**,*
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Centro Internacional de Agricultura Tropical
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***Andy Jarvis*[1], *Jorge Rubiano*[2], *Andy Nelson*[3],**
***Andrew Farrow*[4] and *Mark Mulligan*[5]**

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[1] **Research Fellow, Land-Use Project, International Centre for Tropical Agriculture (CIAT) and the InternationalPlant Genetic Resources Institute (IPGRI), Cali, Colombia, AA6713 (a.jarvis@cgiar.org)**

[2] **Postdoctoral Research Fellow, Land-Use Project, International Centre for Tropical Agriculture (CIAT), Cali, Colombia, AA6713 (j.rubiano@cgiar.org)**

[3] **Research Fellow, Department of Geography, University of Leeds, United Kingdom (a.d.nelson@leeds.ac.uk)**

[4] **Research Fellow, Land-Use Project, International Centre for Tropical Agriculture (CIAT), Cali, Colombia, AA6713 (a.farrow@cgiar.org)**

[5] **Reader, Department of Geography, King's College London, United Kingdom (mark.mulligan@kcl.ac.uk)**

Centro Internacional de Agricultura Tropical (CIAT)
International Center for Tropical Agricultura
Apartado Aéreo 6713
Cali, Colombia

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Introduction

Topography is basic to many earth surface processes. It is used in analyses in ecology, hydrology, agriculture, climatology, geology, pedology, geomorphology, and many others, as a means both of explaining processes and of predicting them through modeling. Our capacity to understand and model these processes depends on the quality of the topographic data that are available. Most countries have much of the land surface covered by cartographic maps at varying scales and of varying accuracies. In most tropical countries, these maps are produced through manual interpretation of stereo pairs of aerial photos, and in some cases the topographic data can be erroneous or missing where cloud was present. With the advent of satellite imagery covering the globe, various global datasets of topography have been produced, of increasingly better resolution, from 10 arc-minutes (approximately 18 km at the equator) to 30 arc-seconds (approximately 1 km at the equator) using the United States Geological Survey (USGS) product, GTOPO30. This topography dataset was widely used for almost a decade, mainly for broadscale assessments. However, the 1-km spatial resolution prevented its use in modeling more detailed earth surface processes, especially in fields such as hydrology, pedology, or small-scale geomorphology. Researchers in these areas had to rely on local maps for the topography. Digitization or photogrammetry, time-consuming and costly processes, was needed to produce high-resolution digital elevation models (DEMs).

In 2003, the National Aeronautics and Space Administration (NASA) released the Shuttle Radar Topography Mission (SRTM) dataset for some regions, with 3 arc-second resolution for the globe, and 1 arc-second for the United States. This giant leap forward in spatial resolution for DEMs with global coverage is likely to change the way in which related research can be performed and applied, bringing local catchment and sub-catchment scale modeling into the realm of global applicability (provided the models require no other non-topographic-derived datasets).

The SRTM DEM data have been produced using radar images gathered from NASA's shuttle. Two antennae received the reflected radar pulses at the same time, one antenna located in the shuttle's cargo bay, the other at the tip of a 60-m-long mast. This configuration allowed single-pass radar interferometry, and consequently the generation of a highly accurate global elevation model with a vertical accuracy of 6 m and a horizontal pixel spacing of 30 m. The data cover the entire globe (latitudes 60N – 60S), with downgraded resolution of 3 arc-seconds. The 1-second original data have been made available to the public only for North America. Whilst the data coverage is global, some regions are missing data because of a lack of contrast in the radar image, presence of water, or excessive atmospheric interference. These data holes are especially concentrated along rivers, in lakes, and in steep regions (often on hillsides with a similar aspect due to shadowing, particularly in the Himalayas and the Andes, for example). This non-random distribution of holes, ranging from 1 pixel to regions of 500 km^2, impedes the potential use of SRTM data, and has been the subject of a number of innovative algorithms for "filling-in" the holes through various spatial analysis techniques. These include spatial filters, iterative hole filling, and interpolation techniques, many of which at the time of publication are still under development and testing.

Given the great demand for a product such as SRTM, it is important to examine carefully the quality of the dataset, comparing it with the best alternative sources for DEM data. Here, we critically examine the quality of SRTM data through direct comparison with cartographically derived DEMs at differing scales and previously available digital topographic datasets. These comparisons are made on simple

altitudinal differences, as well as for first order topographic derivatives, such as slope and aspect, and finally for more complex topographic derivatives calculated through simple hydrological modeling. Specifically, the objectives of this paper are to:

?? **Quantify the differences between SRTM-derived DEMs and previously available DEMs (specifically cartographically derived ones at differing scales and GTOPO30).**

?? **Evaluate the issue of missing data in SRTM, and evaluate a method commonly used for filling these data holes.**

?? **Evaluate the sensitivity and relevance of the differences between DEMs in some practical case studies using simple hydrological models.**

Methods

Five case studies are presented that progressively evaluate the SRTM DEM data in increasing complexity. Each of these case studies uses SRTM data downloaded from the USGS ftp server (ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/), and imported into ArcInfo using a simple Arc-Macro Language program, available for download from http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm. Each individual 1-degree tile is imported and merged to produce continuous DEMs covering the study areas. For this paper, these include all of Ecuador and Honduras, and small catchments (<2000 ha) in the departments of Cauca and Valle del Cauca in Colombia. The spatial resolution of the SRTM data for each of these case studies ranged from 90 m to 92 m depending on the latitude. Each case study discusses the methods adopted individually in greater detail.

Results and Discussion

Ecuador SRTM DEM versus GTOPO30

Introduction

The SRTM product for Ecuador is a 3 arc-second resolution DEM—a far higher resolution than previously has been available publicly for this South American country. Before SRTM data became available, scientists were restricted to the GTOPO 30 arc-second DEM. Apart from the obvious improvement in spatial resolution, we are interested in comparing the absolute differences between these two products in order to assess the consequences of modeling with SRTM data as opposed to GTOPO30, especially any systematic differences between the two sources.

The GTOPO30 DEM is a compilation of various elevation data sources; in Ecuador, two sources were used, the Digital Chart of the World (DCW), and the US Army Map Service in parts of the Amazon Basin. There were also significant areas where no data were available to the USGS team that produced GTOPO30. These no-data areas are found principally on the flanks of the Andes in central Ecuador. The USGS interpolated these data gaps using information from neighboring areas (Bliss and Olsen, 1996).

The vertical accuracy in the DCW is stated as +/- 650 m at the 90% confidence level, although USGS suggests that 160-m linear error is more realistic based on comparisons with higher resolution sources (USGS-EROS Data Center, 1997; Gesch et al., 1999). The vertical accuracy in the SRTM data is stated as +/- 16 m at the 90% confidence level.

Differences between SRTM and GTOPO30 data of more then 176 m therefore will merit some attention, especially if the differences are systematic, and not explained by the source data for the GTOPO30 dataset.

Methods

In order to compare the two sources, it was necessary to aggregate the SRTM data so that there was only one value for each cell in the GTOPO30 surface. We first applied a "block majority" function to the SRTM data to identify areas where no-data values predominated. The blocks of data were 10 × 10 cells and coincided with the extent of the GTOPO30 cells. Predominantly no-data areas in the SRTM surface were discounted. In all other areas, a mean value was calculated for the aggregate elevation value as well as the maximum and minimum elevations encountered in the 100 cells that form the same area as the GTOPO30 cell.

First, we calculated the gross differences between the mean value of the SRTM and GTOPO30 sources. Then GTOPO30 was compared to the range of SRTM values encountered in the larger cell.

Results and discussion

Comparing absolute differences between the GTOPO30 value and the mean value of 100 SRTM values, we have classified five cases. Those where the difference is greater than:

(1) **+666 m (650 m + 16 m from the 90% confidence levels of both sources),**
(2) **+176 m, but less than 666 m (160 m + 16 m from the 90% confidence levels of both sources modified by USGS),**
(3) **–666 m,**
(4) **-176m, but less than –666, and**
(5) **Those that are within the expected accuracies of both sources.**

These results (Table 1) show that 78% of cases are within the strict accuracy limits, 19% are between the two accuracy limits, and 3% are outside all accuracy limits.

Table 1. Relative differences between GTOPO30 and aggregated mean values of Shuttle Radar Topography Mission (SRTM) elevation models.

Difference between sources	Count (1 km^2 cells)	Percentage of study area
<= -666 m	**4376**	**1.42**
-666 m – 176 m	**32070**	**10.38**
-176 m – 176 m	**240463**	**77.81**
176 m – 666 m	**27053**	**8.75**
>= 666 m	**5067**	**1.64**
Total	309029[a]	100

a. The area of Ecuador is about 277,000 km^2. The actual land area of each cell is 0.86 km^2 at the Equator. The study area covers some border areas of Peru and Colombia, and does not consider the Galapagos Islands.

The comparisons shown in Table 1 are for the mean **value of the 100 SRTM cells that form the equivalent area of the GTOPO30 cell. When we compare the GTOPO30 value to see if it falls within the range of the 100 SRTM values, we see that roughly 40%**

of the cells falls within the range, whilst 60% is outside the range. When we combine the two comparisons, we can see how far out are the cells that are outside the range (Table 2). The vast majority is within the range, and of all cases only 11% is greater than +/- 176 m outside the range of maximum and minimum values. However, this is still a large number, and when we observe the spatial distribution of these cases, they are not randomly distributed, but are clustered on the fringes of the Andean cordilleras (Figure 1).

Table 2. Relative differences between GTOPO30 and aggregated mean, maximum, or minimum values of Shuttle Radar Topography Mission (SRTM) elevation models.

How far out of min.-max. range	Count (1 km² cells)	Percentage of study area
Inside range	**124839**	**40.48**
<= -666 m	**2808**	**0.91**
-666 - -176 m	**16341**	**5.30**
-176 – 176 m	**148843**	**48.26**
176 – 666 m	**12752**	**4.13**
>= 666 m	**2828**	**0.92**
Total	308411	100

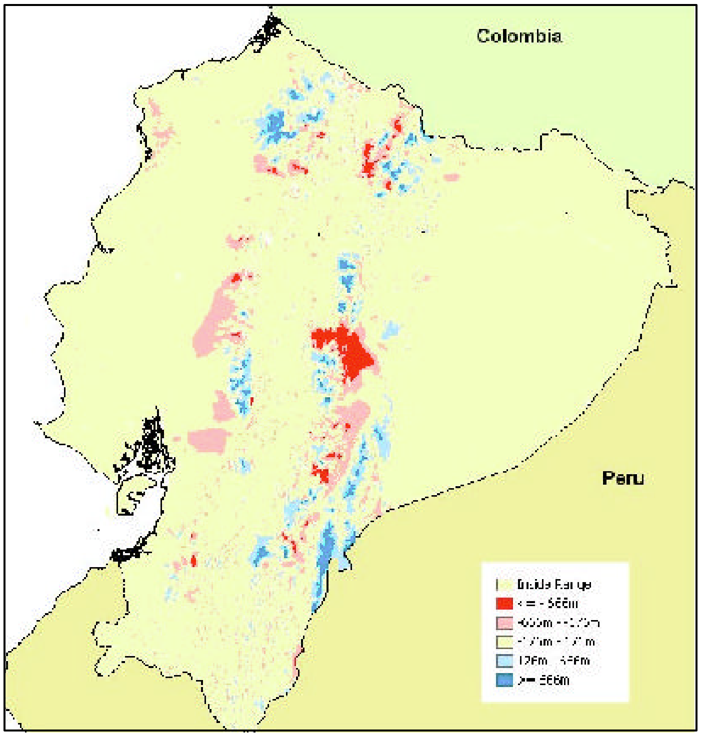


Figure 1. Relative differences in Ecuador between GTOPO30 and aggregated Shuttle Radar Topography Mission (SRTM) elevations where GTOPO30 falls outside the range of SRTM values.

