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Deriving river networks and catchments at the European scale from medium resolution digital elevation data

Roberto Colombo [a,*], Jürgen V. Vogt [b], Pierre Soille [b], Maria L. Paracchini [b], Alfred de Jager [b]

[a] *Dip. di Scienze dell'Ambiente e del Territorio, Università degli Studi Milano-Bicocca, Piazza della Scienza, 1, 20126 Milano — Italy*
[b] *European Commission, DG Joint Research Centre, Institute for Environment and Sustainability,*
Via Enrico Fermi, 1, 21020 Ispra (Varese) — Italy

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Abstract

The extraction of drainage networks and catchment boundaries from digital elevation models (DEMs) has received considerable attention in recent years and is recognized as a viable alternative to traditional surveys and the manual evaluation of topographic maps. However, most studies have covered limited areas due to the lack of detailed information and/or the lack of highly efficient algorithms. In this paper we present an application that delineates river networks and catchment boundaries across the European continent from a medium resolution (250 m) DEM. We exploit novel algorithms based on the concepts of mathematical morphology and implement a landscape stratification for drainage density.

A flow direction grid is computed using an efficient algorithm for the removal of spurious pits. River networks are then derived by imposing a variable threshold for the minimum contributing area needed to form and maintain a channel. This is achieved through a landscape stratification that reflects the ability of the terrain to develop different drainage densities. It is shown that the analysis of environmental characteristics coupled with the analysis of local slope versus contributing area enables river network mapping with a spatially varying drainage density. The result has been validated by comparing the derived data to digital river and catchment data from other sources and with varying scales of observation.

Keywords: Digital elevation model; Automatic extraction of river networks; Continental analysis; Drainage density; Landscape stratification

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1. Introduction

Digital data on rivers and their drainage basins are increasingly recognized as an important pre-requisite for environmental monitoring and management at scales ranging from individual catchments to entire continents. At the European scale, structured flow networks and related catchment boundaries are necessary for environmental monitoring and modelling both by public organisations and research networks. Examples of such applications are the modelling of nitrate loads in large international river basins or even across the entire continent. Flood prediction is another application which requires consistent flow networks as well as knowledge of the limits of the associated catchments for an accurate modelling of water transport across the entire network.

The necessary digital river networks and catchment limits are, however, not readily available. Existing data are often available at large cartographic scales and therefore cover only limited areas. In addition, these datasets do not represent coherent flow networks but are rather digital cartographic products. For example, European digital river data are available at map scales between 1:10,000,000 and 1:1,000,000 (e.g., GISCO—http://europa.eu.int/eurostat.html; Bartholomew—http://www.bartholomewmaps.com). Consequently, these data are of limited use for more detailed assessments (e.g., analysis of the quantity/quality of water resources, assessment of environmental pressures and impacts).

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* Corresponding author. Fax: +39 02 64 48 28 95.
E-mail address: roberto.colombo@unimib.it (R. Colombo).

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Recently, digital elevation models (DEMs) have received considerable attention for the extraction of drainage networks and catchments boundaries at global to continental scales (e.g., Graham et al., 1999; Döll and Lehner, 2002). Extraction techniques require the computation of local slope, flow direction, and contributing area for each grid cell, and pose specific challenges for their accurate computation over flat areas. Outputs from these computations are flow direction and flow accumulation matrices. Finally, the so-called contributing drainage area (CDA) threshold needs to be determined. This threshold represents the minimum contributing area needed to form and maintain a channel.

Considerable effort is required to establish an appropriate CDA threshold for channel initiation at continental scales and therefore river networks are generally derived by imposing a single threshold over the entire area (e.g., Hutchinson and Dowling, 1991; Verdin and Jenson, 1996; Oki and Sud, 1998; Graham et al., 1999; Renssen and Knoop, 2000; Döll and Lehner, 2002). This practice results in a drainage density that does not reflect the real degree of dissection (e.g., Dietrich and Dunne, 1993; Montgomery and Foufoula-Georgiou, 1993).

