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# Modeling small watersheds in Brazilian Amazonia with shuttle radar topographic mission-90 m data

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**Abstract**

This work presents a methodology for the refinement of shuttle radar topographic mission (SRTM-90 m) data available for South America to enable detailed watershed studies in Amazonia. The original data were pre-processed to properly map detailed low-order drainage features and allowed digital estimates of morphometric variables. Spatial-resolution refinement (3″ to 1″, or ~90 to ~30 m) through data kriging was found to be an interesting solution to construct digital elevation models (DEMs) with more adequate presentation of landforms than the original data. The refinement of spatial resolution by kriging interpolation overcame the main constraints for drainage modeling with original SRTM-90 m, such as spatial randomness, artifacts and unrealistic presentation due to pixel size. Kriging with a Gaussian semivariogram model caused a smoothing of the resulting DEM, but the main features for drainage modeling were preserved. Canopy effects on the modeled surface represented the main remaining limitation for terrain analysis after pre-processing. Data regarding a small watershed in Amazonas (~38 $km^2$), Brazil, were evaluated through visualization techniques, morphometric analyses and plot diagrams of the results. The data showed limitations for use in the original form, but could be applied for watershed modeling at relatively detailed scales after the described pre-processing.


*Keywords:* Remote sensing; Geoprocessing; SRTM; Watershed; Amazonia

## 1. Introduction

Many studies dealt with the relation between topographic variables and the characterization of landscape attributes as described in systems approach (Dent and Young, 1981; Meijerink, 1988). Indeed, besides the topographic information itself, the spatial characterizations of other landscape aspects like soils (Moore et al., 1993), weather (Goovaerts, 2000) and vegetation (Florinsky and Kuryakova, 1996) were shown to be improved when coupled with relief modeling. The use of digital elevation models (DEMs) through geographical information systems (GIS) is a powerful approach in this matter, since automatic methods to analyze topographic features are allowed, with both operational and quality advantages. While GIS-based feature extraction are processed with all advantages

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of digital resources (speed, repeatability and computer integration with other databases), the reduction of manual interventions (and thus subjectivity) and the possibility of parametric approach represent qualitative distinctions from interpretative-based methods.

In watershed studies, GIS modeling of DEMs is often applied to erosion estimates (Molnár and Julien, 1998), in which the automatic extraction of its related variables consists as important field of research (Desmet and Govers, 1996). Directly concerned to the comprehension of watershed drainage structure, watershed partition (Band, 1986) and the identification of terrain units (Miliaresis, 2001) are important tasks to be supported by DEM analysis.

In developing countries, the lack of topographic data for great extensions generally hinders the topographic modeling. This deficiency is critical in areas like Amazonia, where inaccessibility and historical reasons kept large territory uncovered by systematic mapping. The increasing use of orbital remote sensing methods represents a strategic alternative to overcome this lack of data.

In February 2000, the shuttle radar topographic mission (SRTM) collected radar data at C- and X-band. For the near-global coverage, however, only the C-band data were processed. Differently from the previous shuttle imaging radar missions, at the SRTM the shuttle was equipped with a second radar antenna, separated from the first antenna by a mast, which allowed the use of interferometric techniques. synthetic aperture radar (SAR) interferometry is a technique that uses information on phase difference between two SAR images acquired from slightly different antenna (sensor) positions. The phase difference between the two positions indicates the average three-dimensional position of the scattering elements/objects at the Earth's surface and, under certain conditions, allows the height of objects to be inferred (Baltzer, 2001). In addition to topographic mapping and DEM construction, interferometric data have been also used to estimate forest height (Wegmuller and Werner, 1995).

The recent release of SRTM-90 m data for South America suggested the direct application of the existing GIS resources in terrain analysis to be feasible for the whole region, thus overcoming the lack of topographic information in a short period of time. Nevertheless, SRTM is a remotely sensed data set with the typical need for evaluations and pre-processing work before its insertion is GIS analysis of the relief. The objective of this work was to evaluate and test the quality and possibilities of using SRTM data for small watersheds modeling with emphasis on morphometry and drainage channel description. This article describes the methodology used for the construction of a DEM for a study area—the Asu river watershed in Brazilian Amazonia—with a refinement of SRTM data from 90 to 30 m. Data, methods and softwares used and the first results obtained were outlined.

## 2. Material and methods

This study was partially carried over a whole 150 km × 100 km sheet corresponding to 1:250,000 quads, as shown in Fig. 1. This SRTM data set, a 1800 × 1200 (columns × lines) image, had 30 × 30 samples submitted to the geostatistical analysis and the whole set was interpolated for the construction of a DEM. After preliminary checks, a small subset comprising Asu river watershed was selected for a detailed analysis including controlled morphometric analyses and further verifications.

Asu is a tributary of Cuieiras river, which is tributary of Rio Negro, the large riverbed oriented northwest–southeast in Fig. 1. It is a fourth-order river in a 38.34 $km^2$ watershed with heights ranging from 40.28 to 125.70 m. The site is characterized by plateaus gently dissected by small streams. The dominant soil at the plateaus is a yellow Oxisol, rich in kaolinite clay, while Spodosols, consisting of sand with topsoil organic matter, prevail in the lowlands. Climate is classified as Ami (Koeppen), with annual rainfall levels averaging 2800 mm.

The watershed is covered by undisturbed vegetation named *terra firme* forest (in uplands) and *campinarana* in the valley floor. In Fig. 2, a 1999 Landsat/Thematic Mapper (TM) image shows undisturbed forest in the study area near the acquisition date of SRTM data. Landsat/TM quicklooks for dates up to 2005 were also checked and confirmed the dense forest cover in the study area. Fig. 2 shows the two types of forest formations covering the study site, according to RADAM-BRASIL (1978) project: In A, uplands are covered with dense forest with emerging trees combined with open forest with palms and dense woody *campinarana*, while flat valley floors may be covered with open woody *campinarana*. In B, dense forest with emerging also prevails, but associated with open forest with palms in dissected valleys.

