Intrinsic properties of channel network structure and the hierarchical classification approach for stream-limits delineation

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ABSTRACT

Delineation of drainage networks is an essential task in hydrological and geomorphological analysis. Manual channel definition depends on topographic contrast and is highly subjective, leading to important errors at high resolutions. Different automatic methods have proposed the use of a constant threshold of upslope contributing area to define channel initiation. Actually, these are the most commonly used for the automatic-channel network extraction from Digital Elevation Models (DEMs). However, these methods fail to detect an appropriate threshold when the basin is made up of heterogeneous sub-zones, as they only work either lumped or locally. In this study, the critical threshold area for channel delineation has been defined through the analysis of dominant geometric and topologic properties of stream network formations. In addition, a hierarchical classification approach has been integrated in order to verify landscape units in relation to dominant intrinsic properties. Such approach provides various critical thresholds as much as necessary in relation to DEM-data resolution as well as homogeneity or heterogeneity of the dominant landforms. The study has been carried out in two controlled drainage basins with different lithology and geomorphic processes. High-resolution DEMs (1m) were used to obtain the best detailed drainage network that the algorithm can generate in a homogeneous landscape, whereas a medium-resolution DEM (30m) was applied in a heterogeneous complex landscape. Validation results revealed that the above approach is adequate for describing terrain dissection, since its function depends on intrinsic properties of the drainage network, being at the same time objective and easy to implement. Likewise, it provides an enhanced approximation to empirical geomorphometric parameters used to describe stream network dimensions.

Key words: critical threshold area, geometric and topologic properties, hierarchical classification approach, intrinsic properties, geomorphometric parameters.

INTRODUCTION

One of the essential tasks in hydrologic and geomorphologic studies is the quantitative description of land surface parameters, mainly river system structure and its corresponding geomorphometrical properties (Hancock 2005). In general, Digital Elevation Models (DEMs) are used to delineate basin's limits and to extract its corresponding channel networks, using either automatic or semi-automatic approaches for such depiction. In many cases, channel networks are defined through a constant threshold area that defines channel initiation in relation to upslope contributing area. However, the majority of these approaches fail to detect an appropriate threshold when the basin is made up of heterogeneous sub-zones, as they only work either lumped or locally. In this work, a new approach is proposed to define an optimum threshold value (A_S) based on the intrinsic properties of the drainage network structure.

The majority of the proposed methods assume A_S as a constant value, and evaluated its validity in a qualitative and quantitative form in judgment to the blue lines generated from topographic maps. However the drawing of blue lines on maps usually involve subjective decision by the topographer. While, automatic approaches may incorporate local factors, and hence previous environmental information is needed, or use DEM-data directly without any reference to auxiliary data. Since channel network depiction and related parameters are needed a priori in different hydrological applications, one would expect that DEMs will be the solely available information to delineate channel networks under such conditions. Several algorithms have been proposed for automatic drainage network delineation, from which the slope-area relationship are the most underlined

$$S = cA^{-\theta} \qquad (1)$$

where S is the local slope, A is the contributing area, c is a constant and θ is a scaling coefficient.

Tarboton et al., (1991) proposed to use the value of A at this breaking point as the critical contributing area (A_S). Throughout the actual work, results of the slope-area relationship are directly compared with the results of the new approach in order to check model-capacity enhancement. In general, using a single A_S value over extended area of heterogeneous landforms is usually applied due to the lack of necessary information. Theoretically, the use of a single A_S is applicable only under homogeneous-landscape conditions. But, under real landscape conditions homogeneity is limited to small-scale size catchments. So, an adequate solution, according to our judgment, could be achieved by using algorithms that best simulate landscape spatial heterogeneity and make use of available data. Thus, the general objective of the actual work is formulated to define the optimal channel network that best describe landscape dissection at a determined scale and resolution. In order to achieve this objective, a new procedure has been proposed, based on the analysis of intrinsic properties of channel network provided by the information extracted directly from DEM-data.

METHODOLOGY

Based on the assumption that a DEM is a dynamic structure able to determine its internal formation, and that channel complexity is best reflected by its corresponding intrinsic properties, a new model approach has been proposed. Basically, the model combines exterior and interior link lengths ratio (R_A) with length and bifurcation properties described in terms of structure regularity framework (Horton 1945) and topological random approach (Shreve 1966), in order to produce a varying ratio in relation to changeable threshold values.

$$R_A = \bar{l}_i / \bar{l}_e \qquad (2)$$

where $\bar{l}_i$ and $\bar{l}_e$ are the average length of interior and exterior links, respectively. The structure regularity framework of Horton consists of bifurcation ratio (R_B) and length ratio (R_L), defined as

$$N_{\omega-1}/N_\omega \approx R_B \qquad \omega = 2, 3, \ldots, \Omega \qquad (3)$$

$$\bar{L}_\omega/\bar{L}_{\omega-1} \approx R_L \qquad \omega = 2, 3, \ldots, \Omega \qquad (4)$$

where N_ω is the number of streams of order ω, $\bar{L}_\omega$ is the arithmetic average of the length of streams of order ω, and Ω is the total network order. Equations 3 and 4 have been expressed by Smart (1972) in a topological form by:

$$\bar{L}_\omega = \bar{l}_i \prod_{a=2}^{\omega} (N_{a-1} - 1)/(2N_a - 1) \qquad \omega = 2, 3, ..., \Omega \qquad (5)$$

where N_a is the number of streams of order a, and Ω is the network order. Individual stream length ratios are given by:

$$\lambda_2 = \bar{L}_\omega / \bar{L}_1 = R_A (N_1 - 1)/(2N_2 - 1) \qquad (6)$$

$$\lambda_3 = \bar{L}_\omega / \bar{L}_{\omega-1} = (N_{\omega-1} - 1)/(2N_\omega - 1) \qquad \omega = 3, 4, ..., \Omega \qquad (7)$$

