AN INTEGRATED APPROACH TO THE RECONSTRUCTION OF THE DRAINAGE NETWORKS IN SOIL CONSERVATION STUDIES

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Abstract

The reconstruction of a drainage network can be solved by using a Digital Elevation Model (DEM). The results one can obtain depend on the spatial and elevation accuracy characteristics of the DEM and, in general, they give a disconnected flow net. In the proposed approach, a geostatistical method of structural analysis and stochastic interpolation (Ordinary Kriging) to obtain a DEM is used. Then, an analytical method is applied to explore the DEM locally and to obtain, for each pixel, both flow lines and the total number of upstreams. Only through a global reasoning the connections between the two streams of the obtained partial flow network can be recovered. Photointerpretation of satellite images (e.g. LANDSAT-TM), superimposed on the disconnected flow network, can help the operator to digitize the missing pixels. This approach lays the bases for a symbolic reasoning developed by an expert system which, as such, can become completely automatic. Our case study concerns the Rendina watershed. The final flow network, after photointerpretation, is completely connected and digital: as such, it can be directly run by Geographic Information Systems (GIS).

Résumé

La reconstruction d'un réseau de drainage est un problème qu'on peut résoudre en utilisant un modèle digital du terrain (DEM = Digital Elevation Model). Les résultats dépendent des caractéristiques spatiales et de précision altimétrique du DEM et, dans la plupart des cas, ils sont représentés par un réseau non connecté. Dans l'approche proposée on utilise une méthode géostatistique d'analyse structurelle et d'interpolation stochastique (Kriging) pour obtenir un DEM. On applique en suite une méthode analytique capable d'explorer, au niveau local, le DEM afin d'obtenir, pour chaque pixel, tant les lignes d'écoulement que le nombre total des points à l'amont. Ce n'est qu'un raisonnement global qui réussit à récupérer les connexions entre les cours d'eau du réseau partiel ainsi obtenu. Un tel raisonnement peut reposer sur la photointerprétation d'images par satellites (LANDSAT-TM) qui, superposées au réseau non connecté, sont utiles à l'opérateur qui digitalise les pixels manquants. Cette approche établit les bases d'un raisonnement symbolique geré par un système expert et, donc, il peut devenir complètement automatique. L'étude de cas a concerné le Bassin du Rendina. Les résultats confirment la validité de l'approche géostatistique dans la reconstruction du DEM. Après la photointerprétation, le réseau final est tout à fait connecté et digital: il peut être donc directement geré par des Systèmes d'Information Géographiques.

In the areas subject to hydrogeological unbalances (landslides, erosion, flooding, shore line variations, etc.) the study of the considered phenomena, of their mechanism, their geomorphological evolution and the planning of protection measures, are based on the quantitative evaluation of land morphology. It is ever more necessary to make such an evaluation through GIS which can give an overall image and, at the same time, simplify and speed up the use of factors and parameters useful for programming, over time and space, rebalance measures. Although increasingly more sophisticated results are possible through the available technologies, applications in this field are frequently based on correlative techniques which mainly use parameters easier to be handled (e.g. watershed circularity ratio, area forking and flow net length ratios, drainage density, etc.).

One way to face the problem is to set up a computer method based on a DEM which, as a numerical product, can be processed automatically.

One should also consider that the 1:25,000 scale, the most appropriate for such kinds of studies, is up dated only numerically. As a consequence, the proposed procedure can be important both as a method and for application purposes in these studies (soil conservation, hydrology) and for land planning.

Reconstruction methods of a drainage network

Different authors contributed to define the methodologies which, based on the DEM, can numerically generate the open networks of a watershed.

One of the first attempts was made by *Peucker* and *Douglas* (1975) who developed a local 2 × 2 operator based on the sequential survey of all the groups of four adjacent pixels. Among the latter, the one of an increasingly higher elevation is marked by a code (flag). The algorithm considers the uncodified pixels of the DEM as belonging to the flow net.

Later on, *Jenson* (1985) proposed a local operator which moves on all the pixels of the DEM through a 3 × 3 mobile window which identifies the 8 pixels adjacent to the one subsequently surveyed. The elevation comparison between the central pixel and each of the other 8 pixels leads to identify the local minima which are subsequently connected to each other following simple morphological criteria.

These first attempts, made at a time when GIS start to be successful, are still influenced by the priority to be given to computation simplicity rather than to the accuracy of results. The latter can be used only for an approximate delimitation of the watershed perimeter whereas, in most cases, the flow net presents many disconnections.

The study by *Carrara et al.* (1988) carried out in the framework of the CNR (National Council of Researches) group activities for protection against hydrogeological catastrophes, contains a significant critical analysis of some studies on automatic generation of flow nets and morphological parameters of the watershed based on DEM.

