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IDENTIFICATION AND ANALYSIS OF NATURAL CHANNEL NETWORKS FROM DIGITAL ELEVATION MODELS

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ABSTRACT

The identification and analysis of natural channel networks from digital elevation models are discussed from the point of view of their environmental applications. An interactive, graphical software package that implements some of the most widely used techniques for the automatic recognition of channel networks and for the computation of some useful geomorphologic indices and functions is presented.

KEY WORDS digital elevation model; channel network; geomorphologic indices

INTRODUCTION

In the last few years an interesting cross-fertilization process has taken place between environmental monitoring and geographic data processing on one side, and hydrologic modelling on the other. The increased availability of detailed information about the earth's surface and near-surface features, and of powerful software tools to process them, has fostered the practical application of distributed approaches to hydrologic modelling and has stimulated the research of new links between geographic and physiographic characteristics and the hydrologic response. Such activities, in turn, gave important feedbacks which opened new perspectives to the monitoring and processing of environmental data. The identification of spatial rainfall patterns, the evaluation of soil water content and wash load production in a truly distributed manner, the automatic extraction of natural channel networks from digital elevation models (DEMs), are examples of this fruitful interaction.

Algorithms for automatic channel network extraction from grid-DEMs for hydrological applications, in particular, have been the object of quite intense research activity (e.g. Peucker and Douglas, 1975; O'Callaghan and Mark, 1984; Band, 1986; Jenson and Domingue, 1988; Fairfield and Leymarie, 1991; Quinn *et al.*, 1991; Tribe, 1991, 1992; Chorowicz *et al.*, 1992). In fact, a knowledge of the exact geometry of channels and hillslopes is a prerequisite for many hydrologic and hydraulic elaborations, including erosion and sediment yield evaluation at the catchment scale. Moreover, the geomorphologic theory of the hydrologic response (Rodriguez-Iturbe and Valdés, 1979; Gupta *et al.*, 1986) has demonstrated the predominant role of network geometry in shaping the hydrologic response, the main characteristics of which can therefore be inferred from readily available information. This obviously has important practical consequences, especially for the problem of estimation of floods in ungauged catchments, where empirical methods are still widely applied.

The most commonly used procedure for automatic generation of channel networks from grid-DEMs consists of two steps: (i) the identification of a connected, space-filling drainage network (SFDN) from the direction of

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flow out of each cell of the DEM, which in turn is determined based on a steepest slope criterion; (ii) the 'filtering' of the SFDN according to the value of the minimum contributing area necessary to initiate and maintain a natural channel (support or threshold area, A_s). The derivation of a fully connected SFDN from DEM may be hindered by two main stumbling blocks, namely the presence of pits and of flat areas. Pits are depressed points, where flowlines converge from all the adjacent cells. Flat areas are zones of zero gradient, where the information available in the DEM is not sufficient to determine the proper drainage direction. Generally, pits are removed by increasing the local elevations or by global smoothing techniques, whereas flat areas are arbitrarily resolved.

Once the SFDN is obtained, the crucial point is the selection of the threshold area. In most applications, A_s is assumed to be constant all over the catchment (Band, 1986, 1989; Jenson and Domingue, 1988; Morris and Heerdegen, 1988; Gardner *et al.*, 1991), but recent research on the relationship with morphology, soil and climate has led to the adoption of variable, slope-dependent values of A_s (Montgomery and Dietrich, 1992, 1994; Dietrich *et al.*, 1992, 1993; Dietrich and Dunne, 1993; Montgomery and Foufoula-Georgiou, 1993).

In this contribution, a program that allows for the automatic identification and analysis of natural channel networks from DEMs is presented. The program works in a fully interactive way on a raw DEM and allows the sequence of operations (depitting, treatment of flat areas, etc.) to be carried out that are needed to get a connected channel network, and enables the calculation of some useful geomorphologic indices and functions, such as the Horton indices and the width and area functions. The paper is organized as follows. In the next two sections, a brief overview is given of the methods for pre-processing the DEM data, in order to remove pits and flat areas, and of the algorithms for the automatic identification of channel networks. The main characteristics of the program are presented in the fourth section, while in the fifth an example of application to a real catchment is discussed.

DEPITTING AND FLAT AREA HANDLING

Pits arise both as a consequence of mistakes in the data acquisition process and due to an unsuitable sampling frequency of the land surface. An additional source of errors may be introduced when the grid-DEM is derived from a contour line vectorial data set. Even if it is true that not all pits reflect errors in the data acquisition process, for most of the time this is certainly the case (Band, 1986; Carrara, 1986). On the other hand, as observed by Tribe (1992), 'It would be advantageous to be able to distinguish between spurious and natural pits because only spurious pits should be eliminated'. Two main approaches to the removal of pits can be identified. The first one is based on the local modification of the elevations in the pit areas, following empirical criteria (e.g. Jenson and Domingue, 1988). The second one is based on the classic separation of noise from signal via suitable filtering techniques (e.g. Band, 1986). The main criticisms to the latter approach are that the pit removal is not complete, and therefore local techniques must be used to terminate it, and that the information content of the original DEM may be degraded by the global filtering (Collins and Moon 1981; Jenson and Domingue, 1988; Tribe, 1992). Therefore, although the physical justifications behind the local correction of the DEM are rather weak, the first approach is often preferred. The depitting method originally proposed by O'Callaghan and Mark (1984) has been implemented in the program. From a conceptual viewpoint, pit removal is achieved by increasing the elevation of the pit cells as if a liquid were dropped into the pit itself, until the lowest altitude outlet is found. As a result of this process, pits are substituted by flat areas.