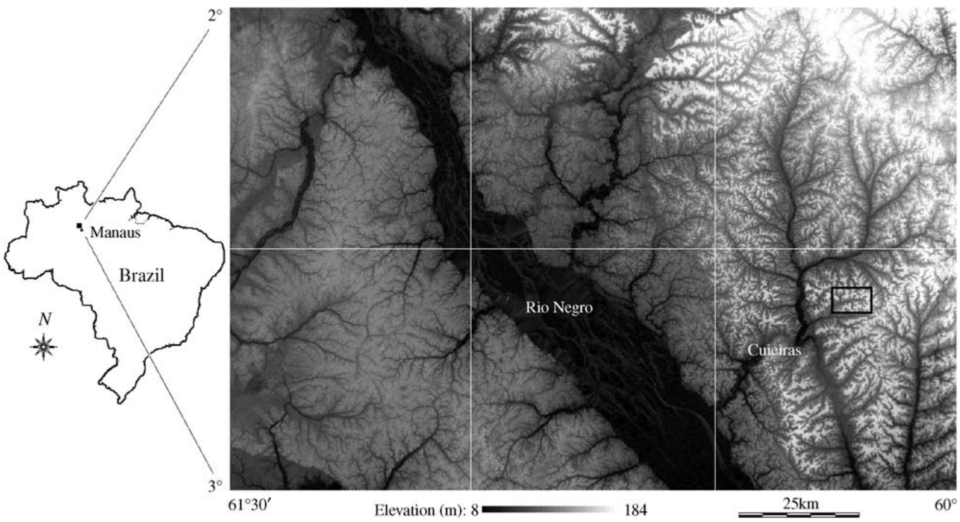


Fig. 1. Study area, with Asu watershed in box.

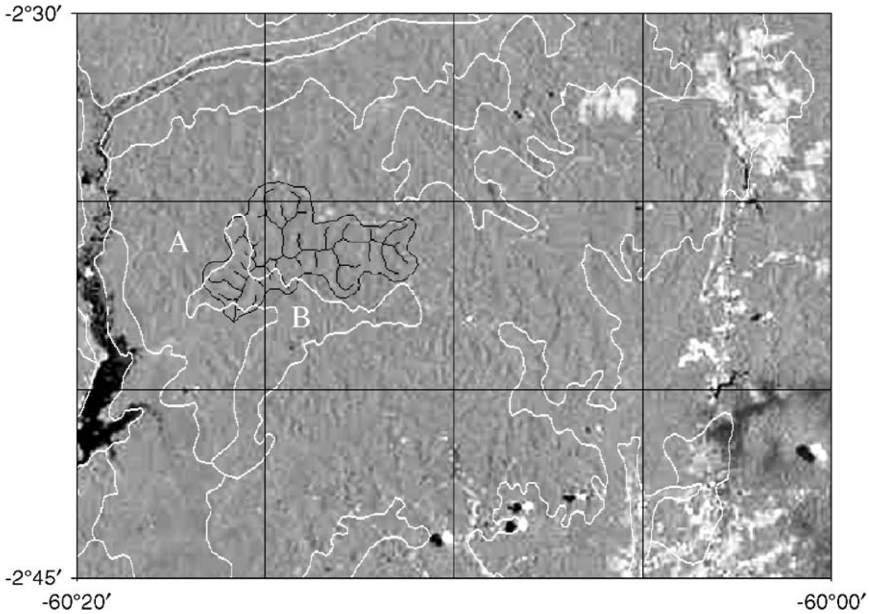


Fig. 2. RADAM vegetation map (white vectors) overlaid on a Landsat/TM gray coded composition of bands TM3, TM4 and TM5. A and B are forest formations occurring in watershed (delimited in black vectors), according to RADAMBRASIL classification (details in text).

The main structural differences between these types of forest formations are related to tree height and density: dense *terra firme* forests are higher than *campinaranas*, with decreasing density of trees and biomass (Ayres, 1993). These differences are also related to their topographic condition. Ferreira (1997) also relates similar structural differences along slope profile in actually non-flooded areas. Wittmann et al. (2002) explained early successional stages (and lower forests) to occur next to river–channels, as an effect of flood height and duration. Nelson (1994) points the mortality of forests due to extreme flood episodes (together with wind and fire events) as the main cause of forest succession in drainage channels, although occurring also in *terra firme* forests.

The processing consisted of modifying original SRTM data into a new DEM with desirable characteristics for watershed modeling. First appreciation of SRTM data showed, besides occasional data failures and artifacts, the data sensitivity for non-terrain objects (trees, buildings, antennas), which were believed to contribute to short-range abrupt near-random variations. The intended modifications were: improved resolution from 3″ to 1″ (~30 m); removal of the data failures; reduction of artifacts; and distribution of the spatial randomness, estimated as nugget effect through the geostatistical analysis.

SRTM data kriging followed basically a geostatistical approach originally designed to prepare DEM from contour lines, computing digitized quotas (and their geographic positions) as samples for geostatistical analysis and interpolation. The method was applied to SRTM data after selecting (and detaching) squared sample areas for the geostatistical analyses. This method uses the residues obtained from trend analysis to assure geostationarity of the data set submitted to the geostatistical analysis. Valeriano (2002b) showed that variogram models calculated with linear trend residues of topographic data showed adequate fits with classical variogram models (Isaaks and Srivastava, 1989), which present a clear defined sill. Variogram analysis of these residues provided the geostatistical coefficients applied in kriging interpolation of the original SRTM elevation data set. Fig. 3 presents the whole data flow, from original downloaded SRTM tiff image until the final DEM.

