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Application of digital terrain analysis to estimate hydrological variables in the Luquillo Mountains of Puerto Rico

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Abstract Techniques of digital terrain analysis were applied to estimate hydrological variables in basins draining the Luquillo Mountains of northeastern Puerto Rico. A 10-m resolution Digital Elevation Model (DEM) was interpolated from 10 m elevation contour lines and used as the template for hydrological analysis. A high density stream network representing all perennial streams, including previously unmapped 1st order streams, was defined using the DEM. Similarly, for each 10 m grid cell within the stream network, mean annual rainfall, runoff, and discharge were estimated using regression equations derived from long-term rainfall and streamflow gauges. The result is a simple spatial framework to estimate hydrological variables in the region.

Key words GIS; Puerto Rico; surface water; stream network; spatial interpolation

INTRODUCTION

Estimating hydrological variables in ungauged drainage basins is challenging in montane environments. Fortunately, digital terrain analysis can be used to derive a wealth of information about the morphology and hydrodynamics of a land surface. When coupled with the spatial distribution of basic hydrological variables, such as rainfall and runoff, digital terrain analysis is a powerful tool for estimating river network variables and generating spatially explicit water budgets (Montgomery *et al.*, 1998). However, digital terrain analysis is often underutilized in tropical drainage basins due to a scarcity of appropriate data. This paper details how digital terrain analysis is used to estimate hydrological variables in the region draining the Luquillo Experimental Forest (LEF), a montane subtropical rainforest in northeastern Puerto Rico.

In the steep landscape of the LEF, estimates of elevation, slope, and drainage areas from topographic maps may not always be accurate. Moreover, the stream network portrayed on US Geological Survey (USGS) maps does not include many 1st order streams in the region. However, the LEF is an ideal landscape to estimate surface water variables using topography because most of the streamflow is derived from surface water and no major groundwater sources contribute to the stream system (Schellekens *et al.*, 2004).

This paper develops a simple framework to estimate hydrological variables for all 10 m × 10 m cells within a stream network that acts as a template for hydrological analysis of the streams draining the LEF. The process involves (1) creation of a hydrologically correct Digital Elevation Model (DEM), (2) definition of the stream network using a drainage area threshold and (3) estimation of mean annual rainfall, runoff, and discharge from topographic factors.

STUDY AREA

The Luquillo Mountains in northeastern Puerto Rico are characterized by rugged terrain and steep gradients in elevation and climate. Over a distance of 10 to 20 km, the mountain range rises from sea level to an elevation of 1075 m. Mean annual rainfall increases with elevation from approximately 2000 mm at the coast to >4500 mm at the highest elevations (García-Martinó *et al.*, 1996).

The climate is characterized as humid tropical maritime, and is influenced by both north-easterly trade winds and local orographic effects. The principal weather systems affecting climate are convective storms, easterly waves, cold fronts, and tropical storms (van der Molen, 2002). Rainfall events at mid-elevations are generally small (median daily rainfall 3 mm day^{-1}) but numerous (267 rain days per year) and of relatively low intensity (<5 mm h^{-1}) (Schellekens *et al.*, 1999). At mid to upper elevations (>100 m), most streamflow results from direct surface runoff in the form of saturated overland flow or through shallow (>30 cm depth) soil macropores. There are no significant groundwater sources or sinks in this montane landscape (Schellekens *et al.* 2004).

The Rio Mameyes is the principal drainage basin highlighted in this study, but the techniques can be applied to other basins draining the LEF. Streams draining the mid to upper elevations are relatively pristine, surrounded by protected forest, and are laterally confined by steep valley walls. In contrast, streams flowing across the broad alluvial coastal plain readily migrate laterally, although many are physically altered to attend to local needs. The main channels of all major rivers in the region have either a dam or water intake device for local municipal use (March *et al.*, 2003).

DEM CONSTRUCTION

The main principle of digital terrain analysis is that a continuous landscape surface can be generated from the abundance of topographic information contained within elevation contour lines (elevation, geomorphic position, slope, etc.). Surface water flow can then be routed across this surface under the assumption that water flows downslope according to principles of least energy, i.e. water follows the path of steepest descent (Jenson & Domingue, 1988). Using this simple rule, the drainage network of a landscape can be extracted.

A high-resolution Digital Elevation Model (DEM) is critical for terrain and hydrological analysis. While a 30 m DEM exists for the entire island of Puerto Rico, this is not sufficient resolution to model the complex topographic structure of the Luquillo Mountains. In particular 1st order streams that typically have an active channel width of <10 m are not defined in the 30 m DEM. Therefore a 10 m × 10 m grid cell resolution DEM was constructed for northeastern Puerto Rico.