Flat areas are often present in DEMs. They may reflect the actual topography of the basin, for instance when reclaimed lands are present. In such a case, obviously the DEM should be complemented with additional information on the artificial drainage directions. More often, however, flat areas are due to insufficient detail during sampling, or may arise as a consequence of the depitting process. The problem of the assignment of flow directions across flat areas has been widely debated. Whilst in some situations the solution may be suggested by a global analysis of the surrounding topography, in the case of large flat areas this is of little help. A widely used algorithm for dealing with flat areas is that proposed by Jenson and Domingue (1988). However, Tribe (1992), in his remarkable review, has shown that such an algorithm tends to create unrealistic parallel flow lines. In order to overcome this limitation, Tribe proposed a new method that creates converging humid, soil-mantled landscapes, the support area may be related to the critical shear stress τ_c exerted by water on the soil surface, and to the local slope. Montgomery and Dietrich (1994) derived the following expressions for laminar flow:

$$a_s = \frac{2\tau_c^3 g}{pk\upsilon\gamma^3} \frac{1}{S^2} \tag{2}$$

and for turbulent flow conditions:

$$a_s = \frac{\tau_c^{5/3}}{pn\gamma^{5/3}} \frac{1}{S^{7/6}} \tag{3}$$

where a_s is the support area per unit contour length, $p(\mathrm{ms^{-1}})$, is the uniform rainfall rate in excess of the infiltration capacity, k is a dimensionless coefficient whose value depends on the geometry of the erodible bed, v ($\mathrm{m^2s^{-1}}$) is the kinematic viscosity of the fluid, $\gamma(\mathrm{Nm^{-3}})$ is the sediment-laden water specific gravity, g ($\mathrm{m\,s^{-2}}$) is the gravitational acceleration, and n ($\mathrm{m^{-1/3}\,s^{-1}}$) is the Manning roughness coefficient.

It is important to observe that, when the soil in the basin is cohesive, the evaluation of τ_c is not straightforward, since it depends both on the hydraulic parameters of the flow and, even more, on the chemical properties of the fluid (e.g. its pH value and molar salt concentration), as shown by Raudkivi and Tan (1984). The problem is considerably simplified in the case of incoherent soil, because the well-known Shields relation for the inception of sediment erosion (Shields, 1936; Yalin, 1977) can be properly used. Say that D(m) is the typical linear dimension of the grains, $\nu_*(\mathrm{ms^{-1}})$ is the shear velocity, γ_s ($\mathrm{Nm^{-3}}$) the submerged weight of the sediments, h(m) is the overland flow depth, and J is the energy grade. Shields has shown that a relation:

$$Y_{cr} = \Phi(X) \tag{4}$$

holds at the onset of transport conditions between the grain Reynolds number X:

$$X = \frac{D\nu_*}{\nu} \tag{5}$$

and the mobility number Y:

$$Y = \frac{\rho\nu_*^2}{\gamma_s D} = \frac{\tau_0}{\gamma_s D} \tag{6}$$

where τ_0 is the boundary shear stress exerted by water:

$$\tau_0 = \gamma h J \tag{7}$$

The critical shear stress can therefore be expressed as:

$$\tau_c = \gamma_s D \Phi(X) \tag{8}$$

The empirical Shields function $\Phi(X)$ depends only on the hydrodynamic condition at the bottom boundary; its pattern, well assessed in rough turbulent regimes, has been identified, for the hydrodynamic conditions prevailing in sheetflows and rillflows, by Yalin and Karahan (1979) and both theoretically and experimentally by Pilotti (1995).

From Equations 2 and 3 it can be seen that the exceedance of a critical threshold area at cell (i,j) can be formulated as:

$$A_{i,j} \geq (A_s)_{i,j} = C_{i,j} S_{i,j}{}^{-\alpha} \tag{9}$$

where $A_{i,j}$ is the area contributing at cell (i,j) and α is an exponent whose value depends on the flow conditions, while coefficient $C_{i,j}$ depends both on climatic conditions and on soil properties, as is clearly shown by Equations 2, 3 and 8.

The available field observations, although very limited in number, seem to support the applicability of Equation 9. Montgomery and Foufoula-Georgiou (1993) found that the channel network obtained for a Tennessee valley basin by applying Equation 9, with $C_{i,j} = C$ constant throughout the catchment and $\alpha = 2$, compare flow patterns on flat areas. In Tribe's algorithm, as a first step, an inlet cell and an outlet cell are identified. Then the straight line interpolated between the two cells is used as the main drainage axis for the whole cluster. In this way, the generation of parallel drainage paths is prevented, but, as observed by Tribe, 'a criticism of the method is that where a pit has an irregular shape this line may be interpolated across non-pit area. In this case, the cells in the line simply have their heights altered to that of the pit, and are treated as though they were part of the pit'. Given that flat areas often occur along the bottom of the valleys, it is not unusual for a cluster of flat cells to have a concave shape.

In the program presented in this contribution, a simple two-step algorithm is implemented, which does not produce the systematically parallel pattern noticed by Tribe and does not alter the elevations outside flat areas. As a first step, for each cluster of flat cells, the outlet, i.e. the cell having a minimum elevation along the boundary of the cluster itself, is identified. Then, starting from a cell of the cluster adjacent to the outlet, the following recursive procedure is applied: the current cell is marked; the minimum elevation in the subset of the neighbouring cells of the cluster that have already been visited is found (at the first step such a cell is the outlet); this elevation value is slightly incremented and is assigned to the current cell; if one of the neighbouring cells, which are scanned clockwise, has not been visited yet, this cell becomes the current cell and the procedure repeats itself, otherwise it stops. The recursive algorithm terminates when all the cells in the cluster have been visited. At this point, their elevations have been slightly and coherently changed and a local drainage network that drains to the outlet can be obtained.