Comparing the two data sources, we see that vast contiguous areas of GTOPO30 elevation cells are either significantly below or above the range of values found in the SRTM data source. We have access only to a low-resolution image of these no-data areas, but they roughly coincide with the no-data areas encountered in the DCW, which were interpolated using data from neighboring areas (Figure 2). If we assume that the SRTM data are accurate to +/- 16 m, then the interpolation errors in the GTOPO30 are significant in these areas, and users should be aware of these discrepancies when using this data source—designed for a global perspective—for local modeling.

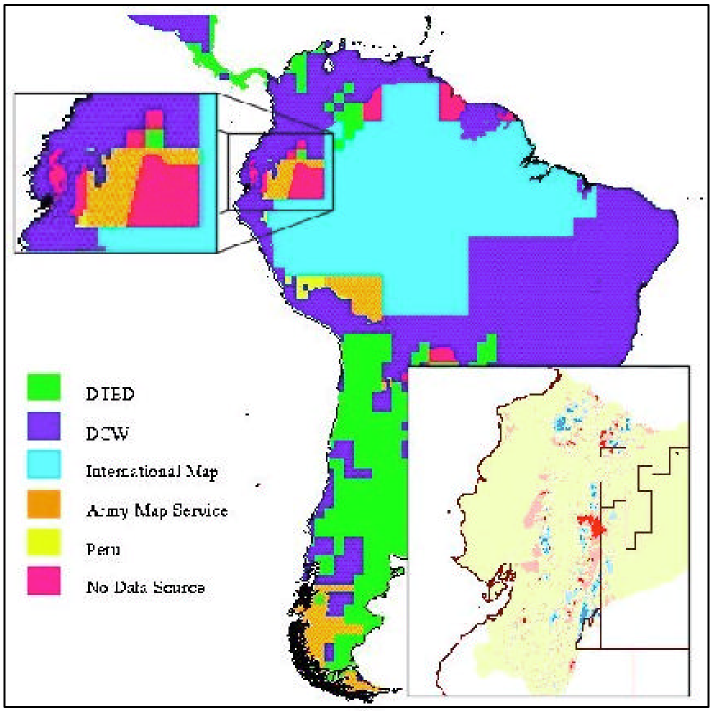


Figure 2. Sources of data for GTOPO30 elevation model in South America, and relative difference between GTOPO30 and Shuttle Radar Topography Mission (SRTM) elevation models with source data boundaries overlaid (inset).

Honduras SRTM DEM versus 1:50,000 cartographically derived DEM

Introduction

This case study examines relative and absolute differences between the SRTM DEM and a cartographically derived (TOPO) DEM using 1:50,000 scale cartography, digitized for all Honduras. Over the last decade, the Centro Internacional de Agricultura Tropical (CIAT) has invested heavily in data collection and data generation in Honduras. Most of the spatial data used in this research has been made freely available via digital products, such as CIAT's Mitch Atlas, a CD-ROM of over 100 digital maps and data tables of Honduras (Barona et al., 1999). CIAT's efforts and the international interest shown in the region, particularly after Hurricane Mitch, have made Honduras unusually data-rich, relative to other countries in the region (Knapp et al. 1998; Leclerc 1999). Three separate methods are used to examine the DEM differences at the national scale.

Methods

The SRTM 3 arc-second data used were processed as described at the start of the methods' section of this paper. The final DEM has a cell resolution of 90 m at this latitude.

CIAT purchased the full set of 280 topographic sheets of the entire country at 1:50,000 scale that were based on multiple surveys over the last 50 years. The Center also obtained an unfinished set of 250 digitized map sheets from the Honduran Forestry Commission (COHDEFOR, the Spanish acronym). CIAT completed the task of digitizing and rectifying these map sheets, and generated a set of coverages that includes lakes, rivers, and contour lines at 100-m intervals with supplementary contours at every 10 m for elevations lower than 100 m above sea level. These three coverages were used to create a 90-m resolution DEM in the ArcInfo TOPOGRID environment, such that the extent and cell size match the SRTM DEM.

Ground truth elevation values for specific point locations were extracted from the National Geodetic Survey (NGS) GPS database from the Central America High Accuracy Reference Network (HARN) project (NGS, 2003). This online database contains 59 elevation values from GPS survey points in Honduras, taken between January and March 2001. Such high accuracy networks are intended to have a vertical accuracy of 5 cm at the 95% confidence level (Zilkoski et al., 1997).

All data were projected to the Honduran National Geographic Institute's (NGI's) official projection for Honduras, Universal Transverse Mercator (UTM) Zone 16. Both DEMs were used as input to the TARDEM software package, and used to fill any "pits" in the surfaces in line with drainage constraints (Tarboton, 2000).

The comparative analysis adopted three distinct methods to evaluate and compare the DEMs, each with increasing levels of complexity:

(1) Elevation values were extracted from both DEMs and compared with the GPS points to determine the difference in meters, and as a percentage.

(2) The TARDEM package and the ArcInfo GRID environment were used to compute slope, aspect, and curvature surfaces for both DEMs. The differences between the indices were assessed and compared using a Pearson's Correlation Coefficient.

(3) Terrain typology was calculated using 15 classes of terrain based on elevation and surface roughness (Meybeck et al. 2001).

These two components (elevation and surface roughness) were modeled using nine window sizes from 3×3 cells to 19×19 cells (270 m × 270 m to 1710 m ×1710 m) to determine the cell-by-cell differences in the typology generated from the two datasets across a range of spatial scales that are typical of national-level studies. The typology was generated at each window size for both DEMs, and a cross-tabulation was performed to determine the level of agreement between the two at each window size.

Results and discussion

Of the 59 GPS points (Figure 3), the SRTM elevation values were closer to the GPS elevation values on 47 occasions (80%). The average difference between SRTM and GPS elevations was 8 m, whereas the difference between TOPO and GPS elevations was 20 m. SRTM data underestimated the elevation on 44 occasions (75%) compared to 52 (88%) for the TOPO elevations. The percentage difference shown in Figure 4 for GPS points at elevations above 100 m show that SRTM data are consistently better than those of TOPO.

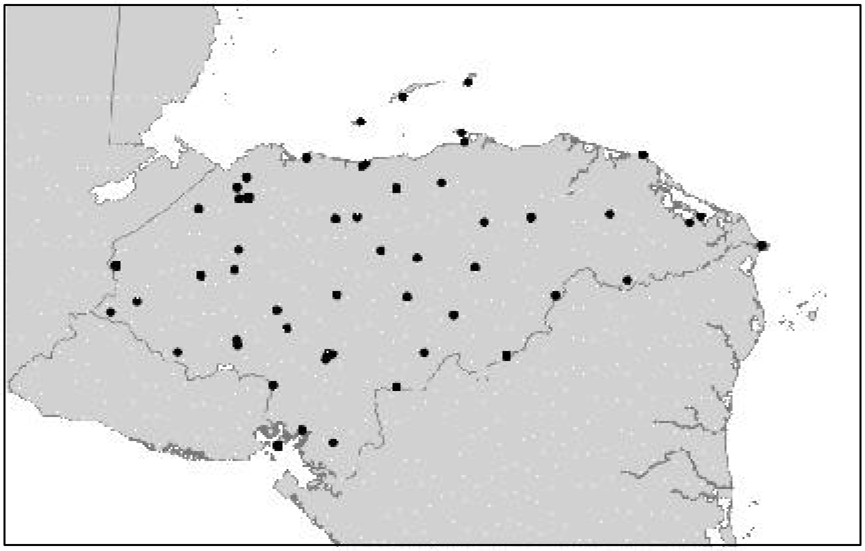


Figure 3. Location of global positioning system (GPS) points in Honduras.

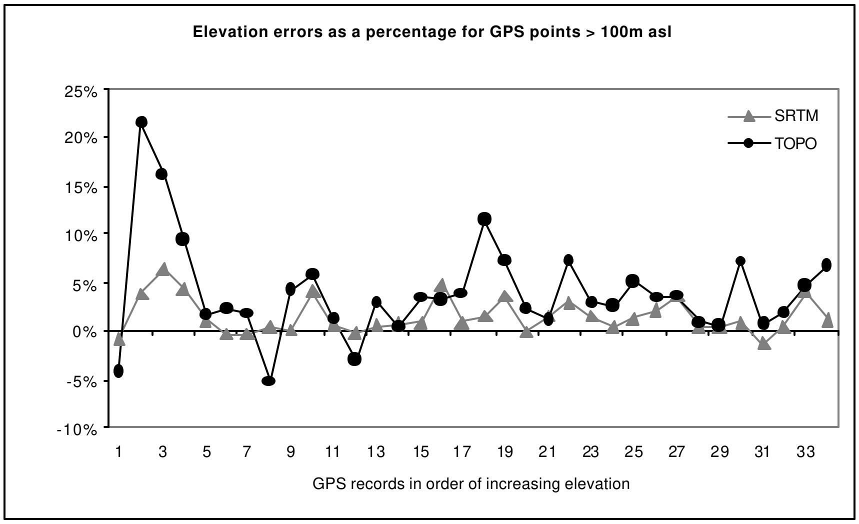


Figure 4. Percentage errors in elevation from global positioning system (GPS) points for SRTM and TOPO digital elevation models.

The elevation differences between the DEMs were mapped and found to be heavily influenced by the aspect of terrain (Figure 5). Figure 6 shows the elevation difference in meters between the two datasets when the terrain is classified into eight aspect directions (north, northwest, etc.). Clearly, there is a trend where SRTM elevation values are higher than TOPO values when the terrain has a north-, northeast- or east-facing slope, and TOPO elevation values are higher when the terrain has a south-, southwest- or west-facing slope, although the differences are not so pronounced. These differences (SRTM data overestimate for northeast-facing slopes and underestimate for southwest-facing slopes) correlate to the shuttle flight path directions available at

http://www2.jpl.nasa.gov/srtm/datacoverage.html. Differences between indices based on higher derivatives (slope, curvature, etc.) also were noted. For example, SRTM slope values were consistently higher by an average of 1.8 degrees across Honduras, but it was found that the spatial pattern of these differences was not systematically related to aspect.

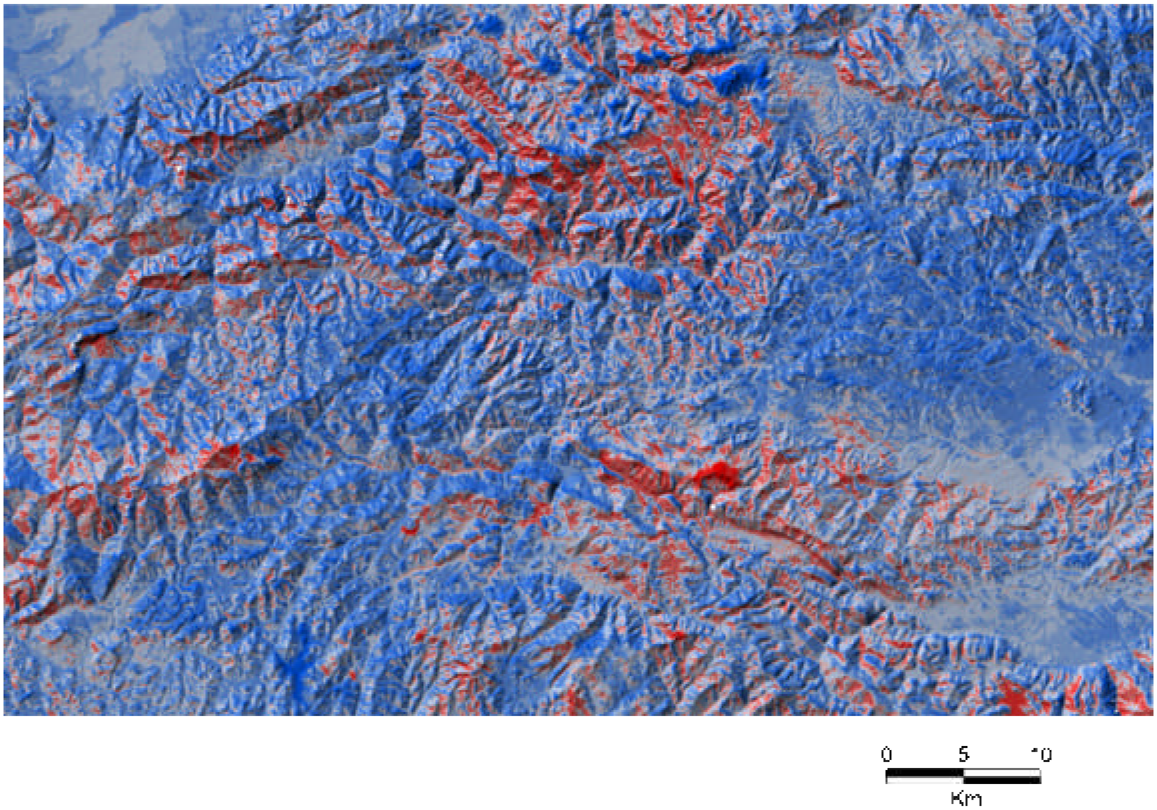


Figure 5. Difference in elevation values shaded by aspect for a specific region within Honduras.

