An Adaptive Approach for Channel Network Delineation from Digital Elevation Models

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1. Introduction

The quantitative description of land surface parameters is one of the essential tasks in hydrologic and geomorphologic studies, mainly river system structure and its related geomorphometric properties (Hancock 2005). Digital Elevation Models (DEMs) are generally 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, methods for stream-limits delineation are broadly based on 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 value, mainly when the basin is made up of heterogeneous sub-zones, as they only work lumped. 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. Such technique provides various critical thresholds in relation to DEM-data resolution and to the heterogeneity of the dominant landform structures.

1.1 Manual and Automatic Approaches

The majority of the existing techniques assume A_S as a constant value, and evaluate its validity in a qualitative and quantitative form in judgment to the blue lines (*BLs*) generated from topographic maps (Band 1986). However the drawing of *BLs* on maps usually involve subjective decision by the topographer (Tarboton et al., 1991). On the other hand, DEM-use in stream network generation may incorporate local factors, and hence a priori information is needed, or alternatively DEM-data would be directly used without any reference to auxiliary data, and hence DEMs will be the solely available information under such approach.

Several algorithms have been proposed for automatic drainage network delineation, from which the slope-area relationship is the most underlined

$$S = cA^{-\theta} \tag{1}$$

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

Researchers (e.g. Montgomery and Dietrich, 1989) underlined that Equation 1 reflects the transition from convex hillslopes to concave valleys, which is expressed by a characteristic change from a positive to negative trend. Tarboton et al., (1991, 1992) proposed to use the value of A at this breaking point as the critical contributing area (A_S). Throughout this work, results of an accepted slope-area relationship (*SAR*) model are directly compared with the results of the new approach in order to check the model performance of the latter.

1.2 Single versus Multiple Approach

In general, using a single A_S value over extended area of heterogeneous landforms is usually applied due to the lack of necessary information (Hutchinson and Dowling 1991). Theoretically, the use of a single A_S is applicable only under homogeneous-landscape conditions (Vogt et al., 2003), which is often limited to small-scale size catchments. It has been argued (Rodriguez-Iturbe and Rinaldo 1997) that a monofractal dimension (i.e. a unique A_S value) does not seem entirely consistent with the properties of measured field data. So, whatever approach used it should best describe existing landforms irrespectively of the terrain heterogeneity. Thus, an adequate solution, according to our judgment, could be achieved by using algorithms that best simulate landscape spatial heterogeneity, represent landscape dominant processes, and make use of available data.

Hence, the general aim of this work is to define the optimal channel network that best describe landscape dissection at a given resolution. Another associated objective is the generalized analysis of channel network complexity to other areas of complex heterogeneity under distinct scales and resolutions in order to obtain the best approach for channel networks description. In order to achieve these objectives, the proposed procedure is based on the analysis of intrinsic properties of channel network structure provided by the information extracted directly from DEM-data.

2. Methodology

The basic assumption is that DEMs are self-contained structures to detect drainage networks, and that channel complexity is best reflected by its corresponding intrinsic properties. Basically, the model combines exterior and interior link lengths ratio (R_A) (Schumm 1956) 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 $\bar{l}_i$ is the average length of interior links and $\bar{l}_e$ is the average length of exterior links.

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 (1968, 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

$$\lambda_\omega \sim R_B / 2 \approx R_B = 2\lambda_\omega \tag{8}$$

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

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

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

The resulted ratio of Equation 9 describes well natural channel networks since R'_A integrates structure-regularity and random topology model approaches, both are widely confirmed by observations in real landscapes (Jarvis, 1977). Accordingly, a changeable relationship is constructed between growing thresholds and its corresponding R'_A values, in which each R'_A is plotted against its related threshold and the optimum A_S is defined by the maximum rate of change (*MRC*) produced by the varying-tendency curve relationship (Fig. 1). The *MRC* bears a range of thresholds, from which the local minima (i.e. minimum rate of change) and local maxima (i.e. maximum change of rate) are detached. These locals are connected, in one way or another to catchment complexity. In this context, we believe that local minima represents the maximum complexity of the generated drainage network with the 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. The resulting rate of change is steady in homogenous landforms, simulating experimental models for stream initiation (Schumm 1977), and unsteady in heterogeneous relief leading to variable rates of change depending on DEM capacity to convey the finest terrain forms at the working resolution (Fig. 2). Such oscillations are attributed to a varying change in R'_A value associated to the transformation of exterior links into interior ones as A_S increases. In order to verify landscape units of similar characteristic properties, a hierarchical classification procedure (*HCP*) has been integrated in the above approach, which allows for a simple reclassification of the generated sub-catchments of decreasing orders. Such classification provides as much as A_S values in relation to the classified sub-basins, which usually approximates to homogenous relief forms. Hereafter, the combination of R'_A and *HCP* procedures will be designated as the $R'_A t$ approach.