CHANNEL NETWORK EXTRACTION

After the DEM has been depitted and all the flat areas eliminated, different methods can be used to determine the flow pathways. The more common algorithms assume that only one flow direction exits from each cell, while multiple-flow-direction algorithms allow more directions to exit from a single cell. According to Quinn *et al.* (1991), single-direction flow algorithms are best suited once the flow has entered the more permanent drainage system, while multiple-flow methods give more realistic patterns of accumulating areas on the hillslope portion of the catchment. However, when the slopes are significant, single-flow algorithms are considered to be sufficiently reliable. Moreover, the accuracy of the DEM and its grid size may be more influential than the flow detection method. Therefore, although a combination of the two methods should give the best results, we consider here the most widely used single-flow direction algorithm, proposed by O'Callaghan and Mark (1984), which is based on a steepest slope criterion.

The local slope $S_{i,j}$ at cell (i,j) is defined as:

$$S_{i,j} = \max\left(\frac{z_{i,j} - z_{i+a,j+b}}{d f_{a,b}}\right) \qquad a,b = -1,0,1 \tag{1a}$$

where z_i is the elevation of cell (i,j), d is the cell size and $f_{a,b}$ is a coefficient defined as follows:

$$f_{a,b} = \begin{cases} \sqrt{2} & \text{if } a \text{ and } b \neq 0 \\ 1 & \text{otherwise} \end{cases} \tag{1b}$$

The flow direction is assumed to be from cell (i,j) to cell $(i+a, j+b)$ which maximizes the term in parentheses at the right-hand side of Equation 1a. The SFDN is obtained starting from the basin outlet, by retracing the flow directions and connecting the cells in a tree-like structure.

The automatic extraction of the natural channel network from the SFDN is far from straightforward. The widespread use of a threshold contributing area criterion involves the principle that erosion, and then channel initiation, occurs when the surface or sub-surface discharge exceeds the erosional resistance of the ground (Montgomery, 1994) and the assumption that discharge is directly proportional to the contributing area. Whatever the driving process that leads to the formation of the channel sources (e.g. overland flow, sub-surface flow, shallow landsliding), threshold area A_s can be expressed as a function of the ground slope and of some soil and climatic properties (Montgomery and Dietrich, 1988, 1989, 1992, 1994; Dietrich *et al.*, 1992, 1993).

In the case of erosion by overland flow, which constitutes a common channel initiation mechanism in

Table I. Topographic and geomorphic parameters computed by the program, with reference to the Cordevole channel network obtained with the fixed contributing area algorithm, assuming a threshold $A_s = 0{\cdot}05\,\text{km}^2$

Source file	C:\sdpp\in\V75.DTM
Threshold on contributing area (km^2)	0·0500000
Area of the basin (km^2)	7·21688
Perimeter (km)	13·756
Average height (m)	2277·59
Maximum height (m)	3122·00
Minimum height (m)	1824·00
Total relief (m)	1298·00
Relief ratio (m km^{-1})	339·55947
Relative relief (m km^{-1})	1·78709
Average slope (m m^{-1})	0·46510
Maximum slope (m m^{-1})	1·92000
Minimum slope (m m^{-1})	0.000000
Average slope main stream (m m^{-1})	0·23350
10–85 slope main stream (m m^{-1})	0·23806
Diameter (-)	20
Magnitude (-)	52
Circularity ratio (-)	0·479
Maximum distance along the channel network (km)	3·323
Maximum distance along the SFDN (km)	3.823
Average topologic distance (-)	11·365
Shape factor (-)	0·49389144
Shape coefficient (-)	1·59022428

Order	No. segments	Average area	Average length	Average slope
		$(km)^2$	(km)	(m m^{-1})
1	52	0·127212	0·360980	0·076834
2	12	0·391875	0·534359	0·125989
3	3	1·518750	0·437132	0·050621
4	1	7·216875	1·624264	0·031648

Total number of segments in the network	68
Total length of the network (km)	28·119
Drainage density (km^{-1})	3·896
Drainage frequency (km^{-2})	9·422
Average runoff length (km)	0·128

Channel network extraction

The depitted DEM can be processed to obtain the SFDN. Initially, the outlet is automatically selected as the most depressed cell along the DEM border. Once the corresponding SFDN has been computed, it can be shown on the screen and the user can select a particular sub-catchment by simply clicking on its outlet cell. The portion of the DEM belonging to the sub-catchment is saved (SOURCEFILE.SBB). The perimeter of the (sub-)catchment may be saved on file both in raster and vectorial formats (SOURCEFILE.BRD), while the structure of the SFDN is coded in two topologic, vectorial files (SOURCEFILE.1SF, SOURCEFILE.2SF) that are then used to set up a non-binary, dynamic, tree-like data structure. Apart from reflecting the spatial topology of the network, this type of data organization turns out to be advantageous for the following processing phases, when the channel network of the basin is derived from the SFDN and, eventually, analysed. Either the fixed threshold area criterion or the slope-dependent one may be used for the channel network extraction. Depending on the choice, the user is asked for the values of C and α in Equation 9. The topologic structure and the geometric characteristics of the channel network are saved in a suitable format in two files (SOURCEFILE.1DR, SOURCEFILE.2DR).

well with that observed in the field and obtained a C value close to 2000 m^2. Gandolfi and Bischetti (1996b) found evidence of a relationship between field-measured local slope and contributing area on a small Alpine catchment. However, the α values that were obtained are larger than 2, suggesting that different channel initiation mechanisms are active in the catchment, and the comparison between generated and observed network was not satisfactory, owing to the significant increase in the scatter of the data when the slope computed from the DEM by means of Equation 1 is used instead of the field-measured one.

