Available online at www.sciencedirect.com

Geomorphology 53 (2003) 281–298

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Deriving drainage networks and catchment boundaries: a new methodology combining digital elevation data and environmental characteristics

Jürgen V. Vogt[a,*], Roberto Colombo[a], Francesca Bertolo[b]

[a] EC Joint Research Center, Institute for Environment and Sustainability, Via Enrico Fermi, s/n, 21020 Ispra, Varese, Italy
[b] 21100 Varese, Italy

Received 8 May 2002; received in revised form 2 October 2002; accepted 4 October 2002

Abstract

Digital data on the position and characteristics of river networks and catchments are important for the analysis of pressures and impacts on water resources. GIS tools allow for the combined analysis of digital elevation data and environmental parameters in order to derive this kind of information. This article presents a new approach making use of medium-resolution digital elevation data (250-m grid cell size) and information on climate, vegetation cover, terrain morphology, soils and lithology to derive river networks and catchments over extended areas.

In general, methods to extract channel networks at small scale use a constant threshold for the critical contributing area, independent of widely varying landscape conditions. As a consequence, the resulting drainage network does not reflect the natural variability in drainage density. To overcome this limitation, a classification of the landscape is proposed. The various data available are analysed in an integrated approach in order to characterise the terrain with respect to its ability to develop lower or higher drainage densities, resulting in five landscape types. For each landscape type, the slope–area relationship is then derived and the critical contributing area is determined. In the subsequent channel extraction, a dedicated critical contributing area threshold is used for each landscape type.

The described methodology has been developed and tested for the territory of Italy. Results have been validated comparing the derived data with river and catchment data sets from other sources and at varying scales. Good agreement both in terms of river superimposition and drainage density could be demonstrated.

Keywords: Drainage network extraction; Catchment delineation; Drainage density; Landscape characterisation; Digital elevation data

1. Introduction

From its source, water is transported along networks of rivers, canals and lakes to the sea. Such networks of drainage channels and associated drainage basins form complex functional entities not only for hydrological processes but also for geomorphological processes at

---

* Corresponding author. European Commission, DG Joint Research Centre, Institute for Environment and Sustainability (IES), TP 262, Via Enrico Fermi, s/n, 21020 Ispra, Varese Italy. Tel.: +39-0332-78-5481; fax: +39-0332-78-9803.

E-mail addresses: juergen.vogt@jrc.it (J.V. Vogt), robi.colombo@jrc.it (R. Colombo), francesca.bertolo@inwind.it (F. Bertolo).

doi:10.1016/S0169-555X(02)00319-7

large. Human pressures on water resources have constantly increased over the last decades. Population growth, intensified agriculture, industrialisation and recreational activities are among the primary drivers for such pressures, and climatic extremes such as droughts can aggravate these problems (EEA, 1998; Vogt and Somma, 2000).

Monitoring systems for water quality and quantity exist in all European countries. The level of detail of the collected information does, however, vary to a large degree. Information on the relationship between the state of the water bodies and environmentally relevant variables (e.g., land use, soil types, population density) is often lacking or not available. Still, such information is necessary for a more holistic analysis and for the analysis of cause–effect relationships between policies and environmental pressures. A Pan-European spatial database of rivers and catchments and their characteristics, therefore, is important for the analysis of these processes and for the monitoring and sustainable management of our water resources. The scales for presenting such information over extended areas such as Europe should preferably range from 1:250,000 to 1:1,000,000, and data should be sufficiently accurate to support the mentioned applications (Vogt et al., 1999).

With a total surface of about 11.2 million km^2, the Pan-European area (from the Mediterranean to northern Scandinavia and from the Atlantic to the Urals) comprises a large variety of landscape types, and the sheer extent of the area calls for the development of efficient and reliable methods to derive the required information. To this end, a methodology has been developed which allows for the derivation of drainage networks and associated catchments from digital elevation data and other environmental parameters in an automatic and repeatable way.

This paper presents the methodology which is sensitive to different natural drainage density patterns as a function of five landscape types that account for spatial variations in hydrologic controls such as climate, vegetation cover, relief, soils and lithology. For each landscape type, a suitable critical contributing area is derived by analysing the relationship between local slope and contributing area. Using this spatially varying threshold in the derivation of channel heads results in a naturally varying drainage density. The methodology has been developed and tested in a case study for Italy, a country that includes areas with large differences in their morpho-climatical characteristics. Results have been validated by comparing the derived data with river and catchment data sets from other sources and at varying scales.

In Section 2, we briefly review standard methodologies to derive drainage networks from digital elevation data as well as the results of investigations into the relationship between environmental factors and drainage density. Section 3 describes the implemented methodology, with special emphasis on the landscape characterisation. In Section 4, the results are presented, and in Section 5, the main conclusions are drawn.

2. Deriving drainage networks from digital elevation data

The extraction of drainage networks and catchment boundaries from digital elevation models (DEMs) has received considerable attention in recent years. A variety of algorithms has been reported in the literature and the most pertinent problems have been highlighted. These are related to the treatment of flat areas and to the location of the channel heads. In the following, we briefly summarise the main findings and discuss the relation between drainage density and environmental factors.

2.1. Pre-processing digital elevation data

Standard techniques of DEM preparation include pit filling, stream burning and the calculation of flow direction and flow accumulation grids.

During pit filling, local sinks are assumed to be artefacts, resulting from DEM generation. They are filled up to the level of the lowest grid cell on the rim of the sink with a defined flow direction. As a consequence, also natural sinks (e.g., in karstic landscapes) are filled up and the technique often results in extended areas of flat terrain. Common approaches are based on the techniques described by Jenson and Domingue (1988), O'Callaghan and Mark (1984), Fairfield and Leymarie (1991) and Martz and Garbrecht (1998).

From the pit-filled DEM, a flow direction grid is calculated. In the simplest case, flow direction between neighbouring grid cells is described by a single direction according to the steepest downward slope in a 3 × 3 neighbourhood (O'Callaghan and Mark, 1984). Such a description is well adapted for zones of convergent flow and along well-defined valleys. For overland flow analysis, however, a partitioning of the flow into multiple directions may be better (Freeman, 1991; Quinn et al., 1991; Desmet and Govers, 1996). A particular case of multiple flow dispersion was proposed by Tarboton (1997) in which flow dispersion is reduced by dividing the flow between a maximum of two neighbouring downslope grid cells.

From the flow direction grid, a flow accumulation grid can be calculated and from this grid drainage networks can be extracted. While most algorithms produce comparable networks in terrain with sufficient relief, major differences occur in areas with relatively flat terrain. Special attention, therefore, has to be paid to modelling the flow of water in (almost) flat terrain. Canalisation of rivers and very small or no altitude gradients usually hamper the automatic derivation of rivers in these areas. Proposed solutions to this problem range from the systematic introduction of small changes in grid cell elevations (Garbrecht and Martz, 1997; Mackay and Band, 1998) to the burning-in of digitised rivers into the original DEM (e.g., by artificially lowering the elevation along these known drainage lines). The latter enforces the resulting drainage network along the known lines (Maidment, 1996; Tarboton, 1997).

The effect of these techniques may vary considerably with the grid cell size of the DEM (Saunders, 1999). Different studies highlighted the influence of the DEM grid cell size on the accuracy of the extracted network (Zhang and Montgomery, 1994; Quinn et al., 1995; Wang and Yin, 1998). Coarse and medium-resolution DEMs, for example, do not allow the resolution of topographic features such as hollows, low-order channels and hillslope characteristics. Wolock and Price (1994) concluded, however, that medium-resolution DEMs (~ 250-m grid) may be appropriate for topographically driven hydrological models, and Walker and Wilgoose (1999) showed that the most prominent features of the slope–area relationship, such as the inflection point that marks the start of the fluvial scaling line, can be determined with high confidence from such DEMs.

2.2. Selecting a critical contributing area

One of the most critical issues in deriving drainage networks from DEMs is the location of the channel head. Many channel initiation models describe the head location as the result of competing sediment transport processes. The prevalence of one or another process depends to a large extent on the amount of water available and, as a consequence, on the size of the area contributing water to a given point.

Based on this concept, a common approach for extracting drainage networks from a DEM is to consider a grid cell as being part of a channel if its contributing area is larger than a defined contributing area threshold (O'Callaghan and Mark, 1984). The underlying hypothesis states that channel heads are located in zones where fluvial transport becomes dominant over diffusive transport, corresponding to the spatial transition from convex to concave slope profiles (Smith and Bretherton, 1972; Kirkby, 1980, 1986; Tarboton et al., 1991, 1992; Moglen et al., 1998).