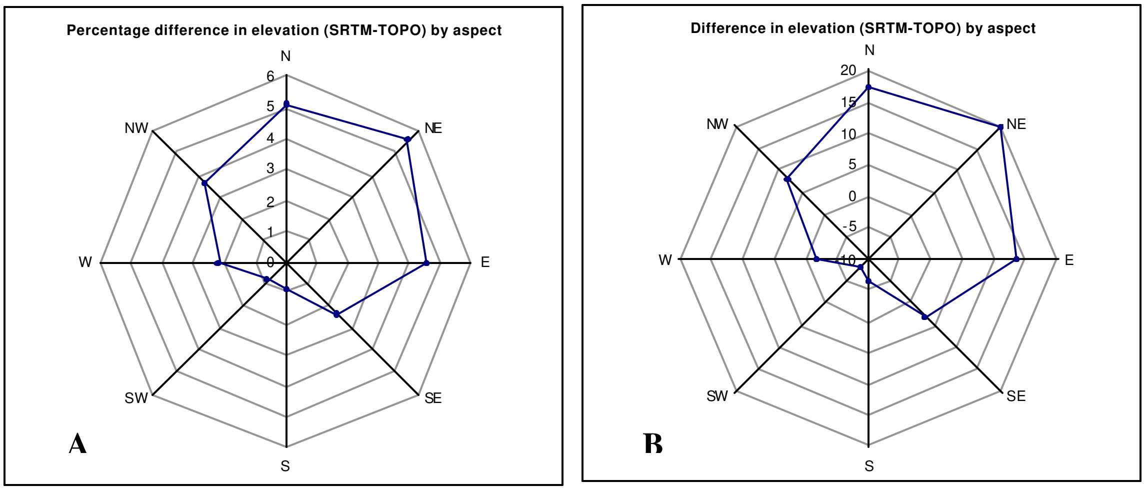


Figure 6. Elevation differences between SRTM and TOPO digital elevation models (A) in meters and (B) as a percentage.

Table 3 shows that the level of agreement between the terrain typology of the two DEMs increased as the window size increased, from 75% agreement at the finest level of detail to 89% at the coarsest level, although most of this increase occurs between window sizes of 3×3 and 7×7 cells, implying that the high level of topographic detail in the SRTM data is quickly filtered out as the window size increases. Tables 4 (SRTM) and 5 (TOPO) show a simplified typology of plains, lowlands, plateaus and hillsides/mountains, with the percentage of cells in each class for each window size. SRTM consistently has a higher percentage of cells in hillsides/mountains than has TOPO. Hillsides/mountains are characterized by high surface roughness, which is more evident in the SRTM data as opposed to the smoother elevation surface derived from the interpolated TOPO surface.

Table 3. Results from terrain typology cross tabulation using 3×3 to 19×19 windows.

Window size			Overall agreement (%)
Pixels	Meters	Area (km^2)	Accuracy
3	**270**	**0.0729**	**75**
5	**450**	**0.2025**	**81**
7	**630**	**0.3969**	**84**
9	**810**	**0.6561**	**86**
11	**990**	**0.9801**	**87**
13	**1170**	**1.3689**	**87**
15	**1350**	**1.8225**	**88**
17	**1530**	**2.3409**	**88**
19	**1710**	**2.9241**	**89**

Table 4. Simplified typology percentages for the SRTM digital elevation model.

Window size			Cells in each class (%)			
Pixels	Meters	Area (km^2)	Plains	Lowlands	Plateaus	Hills/ mountains
3	**270**	**0.0729**	**15**	**12**	**7**	**66**
5	**450**	**0.2025**	**17**	**10**	**7**	**66**
7	**630**	**0.3969**	**18**	**9**	**7**	**66**
9	**810**	**0.6561**	**19**	**8**	**8**	**65**
11	**990**	**0.9801**	**19**	**8**	**9**	**64**
13	**1170**	**1.3689**	**19**	**8**	**9**	**64**
15	**1350**	**1.8225**	**19**	**8**	**10**	**63**
17	**1530**	**2.3409**	**19**	**8**	**11**	**62**
19	**1710**	**2.9241**	**19**	**8**	**12**	**61**

Table 5. Simplified typology percentages for the TOPO digital elevation model.

Window size			Cells in each class (%)			
Pixels	Meters	Area (km^2)	Plains	Lowlands	Plateaus	Hills/mountains
3	270	0.0729	22	8	12	58
5	450	0.2025	21	8	11	60
7	630	0.3969	21	8	11	60
9	810	0.6561	20	8	12	60
11	990	0.9801	20	8	12	60
13	1170	1.3689	20	8	14	58
15	1350	1.8225	20	8	15	58
17	1530	2.3409	20	7	15	57
19	1710	2.9241	20	8	16	57

Conclusions

The results of this case study show that the SRTM DEM is more accurate than the 1:50,000 scale cartographically derived (TOPO) DEM for Honduras, as shown by comparison with field-based measurement of GPS points. The SRTM DEM has an average error of 8 m as opposed to 20 m for the TOPO DEM. However, some systematic errors were identified in the SRTM data, related to aspect. The errors are found to be highest in northeast-facing slopes. This can be attributed to the effect of incidence angle of the original radar images used to produce the SRTM DEM. Finally, the SRTM DEM was found to contain more surface detail and roughness than the TOPO DEM.

Dapa case study: Absolute and relative differences between DEMs at the sub-catchment scale

Introduction

This case study examines relative and absolute differences between the SRTM DEM and a cartographically derived (TOPO) DEM using 1:10,000-scale cartography for a small catchment with special attention to hydrological derivatives. Cartography at this scale is the best source for generating DEMs, but exists for very few areas in most tropical countries. Since, as shown above, 1:50,000-scale cartography fails to stand up to the quality of SRTM DEMs, this study examines whether this continues to be true for cartography at 1:10,000 scale.

Specifically, the objectives of this case study are to:

?? Compare absolute and relative differences between cartographically generated DEMs and SRTM DEMs at 1:10,000 scale using field-based GPS surveys as a baseline; and

?? Examine in detail at the catchment scale the differences in first order DEM derivatives (slope) and some basic hydrological derivatives, such as stream networks, watershed boundaries, and wetness indices.

Methods

The study site is in the Dapa region in Valle del Cauca, Colombia, and includes the area around a 5000-ha micro-catchment. The selected area is an 8- × 5-km rectangle of the eastern flank of the western cordillera of the northern Andes located at

3° 35' N –76° 35' E. Cartography at 1:10,000 scale is available for this region, and has been digitized to produce coverages of contour lines, rivers, and spot altitudes. These data were used to produce two cartographically derived DEMs with differing spatial resolution of 92 m to compare directly with the SRTM DEM at this latitude, and 25 m to show the full level of detail that the cartography contains. TOPOGRID was used and tolerances set at 5 for "tolerance 1", representing the density and accuracy of input topographic data, with a horizontal standard error of 1 and vertical standard error of 0. Throughout the text, these two DEMs are referred to as TOPO 92 and TOPO 25. The SRTM data were extracted also for this region—the original data hereon referred to as SRTM 92—and were re-sampled to 25-m resolution using TOPOGRID (SRTM 25) to provide a higher resolution DEM. Use of these four DEMs may confuse the analysis somewhat, but is necessary in order to permit direct comparison between same-resolution DEMs. Original SRTM data came without data holes.

Absolute differences and attributes derived from the four different DEMs were compared. A GPS survey was carried out in the area to identify relative differences between SRTM and the cartographically derived DEMs. Forty-five different sites were georeferenced with high-precision GPS (Leica WILD GPS – System 300, including CR333 controls, SR299E sensors, and AT202 antennas). The approximate horizontal and vertical errors of these GPS points were below 10 cm, both in the horizontal and vertical. The Leica SKI-Static Kinematic Software Version 2.6 software was used for data processing.

Results and discussion

Figure 7 shows the four DEMs used in this study. The topography in the SRTM 92 appears rougher than that of the TOPO 92. However, at 25-m resolution, the true detail that the cartography contains becomes apparent, with much greater topographic detail in TOPO 25. This observation is more formally explored in the analysis of topographic derivatives later in the case study.

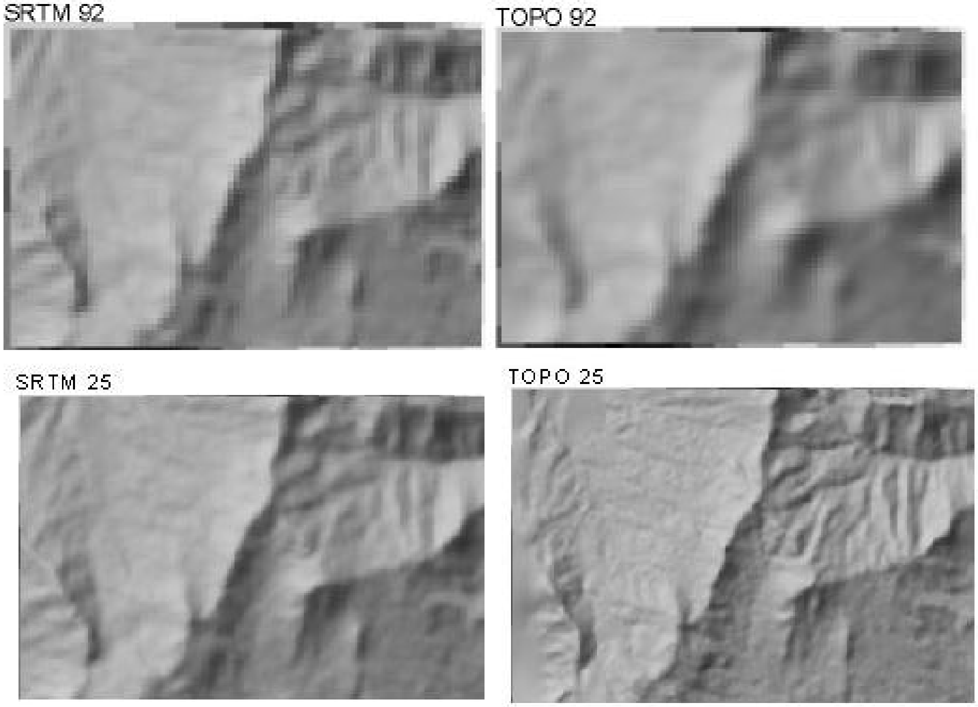
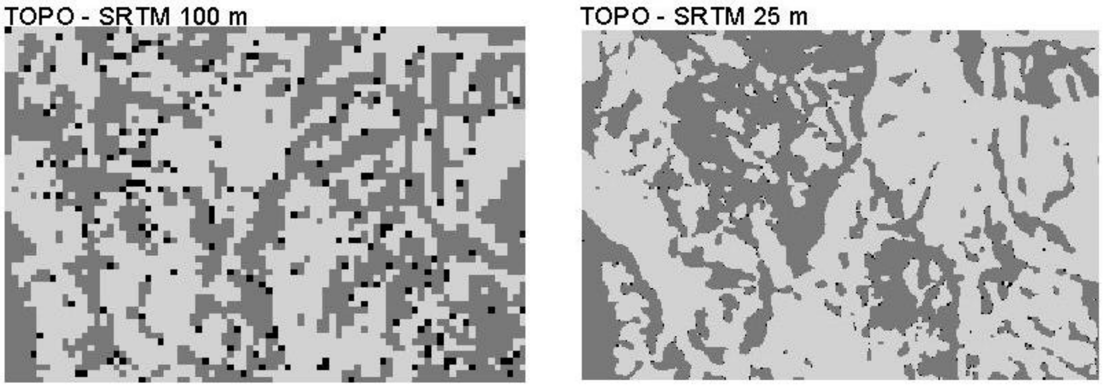


Figure 7. The four digital elevation models used in this study.