Since medium to coarse DEM cell sizes (e.g., 250 m to 1000 m) do not allow resolving detailed topographic features such as hollows, low-order channels, and hillslope characteristics, the resulting first order channels cannot be directly related to the field processes that form it (e.g., Dietrich et al., 1993; Zhang and Montgomery, 1994). The geomorphic processes acting in a catchment, however, are a function of a set of environmental characteristics (e.g., climate, terrain morphology, vegetation cover, soils, lithology, and rock uplift rates) and this, in turn, determines different values of drainage densities (e.g., Tarboton et al., 1991; Montgomery and Dietrich, 1992; Dietrich et al., 1993; Tucker and Bras, 1998; Tucker et al., 2001; Vogt et al., 2003a,b). Geomorphic processes shape terrain with variable intensity in different environments and, as a consequence, the functional relationship between these processes and the drainage density changes from one landscape to another (e.g., Melton, 1957; Dietrich et al., 1992; Kirkby, 1994; Gardiner, 1995; Howard, 1997; Oguchi, 1997; Moglen et al., 1998; Tucker and Bras, 1998). In other words, drainage density reflects the combined action of several environmental factors acting over geological time.

In order to account for this spatial variation in drainage density, a series of studies highlighted the need to apply variable CDA thresholds for mapping river networks from DEMs (e.g., Garbrecht and Martz, 1995; Garcia Lopez and Camarasa, 1999; Colombo et al., 2001; Vogt et al., 2003a,b).

Motivated by the need to derive river networks for the entire European continent, we exploited efficient processing algorithms based on the concepts of morphological image analysis. A detailed description of these algorithms is given in Soille et al. (2003), whereas this paper focuses on the implementation of the CCM River and Catchment Database for Europe. We present a method for the derivation of pan-European river networks and associated catchments using a DEM with a 250 m grid cell size. Since Europe is characterised by its environmental complexity over short distances with geomorphic processes acting on complex landscape patterns, we present a landscape stratification that reflects regions with variable drainage density.

2. Methodology

In Sections 2.1 and 2.2, we explain how we delineated the landscape classes and how we derived the corresponding contributing area thresholds. In Section 2.3 we present the developed methods for the extraction of the river networks and catchment boundaries.

2.1. European landscape stratification

The rationale for implementing a landscape stratification is to overcome the shortcomings of using a single CDA threshold for an extended area. In this context we assume that few basic environmental factors exert a strong control on the channel initiation process and, therefore, on the development of the valley network. The objective is to classify the European area in different landscape types that reflect regions with variable degrees of drainage density.

The landscape classification has been implemented by improving the parametric model described in Colombo et al. (2001) and Vogt et al. (2003a). The proposed approach is based on the hypothesis that a set of five variables (annual rainfall, local relief, vegetation cover, soil transmissivity, and bedrock erodibility/lithology) represents and quantifies the environmental factors governing drainage density. The input data used to derive the landscape classification (CORINE land cover, European soil database, annual rainfall data) are available for large parts of the European continent and have been described in more detail in Vogt et al. (2003a,b). The individual layers were combined using a simple scoring technique, where each environmental variable receives a score depending on its value. The sum of all scores determines an index, called Landscape Drainage Density Index (LDDI). We then assume that regions with a given index value have a similar drainage density, the higher the index, the higher the drainage density. Although it has been widely applied in different disciplines (e.g. Barredo et al., 2000) and it is considered to be a reasonable solution for separating areas with different environmental characteristics, this practical approach is based on semi-empirical concepts. Moreover, it is particularly useful at small cartographic scales, where the lack of detailed data impedes the use of deterministic models for channel initiation. Further analysis within index classes allowed us to define a critical contributing drainage area, which is then used as a proxy for drainage density.

In order to develop a simplified parametric model for the continental landscape stratification, we formalised the relationships between drainage density and environmental parameters through a set of scores (Table 1). The established relationships (and resulting scores) are based on published

Table 1
Classes of environmental variables and corresponding scores for each class as used in the calculation of the landscape stratification at pan-European level

Class-code	Environmental variable		Score	
	Class	Description		
Annual precipitation [mm]				
			(1)	(2)
1	<250	Arid to semiarid	1	1
2	250–500	Semiarid to Humid	8	2
3	500–750	Humid	4	3
4	750–1000	Very humid	3	4
5	>1000	Wet	2	8
Relative relief in a 500 × 500 cell [m]				
1	<5	Almost flat	–	
2	5–50	Undulating sloping	2	
3	50–200	Rolling to hilly steep	3	
4	200–500	Hilly very steep	4	
5	>500	Mountainous	8	
Bedrock erodibility [–]				
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 [m ^{2}/day]				
1	<1.0	Very low	8	
2	1.1–3.0	Low	4	
3	3.1–6.0	Medium	3	
4	6.1–9.0	High	2	
5	>9.1	Very high	1	

(1) With vegetation cover >25%; (2) With vegetation cover <25%.

results from field studies and model simulations, predicting drainage density from a-priori knowledge of the main hillslope processes. The most important considerations underlying the scoring system are provided below.