The computational programs used were (i) for failure correction, sampling and ASCII data export—ENVI (Research Systems Inc., 2002); (ii) for trend analysis and calculation of residues—MINITAB® (MINITAB Inc., 2000); (iii) for geostatistical analysis—VarioWin (Pannatier, 1996) and (iv) for

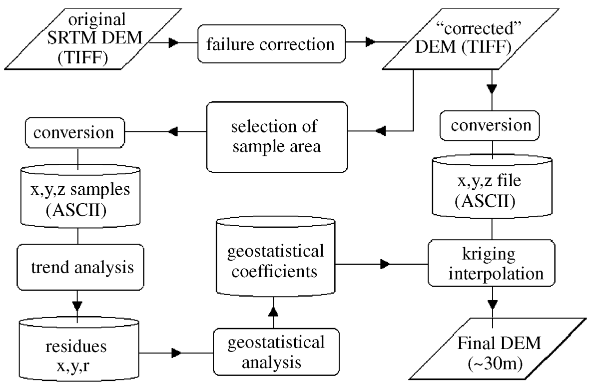


Fig. 3. Processing of SRTM data.

kriging interpolation—Surfer (Golden Software, 1995). After the generation of the new DEM, Idrisi (Eastman, 1995) was used for operations such as test applications and extraction of morphometric variables.

Results were evaluated through visualization of graphical and statistical analyses, and observations on morphometric outputs. The shaded relief rendered by Surfer typically presents the relief in a vertical exaggeration so as to balance illuminated and shaded surfaces in each image, independently of the model actual relief. This property, in combination with the possibility of controlling the illumination geometry, allows detailed observations of the surface characteristics, representing a very important tool for visual evaluation of numerical surfaces before their insertion in GIS. A quick talvegue–divide delineation process was also applied to verify drainage modeling potential of the DEM. The three-steps process shown in Fig. 4 was repeated in the four filter directions and the results were overlaid to produce a talvegue–divide map for all directions.

Slope angle, direction and plan and profile curvatures were calculated using a suite of algorithms developed in previous works. Slope angle images were calculated using a mapping program (Valeriano, 2002a) based on the vector sum of slope orthogonal components, as quantified through moving windows in "×" and "+" orientation systems. According to the best correlation in relation to manual measurements, slope was calculated choosing the maximum resultants between the orientations and the maximum height in each windowed direction. The method to map profile curvature (Valeriano, 2003) is based on local 3 × 3 pixel windows and designed to perform geometrically the second-order derivative through the slope profile. The curvature calculations required the DEM spatial resolution as one of the inputs, so as to calculate a comparable absolute value, with the slope change rate per horizontal distance as unit, in degrees per meter (°/m). The classification of slope direction in octants was used to control the overlapping derivation results, calculated toward the eight neighbor pixels of each windowed position. Analogously, to map plan curvature, a simple approach was based on a similar application of moving windows on the slope direction image instead, providing the slope direction change rate per horizontal distance (°/m) as unit (Valeriano and Carvalho Jr., 2003). For slope direction, aspect function of the GIS (Idrisi) was used.

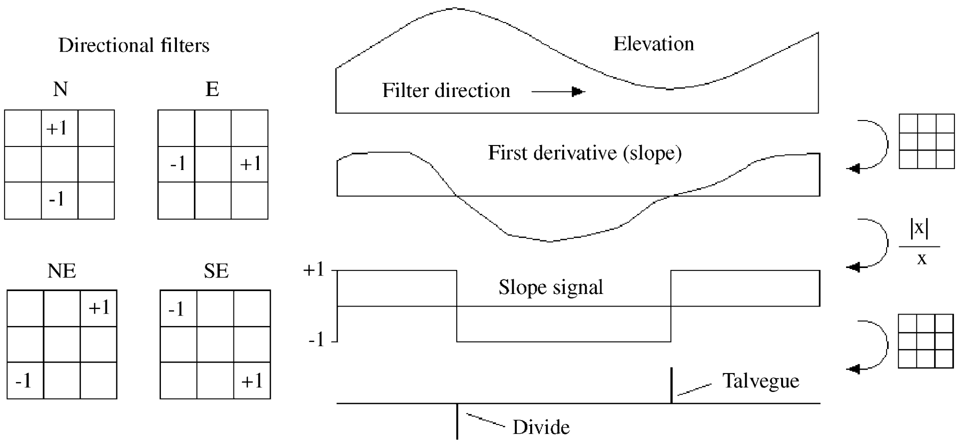


Fig. 4. Simple three-steps process for talvegue and divide delineation.

## 3. Results and discussion

### 3.1. Canopy effects

Since the first examination of SRTM images, the model height was observed to be sensitive to the forest canopy. More than simply increasing height, the forest canopy often works as a smooth blanket over the terrain, therefore hiding minor details. In Fig. 5 (top), a detailed drainage network can be easier observed in the deforested areas (darker) than under forest canopy. In the circled area, abrupt interruptions in drainage pattern can be seen in the deforestation boundary. Besides the loss of detailed information under the canopy, this limitation will require two-fold analysis of drainage patterns when working on site of forested terrain. Similarly, canopy height irregularities are also able to affect the calculation of morphometric variables, yet for slope angle. In Fig. 5 (bottom), clear-cut borders represent an extreme canopy disturbance for morphometric modeling, as it causes the mapping of unreal C-class slopes (above 8%) in the A/B exemplified terrain.

When interpreting radar data, mainly in vegetated terrains, the degree to which the radar beam penetrates through a forest canopy determines the type of information available. Radar C-band refers to wavelengths of around 5.6 cm, which are able to penetrate dense forest canopies, although not reaching the ground (Le Toan et al., 1992). There are many factors that contribute for the radar scattering in a tropical forest, and the number and height of individuals along with closeness of the canopy are determinants of the radiation penetration into the canopies. Assuming a thick tropical forest cover, information on SRTM data refers to the surface and near surface of the canopy. For the radiation that penetrates the canopy, the typical sources of scattering at C-band are branches and leaves and volumetric scattering—as it occurs in the "volume" of tree crowns—is the main scattering mechanism for C-band in tropical dense canopies (Leckie and Ranson, 1998).