The practical implementation of this theory requires the identification of an appropriate contributing area threshold for starting a drainage channel. The selection of this threshold is difficult and needs to be based on some quantitative estimate. Many investigators (e.g., Hack, 1957; Flint, 1974; Gupta and Waymire, 1989; Tarboton et al., 1989; Willgoose et al., 1991; Ibbit et al., 1999) have discussed and reported a power–law relationship between the local slope at any point along the channel (S) and the corresponding contributing area (A), including a constant (c) and a scaling exponent (θ) ranging from 0.4 to 0.7 (Eq. (1)).

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

In a log–log plot of local slope against contributing area, the transition from convex hillslopes to concave valleys is expressed by a characteristic change from a positive to a negative trend. Tarboton et al. (1992) proposed to use the value of the contributing area at this break as the critical contributing area.

Over extended areas, a single contributing area threshold is usually applied due to the lack of more detailed information (e.g., Hutchinson and Dowling, 1991; Verdin and Jenson, 1996; Graham et al., 1999; O'Donnell et al., 1999; Kwabena, 2000). In theory, the use of such a single threshold would require a homogeneous landscape. This assumption appears inappropriate for delineating river networks that have developed under a variety of landscape conditions (Montgomery and Foufoula-Georgiou, 1993; Da Ros and Borga, 1997; Gandolfi and Bischetti, 1997). Several authors, therefore, highlighted the necessity to apply a variable contributing area threshold to account for spatial variation in drainage density in different parts of a catchment (Garbrecht and Martz, 1995; Garcia Lopez and Camarasa, 1999; Colombo et al., 2001).

An alternative view of the channelisation process is that geomorphic thresholds control channel and valley formation. According to such theories, the hillslope–valley transition occurs where the threshold for a selected hillslope process (e.g., runoff generation by saturation or Hortonian overland flow, slope stability, runoff erosion) is regularly exceeded. An overview of the relation between hillslope processes and drainage density can be found in Dietrich et al. (1993) and Tucker and Bras (1998). To date, no definitive model has emerged and channel initiation mechanisms are likely to vary depending on the local characteristics of climate, hydrology, geology, relief and vegetation (Kirkby, 1994).

2.3. Drainage density and environmental factors

Valley development (V) can be understood as the result of a functional relationship between a number of environmental factors as expressed in Eq. (2):

$$V = f(C, R, V, I, S, P, T) \tag{2}$$

where C stands for climate, R for relief factors, V for the vegetation cover, I for lithology and rock structure, S for the soil characteristics, P for the type of hillslope process and T for time.

A useful measure to describe morphological valley development is the drainage density, which defines the extent to which streams dissect a landscape. Horton (1945) defined drainage density (D_d) as the total length of channels in a catchment divided by the area (A) of the catchment:

$$D_\mathrm{d} = \frac{\sum L_i}{A} \tag{3}$$

where L_i is the length of a single stream.

The relationship between various environmental variables and D_d has been extensively analysed and in the following, we report the main findings.

2.3.1. Climate and vegetation

Several studies indicate the influence of climate on drainage density. Melton (1957) determined an inverse relationship between the Precipitation Effectiveness Index as defined by Thornthwaite (1931) and D_d. Gregory and Gardiner (1975) and Gregory (1976) showed that drainage density broadly increases with a precipitation intensity index defined as the ratio between the maximum reported 24-h rainfall and the average annual rainfall.

Channel initiation and landscape evolution models generally predict a positive correlation between D_d and rainfall parameters (Montgomery and Dietrich, 1989; Tucker and Bras, 1998). Abrahams (1984), however, showed that several climatic factors simultaneously affect drainage density in a complex way. Madduna Bandara (1974) describes the combined effect of climate and vegetation and suggests an inhibiting effect of vegetation above a critical level of effective precipitation of about 200 mm/year. In addition, Moglen et al. (1998) showed the importance of vegetation as a limiting factor on D_d and the existence of two distinct regimes of behaviour in drainage density. Their model states that such dependency is associated with the density of vegetation cover and that without vegetation, D_d is positively related to precipitation.

Landscape evolution models that investigate the role of climate on D_d assume that drainage density peaks when wet periods and low soil critical shear stress act simultaneously (Rinaldo et al., 1995a). Tucker and Slingerland (1997), however, suggested that wet periods, together with low critical shear stress, might produce opposite effects in drainage density due to a change in vegetation cover. Vegetation cover may be a responsible factor in altering soil critical shear stress and, thus, in determining different extensions of the source area (Tucker et al., 1997; Foster et al., 1995; Prosser and Dietrich, 1995). Field observations generally show that high drainage density is favoured in arid regions with sparse vegetation cover and in temperate and tropical regions subject to frequent heavy rains (Melton, 1957; Strahler, 1964; Toy, 1977; Morisawa, 1985).

2.3.2. Slope and relief

Slope gradient and relative relief are the main morphological factors controlling drainage density. Strahler (1964) noted that low D_d is favoured where basin relief is low, while high D_d is favoured where basin relief is high. Montgomery and Dietrich (1989) reported a positive relationship between valley gradient at the channel head and drainage density in humid soil-mantled landscapes. For humid badlands, Howard (1997) showed that the relationship between relative relief and D_d changes from positive to negative with increasing relief as a consequence of different channel initiation processes. Oguchi (1997) found an inverse relationship between relief and drainage density in deep valleys located in humid, steep mountains. The combined role of relief and climate on drainage density has also been investigated by Kirkby (1987), suggesting that the relationship between D_d and relief depends on the dominant hillslope processes. He predicts a positive relationship for semiarid environments and an inverse one for humid climates. Tucker and Bras (1998), modelling the role of hillslope processes on drainage density, predict a positive relationship between D_d and relative relief for semiarid, low relief landscapes dominated by Hortonian overland flow. In contrast, a negative relationship results for high-relief landscapes dominated by threshold landsliding as well as for humid landscapes dominated by saturation-excess runoff.

2.3.3. Bedrock and soil

According to Wilson (1971) and Day (1980), differences in drainage density in regions of similar climate are related to bedrock geology. By analysing the relationship between channel slope and lithological formation, Tucker and Slingerland (1996) proposed rules to define bedrock erodibility as a predictor of D_d. Gardiner (1995) showed that greater drainage densities are generally associated with impermeable rocks.

Drainage density is generally inversely related to the hydraulic conductivity of the underlying soil. For steep slopes, an inverse correlation has been modelled by Montgomery and Dietrich (1992). Generally, D_d increases with decreasing infiltration capacity of the underlying rocks and/or decreasing transmissivity of the soil. Soil parameters affect land surface resistance to erosion by surface flow and their variability produces different spatial and temporal trends in drainage density (Dietrich et al., 1992; Rinaldo et al., 1995b; Tucker and Slingerland, 1997).

3. Data and methodology

3.1. Derivation of basic hydrologic quantities

For this case study, a digital elevation model (DEM) for the entire territory of Italy (roughly 300,000 km^2) was available. Grid spacing was 250 m in a Lambert Equal Area Azimuthal projection. To improve results in areas of flat topography, an algorithm of drainage enforcement was applied. The river network at a 1:3,000,000 scale acquired from the Eurostat GISCO database (http://www.europa.eu.int/eurostat.html) was used for this purpose. This coverage was first edited in order to remove lakes, double-lined streams and artificial watercourses, and then used as input for the burning procedure. In some areas, the coarse grid cell resolution of the DEM resulted in interrupted streams and cut-off meanders, and in order to achieve good results, the GISCO coverage had to be edited and revised in an iterative procedure. In addition, the GISCO river network was complemented with data from other sources in extended flat areas such as the plain of the river Po in order to ensure a correct flow pattern of the major tributaries.

Using the TARDEM suite of programs (Tarboton, 1997), all pits were assumed to be artefacts and they were eliminated using the ‘flooding’ approach (Jenson and Domingue, 1988). Flow directions were assigned with the single flow D8 method (O’Callaghan and Mark, 1984). The relief imposition algorithm of Garbrecht and Martz (1997) was applied to resolve ambiguities in drainage directions on flat surfaces and to generate a more realistic flow topography. Finally, the upslope contributing area was calculated for single flow directions using a recursive procedure based on the algorithm proposed by Mark (1988).