The existence of two distinct relationships between rainfall-regime and drainage density has been described by Madduna Bandara (1974), Gregory and Gardiner (1975), and Moglen et al. (1998). These relationships reflect the fact that the degree of vegetation cover can reduce the impact of precipitation and indirectly modulates surface resistance, soil transmissivity, and hillslope processes. Consequently, we positively relate annual rainfall with drainage density when the vegetation cover is less than 25%, independently of the amount of rainfall. When vegetation cover exceeds 25%, however, annual rainfall is positively related to drainage density up to a threshold of 500 mm/year only, above which the relationship becomes negative.

The influence of the terrain morphology has been considered through the relative relief energy, defined as the maximum altitude difference in a moving window of 3 by 3 grid cells (Roth et al., 1996; Oguchi, 1997). The relationship between relief energy and drainage density was set as positive for all environments, although it has been found to depend on the prevailing type of hillslope processes combined with climate conditions and channelization stage (Schumm, 1956; Kirkby, 1987; Montgomery and Dietrich, 1989; Montgomery and Dietrich, 1992; Oguchi, 1997; Howard, 1997; Tucker and Bras, 1998; Tailing and Sowter, 1999; Lin and Oguchi, 2004).

Wilson (1971), Day (1980), Morisawa (1985) and Gardiner (1995), showed that higher drainage densities are generally associated with impermeable rocks, even though differences become less pronounced with higher mean annual precipitation (Day, 1980). In this study, the role played by the structure of the underlying rock was reduced to the effect of the type of lithology as a surrogate for soil erodibility. From the European Soil Database (ESBSC, 1998) the dominant lithology was initially extracted and then the rock erodibility scale proposed by Gisotti (1983) was adopted to scale the highest erodibility to unconsolidated clastic rocks and the lowest erodibility to igneous rocks.

Finally, drainage density generally increases with decreasing infiltration capacity of the underlying bedrock and/or decreasing transmissivity of the soil (Morisawa, 1985). Saturated soil transmissivity was calculated as the product of saturated conductivity and total soil thickness (e.g., Montgomery and Dietrich, 1994). Both values were derived from the European Soil Database. Saturated conductivity was assumed not to vary with depth beneath the surface and was inferred indirectly from soil texture (e.g. Morgan et al., 1984; Foster et al., 1995).

Each environmental factor has been classified into five classes and to each class a score has been assigned, with higher scores indicating a greater aptitude to develop drainage channels (Table 1).

The LDDI was then computed as the sum of the different scores for each grid cell and it was reclassified into ten classes (i.e. *1*: 5–7; *2*: 8–10; *3*: 11–12; *4*: 13–14; *5*: 15–16; *6*: 18–19; *7*: 20–21; *8*: 22–23; *9*: 24–26; *10*: 27–29) (Fig. 1).

In practice, the number of classes increases with the environmental complexity of the study area. For example, rather than the five classes described for the Italian case in Vogt et al. (2003a), we needed ten classes for the European continent in order to capture its higher complexity. The number of landscape classes to some degree depends on subjective judgement, which indicates that the methodology could be improved by implementing a continuously varying threshold, depending on the LDDI and not related to specific landscape classes. This is, however, difficult to achieve, since the derivation of the relationship between local slope and contributing area requires a sample of pairs which need to be related to a geographical entity.

The derived European landscape stratification appears to be mainly affected by relief and geology. A visual comparison between the derived map and external data shows that the regions with low LDDI values are mainly located in the Pannonian basin, the Northern European plains and the Fenno-Scandian shield, while intermediate values correspond to Hercinian ranges and the highest values are found in the Pyrenean and Alpine regions.