Fig. 5 (top) shows attenuation of the drainage features, although the opposite effect may be expected where the decrease in elevations is related to a decrease in tree height and density. Due to forest height and tree density differences, each of the forest type occurring in the study site may result in different heights as modeled through C-band altimetry, but not in a predictable way. Other difficulty to overcome complex canopy effects is the status of vegetation mapping itself, which does not provide information for canopy structure modeling in a desirable precision. Finally, the short-range variations and complex relief–canopy interactions deprive the establishment of a canopy height correction of C-band altimetry.

Fig. 6a outlines exaggeration and attenuation effects in a hypothetical transect. In the condition presented at left, tree growth compensates elevation around drainage channels, obscuring their detection (as observed in Fig. 5). By the other effect (Fig. 6a, at the right), channel depth is exaggerated because canopy over enhances the modeled surface by following the elevation changes at a higher rate than the terrain gradient. Deforestation also plays an undesirable effect in drainage modeling (Fig. 6b), as canopy borders are expressed in the modeled

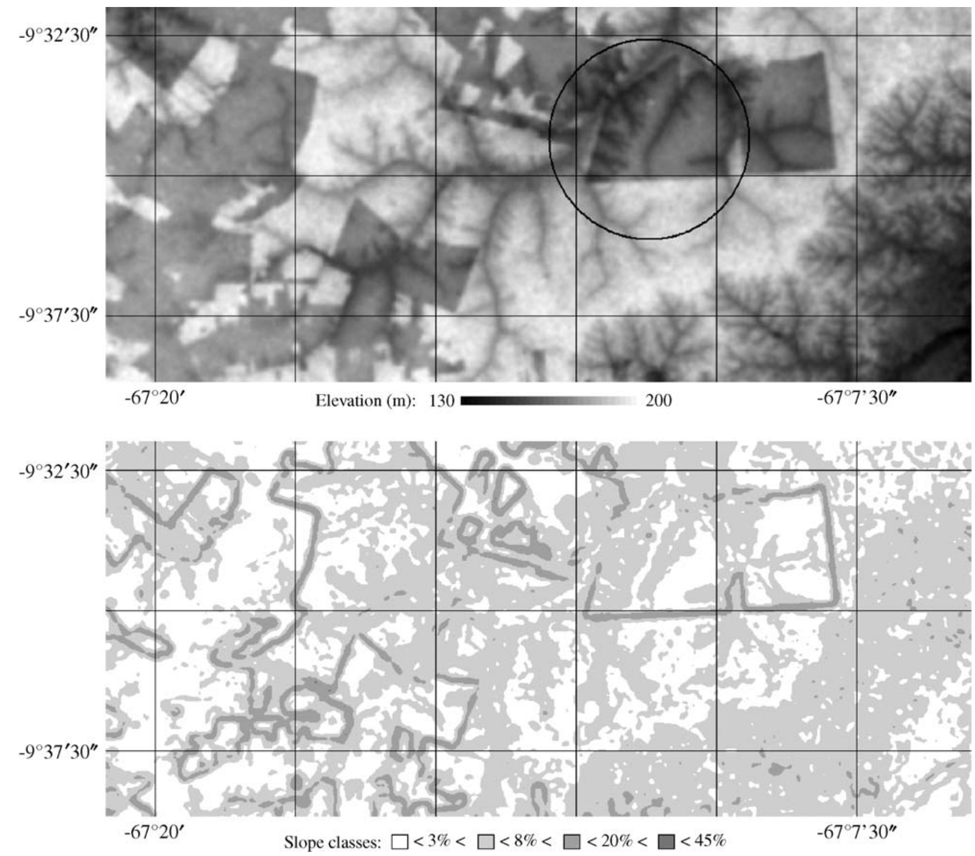


Fig. 5. Gray level SRTM drainage differences between forested and deforested areas (top). Circled area presents boundary between forest and deforested area, where drainage channels disappeared due to attenuation by forest cover. Bottom map shows clear-cut borders affecting mapping of slope angle classes.

surface the same way as ridges and may lead to false channel detection where forest border faces slope upward.

Although the canopy effects showed in Fig. 6 are important, the remaining terrain information is believed to support reasonably terrain and drainage modeling within an accuracy level given by the forest condition. Since the local morphometric variables are calculated through neighbor functions (operations between pixel values encompassed in a moving window position), their results dependent on relative precision rather than absolute accuracy. Thus, the assumption of canopy height uniformity enables the calculation of the local variables.

Despite the assumption of canopy height uniformity, required for calculation purposes, canopy effects must be considered when handling SRTM data of forested areas. All available descriptions of vegetation structure in Asu watershed suggest a canopy exaggeration of slope angle to occur somewhere near the boundary of the valley floor. This would modify slope angle scores locally, with possible effects in the estimate of profile curvatures. Meanwhile, horizontal-related variables, such as slope direction and horizontal curvature, are expected to result free from canopy effects.

### 3.2. Geostatistics

Though elevation data are generally expected to present a high spatial dependence (data similarity at short distances), the noisy patterns observed in detailed presentations suggest unexpected variations to occur within the grid distance. In spatial statistics, this can be evaluated through semivariogram analysis, expressed in the rate of nugget effect. Theoretical semivariogram models present three main coefficients that scales the fit to experimental semivariograms, namely range, sill and nugget effect. Range is a measurement of the curve's horizontal scale (from origin to the beginning of the sill plateau) and corresponds to the maximum