In spite of the observed space variability of the threshold area, reflected by Equations 2 and 3, in most of the practical applications of automatic channel identification procedures, a catchment-wise constant value of A_s has been used (Mark, 1984; O'Callaghan and Mark, 1984; Band, 1989; Zevenbergen and Thorne, 1987; Jenson and Domingue, 1988; Morris and Heeredegen, 1988; Gardner *et al.*, 1991; Gandolfi and Bischetti, 1996a). This is tantamount to assuming $C_{i,j} = A_s$ and $\alpha = 0$ in Equation 9. According to Montgomery and Foufoula-Georgiou (1993), the rationale behind a constant A_s value comes from the hypothesis that slope-dependent sediment transport, typical of hillslopes, gives rise to convex slope profiles, while discharge- and slope-dependent sediment transport, typical of channels, creates concave slope profiles. As a consequence, the channel sources coincide with the points where the transition from a convex to a concave slope profile takes place. On this basis, Tarboton *et al.* (1991, 1992) derived a quantitative method for the calculation of A_s from the scaling diagram of link slopes versus contributing areas. More recently, however, Montgomery and Foufoula-Georgiou (1993) argued that the local slope should be considered instead of link slope (see also Ijjasz-Vasquez and Bras, 1995) and questioned the general validity of the assumption that every concave profile is channelled, which underlies the method.

Tribe (1992), examining the channel networks derived by using a constant support area value, came to the conclusion that the results are reasonably good for rugged basins, while when the slopes are gentle and the valley bottoms flat, a lot of spurious drainage lines are produced. Therefore, at least for the latter class of basins, it seems important to take the local slope into account.

CHARACTERISTICS OF THE PROGRAM

The program SDPP (see Appendix) allows the fully interactive performance of the sequence of operations that stem from the raw DEM, through its depitting and flat-area handling, to the channel network and its analysis. Conceptually, the program is organized in three main modules, each of which performs a specific task, namely pre-processing of the DEM, channel network extraction, and channel network analysis. The main characteristics of these modules will be briefly described.

Pre-processing of the DEM

The pre-processing module allows the user to visualize the master file containing the DEM (e.g. SOURCEFILE.DTM) as colour-coded elevation bands and to perform some simple editing operations, such as data browsing, local data modification (saved in SOURCEFILE.CLS), and cut-and-save of a rectangular portion of the whole DEM (SOURCEFILE.CUT). Moreover, a blanking option is available that allows a no-data value to be assigned to the DEM cells whose elevation falls outside a user-defined range of values (producing SOURCEFILE.THR). All the derived files can then be reloaded as master files.

DEM pre-processing includes a depitting and flat-area handling tool. Upon the user's request, the program searches for pits and flat areas and shows their location on the screen. Then the user may choose to perform pit removal and flat-area tilting either on a pit-by-pit basis, or on a global basis. In the first case, once the user has selected a pit by clicking with the mouse, the program runs the algorithms for depitting and the treatment of flat areas described in the second section. In the second case, the same algorithms are automatically applied to all the pits and flat areas in the DEM. The 'depitted' DEM is then saved as SOURCEFILE.DPT, while some information on the number and type of modifications to the original DEM are written on SOURCEFILE.INF. Finally, a raster file of comparison between the initial (SOURCEFILE.DTM) and the final (SOURCEFILE.DPT) elevations is written on disk (SOURCEFILE.CFR).