Figure 8 shows the absolute differences between the same pixel pairs of the DEMs. There were more pixels (189) without differences in values at 92-m resolution; while in a more detailed 25-m resolution, only one pixel had the same value in both DEMs (Table 6). TOPO 92 had 54% of pixels with higher values for the altitude, while 42% were lower than SRTM 92. The trend was the same at 25-m resolution, but higher values in the TOPO 25 were found in 61% of the pixels, indicating that the topographic-derived DEMs tend to produce higher peaks and ridges.


TOPO - SRTM 100 m

TOPO - SRTM 25 m

Figure 8. Absolute differences between digital elevation models (DEMs), black (no difference), light gray (negative differences), and dark gray (positive differences).

Table 6. Absolute differences between 92-m and 25-m digital elevation models.

Models	**Positive differences**	**Same**	**Negative differences**
SRTM 92 – TOPO 92	**1936 (42%)**	**189 (4%)**	**2467 (54%)**
SRTM 25 - TOPO 25	**23876 (39%)**	**1**	**37429 (61%)**

GPS data correlate better with the 25-m topographic DEM than with the SRTM. Figure 9 shows a comparison between GPS, SRTM, and TOPO altitudinal values where GPS values proved higher in general. When compared with SRTM data, GPS data contained differences, especially on ridges and at peaks. The correlation was still high comparing SRTM and TOPO data (Figure 10).

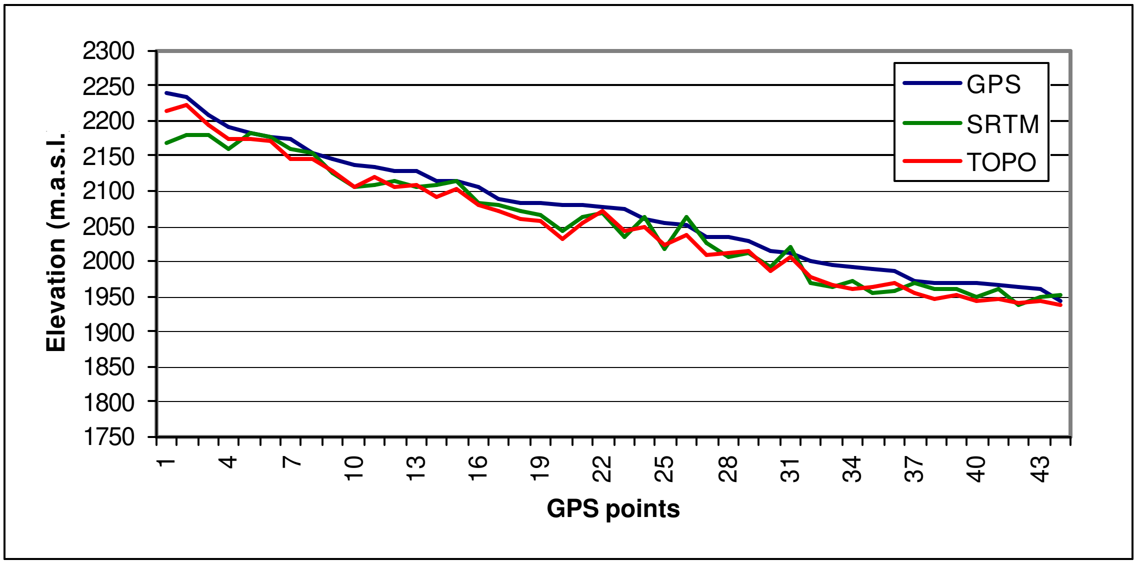


Figure 9. **Relative differences between the altitudinal values of global positioning system (GPS), Shuttle Radar Topography Mission (SRTM), and topographically generated (TOPO) digital elevation models.**

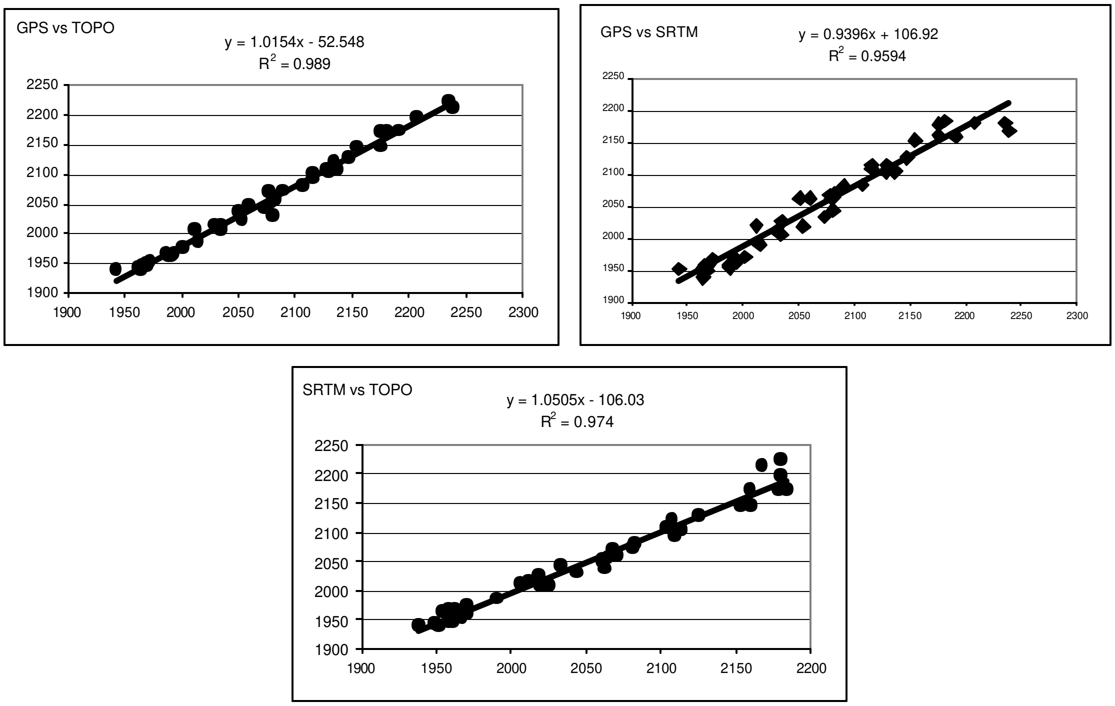


Figure 10. **Regression plots between the global positioning system (GPS) data and altitudinal values of SRTM 25 and TOPO 25 digital elevation model pixels.**

Table 7 presents the basic statistics for the slopes of the modeled DEMs. The mean slope confirms that TOPO 92 is the least rough, but this trend is reversed at the 25-m resolution with TOPO presenting the greatest roughness. SRTM tends to have similar values at 92-m and 25-m resolution, whereas the cartography clearly contains greater detail than is represented in TOPO 92. This can be seen also in the minimum, maximum, and range values of slopes found in the DEMs. Statistics for the SRTM 92 are closer to TOPO 25 than to TOPO 92. The fact that little difference is found between SRTM 92 and SRTM 25 indicates that no extra data are being used to actually improve the resolution, whereas the 1:10,000 cartography being used to produce TOPO 92 and TOPO 25 contains greater topographic richness than is represented in the 92-m resolution DEM.

Table 7. Statistics for the slopes (in percentages) of the digital elevation models (DEMs).

Statistics	DEMs[a]			
	SRTM 92	TOPO 92	SRTM 25	TOPO 25
Number of pixels	**4592**	**4592**	**61306**	**61306**
Mean	**27.34**	**24.58**	**27.97**	**31.28**
s	**12.89**	**11.20**	**12.40**	**16.12**
Min.	**0.85**	**0.42**	**0.23**	**0.07**
Max.	**81.02**	**59.80**	**73.68**	**108.02**
Range	**80.17**	**59.37**	**73.45**	**107.94**

a. SRTM 92 = original data; TOPO 92 = 92 m spatial resolution; SRTM 25 = original data re-sampled to 25-m resolution using TOPOGRID to provide a higher resolution digital elevation model; and TOPO 25 = 25-m spatial resolution.

Figure 11 shows the location of sinks identified in each of the models. TOPO 92 contained a single sink, and TOPO 25 also contains sinks in the same area plus additional sinks in the northwest of the map. The SRTM DEMs contain sinks only in the northwest of the map, and present little difference between the 92-m and 25-m resolution DEMs.

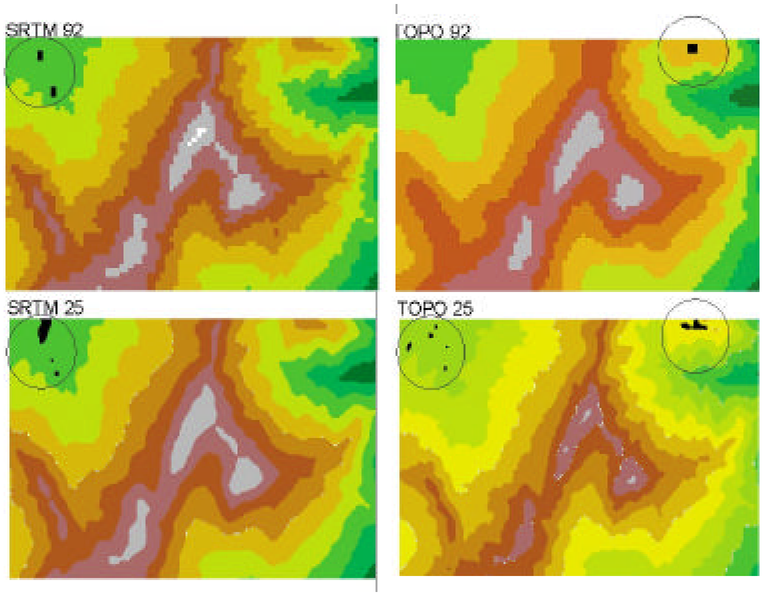
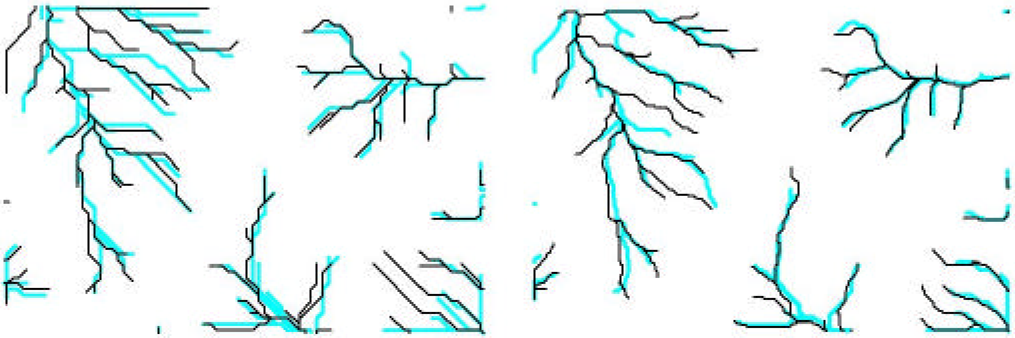


Figure 11. Location of sinks in each of the SRTM and TOPO digital elevation models.