Many Geographical Information Systems (GIS) packages are available that provide the necessary tools and algorithms to generate a hydrologically correct DEM from contour data, e.g. the ArcGIS Spatial Analyst and ArcHydro (Maidment, 2002). The 10 m elevation contours from the US Geological Survey (Seiders, 1971) were used for the basis of the DEM (Fig. 1). Contours were first converted to a Triangulated Irregular Network (TIN) surface, which is constructed by

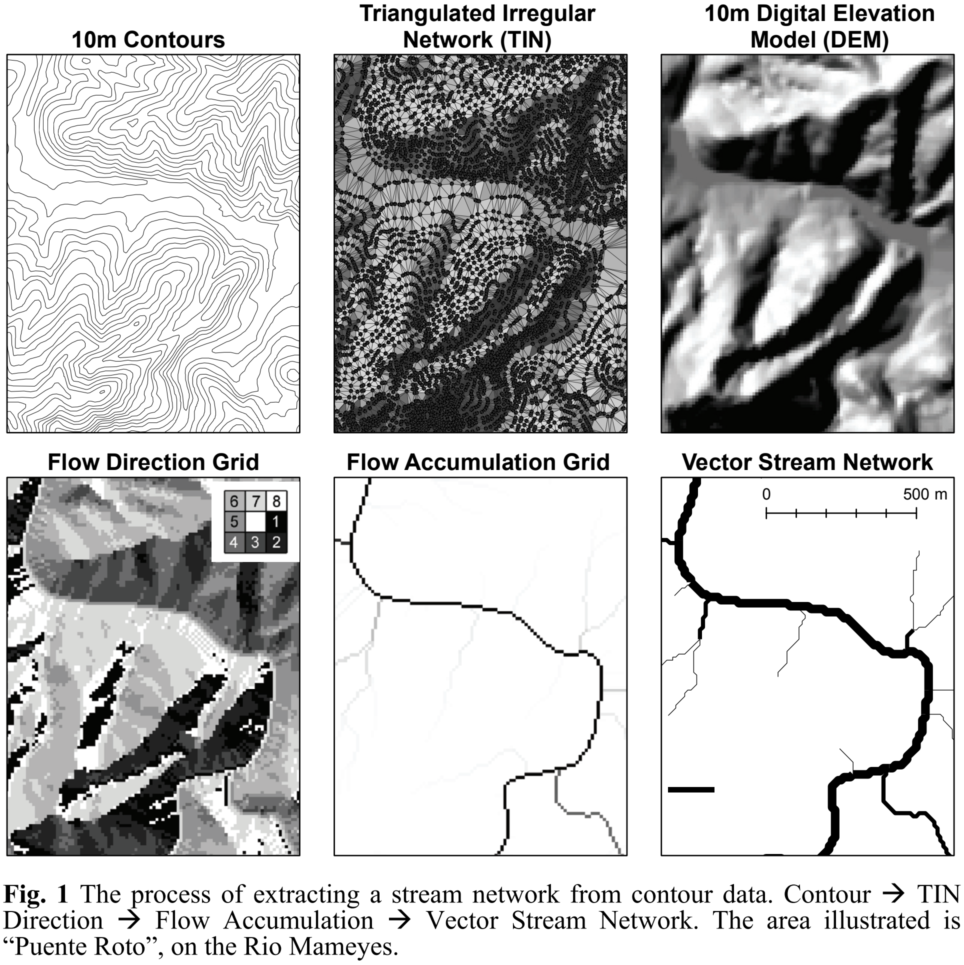

Fig. 1 The process of extracting a stream network from contour data. Contour → TIN → DEM → Flow Direction → Flow Accumulation → Vector Stream Network. The area illustrated is known locally as "Puente Roto", on the Rio Mameyes.

triangulating a set of vertices to form a network of triangles. For the purpose of flow routing, the TIN was interpolated to a raster DEM at 10 m × 10 m grid cell resolution using ArcGIS Spatial Analyst. The resolution of the raster determines how well the raster represents the features of the TIN surface. In the Luquillo Mountains, 10 m resolution is sufficient to capture many elements of the TIN.

The resulting DEM generated from contour lines contains topographic errors that create problems in hydrological models, such as pits and depressions, but are easily corrected to ensure continuous hydrological flow (Tarboton *et al.*, 1991). Similarly, in flat terrain, fine-scale features such as river meanders and river courses may not be well constrained by the contour lines. For better accordance with known river paths, the river can be forced into a DEM by lowering the cells of the river several metres to ensure that they are topographically lower than surrounding cells (Maidment, 2002).