We share the conclusions drawn by the authors: the elevation data only, however sophisticated the algorithm may be, cannot result in a fully connected network, and true to reality. This is due to the poor spatial quality of the DEM and to its elevation accuracy which produce artificial pits which have to be, as far as possible, eliminated. Although these pits are observed in nature in some geomorphological situations, their origin can be more frequently related to the inadequate space resolution of the DEM or to an inefficient interpolation algorithm. In order to reduce the number of pits, the authors of this study propose to scan the DEM through a 3 × 3 local operator. The observed presence of pits is eliminated by increasing the examined pixel by a slightly lower value than the one of the point, among the eight contiguous points, at the lowest elevation. The DEM is scanned twice if some pits are still present. The integrated approach proposed by *Carrara* et al. on the DEM including other information results, for the examined zones, in fully connected and morphometrically consistent nets, depending on the chosen resolution for the DEM, with 100,000 and 25,000 mapping and with the results of photointerpretation at 33,000.

This leads to the first objective of this study: to ensure the use of an interpolation method which enables to obtain a DEM which can give the best presentation of the real shape of relief. The detail of spatial resolution will be highly depending on the calculations available or the auxiliary information

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sources intended to be used. In Italy, the IGM (Military Geographic Institute) delivers the digitized contour lines: the DEM has thus to be built based on such fragmentary information.
Indeed, it is possible to obtain the DEM directly from stereo SPOT type satellite images. The use of such images produces a DEM with 10 m spatial resolution of the pixel and, depending on the visual angle, up to a maximum of 3 meters of elevation error. Apart from costs which still are excessively high, the availability of such DEMs is related to the availability of satellite cover of the concerned area.
The experiences made on the basis of DEM from SPOT are recent. *Fairfield* and *Leymarie* (1991) test the results of two different approaches to identify the structure of the watershed and its river segments through the use of a DEM from SPOT type stere images. These approaches are classified as deterministic and probabilistic. The former were used by *Band* (1989), *Jenson and Domingue* (1988), *Martz and Jong* (1988) and are based on the assignment, to each pixel of the DEM, of a pointer to one of its eight neighbors in the direction of the steepest slope: the water reaching pixel p flows to the pixel indicated by the pointer to p. Based on the matrix of pointers, the algorithm enables to calculate the number of discending pixels to each node, that is the number of pixels of the considered area which drain towards the node. Through a parameter defining the minimum upstream value, the selection of streams is made. This method is followed in an approach more complex defined as *structuralist* by *Riazanoff et al.* (1988). Another opposite method is based on probability and it works locally with 3×3 neighborhood: the principle is the same as for the deterministic method, therefore, the pixel p will have the pointer to pixel q at maximum *rhslope* defined as $z(p)\text{-}z(q)$ for EW neighbors and as $rho4*(z(p)-(q)$ for NS neighbors; *rho4* is interpreted as a random variable generated as $1/(1/r-1)$, r being a uniformly distributed random variable between 0 and 1. *Fairfield et al.* compare the positioning error of spatial segments for the two approaches in the presence of aspects higher than given angular values. In fact, during the analysis of the neighborhood, the steepest slope direction is a discretized value between $[0,\pi]$. The case 3×3, leads to a maximum spatial positioning error of $\pi/8$. It is discovered that the 3×3 deterministic method in the NE, NW, SE, SW directions multiplies the diagonal differences by *0.7071* whereas the probabilistic method multiplies the diagonal differences by a random variable whose average is 0.7071. Therefore, from a comparison between the two approaches it results that for slope aspects greater than 45 degrees (i.e. in rough areas) the two methods give the same results. In flat areas the deterministic method can give rough errors. Moreover, for this type of approach, it is essential to assume that water flows to one and only pixel; then the model can present some difficulties in the cases when soil surface is flat or has a constant slope in a given direction or, in any case, when it has a gradient lower than the DEM resolution capacity. However, there are no indications on how the use of a DEM from SPOT images could affect these results.
Riazanoff et al. (1992) present an automatic method based on a DEM obtained by stereo correlation of SPOT images. The authors review the existing methods dividing them into statistical and structuralist approaches, and inside this last one, they propose a way to override the problems related to the pits and the aspect. The idea is to pass from a real to the integer coordinates of a DEM through polynomials of order 2. The reasoning on polynomials permits to recover the connectivity of drainage network encouraged by planimetric resolution (100 m^9) and altimetric accuracy of DEM from SPOT.
Once a quality DEM is set up, a method which explores the neighborhood of each pixel and which determines, in a way or another, a disconnected flow net can be applied. Connection operations can be conveniently performed by introducing further information and data capable of recovering the most general aspects neglected by the initial method.
Therefore, we analyzed the experiences based on satellite images: the second objective of our study is to use these satellite images as a support for the flow net connection.
The use of image processing techniques to help identifying flow nets was devised by *Wang et al.* in 1983 who applied a global spatial reasoning based on LANDSAT data. It can be thought as a pioneer study in a context in which remote sensing and artificial intelligence techniques were being developed.
Contrary to *Band* (1986) who refers to the network of watershed and divides obtained through a local operator and who considers it as a set of algorithms of image processing and of the recognition pattern, *Wang et al.* use the latter on a satellite image.
In particular, *Wang et al.* set up a relational model which considers a system of valleys and ridges obtained through a LANDSAT image segmentation technique. That is, they separate the background from the objects through a global grey-level thresholding. Although the gradient information is used to select the thresholds, the results depend on the type of objects present on the scene, therefore, in zones with crop ground cover, or heterogeneous spectral objects, it is quite difficult to discriminate the background. It should however be taken into account that areas with crop ground cover are observed in the photographic survey of torrential water courses on which hydraulic works are built, in that the latter create stability domains which favor the growth of spontaneous vegetation (*Puglisi and Trisorio-Liuzzi*, 1990).
The following spatial reasoning is based on a lighting model and on the spectral response interpretation of linear structures detected by the segmentation algorithm which should depend on land shape. In both examined cases, we feel the lack of complementing of contribution that each information source can give to improve the results: *Wang et al.* don't consider the DEM and *Band* doesn't consider the satellite images, although they both use the same method. Wang's attempt to make the global reasoning on satellite image automatic is affected by the present technological constraints. In the following years, many other authors explored and proposed approaches based on artificial intelligence techniques. *Lammers et al.* (1990) propose an object representation of the drainage basin which can be helpful in the automatic recognition of the basic geomorphic objects. In this sense, *Smith et al.* (1990) develop a procedure based on the knowledge making use of local and global information. In particular, they start from a drainage network model and from it they derive all the constraints for the pixels and the downstream segments and the net. For instance, after determining the downstream pixels by a given method (the Haralick method is suggested as it is explained in the same paper), their aggregation into dowstream segments is made by considering the ones which satisfy the following constraints: *a)* except the first and the last pixel of the segment, each pixel is connected with only one parent pixel and to only one child pixel; *b)* the elevation of a given pixel on a downstream segment is greater than the elevation of the farther pixels which are more to the bottom of the list; *c)* in general, the connection of pixels to other downstream segments is possible only for the head and tail pixels of a given segment. The network stage makes the connection of segments with the constraints imposed by viewing a drainage water as a binary tree in which the channel segments have a one-pixel width. In the example presented by the authors, the procedure, although computationally intensive, shows a good agreement with mapped valley features.
Finally, *Qyan* and *Ehrich* (1990) use both local and global reasoning operators by joining lower level structures into globally consistent and fully connected flow nets. The consistency is defined on the fluvial segments by an ideal model as in the flow net by *Smith*. The approach can then be considered to be determined by a low level and a high level processing. The former leads to a situation in which the different fluvial segments have to be connected and this is made, at the latter level, by evidential reasoning (*Shafer*, 1976). The high level integrator has to be capable of making the connection between disconnected segments of a flow net and then to make an upper level global «reasoning» which requires a capacity to handle the uncertainty caused both by the intrinsically imprecise (e.g.