2.1 Validation Procedure

The validation procedure has been realized in the badlands of the Cautivo catchment following two approaches. The first one employs a 1 m DEM resolution and uses the *BLs* as a reference to compare with either models (*SAR* and R'_A) for validation. The comparison procedure is based on a collection of about 27 geomorphometrical indices that cover a vast range of river system properties. Redundancy and correlation are widely dominant between geomorphometric parameters, since various indices measure the same element but in different ways or contain common dimensions. Such problem was tackled through the combination of a multivariate statistical technique that verifies the degree of redundancy and structure detection between variables, and a regression measure in order to quantify the amount of correlation between parameters. Later on, a one-to-one comparison test was applied between the parameters derived from both automatic channel network detection approaches and those from the reference ones (i.e. *BLs*) using the *"Gower Metric (GM)"* measure of dissimilarity (Gower 1971). The second approach utilizes real topographic data obtained by a Laser Scanner device to detect the topographic landforms at 6 cm grid resolution for a small sub-catchment of about 13 m^2. A spatial dependence analysis was then made along stream and hillslope profiles (Fig. 3) to verify directional effect in the field sampled data, in which range values were determined in semivariograms to check for isotropy in the topographic structure. Moreover, a 3D-terrain reconstruction enabled a meticulous inspection of the finest stream limits in the constructed basin.

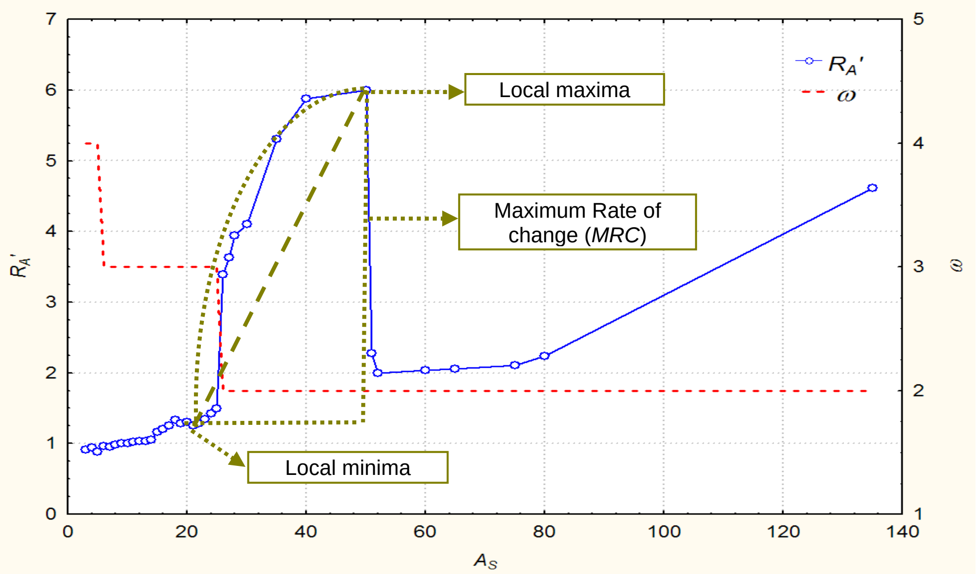

Figure 1. Curve relationship between R_A' and A_S for Tabernas Basin at 30m resolution.

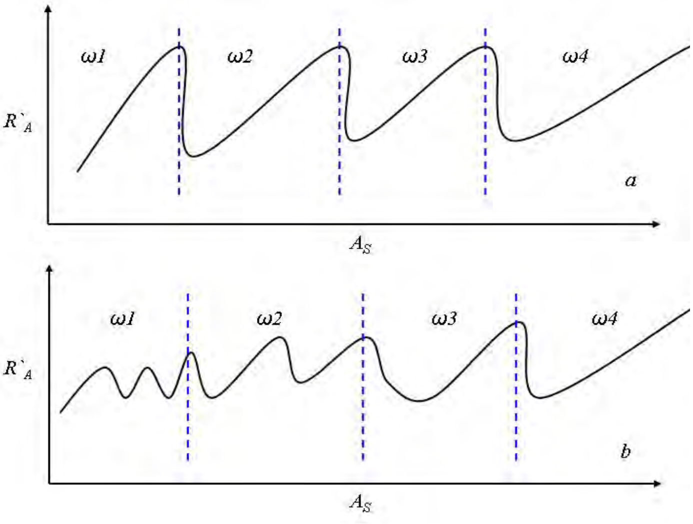

Figure 2. A conceptual framework for R_A' behaviour in, a) a hypothetical homogeneous landscape, and b) a hypothetical heterogeneous landscape