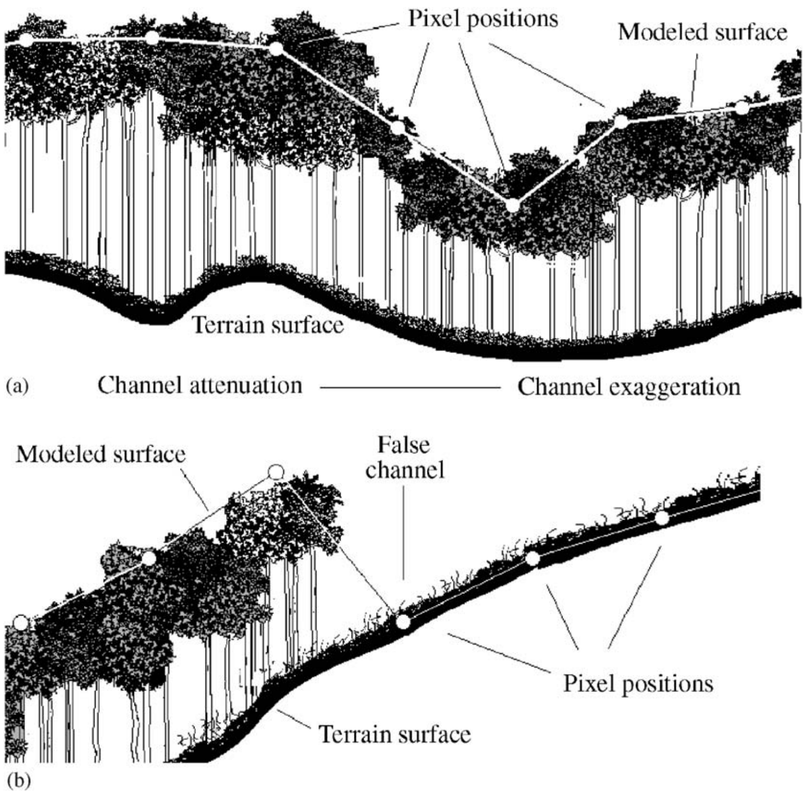


Fig. 6. Undesirable effects from undisturbed canopy (a) and from deforestation (b) on channel modeling with SRTM data.

distance of spatial dependence. Nugget effect is the $y$-intercept height and corresponds to a residual variation at the shortest sampling interval, random and not spatially correlated. Sill is the remaining height of the curve above its $y$-intercept (nugget), and corresponds to the variance due to spatial structure (Isaaks and Srivastava, 1989).

Of the theoretical semivariogram models, Gaussian curves present a region of low slope near the zero distance, which determines samples within that distance to have similar weights for the estimation of points nearby. Data that varies smoothly, such as ground-water levels and landforms, often have semivariograms with this inflection that can be best modeled by the Gaussian model (Burrough, 1987). Fig. 7 presents the semivariogram for SRTM elevation data in the study area.

The short-range effect of kriging interpolation with Gaussian models corresponds to the smoothing effect of a moving average window, which is superimposed to the structure given by higher distance samples. Very often, Gaussian modeled semivariogram of Amazonian elevation data showed around 10% of its height in the nugget effect. The use of such coefficient in kriging interpolation leads to a locally controlled smoothing, where sites of short-distance variations may be more intensely smoothed than gentle ones. As an effect of these smoothing mechanisms (Gaussian weight distribution and nugget effect), the noisy pattern observed at detailed scales has its variance re-distributed in such a way that terrain features hidden in the original data become better perceptible when interpolated under higher resolution (Fig. 8).

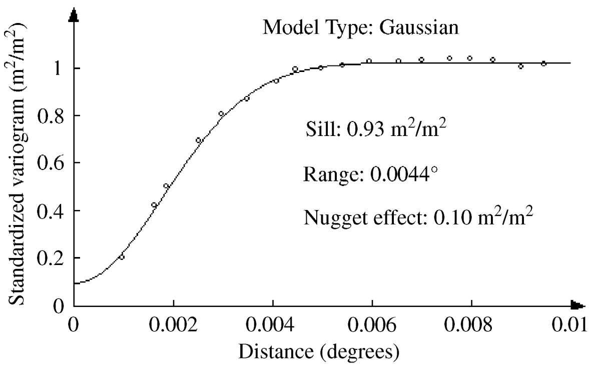


Fig. 7. Semivariogram for SRTM elevation data in study area.

The exemplified shaded relief in Fig. 8 shows a reasonably representative sample of Amazonian relief under two scales: high-density drainage network, with short interfluves and low amplitude. At a first glance, SRTM data seem to describe only the main features under this condition. As regarded to drainage and watershed features, only major (higher-order) channels are characterized, while minor streams remain fuzzy. The improvements observed in the shaded relief presentation correspond to an organization of the surface data in such a way that angles (i.e., slope steepness and direction) become coherent between neighboring pixels. Since the same geometrical features control surface matter transport, it can be said that the visual improvements are related to an increase in the data capability of modeling runoff and drainage features. Indeed, in the processed DEM, meaningful drainage channels and watersheds were turned perceptible where original data showed a near-random pattern.

The above-related improvements are not expected to overcome neither canopy effects nor resolution limitations. Intra-resolution dimensioned features are barely enhanced mainly as a result of noise removal and of the neighbor surface trends. Occasionally, small channels may be enhanced by the trend of the neighboring pixels rather than the local height itself, allowing short interfluves (around 200 m) to be unambiguously characterized.

### 3.3. Morphometric modeling

Although Asu watershed drainage network presents larger interfluves than the relief exemplified in Fig. 8, original SRTM data seem to hardly support digital analysis in acceptable performance due to noisy information, while the processed model resulted in a more easily interpretable set (Fig. 9). Computer analysis of DEM works like a very meticulous interpreter, since the calculations occur mostly through $3 \times 3$ pixel moving windows, depriving the gross perception necessary to overcome punctual surface irregularities.