DEM) data and by the inaccuracy of the rules used to reconnect the drainage flow nets. In order to face the uncertainty and to solve the possible conflicts derived from the local lower level processing, the evidence theory is applied. An evidential reasoning is used to construct a possible global representation which means to describe a set of functions capable of defining how the evidence on different connection assumptions is accumulated and how the inferential processing is made. In practice, an open node (source or sink) is selected and the segments standing for connection are looked for among all those falling within the neighborhood of a given radius. For these standing segments, a number of assumptions are made (five are proposed) which substitute the detection structure of the evidential reasoning. Then, the tests (8 are proposed) which are not mutually exclusive are calculated and, for each assumption, a belief function which accumulates all the evidence is recursively calculated. The decision is taken by examining the belief functions for the assumptions generated according to the selected standing segments. An assumption is accepted only if its belief function is higher than a predefined threshold and if its value is the maximum among all the possible alternatives. The selected assumption triggers an interpolation procedure to build the connection segment between the extremes of the two considered fluvial segments. The process continues by detecting the successive open nodes. Qyan and Ehrich's results, although partial, are extremely reassuring.

The proposed approach

From the analysis of the studies published so far about the identification of drainage network, we can conclude that the most general avenue to be explored is towards integrating typologically different data (remote-sensed, cartographic and ground-based data) and processes (interpolation, local operator, etc.). Such approaches call for the automatic solution of complementary and conflictual aspects of information which have to be solved through inferential techniques.