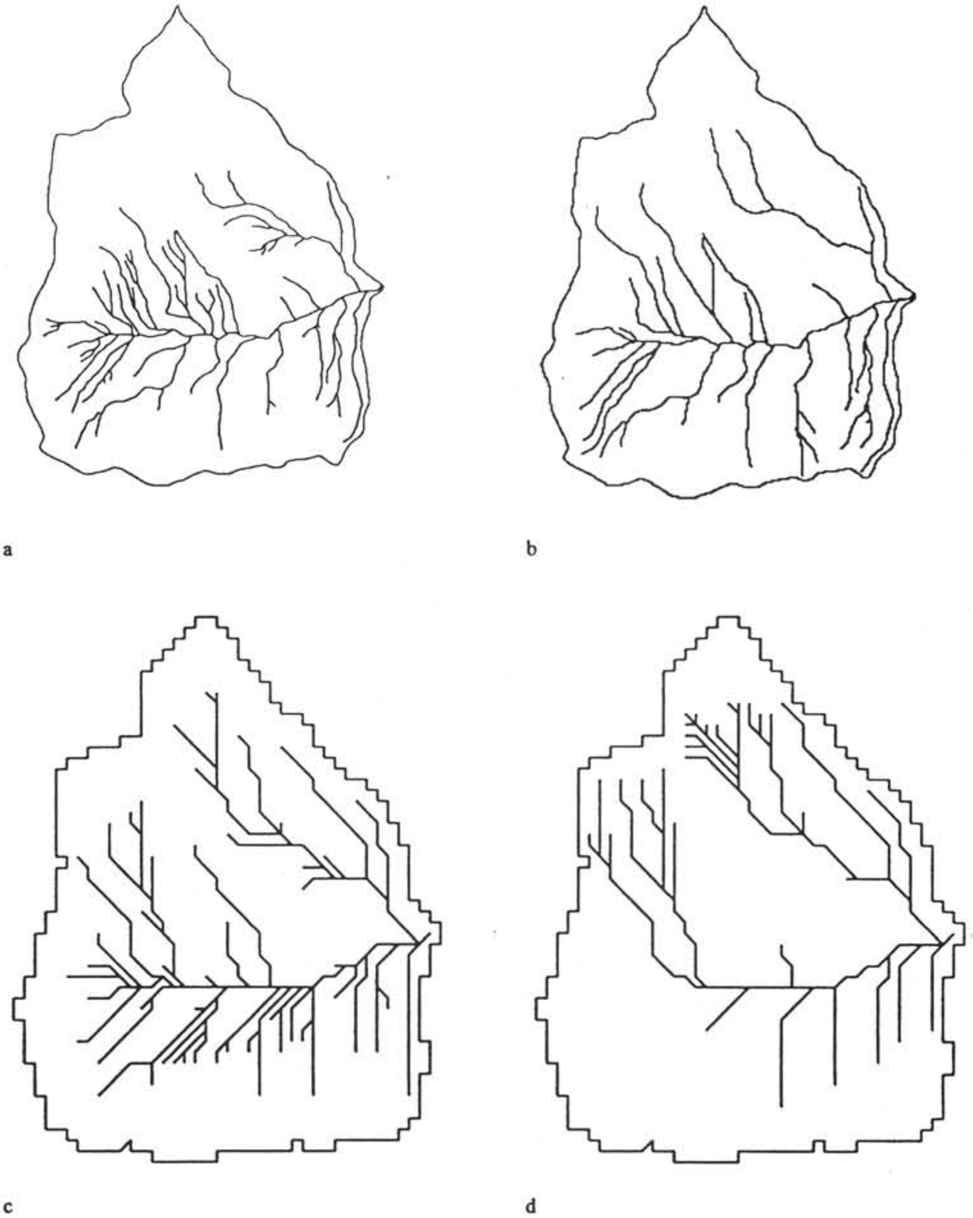

Figure 2. Channel networks of Cordevole creek derived from: (a) field observation; (b) blue lines; (c) DEM extraction with constant threshold area ($C = 0{\cdot}05\,km^2$, $\alpha = 0$); (d) DEM extraction with variable slope-dependent threshold area ($C = 0{\cdot}02\,km^2$, $\alpha = 2$)

AN EXAMPLE OF APPLICATION

As an example of application of SDPP, we show the results obtained for a small ($7{\cdot}0\,km^2$) alpine catchment located in the Dolomite region (northern Italy), the Cordevole catchment (see Figure 1). From the geologic viewpoint, homogeneous formations composed by conglomerate and domomite, mostly covered by quaternary sediments (Gatto *et al.*, 1984), prevail in the catchment. Morphology is characterized by an alternation of gentle slopes and steep glacial terraces, typical of periglacial environments. An abrupt morphological change takes place along part of the divides where the Dolomites form grand vertical walls.

The channel network was obtained through detailed field studies. Field observations included the identification and location of the channel sources and the measurement of the local slope at the sources by means of a clinometer (Gandolfi and Bischetti, 1996a, b). The field-observed network is represented in Figure 2a, while the channel network drawn from the 1:10 000 topographic map of the Veneto Region