Flow directions were also computed using the D∞ method (Tarboton, 1997). These values served for the derivation of the contributing area thresholds by analysing the relationship between local slope and contributing area for each grid cell.

3.2. Landscape characterisation

The rationale for implementing a landscape characterisation approach is to overcome the shortcomings of using a single contributing area threshold for an extended area. The landscape strata, therefore, had to be based on a combination of environmental factors governing drainage density and should reflect the complex landscape evolution in terms of the pattern and density of the channel network. The underlying hypothesis states that a few basic environmental factors exert a strong control on the channel initiation process and, therefore, on the development of the valley network.

The resulting landscape types are assumed to be homogeneous with respect to drainage density and to exhibit a characteristic relationship between local slope and contributing area. As a consequence, the threshold for the minimum contributing area to start a channel is spatially variable over the study area, thus producing different drainage densities for different landscape types. In the following, we discuss the derivation of the different environmental characteristics.

3.2.1. Climate and vegetation

Effective mean annual precipitation as defined by Thornthwaite (1931) was used as one factor predicting drainage density (Eq. (4)). Climate data from the European Database of the Monitoring Agriculture by Remote Sensing (MARS) project with a 50-km grid cell size were used to estimate the index (Terres, 2000). A data series of daily data for the period from 1975 to 1997 was used for this study.

For each grid cell, average monthly temperature and average monthly precipitation were calculated. The Thornthwaite Precipitation Effectiveness Index (I) was then calculated according to Eq. (4):

$$I = 115 \sum_{i=1}^{12} \left(\frac{d_i}{T_i - 10} \right)^{1.11} \tag{4}$$

where T_i is the average monthly temperature in degrees Fahrenheit, and d_i is the average precipitation in month i, in inches.

The percentage surface cover was used in the analysis due to its effect on critical shear stress and, thus, its control on channel initiation (Tucker et al., 1997; Foster et al., 1995). To do so, CORINE Land Cover data (CEC, 1993; http://www.europa.eu.int/comm/eurostat) with a grid cell size of 250 m were reclassified into 14 classes, and monthly cover percentages were assigned to each class according the scheme derived for Europe by Kirkby (1999). A yearly average surface cover has then been calculated for each land cover class as the mean of the monthly values.

3.2.2. Slope and relief

The influence of the morphology on drainage density has been considered by defining different relief classes based on the relation between slope gradient and relative relief. Relative relief was defined as the maximum elevation difference in a 3 × 3 grid cell neighbourhood. These parameters have been selected on the basis of their influence on drainage density (Montgomery and Dietrich, 1989; Roth et al., 1996). The two parameters were derived from the original DEM, using neighbourhood operators working on a moving window of 3 × 3 grid cells. The two factors were combined to obtain different relief classes according to the scheme proposed by Van Zuidam and Van Zuidam-Cancelado (1979).

3.2.3. Bedrock and soil

The role played by the structure of the underlying rock was reduced to the effect of the type of lithology. The rock erodibility scale as proposed by Gisotti (1983) was adopted. From the European Soil Map (ESBSC, 1998), the parent material belonging to each Soil Mapping Unit was extracted by deriving the dominant lithology and scaled by assigning the highest erodibility to unconsolidated clastic rocks and the lowest erodibility to igneous rocks.

Table 1
Factorial scoring system used in the definition of the landscape drainage density index

Code	Environmental factor	Description	Score
Precipitation effectiveness index (I) [–]			
1	≥ 128	humid forest	1
2	64 – 127	forest	2
3	32 – 63	grassland	3
4	16 – 31	steppe	4
5	≤ 15	desert	8
Slope steepness [%] and relative height difference (S) [m]			
1	0 – 2, < 5	flat or almost flat	1
2	3 – 13, 5 – 75	undulating sloping	2
3	14 – 20, 50 – 200	rolling hilly steep	3
4	21 – 55, 200 – 500	hilly very steep	4
5	>56, >500	mountainous extremely steep	8
Vegetation cover (V) [%]			
1	< 10	no cover	16
2	11 – 25	scarce	9
3	26 – 50	moderate	6
4	51 – 75	high	2
5	>75	very high	1
Rock erodibility (R) [–]			
1	very low	igneous, metamorphic	1
2	low	calcareous	2
3	medium	sandy, loamy, pyroclastic	3
4	high	clayey materials	4
5	very high	unconsolidated clastic	5
Soil transmissivity (T) [m^2/day]			
1	< 1.0	very low	16
2	1.1 – 3.0	low	9
3	3.1 – 6.0	medium	6
4	6.1 – 9.0	high	2
5	>9.1	very high	1

Uniform soil transmissivity has been chosen as the main soil factor affecting the drainage density (e.g., Dietrich et al., 1992; Tucker and Bras, 1998). On the basis of the European Soil Map, soil transmissivity was calculated as the product of saturated permeability and the soil depth. Information regarding soil permeability was derived from soil texture.

3.3. Derivation of a landscape drainage density index

The derivation of landscape units that are homogeneous with respect to drainage density was based on a scoring system, combining the environmental variables previously described. Scoring systems provide a powerful technique for deriving homogeneous areas and have been successfully applied in environmental analyses and at a variety of scales (Giordano et al., 1991; Morgan, 1993; Barredo et al., 2000). The methodology is to divide the area into sectors (grid cells in our case) and to score the various environmental variables for each sector separately. Individual variable ratings are combined and a drainage density class is assigned on the basis of the total score.

The environmental factors were classified according to Table 1 and a weighting score was defined for each class based on the relationship between the environmental parameter and drainage density. The choice to apply a simple scoring system is justified on the basis that we are not deriving a physical value of drainage density but rather defining areas with specific environmental conditions.

An inverse power relationship was associated with the climate interval (Melton, 1957), thus, establishing highest drainage densities for desert environments and lowest drainage densities for humid forests. The relationship between relief and drainage density was assumed to be positive.

Percentage vegetation cover and uniform soil transmissivity were ranked decreasingly with drainage density (Strahler, 1957; Morisawa, 1985). Their effects, combined with soil and rock erodibilities, strongly determine the erosional resistance of the surfaces. For this reason, a heavy weighting factor has been assigned.

Based on the results of Tucker and Slingerland (1996), a linear relationship between drainage density and rock erodibility has been implemented.

Finally, all environmental scores were added up in order to determine the landscape drainage density

Table 2
Classes of landscape drainage density

Landscape drainage density class	Drainage density	Total score (LDDI)
I	very low	< 15
II	low	16 – 25
III	medium	26 – 35
IV	high	36 – 45
V	very high	>45

index (LDDI) for each grid cell (symbols according to Table 1):

$$\mathrm{LDDI} = I + S + V + R + T \qquad (5)$$

From the total score, five drainage density classes were defined according to Table 2. Finally, the resulting map has been filtered with a 3 × 3 grid cell majority filter in order to remove single spurious grid cells. The result is shown in Fig. 1.

Based on the assumption that drainage channels will not start in urban areas, marshes or deltas, such areas were not included in the stratification procedure.