Flow direction was calculated according to the simple D8 algorithm, whereby flow is routed to the adjacent cell with the greatest elevation drop (Jenson & Domingue, 1988). With this algorithm, a flow direction matrix is computed where each grid cell is assigned a value (1–8), corresponding to the eight cardinal directions, routing the flow to the appropriate adjacent cell. The flow accumulation grid was computed using this flow direction grid. First, the total number of upslope cells contributing to a given cell was calculated. Cells were then weighted so that the accumulated surface represents the sum of upslope weights. For example, if the weight is a constant 100 m^2 area for each 10 m cell, then the accumulation represents the drainage area. Similarly, if the weight for each cell is the yearly runoff, then the accumulated surface will represent mean annual discharge.

STREAM NETWORK EXTRACTION

To extract a stream network from a DEM, a drainage area threshold can be applied to the flow accumulation surface (Tarboton *et al.*, 1991). The threshold represents the critical drainage area that distinguishes perennial from ephemeral streams; grid cells that exceed this threshold represent streams with year-round flow. The threshold for perennial streams in the mid-elevations of the LEF has been determined to be approximately 6 ha (Scatena, 1989). While this threshold may vary across the landscape due to rainfall differences, a 6 ha threshold is an appropriate mean estimate for the catchment.

The resulting map of the perennial stream network has a higher drainage density than the USGS stream network (Fig. 2). For the Rio Mameyes, the resulting total length of the stream network at 6 ha drainage area is 133 km, compared to a total length of 70 km for the USGS stream network. This increased length is due to the inclusion of a large number of previously unmapped 1st order streams that do not appear at the scale of the 1:24 000 USGS map but are known to exist. Several of these small streams have community water intakes, and thus the extraction of these streams from the DEM is critical for estimating the available water.

The resulting stream network accurately represents the path of major stream channels. However, some of the smaller streams may not be accurately represented. This problem is most apparent in flat terrain, where flow can follow artefacts of the surface interpolation procedures rather than real topographic features. Similarly, small streams have been diverted in the lowland agricultural fields and urbanizations. In these areas, the digital estimation and reality may not agree. Therefore, for the purpose of mapping small 1st order streams, the digitally defined stream network should be used with caution when outside of natural, valley confined upland streams.

RAINFALL, RUNOFF AND DISCHARGE

The spatial distribution of rainfall and runoff the in LEF is strongly influenced by elevation. Small drainages in the uplands have distinctly more runoff than comparably sized lowland drainages. To estimate the spatial distribution of mean annual rainfall, runoff and discharge, the following elevation-based regression equations, estimated from long-term rain and streamgauges throughout the LEF, were used (García-Martinó *et al.* 1996):

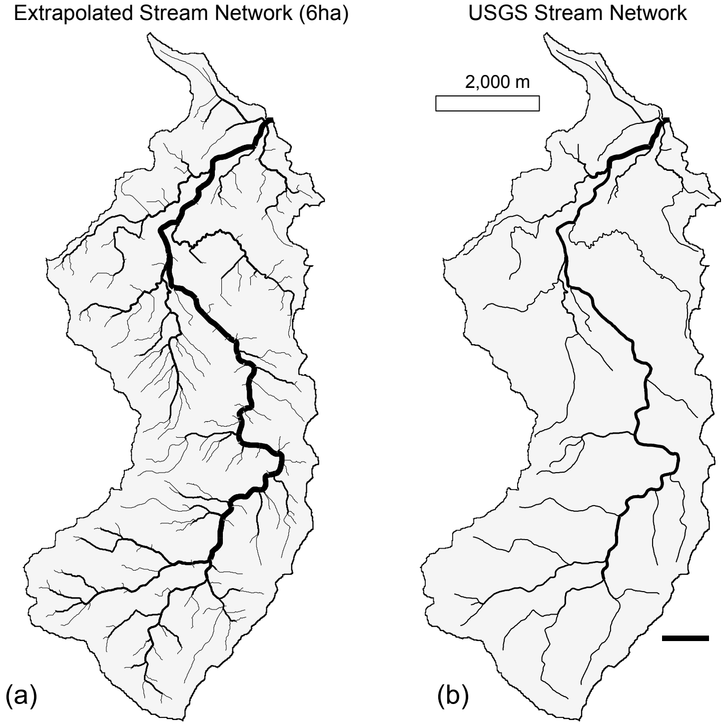

Fig. 2 Comparison of the USGS stream network (a) to the DEM generated stream network at 6 ha drainage area threshold (b) for the Rio Mameyes. Lines widths are scaled according to stream order. While only the Rio Mameyes is illustrated (to show fine scale features), other drainage basins show a similar comparison between USGS and DEM generated stream networks.

$$P = 2300 + 3.8h - 0.0016h^2 \qquad n = 17, r^2 = 0.91, p < 0.001 \tag{1}$$

$$R = 4.26WAE + 360 \qquad n = 9, r^2 = 0.77, p = 0.002 \tag{2}$$

Discharge is estimated from runoff by multiplying by the drainage area:

$$Q = 3.17 \times 10^{-5} A(4.26WAE + 360) \qquad n = 9, r^2 = 0.97, p < 0.001 \tag{3}$$

P = mean annual rainfall (mm), R = mean annual runoff (mm), Q = mean annual discharge (m^3 s^{-1}), h = elevation (m a.s.l.), WAE = weighted average elevation (m), A = drainage area (km^2), n = number of gauges used, p = significance level.