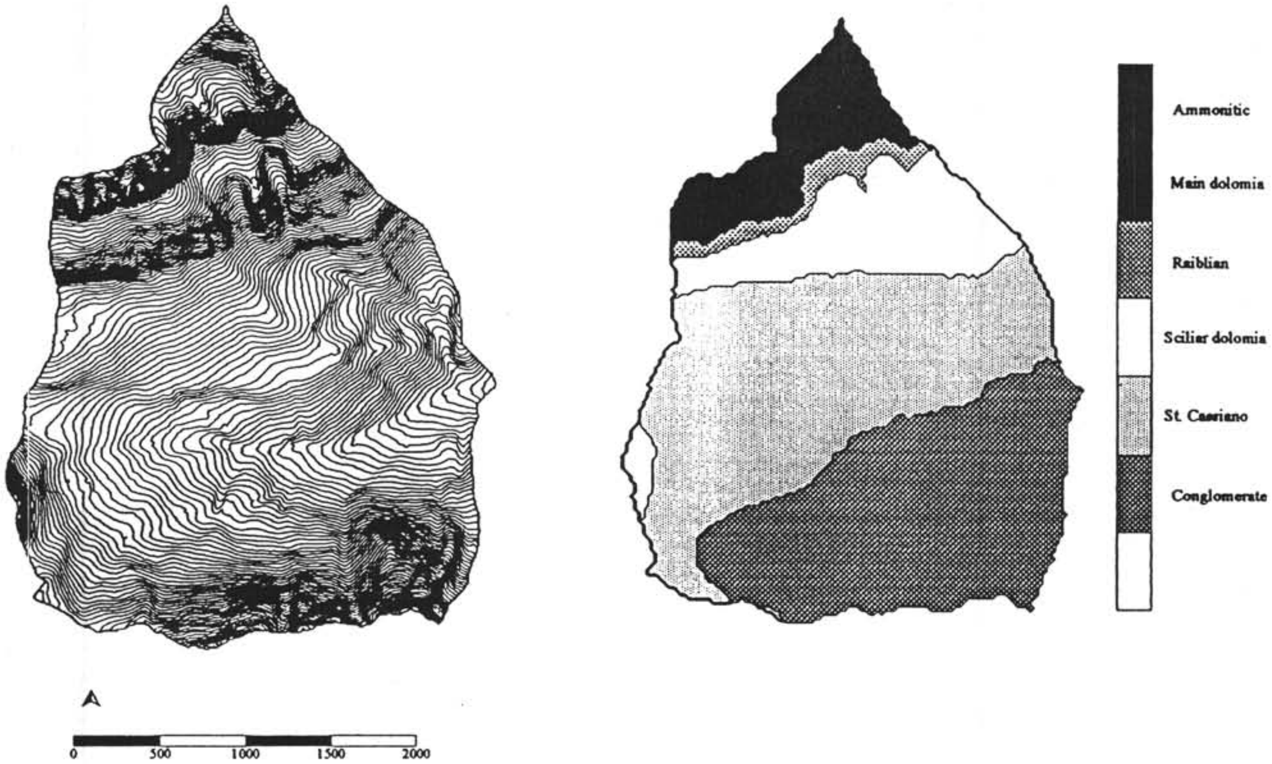

Figure 1. Cordevole creek: (a) contour lines and (b) lithology

Channel network analysis

This module allows the computation of some useful geomorphologic and topologic indices (see Table I). These include simple characteristics, like the area of the basin or the magnitude of the channel network. In addition to these parameters, the network is ordered according to Horton's classification and, for each order, the number of streams, the length, the drained area and the average slope are provided. From these data the computation of Horton's ratios R_A, T_B, T_L and R_S is straightforward (Horton, 1945).

Moreover, the program computes the area function $A(l)$ and the width function $W(l)$ of the channel network. The former gives the area that drains into the network at flow distance l from the outlet, while the latter gives the corresponding number of channels at the same distance. These functions and indices have important hydrological implications, as demonstrated by a vast literature production, starting from the seminal contributions of Kirkby (1976), Boyd (1978) and Rodriguez-Iturbe and Valdés (1979). These authors have explored the links between either the Horton indices or the area (width) function and the hydrologic response, expressed in terms of the so-called geomorphologic instantaneous unit hydrograph (GIUH). For example, in the simple case in which the runoff production and the flow propagation processes are uniform along the whole network, the GIUH, $h(t)$, can be written in the following simple form (Gupta *et al.*, 1986):

$$h(t) = \int_0^L \frac{W(l)}{\mathscr{L}} f(t,l)\mathrm{d}l \tag{10}$$

where L is the length of the longest flow path in the network, $\mathscr{L}$ is the total network length, and $f(t,l)$ is the routing kernel. A fourth module of SDPP that allows the computation of Equation 10 and of other GIUH forms is under development.

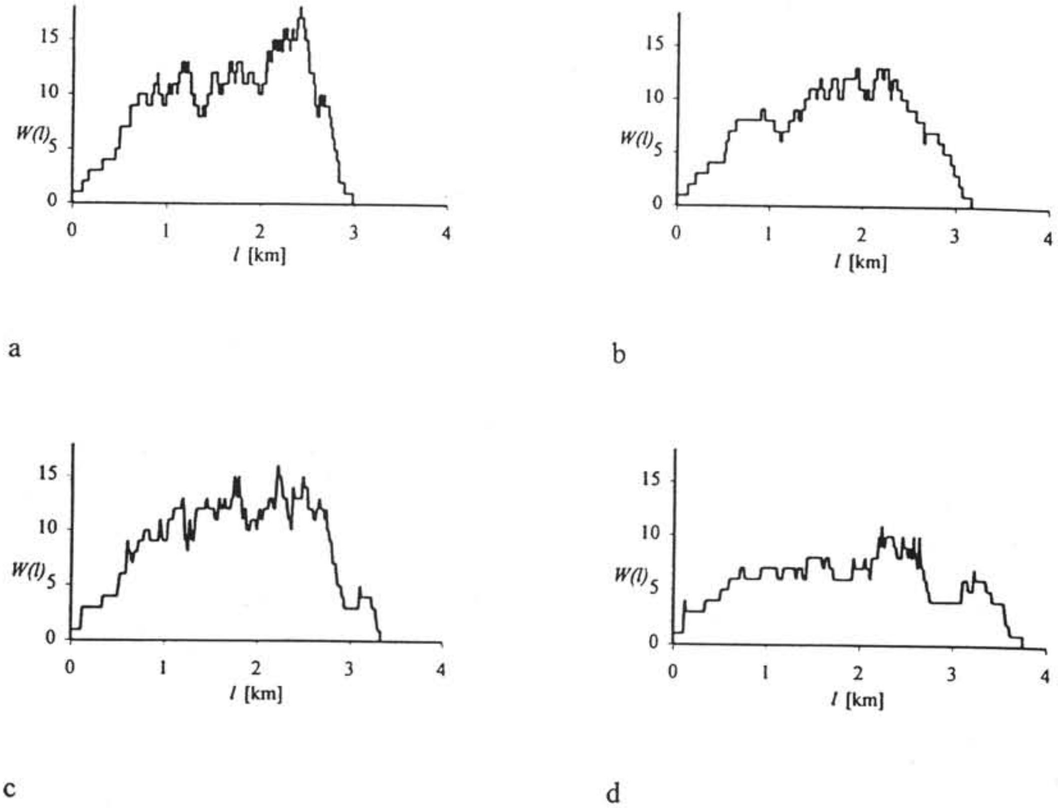

Figure 4. Width function of Cordevole creek as derived from: (a) field observations; (b) blue lines; (c) constant threshold area $C = 0{\cdot}05\,\text{km}^2$, $\alpha = 0$; (d) variable slope dependent threshold area ($C = 0{\cdot}02\,\text{km}^2$, $\alpha = 2$)