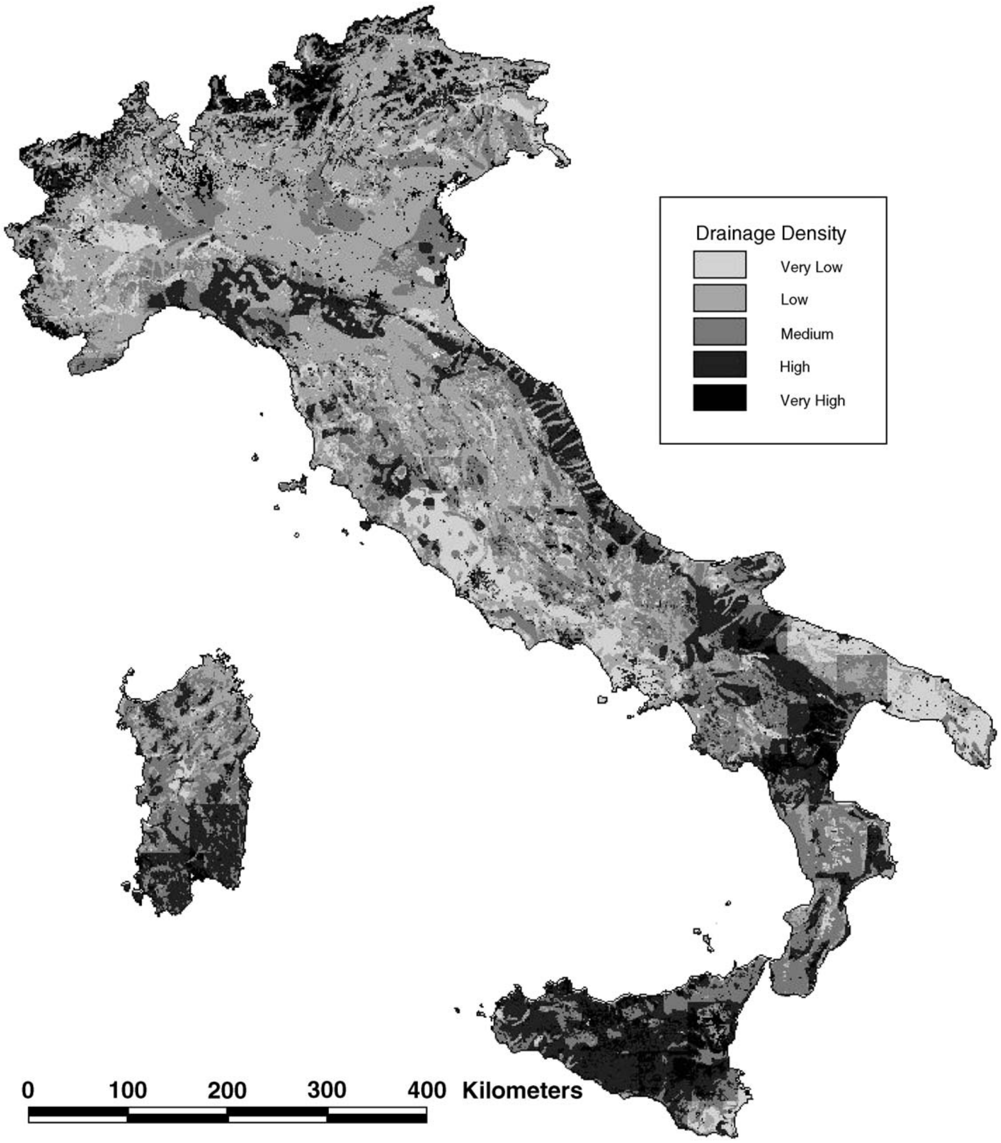

Fig. 1. Drainage density classes for Italy.

3.4. Derivation of the critical contributing area

The critical contributing area (CA) was derived for each landscape drainage density class by analysing the local slope–contributing area relationship derived from the digital elevation data.

In order to have a better representation of the partitioning of water flow, local slope and contributing area were estimated from the DEM using the D∞ method (Tarboton, 1997). The log–log diagrams of local slope and contributing area were analysed for each landscape class. Fig. 2 shows examples of these diagrams for the classes of lowest drainage density (Class I) and of highest drainage density (Class V).

Due to the low spatial resolution of the underlying DEM, it is not possible to distinguish between different hillslope processes in these diagrams. However, the transition from undistinguished hillslope processes to fluvial processes is well marked as a break in the slope of the scaling line (i.e., CA = 3 km^2 for class V and CA = 700 km^2 for class I). While we can assume that the zone to the right of the break belongs to the fluvial regime, the zone to the left of the break appears to be the result of a transition between several hillslope processes.

In order to guarantee that a grid cell belongs to the fluvial network, we decided to extract a drainage channel based on a contributing area greater than the

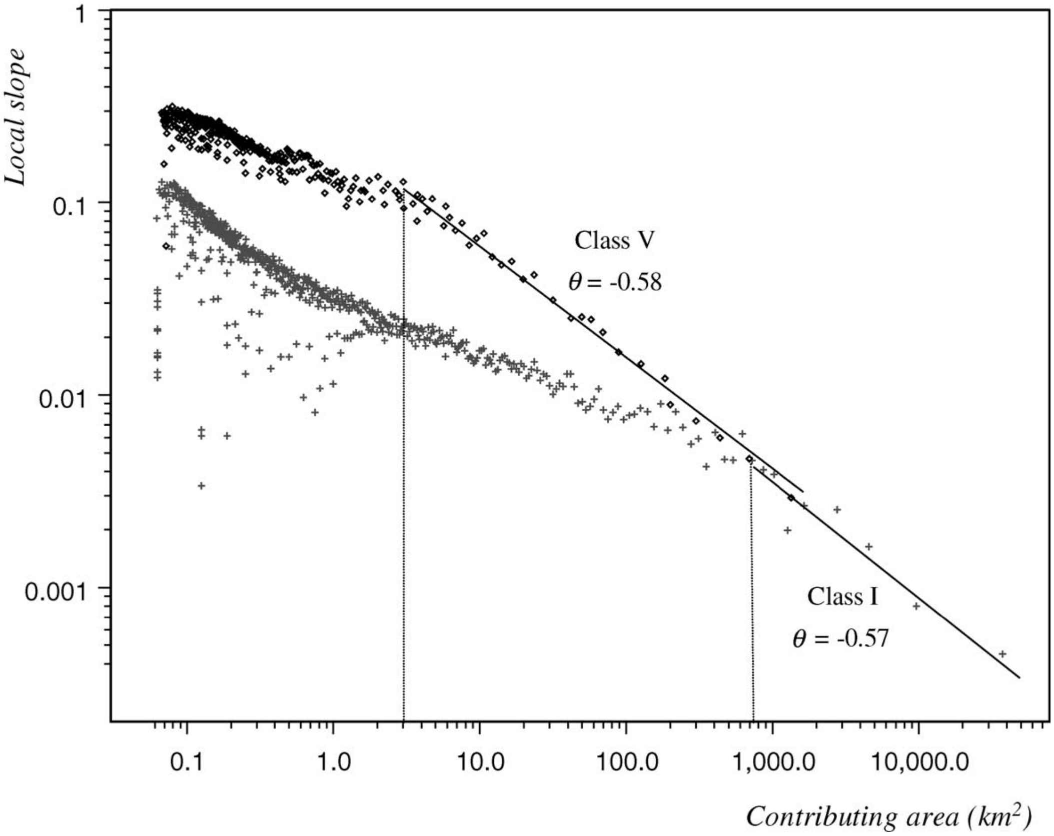

Fig. 2. Graphs of local slope against contributing area for landscape drainage density classes I (low drainage density) and V (high drainage density). Note the logarithmic scale.

Table 3
Minimum contributing area per landscape drainage density class

Landscape drainage density class	Minimum contributing area (km^2)
I	700
II	100
III	50
IV	10
V	3

value defined by this inflection point. Critical contributing areas were found to increase coherently with the defined drainage density classes (Table 3), indicating the adequacy of the implemented landscape characterisation procedure.

3.5. Channel network connection and basin extraction

The extraction of drainage networks with variable contributing area thresholds produces an unconnected river network with flow interruptions at class boundaries. To connect the channel network, a pixel growing algorithm had to be developed. The basic condition of the algorithm is the identification of so-called seed pixels, which mark the start of a drainage channel. After seed pixels are marked, the algorithm defines the drainage network on the basis of the accumulation and flow direction matrices.

Catchment boundaries were finally delimited by automatically identifying all the outlet points in the drainage network and subsequent calculation of the contributing upslope areas (Jenson, 1991).

4. Results and validation

The outlined methodology has been applied to the entire Italian territory, leading to a well-connected and coherent drainage network (Fig. 3).

The method allowed extracting a fully connected and hierarchically structured drainage network taking into account the variability in environmental conditions. Thus, the drainage pattern and the drainage density are depending on the distribution of, and interrelation between, different environmental factors such as climate, morphology, soils, geology and vegetation. Drainage density does not necessarily assume highest values in mountainous regions and lowest values in gently sloping areas, as would be predicted by a slope-dependent method, for example. It is rather modelled according to a combination of several factors acting together. Gently sloping agricultural areas with moderate rainfall, but characterised by a relatively sparse vegetation cover and rather impermeable soils or rocks, may have a greater drainage density than hilly terrain with heavier rainfall, but characterised by a good permeability of the soil and a vegetation cover with dense forest.

All rivers were finally classified according to the Strahler system (increasing order from the river source to the sea) and subcatchments were derived for the different orders (Horton, 1945; Strahler, 1952; Warntz, 1975).

The quality of the final result depends on both the methodology used and the quality of the input data, each one representing potential sources of error. In order to validate the product, various procedures need to be considered.