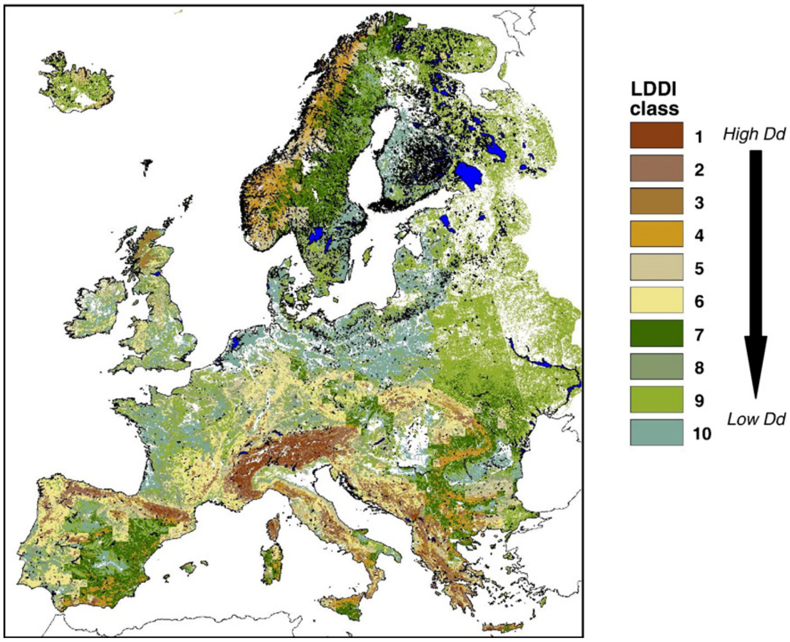

Fig. 1. Landscape stratification for drainage density derived from the simple scoring technique. Europe is classified into ten classes characterised by different degrees of dissection. White areas correspond to flat or impervious surfaces.

Areas for which channel initiation could be considered as extremely improbable were not included in the stratification procedure. In particular, all areas with a local slope of less than 2% were excluded. Urban areas, marshes, lakes, lagoons, and glaciers were considered as impervious surfaces, where no new channels start.

2.2. Threshold definition

For each landscape class a critical contributing area was determined by interpreting the diagram of local slope versus contributing area. The definition of adequate thresholds has been the subject of several studies and often thresholds are established by comparing the derived network with a reference network obtained from digitising blue lines at large scales (Montgomery and Dietrich, 1988). Many efforts have been made to infer an adequate threshold by using the log–log linear relationship between local slope and contributing area as computed from DEMs. Different inflection points can be observed in the log–log plot derived from high-resolution DEMs and many studies suggest that these enable the distinction between various geomorphic and hydrologic regimes (e.g., Tarboton, 1991; Montgomery and Foufoula-Georgiou, 1993; Willgoose, 1994; Montgomery and Dietrich, 1994; Ijjasz-Vasquez and Bras, 1995; Tucker and Bras, 1998; Ibbit et al., 1999; McNamara et al., 1999; Montgomery, 2001; Whipple and Tucker, 2002; Hancock, 2005). Thresholds derived from the log–log analysis of coarser resolution DEMs (250 to 1000 m grid cell size) and their usefulness for deriving river networks at medium to small scales have, for example, been explored by Wolock and Price (1994), Walker and Willgoose (1999), and Ibbit et al. (1999).

For the log–log analysis, local slope and contributing areas were computed using the $D\infty$ algorithm (Tarboton, 1997), which allows for flow dispersion. The log–log plot of local slope versus contributing area was then generated from a random sample of grid-cells for each of the ten LDDI classes. Random samples were taken using the 'Statistics-Generate Random Sample' routine implemented in the ENVI software package and were further analysed with dedicated C routines developed in-house. The number of samples varied between 40,000 and 1,000,000 (see Table 2), depending on the areal extent of the individual LDDI classes. Subsequently,

Table 2
Area and number of random samples per landscape class

Landscape class	Class area (km^2)	Class area (%)	Random samples (number)	Random samples (%)	Random samples (% of class area)
1	88,913	1.98	42,760	1.20	3.0
2	241,440	5.37	128,094	3.60	3.3
3	104,839	2.33	58,238	1.64	3.5
4	250,372	5.57	246,445	6.93	6.2
5	349,334	7.77	281,110	7.91	5.0
6	564,183	12.54	292,219	8.22	3.2
7	600,105	13.34	572,809	16.11	6.0
8	426,103	9.47	284,348	8.00	4.2
9	1,139,173	25.33	1,064,427	29.94	5.8
10	732,831	16.29	584,453	16.44	5.0
Total	4,497,292	100.00	3,554,903	100.00	n.a