If we assume that channel networks are space-filling with a fractal dimension of 2 in the plane, where Hortonian's laws holds exactly at all scales in the network, we can accept the assumption of Smart, in the case of moderately large N_ω, that

$$\lambda_\omega \sim B_\omega / 2 \approx B_\omega = 2\lambda_\omega \qquad (8)$$

Reorganizing equations 6 and 7 in 3 and 4, and substituting in 8 we can get a modified value of R_A given by:

$$R'_A = \left[2 * (\Delta + (\Lambda * R_A))\right] / \Gamma \qquad (9)$$

where $\Delta = (N_1 - 1)/(2N_2 - 1)$, $\Lambda = \sum_{\omega=3}^{\Omega} (N_{\omega-1} - 1)/(2N_\omega - 1) = \lambda_3$, and $\Gamma = \sum_{\omega=2}^{\Omega} (N_{\omega-1} / N_\omega)$

RESULTS AND DISCUSSION

The resulted ratio of equation 9 describes well natural channel networks since R'_A integrates structure-regularity and random-topology approaches, both widely confirmed by observations on natural channel networks and best adapt to natural complex landscapes. Accordingly, R'_A are placed against their corresponding thresholds and the optimum A_S is defined by the maximum rate of change (i.e. stability zone) produced by the varying-tendency curve relationship (figure 1). The stability zone bears a range of thresholds, from which the local minima (i.e. minimum rate of change) and local maxima (i.e. maximum rate of change) are detached. These locals are connected, in one way or another to catchment complexity. In this context and according to landscape heterogeneity, we believe that local minima represents the maximum complexity of the generated drainage network with minimum possible feathering in a heterogeneous complex landscape, whereas the local maxima represents the minimum complexity with the minimum possible feathering in a homogeneous simple landscape. Accordingly, local minima will be applied to heterogeneous landforms and local maxima to homogeneous terrain features. The rate of change is steady in homogenous landforms simulating experimental models for stream initiation, and unsteady in heterogeneous relief leading to variable rate of changes pertaining to DEM capacity to recognize finest terrain forms at the available scale and resolution. In addition, a hierarchical classification model has been integrated in the above approach to verify landscape units in relation to dominant intrinsic properties in the generated sub-catchments of decreased orders. Such classification provides as much as A_S values in relation to the sub-classified catchments, which usually approximates to homogenous relief forms (figure 2).

CONCLUSIONS

Results underline the following conclusions: *i*) the presented approach is adequate for describing terrain dissection, since its function depends on intrinsic properties of the drainage network, being at the same time objective and easy to implement; *ii*) the spatial analysis is a useful tool for channel and stream detection; and, *iii*) Morphometric properties vary considerably with A_S, and thus values reported without their associated A_S are meaningless and should be used in hydrological analysis with caution.

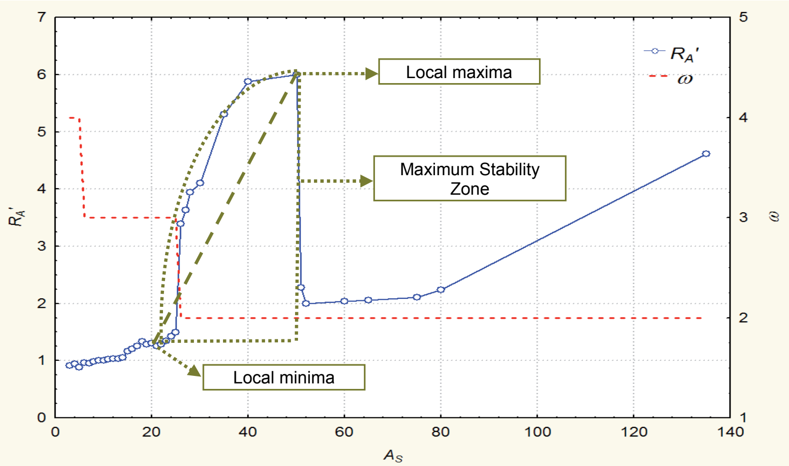

Figure 1. Curve relationship between R'_A and A_S for El Cautivo catchment at 1m resolution.

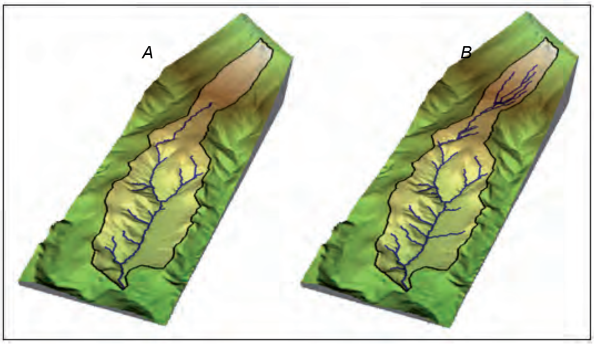

Figure 2. Channel network limits at the Cautivo Catchment. A) Stream limits with R'_A approach. B) Stream limits with local slope and contributing area relationship approach.

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