A first limitation stems from the spatial resolution of the DEM. The grid cell size determines the minimum area resolved on the ground. As a consequence, a meandering river system cannot be resolved if the radius of the meander is in the order of magnitude of the grid cell dimension. The grid cell size also determines the maximum positional accuracy (i.e., the exact position of a river is limited by the grid cell size). The precision of the coverage used for river burning in flat areas is a further limitation.

The most crucial point, however, is the determination of the extent of the channel network, which depends on the accuracy of the contributing area threshold. Although the relationship between local slope and contributing area can be defined with good accuracy from a low-resolution DEM (Walker and Willgoose, 1999), and even though we have computed this relationship using a multiple flow algorithm (Tarboton, 1997), the exact location of the starting point of the fluvial scaling line is not always evident. However, the differences between the thresholds of the different landscape types are very large compared to the expected uncertainty on the threshold (Table 3). In order to optimise the final product, thresholds need to be fine-tuned by an iterative procedure, comparing the result with reference data sets.

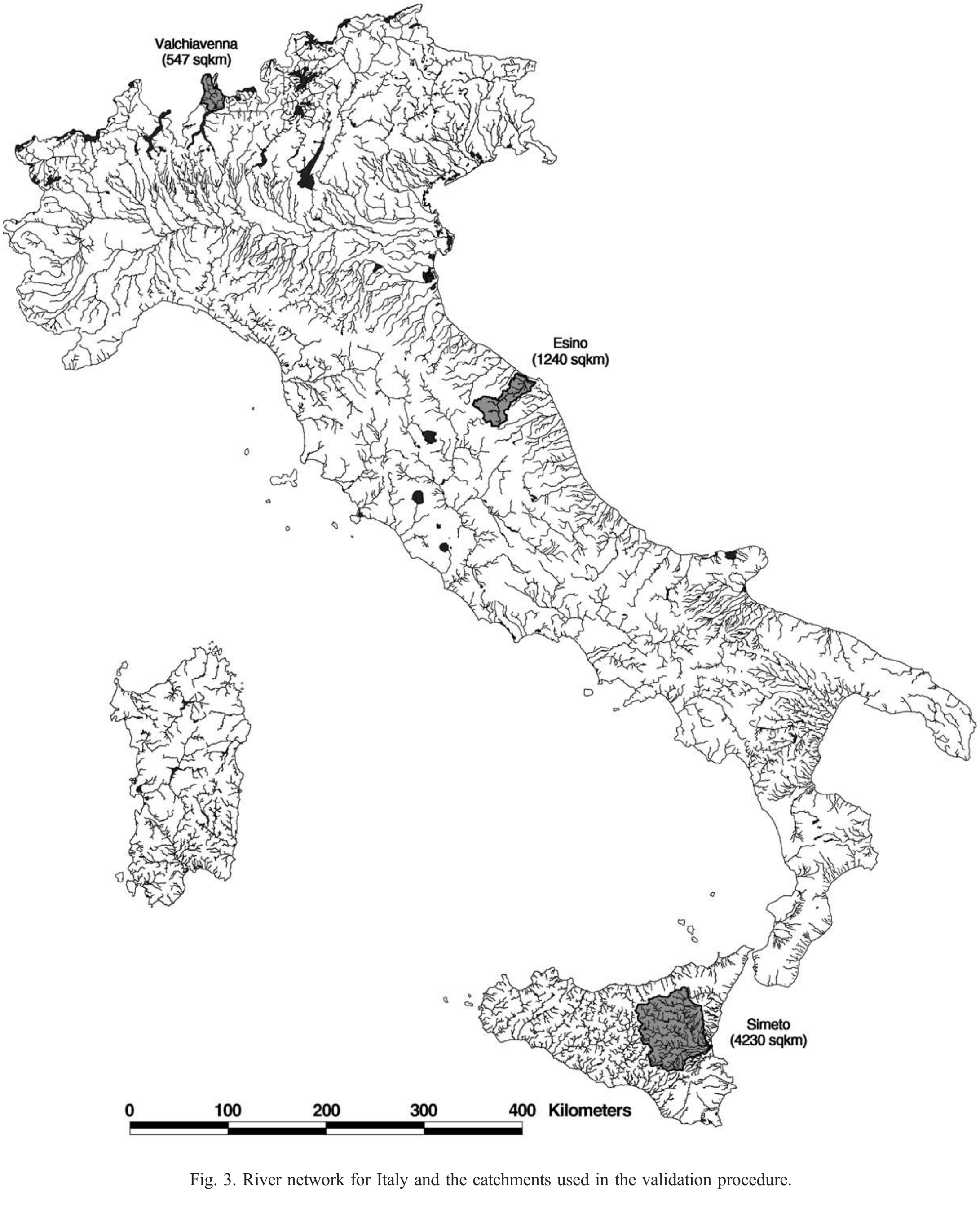

Fig. 3. River network for Italy and the catchments used in the validation procedure.

Validation of automatically derived catchment data sets is often performed through a comparison of the size of a sample of the derived catchments with the size as given in independent sources (Graham et al., 1999). Such comparison can give a first indication. However, it remains of limited value, especially with regard to the position of the rivers.

In order to provide a more precise evaluation of a European data set, the drainage network and catchment boundaries can be quantitatively and qualitatively compared to a series of independent European-wide data sets, including, for example, the Bartholomew river network (http://www.bartholomewmaps.com), the size of the catchments draining to the Eurowaternet station network of the European Environment Agency (Nixon et al., 1998; Boschet et al., 2000), or the Erica catchment boundaries (Flavin et al., 1998). Officially reported sizes of larger catchments are another possibility. National data sets of digitised rivers and catchments are further options, usually providing a higher level of detail. Finally, large-scale digital maps for selected catchments can be used.

For this study, we compared the computed size of some catchments with their officially reported size (Table 4). More significantly, a comparison with the Bartholomew river network at a scale of 1:1,000,000 as well as a more detailed comparison with a limited number of local data sets at a scale of 1:10,000 has also been carried out.

The values shown in Table 4 in general demonstrate a good agreement between the officially reported catchment size and the DEM-derived value. Small differences can, for example, be due to the fact that part of a catchment is located outside Italy and these parts had to be estimated from various sources. In addition, figures in official documents often vary. A major discrepancy can be seen for the Esino catchment. This is due to the inclusion of a small coastal catchment and a karstic area in the upper part of the catchment. Both areas should be treated separately. The first source of error can be corrected through a burning procedure in the flat coastal plain, while the handling of karstic areas still poses some more fundamental problems.

Table 4
Comparison between DEM-derived and official catchment surface

Catchment	DEM-derived area (km^2)	Official area (km^2)	Difference (%)
Po	67,958	67,067[a]	1.33
Tevere	17,645	17,490[a]	0.89
Valchiavenna	547	534[b]	2.43
Esino	1241	1133[b]	9.53[c]
Simeto	4230	4188[b]	1.00

[a] Figures according to Basin Authorities. Po: Italian part of the catchment. Some 4000 km^2 in Switzerland and France excluded.

[b] Digitised from 1:10,000 maps. Valchiavenna: Italian part of the catchment. Some 187 km^2 in Switzerland excluded.

[c] Error due to inclusion of a small coastal catchment (~ 50 km^2) and a small karstic area in the upper part of the catchment (~ 50 km^2).

The Bartholomew river data set is widely accepted as one of the most accurate at its scale of 1:1,000,000. In order to compare this data set with our river network, the percentage of Bartholomew rivers falling within a buffer of varying width around our rivers has been calculated. In other words, we calculate how much of the Bartholomew river network has been traced correctly.

The principle of this approach and the results from a comparison using buffers of 250, 500 and 1000 m around the derived river network are shown in Fig. 4. While for the 1000-m buffer on average almost 75% of the Bartholomew rivers are traced, this value falls to 58% for the 500-m buffer and to 38% for the 250-m buffer. Splitting up the results according to the drainage density classes reveals some systematic differences: in the landscape classes with high drainage density, results are significantly better than in the lower and especially the medium drainage density classes.

The following reasons may explain these results and especially the difference between the three buffer dimensions.