The stream network derived from DEMs represents the pattern of flow accumulation and the potential location of river networks. The configuration of the landscape is used to generate this feature. As Figure 12 shows, the 92-m resolution has greater difference in stream network than has the 25m-resolution. Much greater detail is evident at 25 m in both DEMs, with greater meandering and therefore longer flow lines. No big differences are evident between 92-m and 25-m resolution, with all the major channels correctly identified.



(A) (B)

Figure 12. Comparison of stream networks from the (A) 92-m and (B) 25-m digital elevation models (DEMs). Blue = SRTM DEM and black = cartographically derived TOPO DEM.

The watershed system generated with the different models (Figure 13) shows differences in the number of watersheds and in their configuration. Differences were higher between the 92-m DEMs than in the 25-m DEMs.

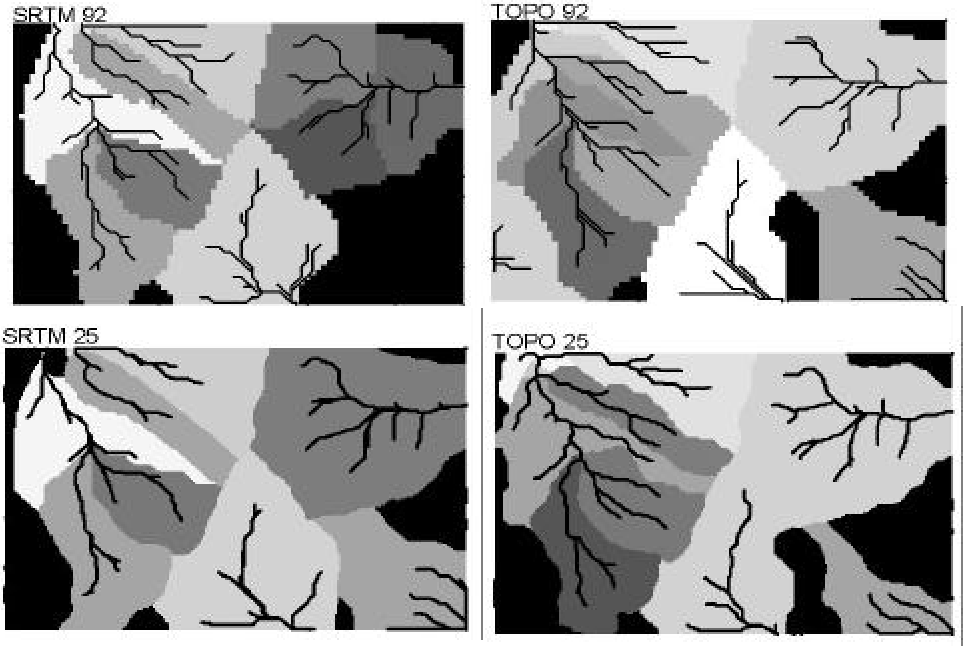


Figure 13. Watershed boundaries from the four different digital elevation models.

Table 8 summarizes the differences found in this topographic feature. For the Lambda value, or mean in this table, there were no great differences between DEMs of the same resolution. Differences in the hydrological responses of catchments having these slight differences are unlikely.

Table 8. Summary statistics for the wetness index of each of the four digital elevation models (DEMs).

Statistics	DEMs[a]			
	SRTM 92	TOPO 92	SRTM 25	TOPO 25
Number of pixels	**4592**	**4592**	**61301**	**61306**
Mean	**11.59**	**11.94**	**9.93**	**9.41**
s	**1.73**	**1.66**	**1.70**	**1.83**
Min.	**9.26**	**9.56**	**6.74**	**6.36**
Max.	**19.90**	**19.87**	**26.28**	**24.71**
Range	**10.64**	**10.31**	**19.54**	**18.35**

a. SRTM 92 = original data; TOPO 92 = 92-m spatial resolution; SRTM 25 = original data re-sampled to 25-m resolution using TOPOGRID to provide a higher resolution digital elevation model; and TOPO 25 = 25-m spatial resolution.

Conclusions

This analysis shows that the SRTM DEM tends to underestimate elevation in peaks and ridges, and at this fine scale the 1:10,000 cartography produces a more accurate and more detailed DEM. This is far more evident at 25-m than at 92-m resolution, indicating that cartography at this scale can provide much more topographic detail. Some basic hydrological analyses show that the greater differences are found between changing the cell resolution as opposed to between the DEM sources (i.e., SRTM vs. TOPO).

Tambito case study: Evaluation of a hole-filling algorithm

Introduction

This case study seeks to examine in detail the accuracy of the "no-data hole-filling" algorithm popularly used in processing SRTM DEM data. This involves the contouring of the raw DEM with a defined contour interval, and the subsequent re-interpolation of these contours to create a new DEM that includes interpolated elevational values through no-data holes. The final DEM contains the original elevation values of the areas with data, but includes the interpolated elevation values in place of the holes. This process is essential if the DEM is to be used for hydrological applications, maintaining the integrity of flow lines across the landscape.

In the context of this case study, a processed SRTM DEM is compared with a TOPO DEM to examine the accuracy of this hole-filling algorithm. We assume that the elevations in the original cartography are correct, although evidence contained in this paper indicates that errors can be significant.

Methods

The study site is the area around the Reserva Tambito in Cauca, Colombia, which has been studied extensively for its hydrology, ecology, and biodiversity (Jarvis, 2000;

Rincon-Romero, 2000; Gonzalez and Jarvis, 2004). It is a private nature reserve, located on the western flank of the western cordillera of the Northern Andes, with steep topography and a wide altitudinal range from 1100 m to 2900 m.

Contours with a vertical interval of 50 m were digitized from 1:50,000 cartography. ArcInfo's TOPOGRID algorithm then was used to produce a 92-m DEM (TOPO 92), with the tolerances set at 5 for "tolerance 1", representing the density and accuracy of input topographic data, and a horizontal standard error of 1 and vertical standard error of 0. The SRTM DEM data also were imported for this area, and cut to the size of the Reserva Tambito region (6 km × 7.3 km). At this latitude, the 3 arc-second product has a cell size of 92 m (hence the name SRTM 92). Both DEMs are shown in Figure 14.

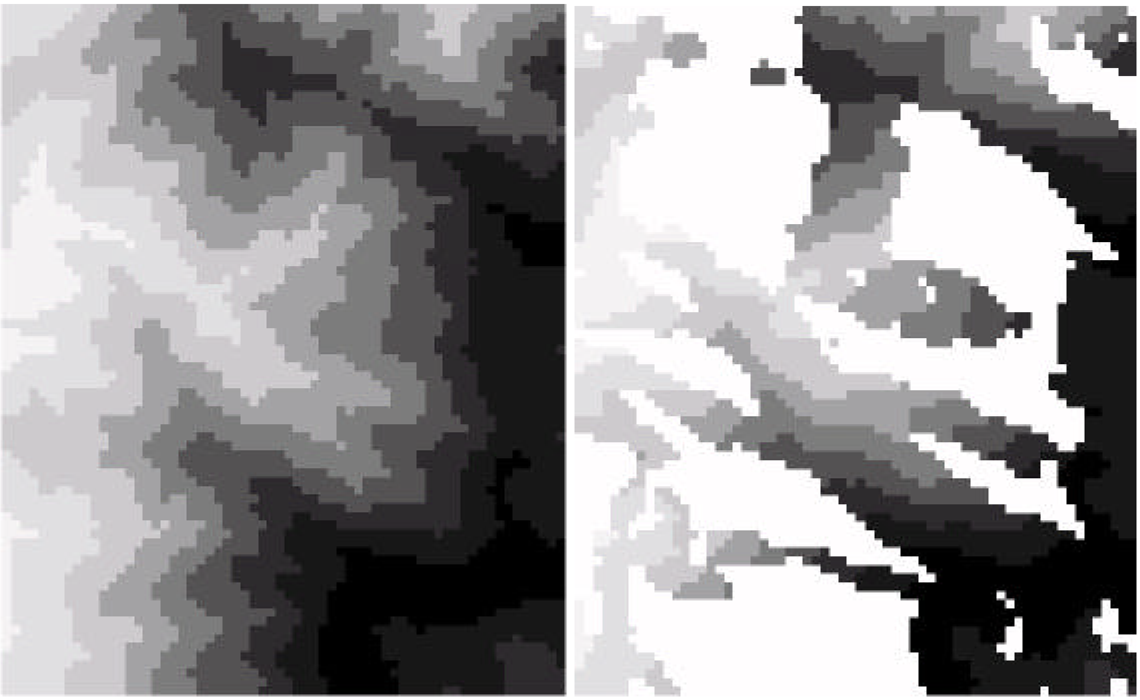


Figure 14. Original digital elevation models (DEMs) for the Tambito study site: (A) TOPO 92, cartographically derived DEM from 50-m interval contours, and (B) SRTM original DEM, with no-data holes in white.

The raw SRTM DEM was contoured with intervals of 10 m, and re-interpolated within ArcInfo TOPOGRID using the same tolerance parameters. Those areas originally with no-data values were replaced by the interpolated values (maintaining the original DEM values where data were available in the raw image) to produce the processed SRTM DEM.

The resultant DEMs were statistically compared under two circumstances:

(1) **SRTM original DEM versus TOPO DEM only in areas with original SRTM data.**
(2) **SRTM interpolated DEM versus TOPO DEM only in areas with originally missing SRTM values.**

The comparisons are made for elevation, but also first-order derivatives of elevation, including slope and aspect. Aspect was calculated using a northness index so that the variable was continuous and quantitative (aspect cannot be correlated because

359 degrees is actually just 2 degrees different to 1 degree despite the 358 degree numerical difference). Northness was calculated using the following equation, after Zar (1999):

Northness = cos ((aspect in degrees * PI)/180)

Results and discussion

The original SRTM DEM had 2158 cells of missing data (42.7%), covering 20.0 km^2. Figure 15 shows the processed DEM, with all data holes filled in through interpolation. Many of the large areas with missing data have a very smooth topographic appearance. Comparing this directly with the TOPO DEM, the general topographic trend is captured, but some micro-valleys and ridges are not detected (Figure 16).