Using these equations, maps of mean annual rainfall, runoff, and discharge for the Rio Mameyes are shown (Fig. 3). Rainfall and runoff very closely resemble the elevation structure, while discharge pattern is similar to flow accumulation grid. This is due to the fact that both rainfall and runoff are based on elevation, while discharge is a largely a function of drainage area.

The weighted upstream elevation variable, used in calculating runoff, is an accumulated function. That is, it is the sum the elevation of all upslope cells, divided by the number of accumulated cells. This accounts for the fact that basins at higher elevations have greater mean annual runoff than corresponding basins of equal area at lower elevations.

A simple water budget was constructed for the Rio Mameyes drainage basin, using equations (1) and (2): mean annual rainfall is 3320 mm, runoff is 2090 mm, and by difference, evapotranspiration is 1230 mm (García-Martinó *et al.*, 1996). This budget is comparable to a recently estimated evapotranspiration rate, averaged for the entire LEF, of 3.08 mm day^{-1}, or 1120 mm $year^{-1}$ (Wu *et al.*, 2006). According to this budget, 63% of rainfall becomes runoff, and estimates of discharge derived from runoff (equation (3)) agree with the water budget. Similarly, the discharge equation derived from runoff is superior to a simple drainage area–discharge relation because it takes the upstream elevation and rainfall into account. Thus, the simple regression-based approach mentioned here is sufficient to make accurate predictions of rainfall, runoff, and discharge in these drainages.

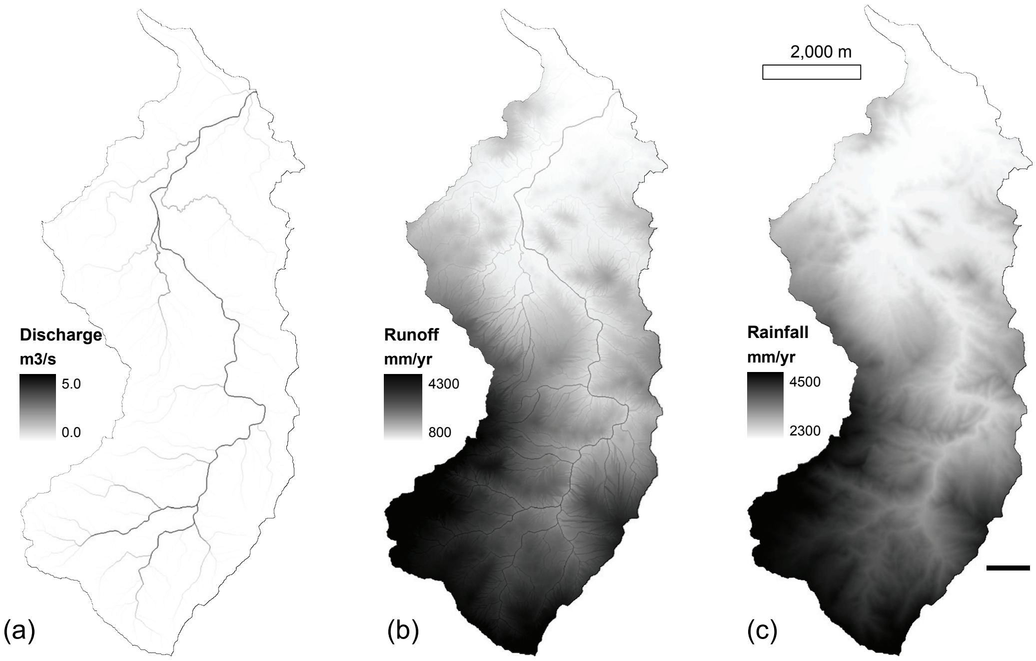

Fig. 3 Spatial distribution of mean annual (a) rainfall, (b) runoff, and (c) discharge within the Rio Mameyes drainage basin according to elevation-based regression equations.

CONCLUSIONS

The stream network and mean annual rainfall, runoff, and discharge can be accurately estimated at 10 m spatial resolution according to a simple DEM-based process for basins draining the LEF. The estimates are better applied to streams in the forested upland regions than flat and anthropogenic disturbed areas. However, the simplicity of this DEM-based approach allows any researcher with limited rainfall and runoff data to estimate key hydrological variables in ungauged areas.

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