1. The thresholds for the low drainage density classes have been overestimated and as a consequence, the DEM-derived rivers are too short (start too late) in many cases. This error is to be corrected by an iterative adjustment of the thresholds, giving specific emphasis to the low and medium drainage density classes.
2. The data sets could not be precisely referenced one to another. Small nonlinear spatial deviations could be observed. These are probably due to various reprojections in the course of the development of the Bartholomew database and the DEM. A small difference in the radius of the sphere of reference,

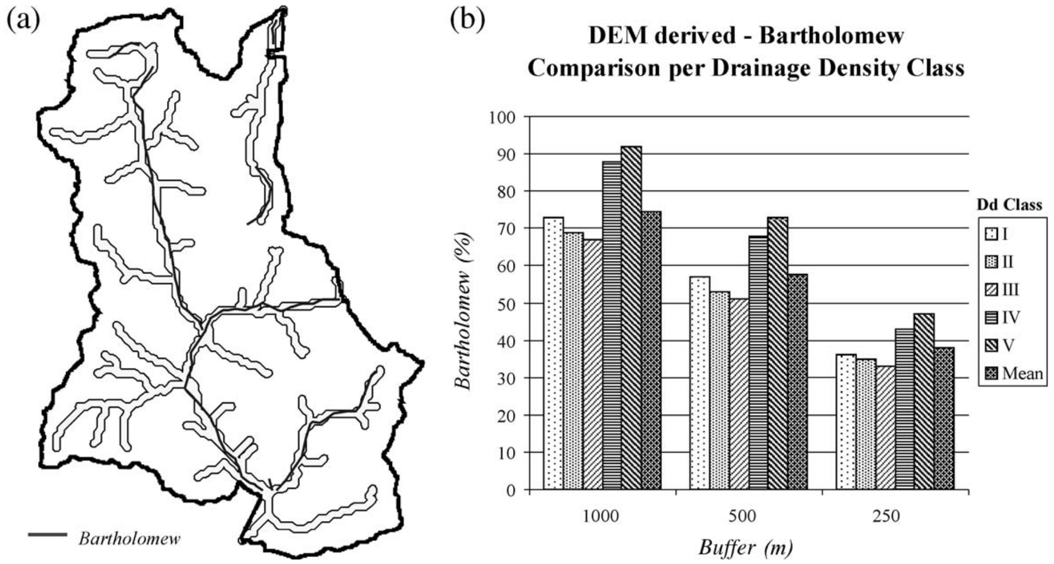

Fig. 4. Comparison of DEM-derived and Bartholomew river networks through buffers of various widths. (a) The principle: the 250-m buffer around the DEM-derived network (light grey) and the Bartholomew river network (black). (b) Results for the different buffers for the whole of Italy.

for example, can cause large differences for the narrow buffers.

3. It must be recognised that also Bartholomew does not represent *the* truth. Generalisations and errors are present and, therefore, differences between the two data sets must exist. While Bartholomew has been digitised from maps of various scales, our river network is extracted from a DEM with a 250-m grid cell size. As a consequence, the length of the Bartholomew rivers will depend on the subjective judgement of the operator performing the digitalisation, for example, with respect to the choice of the main reach. The positional accuracy of the DEM-derived river network, on the other hand, is limited to the size of the underlying grid cell. The use of a buffer of 250 m width, therefore, requires an exact co-registration of the two data sets.

The comparison with local data sets highlights some of these validation problems in more detail. Based on available digital data from local catchment data sets at a scale of 1:10,000, detailed comparisons could be made with respect to the positional accuracy of rivers. The catchments studied represent a humid Alpine environment (Valchiavenna), a humid Apennine environment (Esino) and a low relief semiarid environment (Simeto). The location and size of these catchments is shown in Fig. 3. As an example, the different river networks for the Esino catchment are shown in Fig. 5.

While the comparison between the river network on the 1:10,000 maps (blue lines) and the Bartholomew river network showed considerable deviations in river position in many cases, the location of the DEM-derived channel network was observed to be in good agreement with the main trunks of the large-scale river network on the maps. Since the blue lines have been digitised from maps at a 1:10,000 scale, they are naturally much denser than the DEM-derived network, which corresponds to a scale of approximately 1:500,000. The channel network extracted from the 250-m DEM was in all cases denser than the Bartholomew network, which was to be expected due to the difference in scale. More importantly, however, Fig. 5 demonstrates that the position of the DEM-derived network is more accurate than the

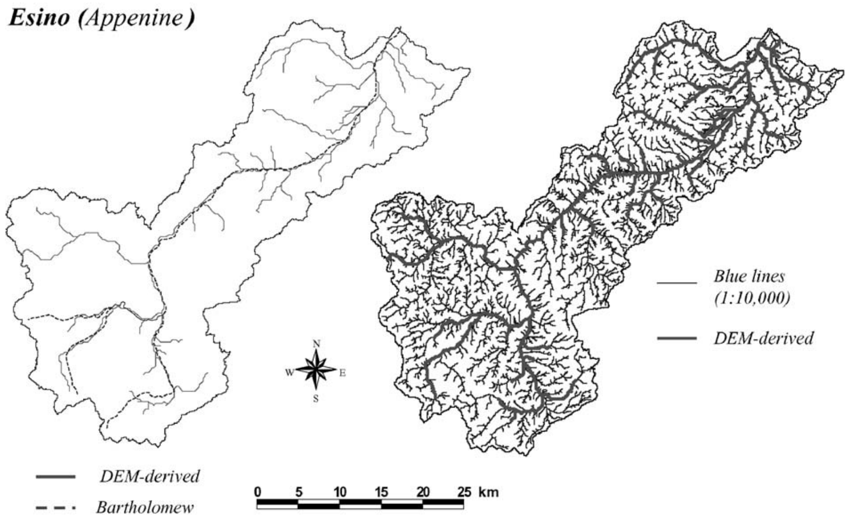

Fig. 5. Comparing the DEM-derived river network with the Bartholomew river network and with the river network digitized form large scale maps. Example of the Esino catchment.

Bartholomew network in many cases. Positional shifts of river reaches can be seen, which are probably due to the fact that the Bartholomew network has been digitised from small-scale maps with related generalisations. The DEM-derived network, on the other hand, coincides very well with the main trunks of the blue network of the large-scale maps. However, inaccuracies can be seen in small flat areas where no burning procedure has been used.

In general, the validation procedure has shown that the developed methodology is capable of deriving drainage networks and associated catchment boundaries with reasonable accuracy from DEMs with a 250-m grid cell size. The quantitative comparison with an established database such as Bartholomew allows fine-tuning of the thresholds for the minimum contributing areas and to optimise the result. The absolute values of the coincidence between data sets like Bartholomew and the derived river network need, however, to be interpreted with care, since the detailed analysis of selected catchments has shown that the Bartholomew database cannot be accepted as representing *the* truth. This is due to well-known problems related to the generalisation of information, but also to problems of the projection of underlying maps and their accuracy and to the subjective influence of the digitising operator. Similar considerations apply to the generation of the DEM and to its spatial and vertical precision.

In summary, we believe to have shown that the combined use of a medium-resolution DEM (i.e., 250-m grid cell size) and environmental data can be a good basis for the derivation of river networks and catchment boundaries at national and continental scales.

5. Summary and conclusions

In this paper, we report on a study to derive channel networks from digital elevation data, using a new approach based on a variable contributing area threshold. On the basis of a landscape stratification, this threshold has been calculated for five distinct landscape types in Italy. It proved to be a suitable approach for analysing large areas, producing a well-connected and coherent channel network.

The methodology takes account of the spatial variability of the most important environmental factors governing drainage density and landscape development. Taking into consideration precipitation effectiveness, vegetation cover, terrain morphology, soil transmissivity and lithology in a multi-criteria evaluation procedure, the natural variation in drainage density could be reproduced.

The critical contributing area for each landscape type has been derived by calculating the slope–area relationship for each type and subsequently identifying the inflection point that separates indistinct hillslope processes from fluvial transport processes. While medium-resolution DEMs do not allow further distinction of various hillslope processes, they do allow derivation of the limit between hillslope and fluvial processes with reasonable accuracy.

The derived channel network and catchments were compared with the Bartholomew river network at a 1:1,000,000 scale, officially reported basin sizes, and local catchment data sets at a 1:10,000 scale. In general, the results of these comparisons show good agreement between our data and the reference data. At the same time, they highlight intrinsic limitations of each of the data sets. The Bartholomew river network, for example, is generally accepted as being of good accuracy at its scale. However, inconsistencies with our river network can be found. They are due to the digitisation procedure (e.g., scale of underlying maps, operator decisions) or to scale-dependent generalisations.