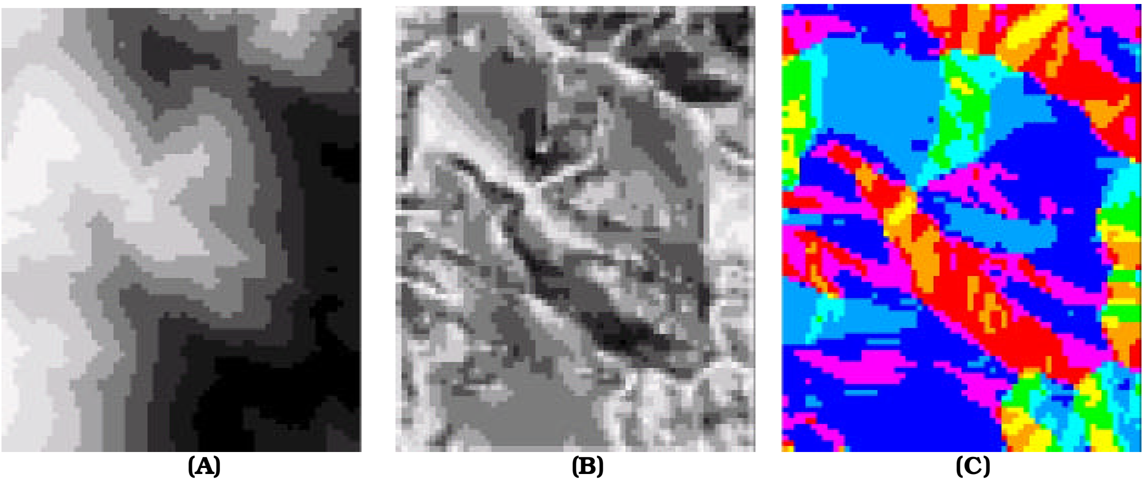


Figure 15. Processed SRTM digital elevation model and derivatives: (A) SRTM 92, (B) Derived slope, showing homogenous slopes in filled data holes, and (C) Derived aspect, also with homogenous areas within filled data holes.

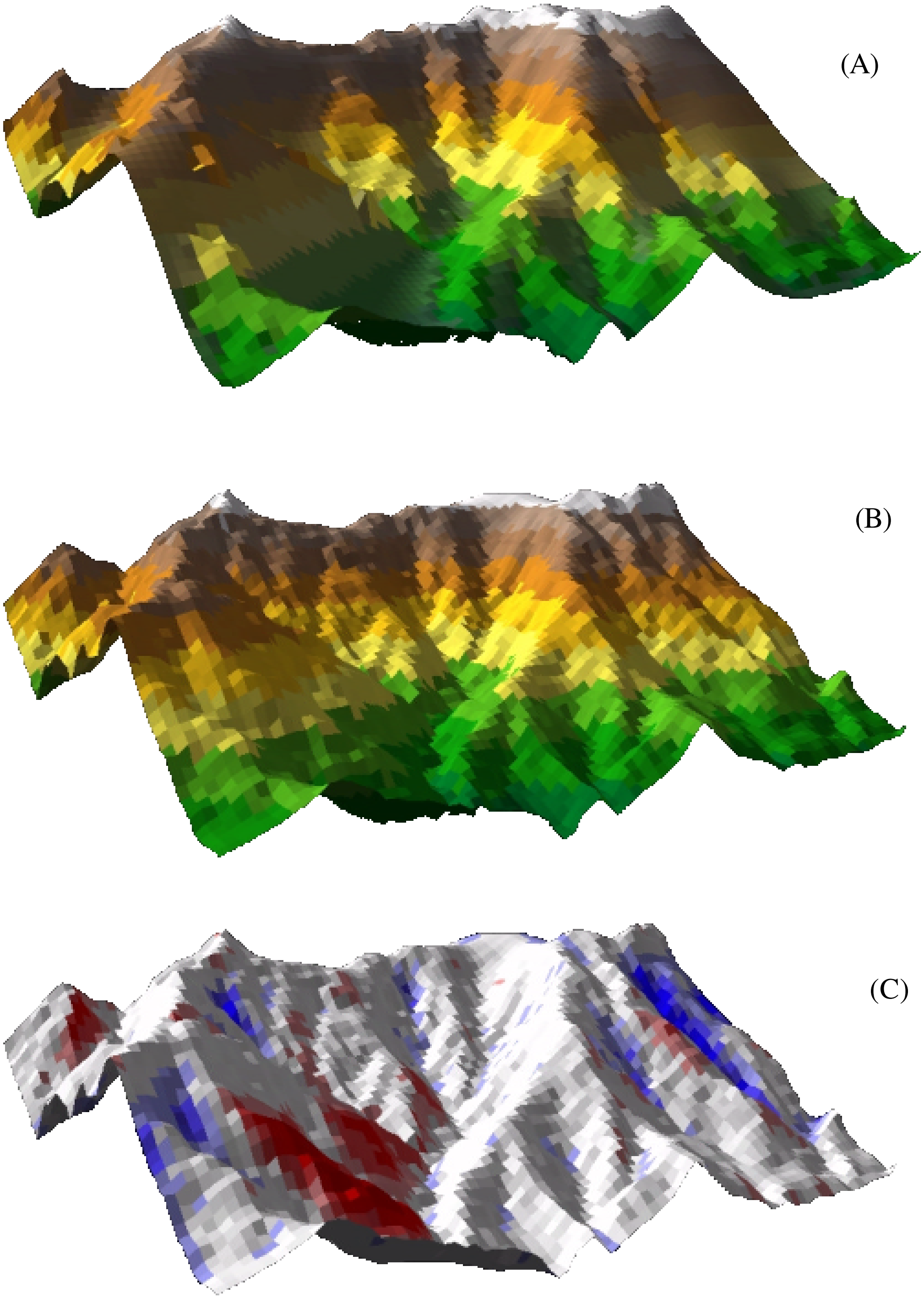


Figure 16. Three dimensional visualization of (A) The processed SRTM digital elevation model (DEM), SRTM 92, with dark shading on the areas where there were missing data, (B) TOPO 92 DEM, and (C) the difference between the two (red indicating that TOPO 92 > SRTM 92).

As can be seen in the 3D drape of the difference between the two DEMs (Figure 16), some ridges and valleys are not represented in SRTM 92 because the missing data hole is too large for the surrounding areas to indicate their existence for the interpolation. Also evident is a clear aspect effect, where many of the missing data holes occur in southeast-facing hillsides, with high slopes.

Performing a more rigorous statistical analysis of these differences, Figure 17 shows a number of scatterplots examining the difference between the DEMs, separated for areas with original SRTM data, and areas originally with missing SRTM data values. In the data areas, both DEMs compare very closely, with an average difference of just 14.4 m (standard deviation 27.3, maximum 99.6 m), and an R^2 of 0.997. In missing data areas, the two DEMs still compare quite closely, with an average difference of just 5.0 m (standard deviation 69.6, maximum 257 m), and an R^2 of 0.974. This indicates that the interpolation method for filling missing data areas provides very representative altitudinal values. However, examining the effect of the interpolation on first-level DEM derivatives shows a weaker relationship. Slope values differ more greatly for data regions, with an R^2 of just 0.78, but this is evidently worse for missing data regions, with the relationship slipping to an R^2 of 0.37. Aspect also is represented poorly by the interpolation process, with an R^2 of 0.60 for data regions, and just 0.30 for missing data regions.

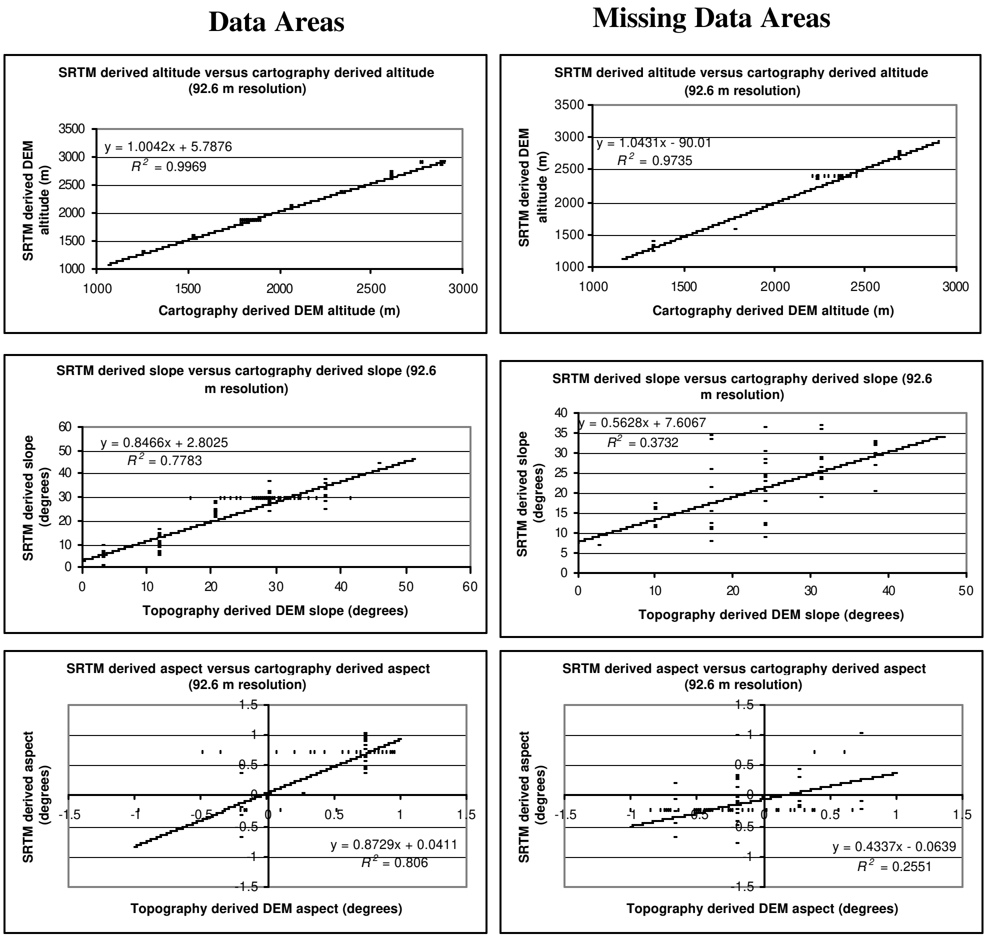


Figure 17. Scatterplot comparison of digital elevation model (DEM) values for altitude, slope, and aspect, separated for areas with original SRTM data, and areas originally with missing SRTM data values.

Conclusions

The interpolation method provides a very good means of filling in missing data values, on the whole reproducing the topography with high altitudinal accuracy. However, much of the detailed topographic features are lost, and this is reflected in the poorer relationships for the first order topographic derivatives of slope and aspect. The effect of the no-data holes is examined in greater detail for more complex topographic derivatives in the next case study.

The region studied here is an extreme case for missing data values, with 42.7% of the area originally containing missing data. Given the extremity of this case, and the degree to which the hole-filling interpolation reflected the true topography, the missing data areas in SRTM data do not necessarily always create such problems for data users. Regions with smaller missing value areas, and less complex topography, probably will have better correlations than those found here.

The hydrologically significant differences between SRTM and cartographically generated DEMs

Introduction

Digital elevation models are an important data source for distributed hydrological modeling because they provide some important parameters. These include slope gradient, which is important in soil moisture, subsurface throughflow, and runoff generation processes, and slope aspect, which determines solar radiation loads, and thus potential evapotranspiration. DEMs are used also as a controlling variable for the spatialisation of other hydrologically important variables such as temperature, rainfall, soil properties including soil depth, and vegetation characteristics. Moreover, DEMs are the information source for computing surface flow networks and their topology. Such flow networks are critical for modeling runoff accumulation, stream flow, and flood response, and are derived using a neighborhood operator over a DEM represented as raster grids, or from a triangular irregular network (TIN) (O'Callaghan and Mark, 1984; Tarboton, 1997). The calculation of flow networks allows the delineation of catchments and sub-catchments, the routing of lateral flows of water, the calculation of stream properties, such as stream order, and of trends in controlling variables, such as slope gradient down the hydrological network.

The correct specification of primary parameters, such as slope, aspect, and drainage direction, is critical to accurate modeling of catchment-scale hydrology since most models are, quite rightly, highly sensitive to these properties. This is particularly the case for the physically based models that are widely applied and distributed, such as the Système Hydrologique Européen (SHE) model (see Abbott et al., 1986) and its descendants. Examples of the latter include MIKE SHE and SHETRAN (Bathurst et al., 1995; Refsgaard and Storm, 1995), the Institute of Hydrology Distributed Model (IHDM) (e.g., Calver and Wood, 1995), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) TOPOG model (e.g., Vertessy et al., 1993), Thales (Grayson et al., 1992), and WEC-C (Croton and Barry, 2001).