This is the objective assumed in our project which will lead to an automatic system producing fully connected flow nets. At present, we can give partial results intended to be produced through a semi-automatic approach which is preliminary and functional to the project. This approach is based on contour lines values and on geostatistics to supply a quality DEM. A local type method can explore the DEM to produce the upstream flow lines and points referring to each pixel. Simple geomorphological considerations enable to detect the disconnected network. The connection step of stream segments is semi-automatic. Through photointerpretation of remotely sensed satellite imagery it is possible to recognize the connection pixels of a knowledge base within our project. In fact, photointerpreters employ a variety of implicit spatial models. The process of making the implicit models explicit and the subsequent use of the explicit models in computer processing is the next step at hand: it will enable to make the flow net reconstruction automatic.

The Dem

At present, the IGM provides for 75% of the surface in Italy, the digitized contour lines at 25,000 with a planimetric accuracy of 15 m, an elevation tolerance of 3 m for the spot heights and 6 m for the contour lines. The construction of a DEM calls for some steps.

a) Definition of the spatial and geographic characteristics of the reference grid of the discretized land model.

The number of pixels into which the land has to be discretized needs to be defined. The z matrix with a fixed number of lines and columns is the mathematical representation of such discretization. The area size of the pixel characterizes the spatial resolution of the model. It has to be consistent with the input data and the type of processing for the specific application. In the case of IGM, the planimetric accuracy of the points of the curves at 25,000 suggests a spatial resolution for the z model not lower than 15 m.

b) Georeferentiation

For at least four pairs of points, the geographic coordinates (UTM, latitude and longitude, etc.) and the corresponding coordinates of the z model in terms of lines and columns have to be calculated. These pairs enable to calculate special polynomials, called georeferentiation polynomials, capable of associating the corresponding geographic coordinate to any point of the DEM and vice versa. These functions are essential in the processes of data integration since they guarantee the possibility of superimposing different types of data on one and only reference system.

c) Altimetric data assignment to the model

When the number of data to be run is so high to make the estimation process critical, such information need to be run efficiently. This is our case. A way to organize the data is suggested by *Journel* and *Huijbregts* (1978): such of method foresees that the set of elevations to which the contour lines refer be assigned to the discretized land model represented by the z matrix. It is intuitive to think that the management of such an orderly structure favours the immediate access to the data. The concerned values ($UTMx_i$, $UTMy_i$, $elev_i$) have then to be selected from the set containing other pieces of information and, through the georeferentiation function, the pair ($UTMx_i$, $UTMy_i$) has to be transformed into the corresponding line and column (r_i, c_i) of the z model. It may happen that for the same pixel (r_i, c_i) several elevation values be assigned to the same element of the $z(r_i, c_i)$ model. Then, the average should be made and so:

$$z(r_i,c_i) = (1/n)\Sigma_i \ elev_i$$

If the acquisition scale of curves, the resolution of the model and the orographic complexity are consistent, the σ standard deviation must be below a preestablished threshold.

d) Interpolation of the incomplete matrix of altimetric data

Different authors worked on the experimentation of methods to interpolate the altimetric values drawn from the contour lines to obtain the DEM. In addition to the attempts to distinguish and compare the geostatistical approach with others, very significant experimentations of DEM from geostatistics (e.g. *Morris*, 1991) are reported in literature; theoretical studies, too. *Matheron* (1981) had previously proved that the Kriging interpolation methods, under some assumptions, becomes of the splines type. *Dubrule* (1984) gives a deterministic interpretation of the Kriging stochastic methods. Another approach used in photogrammetry and successively developed to interpolate the altimetric data of contour lines is the collocation method. *Dermanis* (1984) shows that, under some assumptions, the two techniques are theoretically similar. The methods using the fractal dimension by *Mandelbrot* (1982) in the construction of the DEM are included, as a particular case, in geostatistics (*Bruno* and *Raspa* 1989). Finally, different methods based on triangulation of data (*Klucewitz* 1978, *Akima* 1978) are available and aim at constructing a map. They fit such triangles to polynomial shapes submitted to analytical constraints. Therefore, we think that the efforts to compare these methods with the geostatistical methods suffer from the diversity of final objectives: geostatistics provides the tools to study and interpret the phenomena; the methods based on triangulation are used to have good topographic representations of data. Universality and flexibility of geostatistics lead to a DEM based on structural analysis and Kriging interpolation techniques, these being phases which characterize such approaches. Through the structural analysis, the pattern of average squared increments $z^2_{ij} = (z(r_i,c_i) - z(r_j,c_j))^2$ between these generic pairs of pixels (r_i,c_i) and (r_j,c_j) is modelled through a theoretical function called variogram γ. The variogram is the tool to describe the spatial structure of the phenomena. On the average, it is expected that the neighboring points, independently of their geographic localization, measure small squared altimetric variations and they increase with increasing distances. Intuitively, from a given distance on, these variations follow random patterns. The modelling of a variogram is made on the basis of experimental data, therefore, we calculate, for all the pairs of pixels to which an altimetric value has been assigned, the squared deviations and the Euclidean distances d_{ij}. The subdivision of distances into w intervals enables to identify, for each of them, a subset