The calculation of local morphometric variables is a consistent way to evaluate DEM performance in relation to drainage modeling. Local morphometry is a numerical description of landforms, which are recognized as the topographic constraints acting on matter (water included) transport through the terrain surface. Slope (steepness) and direction determine the local first-order vector of the potential runoff flow. Plan and profile curvature are considered second-order constraints, since they control flow acceleration and lateral forces of convergence/divergence. A simple talvegue–divide delineation, analogous to second-order derivative maximum and minimum detection, is overlaid on a synthetic hill shading, here called the azimuth, drainage and divide (ADD) process, completes the collection (Figs. 10–12). A draft vector of watershed limits and drainage channels was digitized on the gray level-coded elevation image (Fig. 10, left). The final vectors of the limits and drainage channels were digitized on their precise positions given by ADD image (Fig. 10, bottom right) after overlaying the draft vectors on it, and further precision is achieved adjusting the vector lines to features enhanced by the zoomed slope direction map. This step-by-step digitizing is necessary because slope direction, when coded

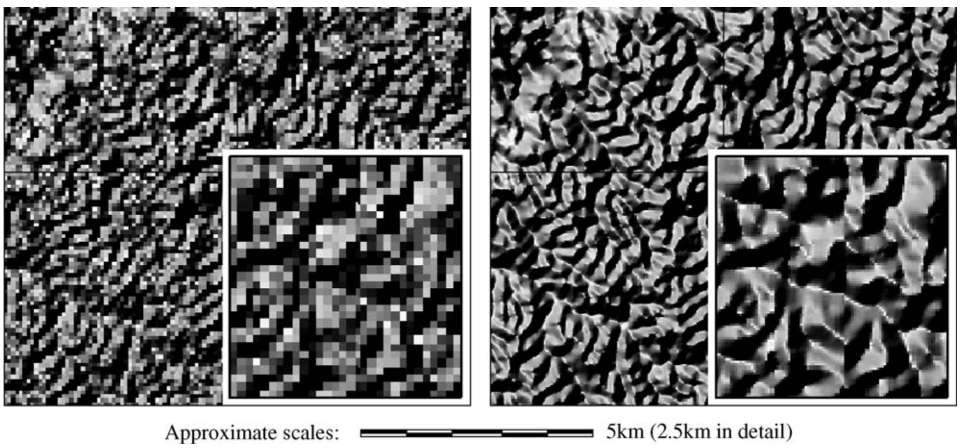


Fig. 8. Shaded relief of original (left) and processed (right) SRTM data.

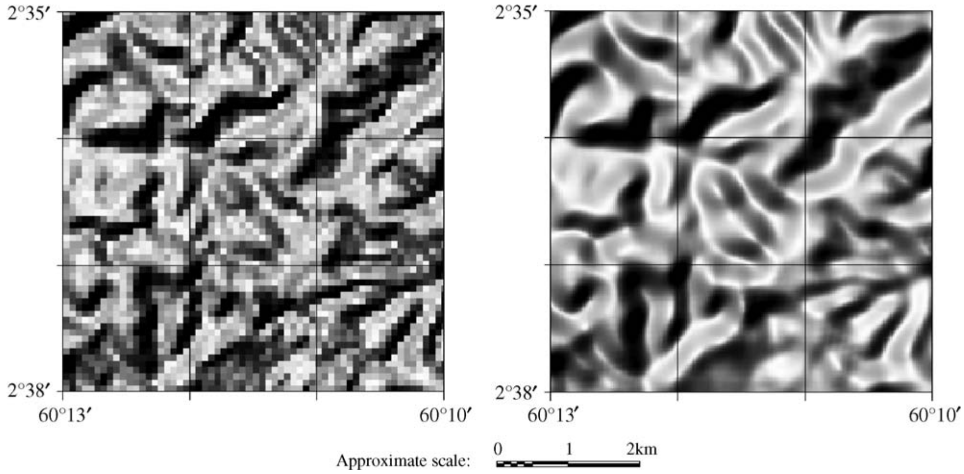


Fig. 9. Shaded relief from original (top) and processed (bottom) SRTM data. Detail extracted from Asu watershed uplands.

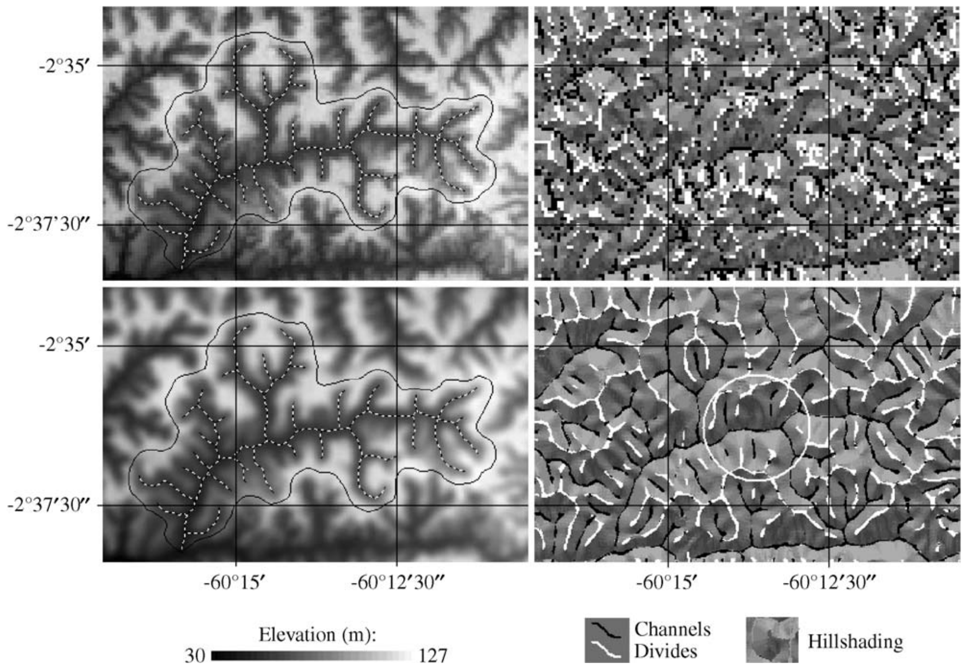


Fig. 10. Morphometric maps of Asu watershed: elevation and talvegue–channel delineation, extracted from original (top) and refined (bottom) DEM.

with a illumination from north, is a good guide to precisely locate the drainage and divide lines, but easily leads to mistaken interpretation of the major networks of a watershed. The definitive vectors were overlaid on the morphometric maps of Figs. 10–12 on the maps where these features were not enhanced, with dashed line for drainage channels and solid line for the watershed limits.