Many hydrological properties are tied fundamentally with terrain derivatives (see Moore et al., 1991), and the quality of the terrain data, their cell size (resolution), and the algorithm used to derive the terrain derivatives affect the accuracy of the resulting hydrological modeling (see Mulligan, 2003).

This case study aims to quantify the hydrologically significant differences between filled SRTM data at 92 m and cartographically generated (TOPO) DEMs for the runoff simulation using a simple kinematic wave model implemented in the PCRASTER geographic information system (GIS) (Wesseling et al., 1996).

Methods

Three DEMs, SRTM 92, TOPO 92, and TOPO 25, are used. SRTM 92 and TOPO 92 are the same as those used in the previous case study. TOPO 25 is a DEM produced using the same contours from the 1:50,000 scale cartography, with the interpolation being made to a 25-m grid using TOPOGRID in ArcInfo, with tolerance parameters equal to previous case studies. These three DEMs were subjected to the following analyses in order to compare their hydrologically significant differences.

General terrain indices and flow cumulation analysis involves the calculation of landscape characteristics that are hydrologically significant (topmodel, streamorder, upslope area), with the results being compared between the DEMs.

Flow path diversion analysis compares characteristics of the local drainage directions (LDD) between the DEMs, and the impact of DEM used on LDD network produced (for the D8 algorithm [O'Callaghan and Mark, 1984] as implemented in PCRASTER). A simple kinematic-wave model of rainfall runoff is run across each DEM timestep for 8760 hours of measured rainfall data at the Tambito site. In this model, rainfall and infiltration rate was assumed uniform across catchment for simplicity. Model runs were made for uniform infiltration rates from 0 mm/h to 200 mm/h. Runoff water is allowed to re-infiltrate downslope, if the infiltration rate and opportunity time allow, in all but the 0 mm/h infiltration rate simulations where the infiltration rate never allows this.

Finally, in flow discharge analysis, channel and whole_DEM runoff are compared for the different DEMs, paying special attention to the effect of the DEM at different infiltration rates.

Results and discussion

The difference between SRTM 92 and TOPO 92 will depend upon (a) the difference between non-filled portions of the SRTM DEM (a function of the DEM production techniques), and (b) the difference between the filled portions of the SRTM DEM (a function of the filling algorithm used). Space precludes separating the analysis here, so in each case results are shown for these two effects combined. The results thus represent a worst-case scenario in terms of the SRTM data because, in this catchment, the alignment of the topography relative to the sensor places a large proportion of the catchment in radar shadow, which thus is returned as missing data.

SRTM 92 and TOPO 92 have small catchment scale differences in variables such as slope, aspect, topmodel wetness index, stream order, and upslope area. In general, the SRTM data show lower slopes, more north- and less south- and west-facing LDDs, more west- and less south-facing aspects, similar topmodel wetness indices, more first-order streams (that is, non-channelized land), and fewer higher order streams. The SRTM data also show lower cumulative upslope areas. This is as one might expect as a result of broad interpolations over large areas of missing data.

Table 9 shows the diversion of flow paths from TOPO 92 to SRTM 92. These diversions are similar to those generated in transition from a 25-m resolution to a 92-m resolution topographic DEM (Table 10).

Table 9. Flow displacement from TOPO 92 to SRTM 92 digital elevation models.

Angle displaced	Number of cells	Percentage of cells
0	37890	55
45	12152	18
90	4313	6
135	14579	21
180	270	0
Total	69204	100

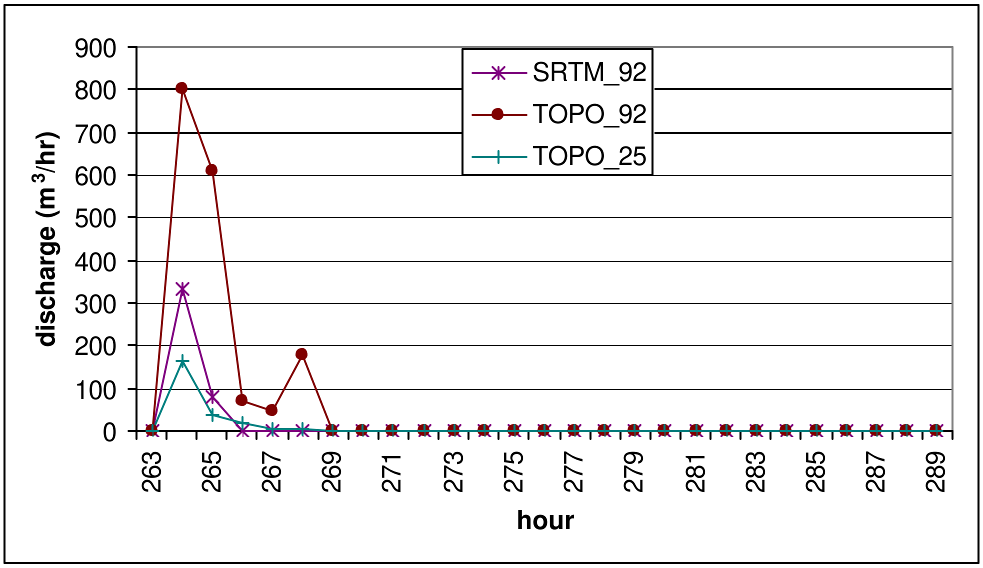
Table 10. Flow displacement from TOPO 25 to TOPO 92 digital elevation models.

Angle displaced	Number of cells	Percentage of cells
0	38696	56
45	15356	22
90	3218	5
135	11715	17
180	219	0
Total	69204	100

Flow direction in almost 30% of cells does not change at all (i.e., it is stable) from TOPO 25 to TOPO 92 and SRTM 92. Differences between the TOPO 25 and TOPO 92 are much greater than those between the TOPO 92 and SRTM 92, in terms of both the effect on catchment scale flow patterns and on runoff volumes. So changing DEM resolution has as significant an effect as the source data of the DEM.

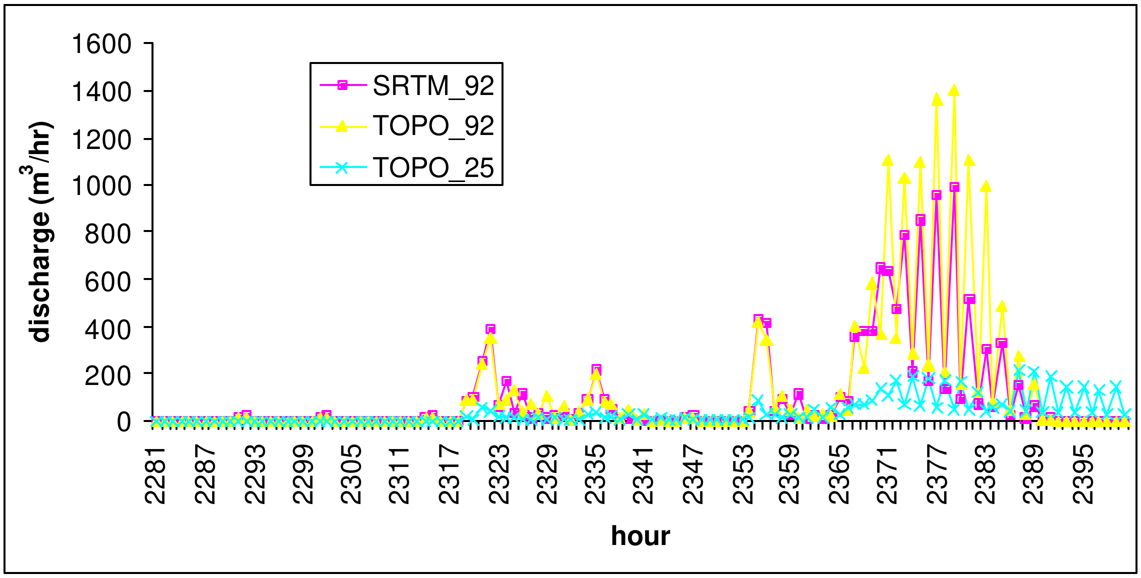
Flow discharge was analyzed in (1) the hourly discharge from the main Tambito Channel for the simulation-day period, and (2) the hourly discharge from the whole model area.

Figures 18 and 19 show discharge through the main Tambito channel for individual rainfall events. The figures and accompanying tables indicate that total discharge is highest for TOPO 92, followed by SRTM 92 and TOPO 25; peak discharge follows the same pattern, and this is true for the 0 mm/h infiltration rate (i.e., no re-infiltration) and the 5 mm/h rate that allows re-infiltration. These differences may be due to differences in catchment area for the DEMs, since that is a derivative of the calculated flow network. For the 5 mm/h (re-infiltration) scenario, the difference between the total and peak discharge for the different DEMs is less when the catchment areas are considered (through division by the measured areas of the catchments), but the overall pattern of TOPO 92>SRTM 92>TOPO 25 still remains for total discharge. Peak discharge is higher for SRTM 92 when considered per unit catchment area for the 0 mm/h (no re-infiltration) scenario.



	SRTM 92	TOPO 92	TOPO 25
Sum	**414.9**	**1709.0**	**235.4**
Maximum	**333.8**	**803.5**	**163.7**
Catchment cells	**2492**	**2505**	**34338**
Catch area (m^2)	**21379993**	**21491526**	**21493619**
Sum/area	**1.94E-05**	**7.95E-05**	**1.1E-05**
Maximum/area	**17201444**	**10104644**	**14942449**

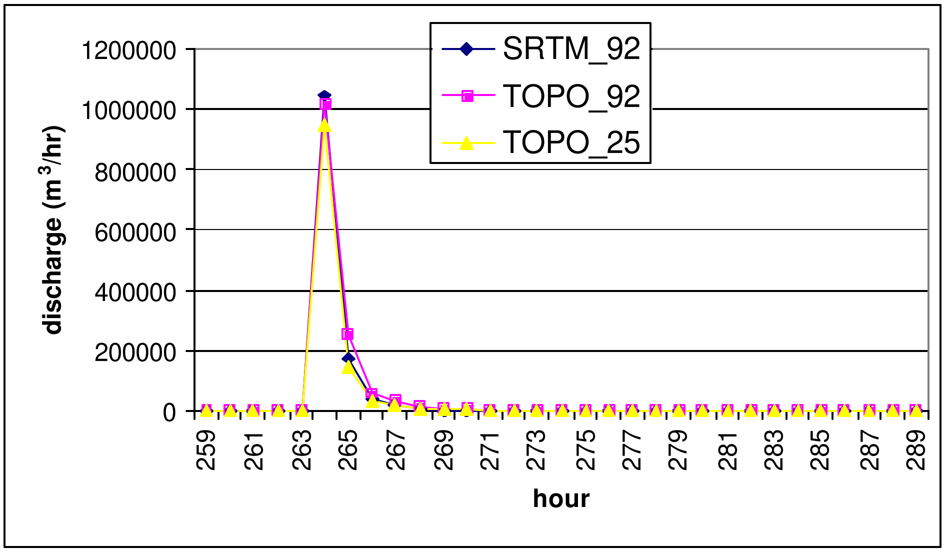
Figure 18. Discharge to the main Tambito channel at 5 mm/h infiltration (re-infiltration allowed) for the three digital elevation models, with summary table for this period.