of k pairs (d_{ij},z_{ij}) which can be averaged. The graph which represents the w averages of (d_{ij},z_{ij}) is called experimental variogram γ^*. The observation of the graph γ^* helps to choose the type of shape to be adopted for γ whereas its parameters are imposed roughly or calculated through a non-linear fitting technique. The validation of the chosen model and its parameters is made on a subset of available data. The evaluation of γ^* requires a great number of calculation resources. The number of total pairs to be examined is $n(n-1)/2$, if n is the total number of data.
The processing of thousands of data, as in the case of DEM, can make the procedure critical. In this case, *Journel* and *Huijbregts* (1978, p. 213) suggest to group the data into mean experimental variograms. In practice, one should consider the A_i zone and calculate the corresponding experimental variograms γ^*_{Ai}. Supposing that the analysis of each single variogram does not produce significant variations, one can adopt a single average variogram. The theoretical functions γ depend on three parameters of physical significance: the *range*, the *sill* and the *nugget*. The *range* represents the maximum distance of influence between two points within the examined area beyond which the squared increments do not follow an increasing pattern. The *sill* is the value of the mean square deviations at the *range*. In the case of homogeneous zones it is observed that the *sill* corresponds to the global variance of data. The *nugget* is related to the effects of micro structures which are not evident at the observation scale to which data refer. Both the data and the γ variogram are used in Kriging estimation techniques. They linearly weight the altimetric values of the contour lines belonging to the neighborhood of the point $(UTMx_O,UTMy_O)$ to be interpolated: since the data are arranged in the z matrix, the neighborhood can be defined through the centered masks at the point $(UTMx_O,UTMy_O)$. The linear weights λ_i, are calculated in such a way that the estimation be unbiased and optimal. Among others, Kriging techniques are defined concerning the way to treat the presence of a trend into the data. Ordinary Kriging is applied when the data are without trend. The probabilistic premises on which geostatistics is based, enable to obtain both the estimation and the variance σ_k of estimation at each point. The values of σ_k are 0 in the pixels which contain the data and, according to the spatial distribution of the sample, they take increasing values. σ_k can be read as the significance of the estimation made by Kriging. The two statistical tests which can validate a γ model for an experimental variogram γ^* are:

$$U = 1/n\Sigma_{i=1}^{n} elev_i - elev_i^*$$

and

$$V = 1/n\Sigma_{i=1}^{n} \frac{(elev_i - elev_i^*)^2}{\sigma_k^2}$$

with $elev_i^*$ the estimation of $elev_i$ and σ_k the variance of Kriging estimation. The unbiased U has to be significantly zero, whereas the consistency of V which compares the calculated variance on the sample with the variance of the estimation of Kriging techniques has to be significantly 1.

The local operator

The model used can lead to the geometric and logical identification of a drainage network on the basis of the DEM data. At this first stage an analytical deterministic model suggested by *Fairfield et al.* (1991) was adopted. It enables to calculate the flow lines of the considered area, for the subsequent selection of the rivers depending on some parameters. After this first stage, hierarchization of the detected channels and, possibly, the extraction of watersheds are made. Particularly, one describes a global flow system which, starting from the relative peak points, interconnects the pixels up to an arrival point which, in the model, is represented by a border pixel of the image, a relative minimum or by a confluence point with another river.
Based on a DEM formed by a z matrix of elevations, a pointer matrix is made through a 3×3 local operator: if the eight pixels close to pixel p are at a higher elevation than p, then the pointer of p points to itself; otherwise, the pointer p points to point q of maximum difference in level. Such a difference in level is defined through $z(p)-z(q)$ if q is a near top in the North, South, East, West direction with respect to p, or by $[z(p)-z(q)]^*\sqrt{2}$ if q is in the *NE, NW, SE, SW* direction. Information about the flow lines are contained in a pointers matrix whereas each codes correspond to a direction following these codes: *1 for E, 2 for NE, 3 for N, 4 for NW, 5 for W, 6 for SW, 7 for S, 8 for SE* and, finally, *0 for a pit*. Starting from the tree structure of the pointer matrix, the algorithm enables to calculate the number of descending pixels to each node, i.e. the number of pixels of the considered area which drain towards such node: by a parameter defining the minimum upstream value, the selection of rivers is made by assuming the latter to consist of the nodes which have many points upstream of them.