The improvement after refinement of SRTM data is more perceptible in channel/divide with hillshading image (right) than in gray level-coded elevation (Fig. 10). It can be seen that the processed SRTM data generated meaningful morphometric maps of the watershed, since the variables are distributed in a naturally expected arrangement, although numerically all results may be affected by canopy. In the circled detail of Fig. 10 (bottom

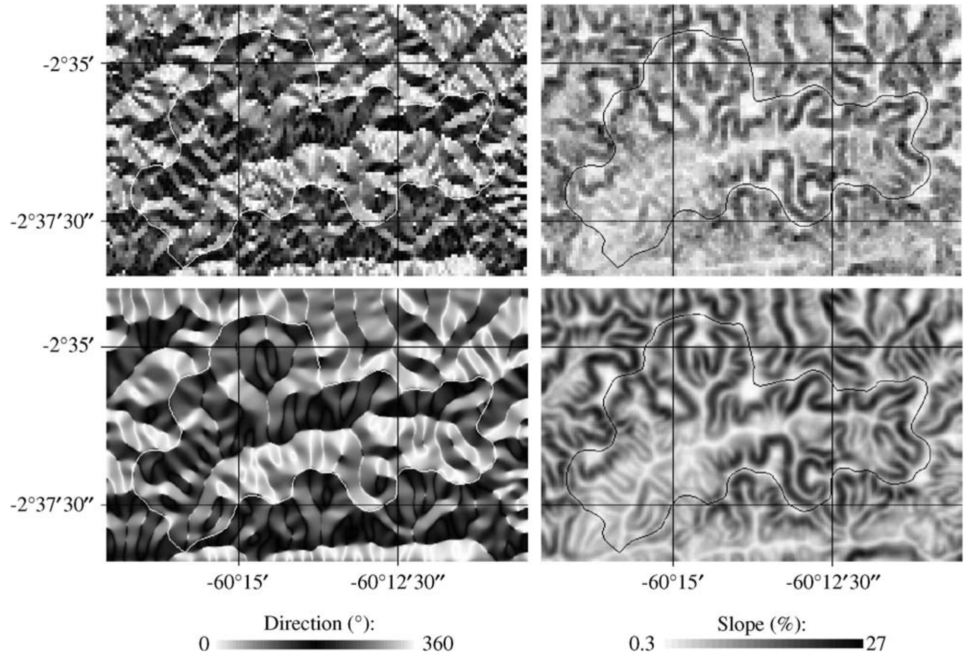


Fig. 11. Morphometric maps of Asu watershed: slope direction and angle, extracted from original (top) and refined (bottom) DEM.

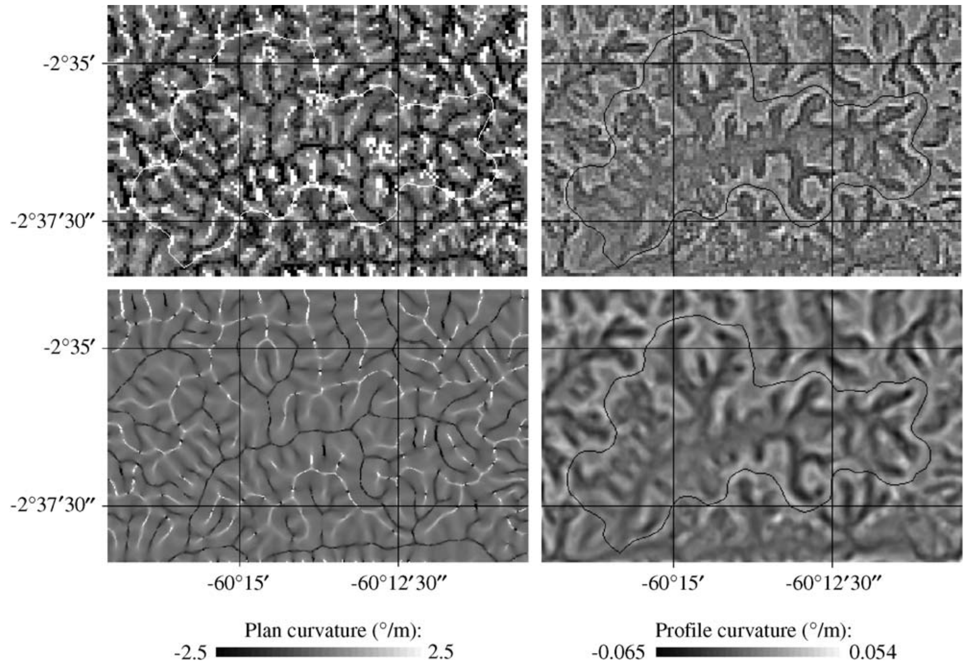


Fig. 12. Morphometric maps of Asu watershed: profile and plan curvature, extracted from original (top) and refined (bottom) DEM.

right), first-order channels had their springs detected, but the junction with the main river could not be enhanced by the applied transversal second-order derivative enhancement. In other words, channel detection under this condition (i.e., under the combination of tropical forest and processed SRTM data) is not possible by simply analyzing drainage cross sections. To model drainage features as a functionally meaningful network, a more complex algorithm is required.

Slope angle and direction (Fig. 11) also showed a notable improvement due to pre-processing, with the latter providing an unambiguous delineation of the watershed drainage structure in the refined DEM (bottom left). Slope angle improvements were related to the surface smoothness rather than to its descriptive potential.