	SRTM 92	TOPO 92	TOPO 25
Sum	**12075.7**	**15596.7**	**4403.4**
Maximum	**990.8**	**1401.6**	**213.6**
Catchment cells	**2492**	**2505**	**34338**
Catchment area (m^2)	**21379993**	**21491526**	**21493619**
Sum/area	**0.000565**	**0.000726**	**0.000205**
Maximum/area	**1754176**	**1931283**	**1042764**

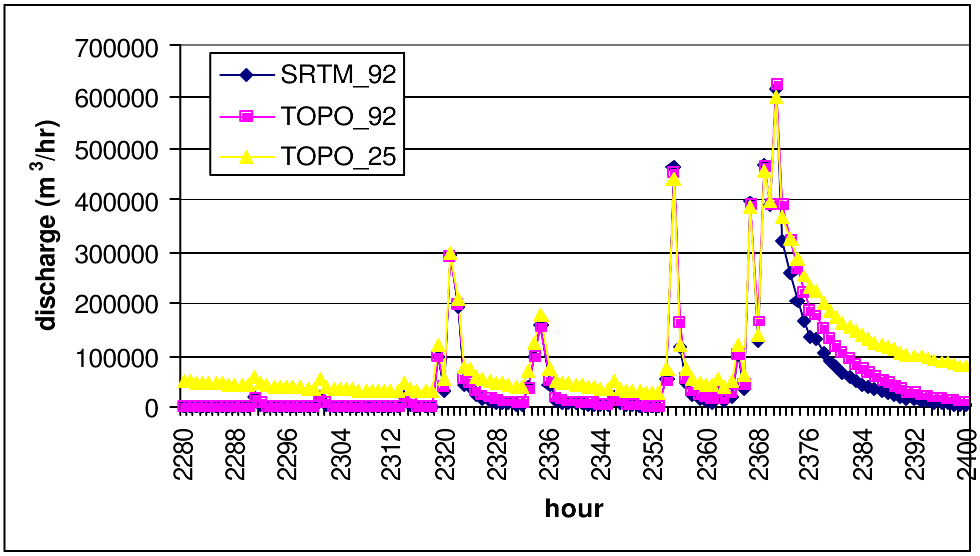
Figure 19. Discharge to the main Tambito channel at 0 mm/h infiltration (no re-infiltration) for the three digital elevation models, with summary table for this period.

When considering the whole study area, processes are aggregated, and thus patterns are somewhat clearer. For the 5 mm/h (re-infiltration) scenario, the differences between total discharge for the different DEMs are less, although the order remains the same (TOPO 92>SRTM 92>TOPO 25). However, for maximum (peak) discharge, the order becomes SRTM 92>TOPO 92> TOPO 25 (Figure 20). For the 0 mm/h (no re-infiltration) scenario, the pattern for maximum discharge remains at TOPO 92>SRTM 92>TOPO 25, but the pattern for total discharge is quite different, with TOPO 25>TOPO 92>SRTM 92 (Figure 21). This results from much longer and shallower recession curves for TOPO 25 compared with TOPO 92 and SRTM 92.



	SRTM 92	TOPO 92	TOPO 25
Sum	**1285064**	**1394482**	**1166348**
Maximum	**1043080**	**1020180**	**948151**

Figure 20. Discharge to the whole study area at 5 mm/h infiltration (re-infiltration allowed) for the three digital elevation models, with summary table for this period.



	SRTM 92	TOPO 92	TOPO 25
Sum	**6169956**	**7350585**	**11423683**
Maximum	**614917**	**622859**	**601079**

Figure 21. Discharge to the whole study area at 0 mm/h infiltration (no re-infiltration allowed) for the three digital elevation models, with summary table for this period.

Clearly, whether the flow-routing algorithm allows re-infiltration or not has an important effect on the absolute outcome. The less re-infiltration, the more cumulation of flow down the flow lines, and thus the greater the magnification of small differences in the flow network in terms of their impact of runoff from the catchment. This is illustrated clearly in Figures 22 and 23, which show the effect of infiltration rate on total discharge for the Tambito main channel (Figure 22) and for the whole study area (Figure 23). For the Tambito main channel, the response of SRTM 92 and TOPO 92 are similar irrespective of infiltration rate, and TOPO 25 is always very different. For the whole study area, the three DEMs have broadly similar responses to infiltration rate except at zero infiltration, when the responses diverge.

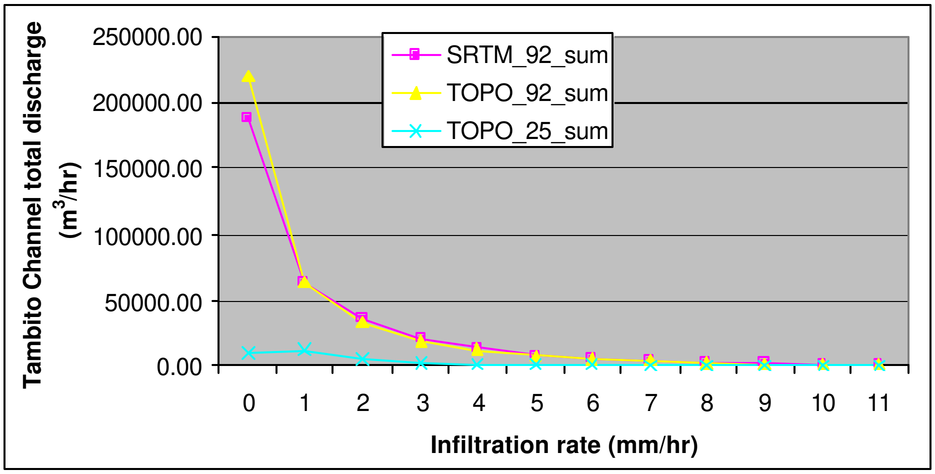


Figure 22. The effect of infiltration rate on runoff for the Tambito main channel for the three digital elevation models.

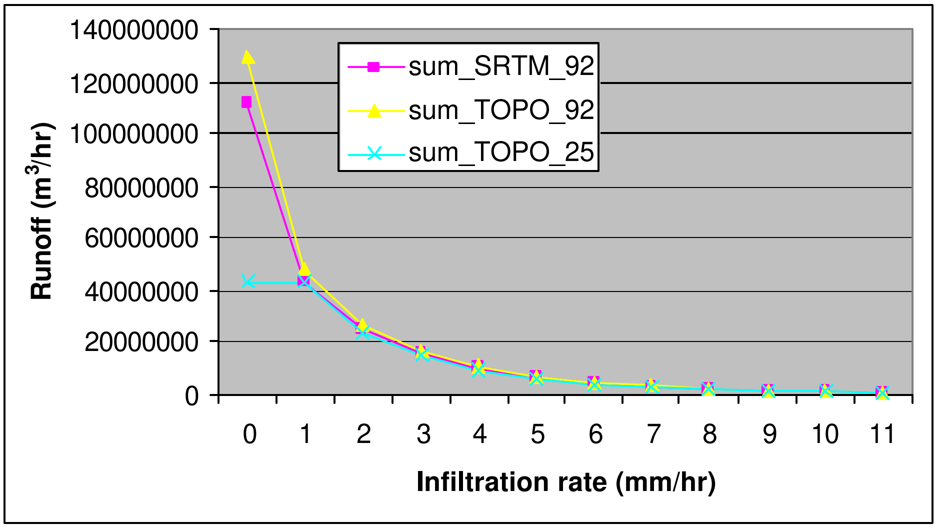


Figure 23. The effect of infiltration rate on runoff for the whole study area for the three digital elevation models.

Conclusions

In terms of hydrological modeling, these results are encouraging since they show that, even for a poor quality SRTM DEM with many holes that have been filled rather crudely, the effect of changing the cell size resolution from 25 m to 92 m is greater than the difference between a cartographically produced 92-m DEM and its SRTM equivalent, in terms of both at-a-station channel discharges and whole DEM runoff volumes. Although the SRTM 92 DEM has some differences in slope angles from the TOPO 92 DEM, which causes diversion of some flow paths, this has little effect at the catchment scale because of the dampening effect of re-infiltration of runoff downslope of its generation. Only in the extreme case where a catchment is saturated or highly impermeable, and thus re-infiltration does not occur (the case of zero infiltration rate here), do small changes in the flow network propagate their effects on runoff down the drainage network, which makes the catchment scale runoff highly sensitive to small changes in DEM properties. Fortunately, these situations are rare (although this does not make them insignificant hydrologically, Hurricane Mitch being a notable example). So, in most cases, even filled SRTM data are a better alternative for distributed hydrological modeling than coarser resolution cartographic data are likely to be.

The large discrepancies between SRTM 92 or TOPO 92 and TOPO 25 serve to highlight the importance of grid resolution to hydrological modeling and the fact that 92-m DEMs are on the margins of usability for hydrological modeling purposes, such that for all but the most basic of hydrological studies, hydrological modelers must patiently await the arrival of the SRTM 30-m datasets.

Overall Conclusions

The five case studies provide a broad range of analyses on the quality, accuracy, and usability of SRTM data. First, we have shown that the SRTM DEM is a vast improvement on previous global DEM products (in this case using GTOPO30), and shown that previous studies based on GTOPO30 may have significant errors in some parts. One important implication of this is that care must be taken when using GTOPO30 as a co-variable in the interpolation for filling in no-data regions (see, for example, the method offered by Landformer Pro, available in http://www.geomantics.com/, because large errors occur in some areas.

Second, a national scale assessment of the precision of SRTM data in the tropics is made using GPS data, also assessing whether TOPO DEMs provide better or worse elevational information. The SRTM DEM is found to be more accurate (average error of just 8 m as opposed to 20 m for the TOPO DEM), and we find that the error is not random, but systematically related to aspect. In this case, northeastern slopes presented the greatest error due to the incidence angle of the original radar images. The angle itself is likely to be different for different regions, but this is an important factor to take into account when using SRTM data for precise analyses.

Taking a similar analysis to the smaller scale, the third case study compares GPS data with SRTM elevation for a single catchment, and makes some basic comparisons of hydrological derivatives for an SRTM DEM entirely without missing data holes. At the catchment-scale we find that the high quality 1:10,000 cartographic maps produced a more detailed DEM than the 92-m SRTM DEM, although the vertical errors were highly similar (20 m for the SRTM DEM and 21 m for the TOPO DEM). However, the greatest errors in the SRTM data were found on ridges and peaks, where they consistently underestimated the elevation. This is explained partly by the fairly coarse cell-size for the degree of topographic variation present in the site. Despite the greater detail in the

TOPO DEM, little difference was found between SRTM and TOPO hydrological differences, such as stream network, catchment boundaries, and topmodel wetness index.

The fourth case study looked at the problem associated with the missing data holes, and provided a detailed analysis of the errors induced through an interpolative technique for filling in the SRTM holes. Despite 43% of the area containing no data, there was an average error of just 5 m between a TOPO DEM (without missing data) and the interpolated elevation values from the SRTM DEM. However, some detail in the topography is lost, and first order derivatives such as slope and aspect show significant errors in missing data areas.

Finally, a detailed hydrological analysis of the same region shows that the interpolative technique for filling in missing data holes performs very well in terms of representing the hydrological characteristics of the catchment on the whole. In this case, cell size was shown to make the greatest difference, with the cartographic maps (1:25,000 scale) providing greater topographic detail and causing significant differences in the hydrological characteristics of the catchment.

Perhaps the most important message is that SRTM-derived DEMs provide greater accuracy than TOPO DEMs, but do not necessarily contain more detail. Cartography at scales of 1:25,000 and below (i.e., 1:10,000) contains topographic features not captured with the 3-arc second SRTM DEMs. However, if only cartography with scales above 1:25,000 (i.e., 1:50,000 and 1:100,000) is available, it is better to use the SRTM DEMs. This statement holds for use of SRTM DEMs for terrain derivatives (slope, aspect, landscape classifications, etc.) as well as pure elevation. For hydrological modeling, SRTM 3-arc second DEMs perform well, but are on the margin of usability. If good quality cartography of scale 1:25,000 and below is available, better results may be expected through digitizing and interpolating the cartographic data.

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