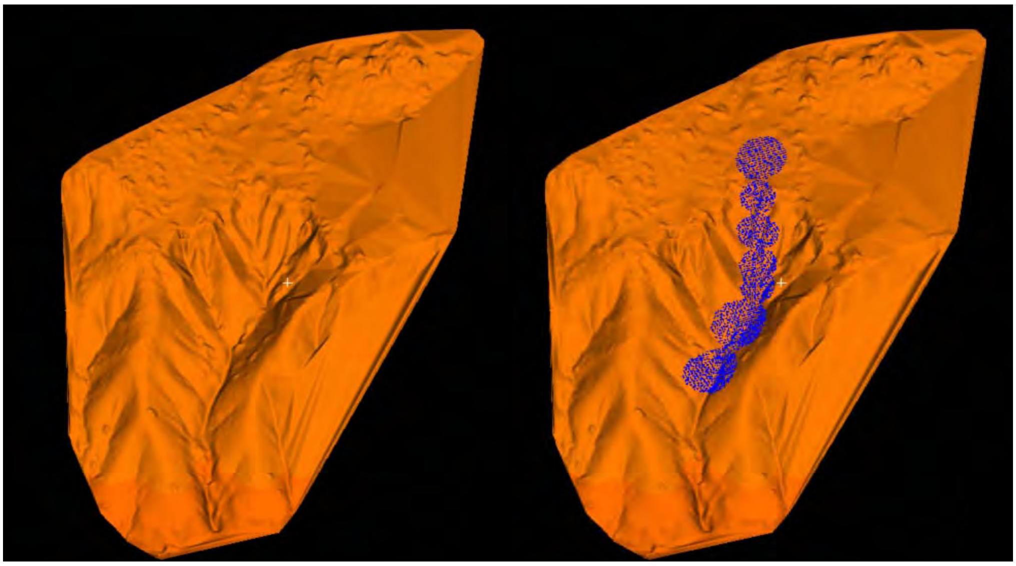

Figure 3. DEM of a small sub-catchment at 6 cm resolution built using data from a Laser-scanner device. Blue plots indicate the sampling network for the spatial analysis along a hillslope to stream profile

3. Results and Discussions

The visual comparison reveals a clear feathering for the *SAR* approach, mainly in the upper part of the catchment, and moderately reliable similarity between $R'_A t$ and *BLs* streams (Fig. 4). In the direct comparison using the geomorphometric indices, again the *GM* test confirms that stream network defined by the $R'_A t$ approach simulates better digitized *BLs* than the *SAR* does (Table 1). Finally, the spatial analysis of semi-variograms along the main stream profile shows anisotropic effect in the hillslope and isotropic variation on the stream profile (Fig. 5). Such tendency has been confirmed in all initiation areas of first order streams of the $R'_A t$ approach, whereas in the *SAR* approach limits of exterior streams were observed in hillslope sectors.

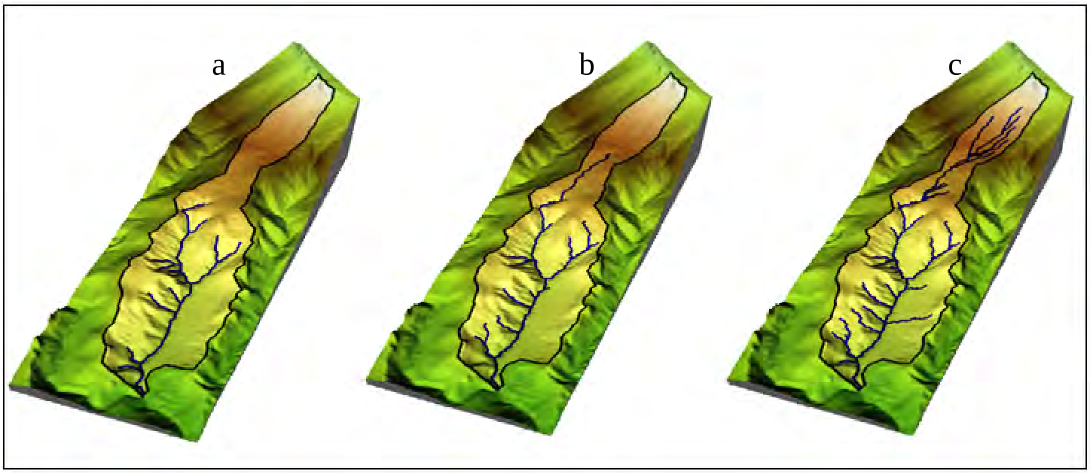

Figure 4. Channel network limits in the Cautivo Catchment at 1 m DEM resolution. a) Digitized *BLs*. b) Stream network with $R'_A t$ approach. c) Stream network with *SAR* approach.