The plan curvature mapping was shown to be specially improved by the smoothing effect on SRTM data after kriging refinement. Original DEM resulted in speckle-like pattern of plan curvature, due to abrupt variations which are unavoidable under coarse resolution. Otherwise, refined data resulted in a meaningful description of the surface hydrology, exhibiting a drainage network as extreme convergence areas (dark) and a clear set of divide lines as extreme divergent areas (bright). Profile curvature analysis of the refined DEM was not improved the same way, showing mainly smoothing effects, undesirably strong, if compared to the perceptible details enhanced on the original data (Fig. 12).

The attenuation effect of the canopy (enhanced in channel delineation, Fig. 10) was also observed in the channel network shown by horizontal curvature (Fig. 12). However, the resulted morphometric maps showed that relief hydrological constraints could be fairly characterized through DEM modeling with the processed SRTM data. Scatter plots of elevation, slope angle, plan curvature and profile curvature (Fig. 13) showed processed SRTM to result in narrower ranges of these variables than the original data and to reduce dispersion of point clouds, essentially. The refinement of SRTM data changed the interrelation between slope angle and profile curvature (Fig. 13d), as compared to results from original SRTM-90 m. For original data, the higher slopes were related to higher convex and concave curvatures, whereas processed data produced independent data sets for these variables.

In the scatter plots in Fig. 13, it can be seen that steepness (a) and profile curvature (b) coherently indicate the slopes to be convex–concave (upward). Also shown in (b) is a slight predominance of convexities. Despite very few exceptions, extreme convergent flow (c) occurs only in lowlands, while, reciprocally, extreme divergence is restricted to uplands. Profile curvature was shown to decrease at extreme (high and low) slope angles (d), though most of its range varied regardless of steepness in refined data, while original data showed a direct relation between slope angle and profile curvature modules, concave or convex. Otherwise, plan curvature was unambiguously restricted by steepness (e), since high angles exhibited near zero (planar) curvature. This particular relation may indicate the relative morpho-pedogenic stability of the watershed, the absence of ravines and a low dissection rate. Taking the distribution of plan and profile curvatures (f), divergent-convex and

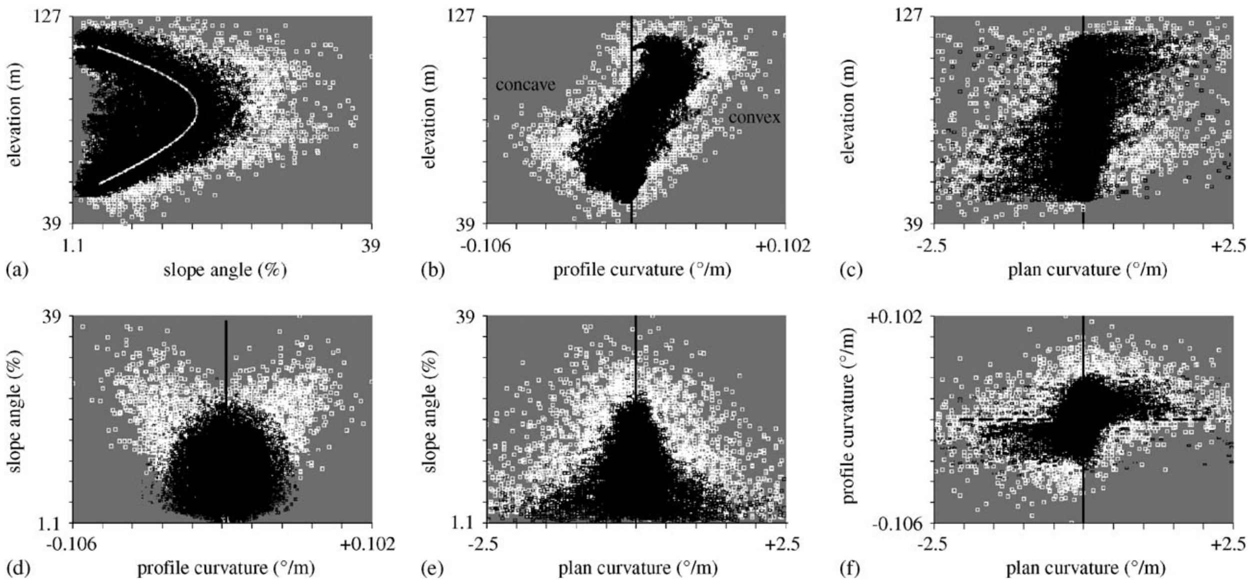


Fig. 13. Scatter plots between morphometric variables in Asu watershed (results from original SRTM-90 m data in white and from refined data in black).

convergent-concave pixels prevail over divergent-concave and convergent-convex ones. If no other factor is acting on water infiltration and retention (hydrologically uniform soil), the predominance of these highly contrasted landforms are expected to bring diverse soil-physic environments and consequent biotic expressions.

The above observations are remote inferences about the watershed environment, based on morphometric analysis. Nevertheless, the morphometric variables showed meaningful distributions and coherent interrelations. More than supporting such type of description, these morphometric relations are expected to feed numerical analyses for a hydrological state-and-process-based classification of watersheds in GIS, as well as to model erosion, sediment, transport and other related processes.

## 4. Concluding remarks

This research showed a methodology for the use of SRTM data to model small watersheds, with emphasis on morphometry and drainage channel detection. Results lead to the following conclusions:

Original SRTM-90 m data have a limited capability to model detailed Amazonian drainage features, visually or digitally. Only visual interpretation of major features was possible with this data.

Canopy showed smoothing effects that obscure the perception of low-order channels. In spite of this and of the possible opposite effect (channel depth exaggeration), the canopy condition must be accounted for when modeling relief with SRTM in forested areas.

The methodology of kriging SRTM-90 to 30 m resulted in important improvements for both visual and digital analysis of the terrain, enabling the application of digital morphometric mapping.

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