Photointerpretation of LANDSAT image

At this stage we stated that the connection of the flow net is made by a semi-automatic operation which enables an operator to digitize the discontinuity points between two successive river segments. It is a matter of displaying the LANDSAT-TM image of the area and superimposing the flow net resulting from the analytical deterministic method. Assuming to have mutually recorded the image and the DEM, the operator will be able to photo interpret the area and, through track ball, to insert the connection pixels between disconnected segments. The purpose of this stage is to enrich the knowledge base of an expert system which will be able to operate fully automatically. For mechanizing the photointerpretation process, some effort has to be devoted to constructing explicit definitions of many of the subtle (possibly vague) processes applied by a skilled photo interpreter as he analyzes the scene.

Experimentation on a test Area

The approach proposed was experienced on a test area. Later in this chapter we will describe the characteristics of the area, the data used, the digital altimetric model resulting from the geostatistical approach, the results of the analytical deterministic method and the connected flow net obtained after the photointerpretation of the satellite image. This process is semi-automatic because man has to intervene at the last stage: results are therefore influenced by him. The automatic approaches take the hydrographic network reported on the topographic bases as a comparison. It is detailed as a function of the scale and the criteria adopted by the topographer and the map-maker in preparing the map. For this reason, we rejected this as a comparison truth with our results which are, however, numerical. In this sense they can be directly run by GIS for up-to-date mapping.

Test Area

The survey area consists of the watershed of Rendina watercourse, upstream of the Abate Alonia artificial reservoir, covering an area of about 40,000 hectares. The area stretches from Melfi and Vulture water stream up to Palazzo S. Gervasio as longitude and from Forenza and the Abate Alonia (near Lavello) as latitude and it includes the whole Rendina watershed, upstream of the reservoir, basically formed by the two sub-watersheds of the main affluents of the reservoir: Arcidiaconata and Venosa «fiumara» (**figure 1**).

Elevation data

The contour lines digitized through a raster scanning and the subsequent vectorialization of the «curve» mapping type at 1:25,000 scale were supplied by the IGM. The spot heights are acquired from the planimetric type, at the same scale, through a digitizer table. It contains the four vertexes of the mapping element which can be used as fiducial points for the transformation of coordinates. For the considered area, 320,215 triplets $(UTMx_i, UTMy_i, elev_i)$ were selected from the file supplied by the IGM for interpolation and 1,000 triplets of test points. The altimetric matrix represents a land discretized at a 50×50 m^2 step and, consequently, the total number of elements of the model was 419×684 equal to 716.5 km^2. The spatial resolution imposed on the DEM is drawn from the following remarks. The spatial accuracy supplied by the IGM for the contour lines is 15 m, the spatial resolution of LANDSAT-TM image is 30×30 m², therefore, since the DEM has to be registered on the image, the 30×30 m² resolution has to be assumed for the DEM. Computational problems suggest a 50×50 m² spatial resolution being compatible to a map at 1:25,000 scale (*Carrara et al.* 1988 p. 21).

With such a resolution, the number of elements of the z matrix was 138,920, a little less than half percent of the initial total. In almost all the cases, the points associated with the pixels belonged to the same contour line and, so, the loss of altimetric information was null. In the worst case, points of 5 meters apart altimetric curves were considered. All the above is consistent with the objectives of the study. **Figure 2** shows a histogram of the altimetric data: they vary from 300 m above sea level to 1,325 m of Vulture mountain.

The 400-500 m range is the most frequent: 32,163 elements, whereas there are 10 pixels with an elevation of more than

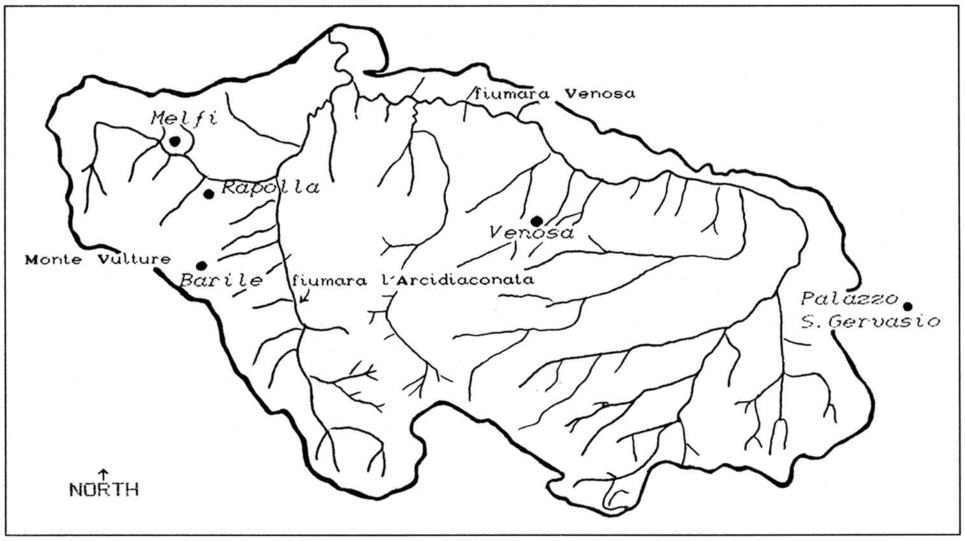

Figure 1 - Test area of the Rendina watersheed.