generated and field-observed networks is comparable to that between *blue lines* and field observation. It is also apparent that the network obtained with the constant threshold area compares better with field observations than the one obtained when the dependence from the local slope is considered. These results largely match those obtained by Gandolfi and Bischetti (1996b) by adopting a much smaller grid size (10 m). According to these authors, the failure of the variable threshold area criterion to improve on the constant threshold area assumption may be due to several reasons, the most obvious being the poor correlation between threshold area and slope as obtained from DEM data, and the presence of various channel initiation mechanisms. However, it can be noticed from Figures 2 and 2c that the generated network fails to match the observations mainly in the case of the left-bank tributaries, which greatly exceed the field-observed ones, while the mainstream and right-bank tributaries are better reproduced. By looking at Figure 1b it is clear that the critical region is characterized by vast dolomite outcrops, partly covered by colluvial deposits, where, although no karst phenomena are present, sub-surface flow prevails. On the contrary, owing to the very steep slopes in this area (see Figure 1a), the use of Equation 9 with a constant C value and $\alpha = 2$ obviously gives a high channel density. It is therefore very likely that the capability of the variable threshold area criterion to delineate the actual channel network may be significantly improved by adopting a space variable C value, related to the local soil characteristics. An improved version of SDPP which can deal with space variable C values is under development.

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Table II. Selected geomorphic parameters for the Cordevole catchment as computed by the program and derived from field observations and blue lines. Notice the striking under-estimation of the $\mathscr{L}_\Omega$ value in the case of variable threshold area, due to the high sensitivity of the Horton indices to the threshold area value (e.g. Gandolfi and Bischetti, 1996b)

	Field observed	Blue lines	Constant threshold area	Variable threshold area
Total channel network length $\mathscr{L}$ (km)	27·35	24·28	28·12	20·92
Number of streams, N	74	40	68	40
Length of higher order stream, $\mathscr{L}_\Omega$ (m)	1726	2099	1624	106
Drainage frequency, F_r (km^{-2})	10·35	6·25	9·42	5·54
Drainage density, d_d (km^{-1})	3·83	3·79	3·90	2·90
Basin order, Ω	4	3	4	4
Bifurcation ratio, R_b	3·91	5·57	3·76	3·13
Length ration, R_l	1·67	1·93	1·54	0·74
Area ration, R_a	4·21	6·91	3·85	3·56

(Regional Technical Cartography) is represented in Figure 2b. The corresponding geomorphic indices are listed in Table II.

The DEM of the catchment, which is provided as a demo file (*v75*.dtm), was obtained from the contour lines digitized from the same maps (line spacing 10 m), shown in Figure 1a. By adopting a grid size of 75 m, a 50×48 elevation matrix was produced, from which, after removing pits and flat areas, the SFDN was obtained (Figure 3). It must be observed that, owing to the steepness of the slopes, both were limited in number. The automatically identified basin boundaries turned out to match those drawn on the map almost perfectly. As an example of the channel networks obtained with SDPP, the one with a fixed threshold area $A_s = 0{\cdot}05\,(\mathrm{km}^2)$ (equal to the average observed threshold area) and the one with a slope-dependent threshold area $(A_s)_{i,j} = 0{\cdot}02 S_{i,j}^{\ -2}$ (km^2) (corresponding to an average threshold area of $0{\cdot}05\,\mathrm{km}^2$) are shown in Figure 2c and 2d and the corresponding width functions are shown in Figure 4 along with those of the *blue lines* and of the field-observed network. According to Gandolfi and Bischetti (1996b), who compared the networks generated for different values of A_s and C, these two networks are the closest to the field-observed one. From the analysis of Figure 2 and Table II, it can be noticed that the agreement between the

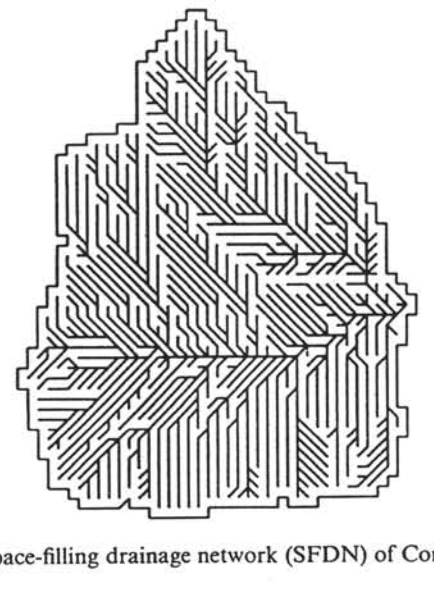

Figure 3. Space-filling drainage network (SFDN) of Cordevole creek

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Table AI. Content of the file FLSLINK

FLSLINK	
C:\SDPP\IN	Directory for input files and for raster outputs from SDPP
C:\SDPP\OUT	Directory for vectorial outputs from SDPP
C:\SDPP\BGI	Directory containing graphic drivers (*.BGI, *.CHR)

Table AII. Items of the Global Data Processing pull-down menu

Item	Scope
Manual depitting	Enables manual depitting and flat-area treatment
Automatic depitting	Starts the automatic depitting and flat-area treatment procedure.
Cut and save	Enables the selection of a rectangular patch of the active file that will be saved on disk.
DEM topologic file	Creates the SFDN of the basin. This is the starting point that allows the activation of the other geomorphic options.
Drainage network models	Creates the drainage network according either to a fixed threshold contributing area principle of a slope-dependent criterion.
Drainage network Stats.	Orders the drainage network according to Horton–Strahler ordering and computes several topographic and geomorphic parameters. Computes the area and width functions.
Sub-basin extraction	After a drainage network has been created and shown on the screen (SCREEN option), the user can extract a sub-basin draining to a point of the channel network simply by pressing the left key of the mouse on the cell corresponding to the sub-basin outlet. If during the same session more than a single sub-basin is selected, then an ordering number (e.g. SOURCEFILE2.SBB is added at the root of the file.
Basin border scanning	When this option is invoked, the border of the basin is scanned and saved in a raster file, containing 0 everywhere but along the border itself, where a flat 1 is assigned.
Filter and save	When this option is chosen, only values of the DEM between the two selected cutoffs are saved on file. This makes it possible, for example to save DEMs corresponding to different bands of height.