Index	*BLs*	*SAR*	$R'_A t$	*GM*	
				BLs-SAR	*BLs-* $R'_A t$
Ω	3	3	3	0	0
La	235.4	377.9	312.9	0.41666	0.22661
Dd	0.0261	0.0568	0.0291	$8.9*10^{-05}$	$8.6*10^{-06}$
μ	13	35	13	0.06432	0
ε	1.847	1.8922	1.8707	0.00013	$6.9*10^{-05}$

Table 1. Gower Metrics dissimilarity index values for some geomorphometric parameters. Ω: order, La: longest stream, *Dd*: drainage density, μ: magnitude, ε: fractal dimension.

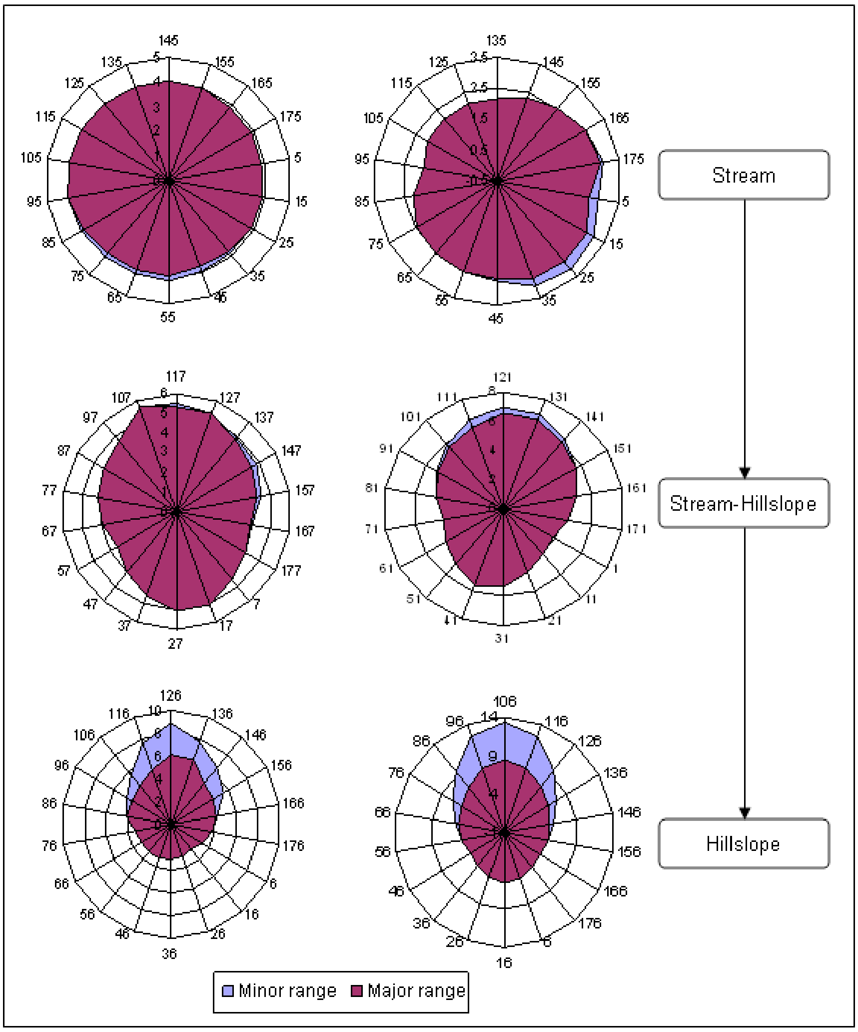

Figure 5. Change in range values of the generated semivarigrams from the red plots in Fig 3. Major ranges indicate hillslope formations whereas minor ones point out to a stream profile section.

3. Conclusions

Results underline the following conclusions: *i*) the $R'_A t$ approach has improved channel networks delineation over the *SAR* approach, since its function depends on intrinsic properties of the drainage network, being at the same time objective and easy to implement; *ii*) each geomorphometric index has variable dimensions, and their geomorphic and hydrologic importance are varied in relation to the parameters included in each index; *iii*) the spatial analysis is a useful tool for hillslope and stream-pattern detection; and, i*v*) 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.

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