2

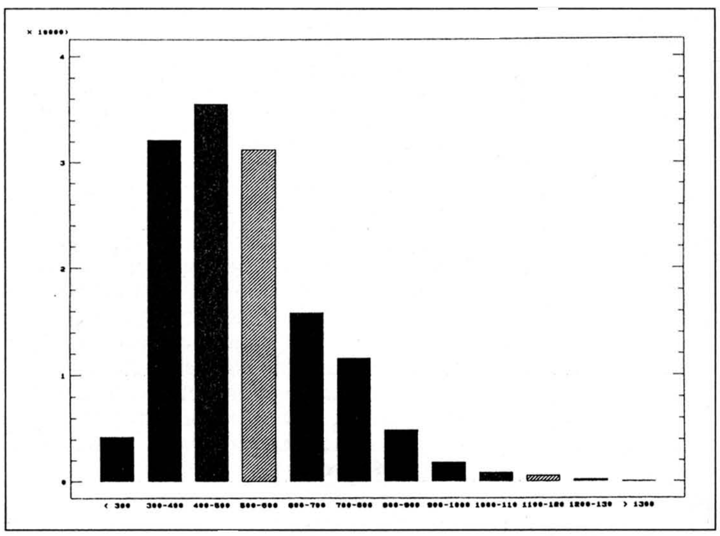

Figure 2 - Histogram of elevation data.

3

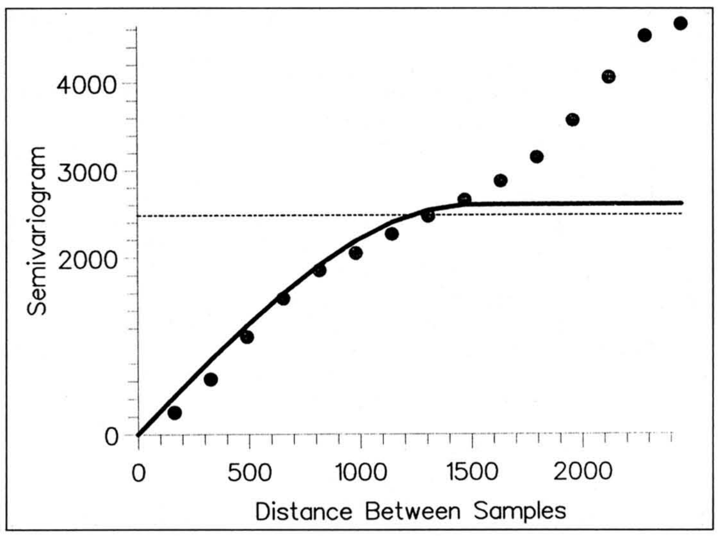

Figure 3 - Spherical variogram. Dots are referred to the experimental variogram. Units for abscissas are meters and for ordinates are squared meters.

4

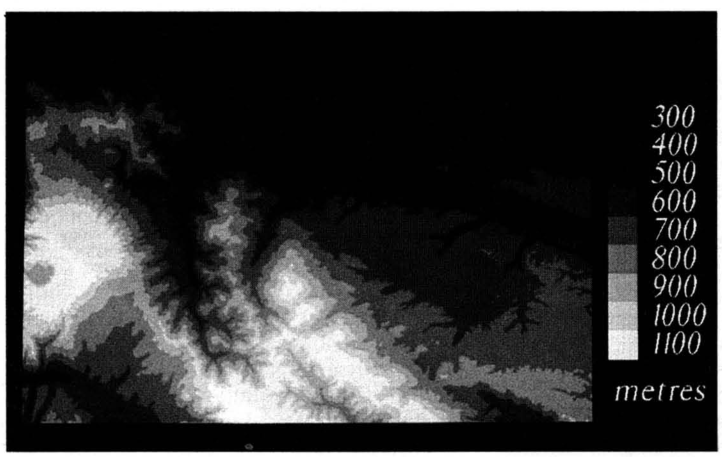

Figure 4 - Digital Elevation Model.