At the same time, the DEM-derived river network is limited by the spatial resolution and vertical accuracy of the underlying DEM. While the derived river network is of high quality and superior to existing data sets in terrain with reasonable relief energy, digitised river networks are necessary to guide the algorithm in extended flat areas. Other problems relate to the handling of karstic areas and natural depressions, which currently are not treated appropriately.

In order to improve on these shortcomings, ongoing research is targeting the consideration of lakes, coastal lagoons and natural depressions during river extraction. The implementation of a faster and more reliable algorithm for computing the contributing drainage area is further expected to significantly improve the results in critical areas. This algorithm is based on the concepts of morphological image analysis and is further described by Soille (2002). It will also improve the processing speed, an important aspect when implementing the methodology over the entire continent of Europe.

In summary, the study has shown that it is possible to derive drainage networks and associated catchments with a good accuracy from DEMs with a medium spatial resolution. The developed methodology has now been implemented over the whole European continent in order to derive data sets suitable for environmental monitoring.

Acknowledgements

The authors like to thank David Tarboton (Utah State University) and Riccardo Rigon (University of Trento) for fruitful discussions, as well as Andrea Baraldi (JRC) for developing the river connection algorithm. Thanks are further due to T. Oguchi (University of Tokyo) and an anonymous referee for valuable comments on an earlier version of the manuscript.

References

Abrahams, A.D., 1984. Channel networks: a geomorphological perspective. Water Resour. Res. 20, 161–168.

Barredo, J.I., Benavides, A., Hervas, H., van Westen, C., 2000. Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain. Int. J. Appl. Earth Obs. Geoinf. 2 (1), 9–23.

Boschet, A.F., De Paepe, V., Lack, T.J., 2000. Inland waters. Annual Topic Update. European Environment Agency, Topic Report 1/2000. Office for Official Publications of the European Communities, Luxembourg. 30 pp.

CEC Commission of the European Communities, 1993. CORINE Land Cover—Guide Technique. Office for Official Publications of the European Communities, Luxembourg. EUR 12585. 144 pp.

Colombo, R., Vogt, J.V., Bertolo, F., 2001. Deriving Drainage Networks and Catchment Boundaries at the European Scale. A New Approach Combining Digital Elevation Data and Environmental Characteristics. Office for Official Publications of the European Communities, Luxembourg. EUR 19805 EN. 58 pp.

Da Ros, D., Borga, M., 1997. Use of digital elevation model data for the derivation of the geomorphological instantaneous unit hydrograph. Hydrol. Process. 11, 13–33.

Day, D.G., 1980. Lithologic controls of drainage density: a study of six small rural catchments in New England, N.S.W. Catena 7, 339–351.

Desmet, P.J.J., Govers, G., 1996. Comparison of routing algorithms for digital elevation models and their implications for predicting ephemeral gullie. Int. J. Geogr. Inf. Syst. 10 (3), 311–331.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., Bauer, R., 1992. Erosion thresholds and land surface morphology. Geology 20, 675–679.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., 1993. Analysis of erosion thresholds, channel networks, and landscape morphology using a digital terrain model. J. Geol. 101, 259–278.

EEA European Environment Agency, 1998. Europe's environment: the second assessment. Office for Official Publications of the European Communities, Luxembourg and Elsevier Science, Oxford, 293 pp.

ESBSC European Soil Bureau Scientific Committee, 1998. Georeferenced Soil Database for Europe, Manual of Procedures. EUR, vol. 16393 EN. CEC-JRC, Ispra, 184 pp.

Fairfield, J., Leymarie, P., 1991. Drainage networks from grid digital elevation models. Water Resour. Res. 27, 709–717.

Flavin, R.W., Andrews, A.J., Kronvang, B., Müller-Wohlfeil, D., Demuth, S., Birkenmayer, A., 1998. ERICA, European Rivers and Catchments. European Environment Agency, Copenhagen.

Flint, J.J., 1974. Stream gradient as a function of order, magnitude and discharge. Water Resour. Res. 10, 969–973.

Foster, G.R., Flanagan, D.C., Nearing, M.A., Lane, L.J., Risse, L.M., Finkner, S.C., 1995. Hillslope erosion component. In: Flanagan, D.C., Nearing, M.A. (Eds.), WEPP: USDA-Water Erosion Prediction Project. NSERL Report, vol. 10. USDA ARS, Lafayette, IN, pp. 11.1–11.12.

Freeman, T.G., 1991. Calculating catchment area with divergent flow based on a regular grid. Comput. Geosci. 17, 413–422.

Gandolfi, C., Bischetti, G.B., 1997. Influence of the drainage network identification method on geomorphological properties and hydrological response. Hydrol. Process. 11, 353–375.

Garbrecht, J., Martz, L.W., 1995. Advances in automated landscape analysis. Proc. First International Conference on Water Resources Engineering. American Society of Civil Engineers, San Antonio, pp. 844–848.

Garbrecht, J., Martz, L.W., 1997. The assignment of drainage direction over flat surfaces in raster digital elevation models. J. Hydrol. 193, 204–213.

Garcia Lopez, M.J., Camarasa, A.M., 1999. Use of geomorphological units to improve drainage network extraction from a DEM. Int. J. Appl. Earth Obs. Geoinf. 1 (3/4), 187–195.

Gardiner, V., 1995. Channel networks: progress in the study of spatial and temporal variations of drainage density. In: Gurnell, A., Petts, G.E. (Eds.), Changing River Channels. Wiley, New York, pp. 65–85.

Giordano, A., Bonfils, P., Briggs, P., Menezes de Sequiera, E., Roquero de Laburu, C., Yassoglou, N., 1991. The methodological approach to soil erosion and important land resources evaluation of the European Community. Soil Technol. 4, 65–77.

Gisotti, G., 1983. Geologia e pedologia nell'assetto del territorio. Edagricole, Bologna.

Graham, S.T., Famiglietti, J.S., Maidment, D.R., 1999. Five-minute, 1/2, and 1 degree data sets of continental watersheds and river networks for use in regional and global hydrologic and climate system modelling studies. Water Resour. Res. 35, 583–587.

Gregory, K.J., 1976. Drainage networks and climate. In: Derbyshire, E. (Ed.), Geomorphology and Climate. Wiley, Chichester, pp. 289–315.

Gregory, K.J., Gardiner, V., 1975. Drainage density and climate. Z. Geomorphol. 19, 287–298.

Gupta, V.K., Waymire, E., 1989. On the formation of an analytical approach to hydrologic response and similarity at the basin scale. J. Hydrol. 65, 98–123.

Hack, J.T., 1957. Studies of longitudinal stream profiles in Virginia and Maryland. U. S. Geol. Surv. Prof. Pap., 294-B.

Horton, R.E., 1945. Erosional development of streams and their drainage density: hydrophysical approach to quantitative geomorphology. Geol. Soc. Amer. Bull. 56, 275–370.

Howard, A.D., 1997. Badland morphology and evolution: interpretation using a simulation model. Earth Surf. Processes Landf. 22, 211–227.

Hutchinson, M.F., Dowling, T.I., 1991. A continental hydrological assessment of a new grid-based digital elevation model of Australia. Hydrol. Process. 5, 45–58.

Ibbit, R.P., Willgoose, G.R., Duncan, M., 1999. Channel network simulation models compared with data from Ashley River (New Zealand). Water Resour. Res. 35 (12), 3875–3890.

Jenson, S.K., 1991. Application of hydrologic information automatically extracted from digital elevation models. Hydrol. Process. 5 (1), 31–44.

Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogramm. Eng. Remote Sensing 54 (11), 1593–1600.

Kirkby, M.J., 1980. The stream head as a significant geomorphic threshold. In: Coates, D.R., Vitek, J.D. (Eds.), Thresholds in Geomorphology. Allen and Unwin, Winchester, MA, pp. 53–73.

Kirkby, M.J., 1986. A two-dimensional simulation model for slope and stream evolution. In: Abrahams, A.D. (Ed.), Hillslope Processes. Allen and Unwin, London, pp. 203–222.

Kirkby, M.J., 1987. Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development. Catena, Suppl. 10, 1–14.

Kirkby, M.J., 1994. Thresholds and instability in stream head hollows: a model of magnitude and frequency for wash processes. In: Kirkby, M.J. (Ed.), Process Models and Theoretical Geomorphology. Wiley, Chichester, pp. 295–314.

Kirkby, M.J., 1999. Definition and practical demonstration of a preoperational system for desertification monitoring in the Mediterranean Basin based on remote sensing methods. First Annual Report, MODEM, JRC, SAI EMAP, Ispra (Va), Italy.