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APPENDIX

Program installation and usage

The program runs in DOS environment and a standard serial MicroSoft mouse driver must be loaded. The executable file SDPP.EXE must be copied in a user-created directory (e.g. C:\SDPP) along with the ASCII file FSLINK and the two files DPMI16BI.OVL and RTM.EXE. In the FLSLINK file the paths of the directories containing information relevant to the execution of the program are specified, as shown in Table AI. Note that there is no restriction on the names.

As shown in Table AI, the *.BGI and *.CHR files must be copied in the graphic directory and the file(s) containing the DEM must reside in the input directory. No other operation is needed for the installation.

The program SDPP reads only ASCII files. The maximum dimension of the DEM files that can be managed by the present PC version of the program is 65 × 65. The first line of the DEM file must contain some information needed by the program; these are the number of rows, the number of columns, an integer flag (1 for

Table AIII. Items of the Local Data Processing pull-down menu

Item	Scope
Info z(x,y)	Allows data browsing. When the user presses the left mouse key on a cell of the active DEM, the elevations of a three by three window centred around the current cell are visualized. If the user wants to modify the local elevation, he has simply to press the left key on the square area marked with M and then insert the new elevation value. To stop browsing, press the right key.
Delete z(x,y)	Allows data erasing. By pressing the left mouse key the user deletes the cell, substituting its elevation with an out-of-basin flag -9. To stop deleting, press the right key.

Table AIV. Items of the Screen pull-down menu

Item	Scope
Zoom/unzoom	Allows magnification of a selected portion of the DEM.
Choose coordinates	When external coordinates are chosen, several informations provided by the program are referred to georeferenced coordinates, through the coordinates of the DEM lower left corner.
Show drainage network	Shows the selected channel network on the screen.When the user selects this option,he is then asked to specify the minimum order, according to Strahler's classification, of the channels that will be shown on the screen. If the user inserts 1, the whole channel network is shown.
Redraw	Redraws the DEM on the screen.
Clear screen	Clears the panel

Table AV. Items of the Files pull-down menu

Item	Scope
Select file	Makes possible the choice of the 'master' file, selecting it among files with different extensions and located in the input directory.
Set cutoffs	When this option is chosen, only the cells in the DEM whose height lies in between the two selected cutoffs are shown on the screen. This makes it possible, for example, to visualize different bands of height one at a time on the screen.
Superimpose	Makes it possible to visualize two or more files, superimposing them one on the other (e.g. the border of a basin and a drainage network for the same basin).
Read file	Reads the selected file and shows it on the screen. The user is asked to specify the location of the upper left corner and lower right corner of the window used for visualizing the file. More than a single file can be visualized at a single time on the screen but only the last loaded is the 'master'. Accordingly, all the options operate on this file only.

the DEM file), the area of the cell in square metres, a flag for the elevation unit of the data (1 = cm, 2 = dm, 3 = m) and the cartesian coordinates (north, east) in metres of the lower left corner in the source DEM. The following lines must contain the elevations row by row. A no-data flag -9 shall be assigned to the cells in the matrix that do not belong to the DEM. As tutorial examples, two DEM files are provided along with the program: VI75.DTM and B200.DTM.

The program works in graphic mode and all the selections are operated through the mouse, except when a numeric input (e.g. threshold area value) is required, which must be provided using the keyboard. When SDPP is run, the command bar, containing five options, appears at the top of the screen. Any one of the options can

Table AVI. Input and output files. The files labelled as output/input are originally produced as outputs but can, in turn, be loaded as input files

Type	Extension	Content
Input	*.DTM	'Source' raster DEM file
Output/input	*.DPT	Depitted DTM
	*.CFR	Comparison (*.DTM−*.DPT) file
	*.BRD	Boundary of a raster file
	*.CUT	Patch of the original master file, obtained through 'cut and save'
	*.SBB	Sub-basin extracted from the original master file
	*.CLS	Raster file obtained using the option 'delete'
	*.MDF	Raster file obtained by manual correction (option 'info (x,y)')
	*.THR	Filtered file
Output	*.1SF	First topologic file on the SFDN
	*.2SF	Second topologic file on the SFDN
	*.1DR	First topologic file of the channel network ordered according to Strahler
	*.2DR	Second topologic file of the channel network
	*.HRT	Topographic and geomorphic indices
	*.INF	Info file on the depitting process
	*.PIT	List of pits and cells with zero gradient
	*.SLP	Slopes raster file ($m\,m^{-1}$)
	*.PRM	Perimeter of the basin (Arc/Info GENERATE/UNGEN file)
	*.ARL	Vectorial representation of the selected channel network (Arc.Info GENERATE/UNGEN file)
	*.AR2	Vectorial list of links code and Horton's order (Arc.Info GENERATE/UNGEN file)
	*.WDF	Width function
	*.ARF	Area function

be highlighted with the left key of the mouse and opened with the right key of the mouse. Then a pull-down menu appears and all the following choices are operated simply by pressing the left key of the mouse on the selected menu item. Note that some items may be inactive at the initial stages of the DEM processing: active items are highlighted in white, while the inactive ones are shaded in grey. The menu items and their scopes are listed in Tables AII, AIII, AIV and AV. All output files produced by the program share the same name of the input DEM file (e.g. SOURCEFILE) and suitable extensions are automatically assigned by the program (e.g. DPT for depitted files). Table AVI lists the extensions and contents of the input and output files.