5

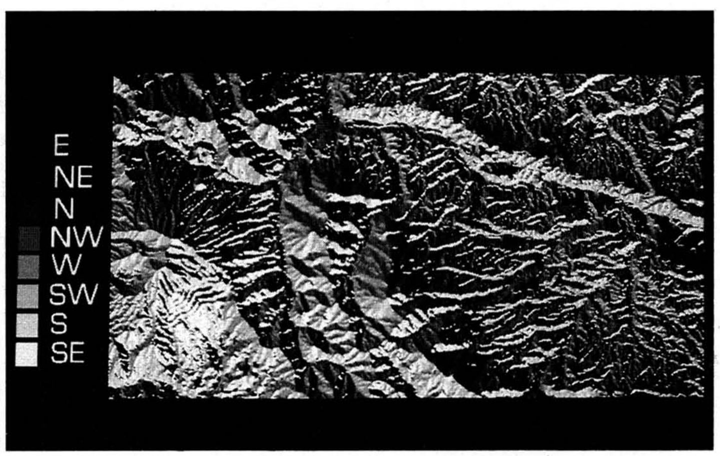

Figure 5 - Matrix of the links. The grey levels are associated to the identifier for the flow direction.

Table 1 ***Ranges of upstream values and pixel number related to them.***

30-50	(4,936);	90-110	(879);	150-170	(367)
50-70	(2,543);	110-130	(632);	170-190	(260)
70-90	(1,478);	130-150	(475);	>190	(994)

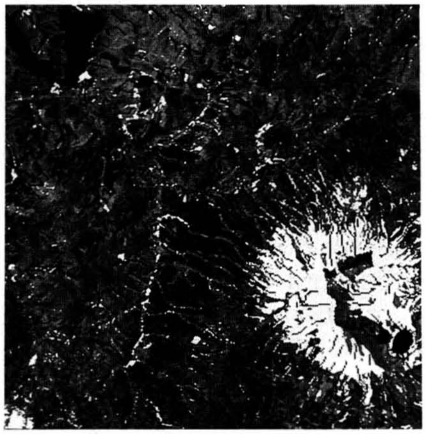

Figura 6 - Incomplete drainage network overlapped to LANDSAT-TM image

1,300 m. This results in an area which is rather complex from the orographic point of view.

The DEM

The DEM was obtained after a structural analysis on the altimetric data. For better running the analysis, the variogram was analyzed in 24 zones. In each zone, an isotropic behaviour of the variograms was obtained; each of them is spherical and limited by the variance of the sample for the zone and by a range from 3 to 4 km. We decided that the nugget was 0 since there were neither undersampling nor errors in the measurement. The average experimental variogram in the 24 zones is still spherical (**figure 3**) of the following mathematical form:

$$\gamma(d) = sill[1.5\ d/range - 0.5\ (d/range)]^3$$

d being the Euclidean distance between two points, $range = 3.000$ m and $sill = 2.500$ m^2.
From the physical viewpoint, we expect that the structure of the orographic phenomenon be limited by a *sill* since the root mean square deviations of elevation (*sqme*) between pairs of points, refer to a level above sea level. Moreover, since the *sqme* are related, in a sense, to slopes, the spherical γ leads to assume the examined zone as a zone with a quite steep average slope: in fact, the spherical model reaches the sill more rapidly than other models with a sill proposed in literature. Finally, the range of 3 km gives us information about the average length of slopes on the geographic datum: for distances greater than the range the mean sqme either refer to a valley or to altimetric variations relating to non significant shapes.

The previous spherical variogram was validated through $U = 0.021$ and $V = 1.202$ statistics which make the chosen γ model unbiased and consistent. The ordinary Kriging worked with neighbourhoods up to a maximum of 10×10 pixels, that is of a radius of 500 meters. The DEM is illustrated in **figure 4**.

Flow net calculation

Starting from the DEM, the proposed approach determines a link and an upstream matrix and it constructs connection segments between two successive pixels when, along an assumed direction of water flow, the sill value for the upstream is exceeded. **Figure 5** illustrates the link matrix and **figure 6** shows the drainage network obtained by an upstream threshold equal to 30 units. Everyone can notice that LANDSAT-TM image values (bands 1-2-4) is used background. The **figure 6** has got LANDSAT stretched values because of photographic b/w requirements. The threshold value is the one which makes the flow net more consistent with the one present on the topographic map of the zone at the scale 1:25,000.
The number of pixels with upstreams greater than 0 is 187,021 and, among them, 12,980 are greater than 30. **Table 1** presents this pixel distribution.
From **figure 6** one can notice that a connection step of the flow net is required referring, as previously said, to other information sources. The LANDSAT-TM images, for instance, can be used as background and interpreted to solve the ambiguities of the algorithm. This means that, if a pixel cuts the water flow interpreted as a sink (pointer to zero) the connection of the pixel to the rest of the net has to be made through track ball, when this is not checked by the satellite. The result is a semi-automatic approach but with a fully connected final result and as such, usable for morphometric analyses.

Conclusions

The initial assumption that the flow net can be constructed for methodological and application purposes was confirmed by the results of the study. By applying the geostatistical method of structural analysis and stochastic interpolation we obtained a DEM which was explored analytically and globally through photointerpretation of satellite image.
The numerical product obtained was tested by the application to a real case. The results obtained gave the way for a completely automatic processing. ●

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