Kwabena, O.A., 2000. Approaches to continental scale river flow routing. PhD thesis, The University of Texas, Austin.

Mackay, S.D., Band, L.E., 1998. Extraction and representation of nested catchment areas from digital elevation models in lake-dominated topography. Water Resour. Res. 34, 897–901.

Madduna Bandara, C.M., 1974. Drainage density and effective precipitation. J. Hydrol. 21, 187–190.

Maidment, D.R., 1996. GIS and hydrologic modeling: an assessment of progress. Third International Conference on GIS and Environmental Modeling, Santa Fe, New Mexico. http://www.sbg.ac.at/geo/idrisi/gis_environmental_modeling/program.html.

Mark, D.M., 1988. Automatic detection of drainage networks from digital elevation models. Cartographica 21 (2/3), 168–178.

Martz, L.W., Garbrecht, J., 1998. The treatment of flat areas and depressions in automated drainage analysis of raster digital elevation models. Hydrol. Process. 12, 843–855.

Melton, M.A., 1957. An analysis of the relations among elements of climate, surface properties and geomorphology. Dept. Geol., Columbia Univ. Tech. Rep. 11, Proj. NR 389-042, Off. of Nav. Res., New York.

Moglen, G.E., Eltahir, E.A.B., Bras, R.L., 1998. On the sensitivity of drainage density to climate change. Water Resour. Res. 34, 855–862.

Montgomery, D.R., Dietrich, W.E., 1989. Source areas, drainage density, and channel initiation. Water Resour. Res. 25, 1907–1918.

Montgomery, D.R., Dietrich, W.E., 1992. Channel initiation and the problem of landscape scale. Science 255, 826–830.

Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resour. Res. 30, 1153–1171.

Morgan, R.P.C., 1993. Soil erosion assessment. In: ESSC-CSEI (Ed.), Workshop on Soil Erosion in Semi-Arid Mediterranean Areas, Taormina, Italy, pp. 3–17.

Morisawa, M., 1985. Rivers: Form and Process. Longman, New York. 222 pp.

Nixon, S., Grath, J., Bogestrand, J., 1998. Eurowaternet. The European Environment Agency's monitoring and information network for inland water resources. European Environment Agency, Technical Report no. 7, Copenhagen. 47 pp.

O'Callaghan, J.F., Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Comput. Vis. Graph. Image Process. 28, 323–344.

O'Donnell, G., Nijssen, B., Lettenmaier, D.P., 1999. A simple algorithm for generating streamflow networks for grid-based, macroscale hydrological models. Hydrol. Process. 13, 1269–1275.

Oguchi, T., 1997. Drainage density and relative relief in humid steep mountains with frequent slope failure. Earth Surf. Processes Landf. 22, 107–120.

Prosser, I.P., Dietrich, W.E., 1995. Field experiments on erosion by overland flow and their implication for a digital terrain model of channel initiation. Water Resour. Res. 31, 2867–2876.

Quinn, P.F., Beven, K.J., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. Hydrol. Process. 28, 328–344.

Quinn, P.F., Beven, K.J., Lamb, R., 1995. The lna/tanβ index: how to calculate it and how to use it within the TOPMODEL framework. Hydrol. Process. 9, 161–182.

Rinaldo, A., Dietrich, W.E., Rigon, R., Vogel, G.K., Rodriguez-Iturbe, I., 1995a. Geomorphological signatures of varying climate. Nature 374, 632–634.

Rinaldo, A., Rigon, R., Vogel, G.K., Rodriguez-Iturbe, I., 1995b. Can one gauge the shape of a basin? Water Resour. Res. 31, 1119–1127.

Roth, G., La Barbera, P., Greco, M., 1996. On the description of the basin effective drainage structure. J. Hydrol. 187, 119–135.

Saunders, W., 1999. Preparation of DEMs for use in environmental modeling. Proc. International ESRI User Conference, 24–30 July 1999, San Diego, California. http://www.gis.esri.com/library/userconf/proc99/proceed/papers/pap802/p802.htm.

Smith, T.R., Bretherton, F.P., 1972. Stability and the conservation of mass in drainage basin evolution. Water Resour. Res. 8, 1506–1529.

Soille, P., 2002. Advances in the analysis of topographic features on discrete images. Lect. Notes Comput. Sci. 2301, 175–186.

Strahler, A.N., 1952. Hypsometric (area–altitude) analysis of erosional topography. Geol. Soc. Amer. Bull. 63, 1117–1142.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Am. Geophys. Union Trans. 38, 913–920.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: Chow, V.T. (Ed.), Handbook of Applied Hydrology. McGraw-Hill, New York, pp. 4.39–4.76.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res. 33, 309–319.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1989. Scaling and elevation in river networks. Water Resour. Res. 25, 2037–2051.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1991. On the extraction of channel networks from digital elevation data. Hydrol. Process. 5 (1), 81–100.

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1992. A physical basis for drainage density. Geomorphology 5, 59–76.

Terres, J.-M., 2000. The crop growth monitoring system implemented by the JRC/ARIS unit for the information needs of the EC DG VI—Agriculture. In: Conese, C., Falchi, M.A. (Eds.), Proceedings of the 7th International Congress for Computer Technology in Agricultural Management and Risk Prevention, 15th–18th November 1998, Florence, Italy Supplemento agli Atti dei Georgofili, pp. 225–230.

Thornthwaite, C.W., 1931. The climates of North America according to a new classification. Geogr. Rev. 21, 633–655.

Toy, T.J., 1977. Hillslope form and climate. Geol. Soc. Amer. Bull. 88, 16–22.

Tucker, G.E., Bras, R.L., 1998. Hillslope processes, drainage density, and landscape morphology. Water Resour. Res. 34, 2751–2764.

Tucker, G.E., Slingerland, R.L., 1996. Predicting sediment flux from fold and thrust belts. Basin Res. 8, 329–349.

Tucker, G.E., Slingerland, R.L., 1997. Drainage basin responses to climate change. Water Resour. Res. 33, 2031–2047.

Tucker, G.E., Gasparini, N.M., Lancaster, S.T., Bras, R.L., 1997. An integrated hillslope and channel evolution model as an investigation and prediction tool. Technical Report prepared for U.S. Army Corps of Engineers Construction Engineering Research Laboratories.

Van Zuidam, R.A., Van Zuidam-Cancelado, F.I., 1979. Terrain analysis and classification using aerial photographs: a geomorphological approach. ITC Textbook of Photointerpretation. Int. Inst. for Aerospace Surv. and Earth Sci., ITC, Enschede, The Netherlands. 333 pp.

Verdin, K.L., Jenson, S.K., 1996. Development of continental scale DEMs and extraction of hydrographic features. Third International Conference/Workshop on Integrating GIS and Environmental Modeling. January 21–25, 1996 Santa Fe, New Mexico, USA. http://www.sbg.ac.at/geo/idrisi/gis_environmental_modeling/program.html.

Vogt, J.V., Somma, F. (Eds.), 2000. Drought and Drought Mitigation in Europe. Kluwer Academic Publishers, Dordrecht. 325 pp.

Vogt, J.V., Kennedy, P., Folving, S., 1999. European watershed characterisation and modelling. Summary and Conclusions of the Expert Meeting on 14th and 15th July 1999. European Commission, JRC Ispra, 23 pp., http://www.eurolandscape.jrc.it.

Walker, J.P., Willgoose, G.R., 1999. On the effect of DEM accuracy on hydrology and geomorphology models. Water Resour. Res. 357, 2259–2268.

Wang, X., Yin, Z.-Y., 1998. A comparison of drainage networks derived from digital elevation models at two scales. J. Hydrol. 210, 221–241.

Warntz, W., 1975. Stream ordering and contour mapping. J. Hydrol. 25, 209–227.

Willgoose, G.R., Bras, R.L., Rodriguez-Iturbe, I., 1991. A physical explanation of an observed link area–slope relationship. Water Resour. Res. 27, 1697–1702.

Wilson, L., 1971. Drainage density, length ratios, and lithology in a glaciated area of southern Connecticut. Geol. Soc. Amer. Bull. 82, 2955–2956.

Wolock, D.M., Price, C.V., 1994. Effects of digital elevation model map scale and data resolution on a topography based watershed model. Water Resour. Res. 30, 1665–1680.

Zhang, W., Montgomery, D.R., 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. Water Resour. Res. 30, 1019–1028.