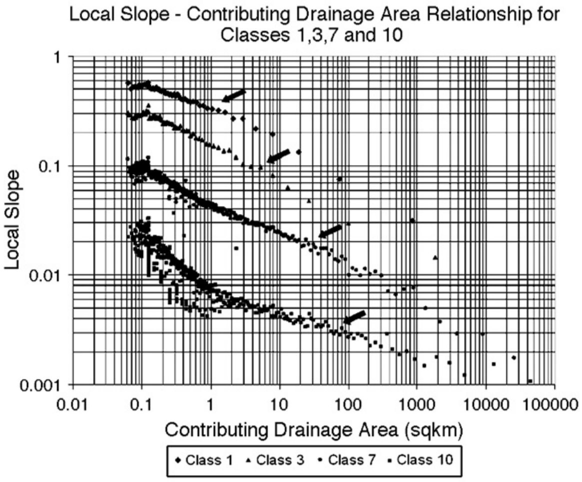

Fig. 2. Local slope versus contributing drainage area relationship for classes 1, 3, 7 and 10 shown in Fig. 1. Each point represents the average of 600 (classes 1 and 3) or 800 (classes 7 and 10) original samples. Arrows indicate breakpoints related to the Critical Contributing Drainage Area.

samples were aggregated by binning 600 or 800 samples and calculating the average and standard deviation for each bin.

In Fig. 2, the graphs of the local slope–contributing drainage area relationship are shown for four out of the ten LDDI classes at the continental scale. The graphs of the remaining classes show a similar relationship. In general, three sections with different scaling responses can be distinguished in each graph. A trend towards increasing slope can be observed in the first section. This part of the graph ends with a gradient change at a contributing drainage area of about 0.15 km^2 for all classes. The second section of the graph is characterised by constantly decreasing slopes. With increasing class number, the shape of the graph appears more similar to the typical form having a steeper curve at the beginning of section two, which then flattens off before the slope of the graph slightly increases again to approach a theoretical straight line with a slope around '-0.5'. This latter (straight) part of the graph characterises Section 3, which is the so-called fluvial scaling line that represents areas of predominant fluvial transport. The point where the slope of the graph starts to increase again is defined as the breakpoint between sections two and three. This point is varying in its position along the x-axis with an increasing contributing drainage area from class one to class ten. It enables the definition of different critical contributing drainage areas for our landscape classes. Even though there is a certain uncertainty in the exact determination of the breakpoint, the apparent shift of this point is in agreement with our hypothesis that the landscape classes represent areas of different drainage density. It is difficult to make any further physical interpretations of these plots and more efforts are needed to better understand the process "fingerprints" in the slope–area relationship derived from coarse spatial resolution DEMs.

These final inflection points have been selected by visual inspection of the different graphs and they are considered to be the critical contributing area for each landscape class at the given spatial resolution. The resulting thresholds per landscape class are shown by the arrows in Fig. 2 and given for all classes in Table 3.

2.3. Detection of river networks and catchment boundaries

The primary DEM-hydrological quantities (local slope, flow direction, and contributing area) were derived by a suite of algorithms based on the concepts of morphological image analysis (Soille, 2003) and described in detail in Soille et al. (2003). These algorithms remove spurious pits efficiently by carving into the DEM. The carved DEM was the input for an adaptive drainage enforcement process that creates a more precise flow direction path in flat terrain (Soille et al., 2003). This adaptive stream burning algorithm uses as input selected segments of a reference river network and, by an iterative process, defines the places where the reference network deviates substantially from the automatically detected river networks. While stream burning can itself create some artifacts (e.g., Saunders, 1999), this procedure ensures that rivers are burned only where necessary. It also reduces co-registration problems that may produce double streams and alleviates discrepancies in the level of scale or generalisation between the DEM and the external streamlines that may lead to the removal or creation of features such as meanders.

By providing information on the position of lakes, coastal lagoons, estuaries, intertidal flats and glaciers, the algorithms produce a flow direction that is consistent with these water classes. For the classes connected to the sea (coastal lagoons, estuaries, intertidal flats), the flow direction is terminated at their border (i.e., before reaching the sea), while in all other cases the flow path is always connected to the sea (i.e., continuing through the lakes). This allows deriving a fully connected and hierarchically structured river network, which is coherent with lakes and the other mentioned water types. CORINE Land Cover vector data (CEC, 1993) were used as the main data source to obtain water-related classes.

In order to arrive at a realistic drainage density, the contributing drainage area threshold for each landscape class was applied in the course of this process. Using the described

Table 3
Contributing drainage area (CDA) threshold per landscape class

Landscape class	CDA threshold (km^2)
1	1
2	3
3	6
4	15
5	20
6	30
7	35
8	50
9	60
10	80

algorithms, the processing of continental Europe (about 350 Mb) on a 2 GHz personal workstation equipped with 4 Gb of random access memory can be achieved in less than an hour without tiling the DEM.

Once the river network is defined, catchment boundaries are delimited by automatically identifying all outlet points (confluences, lake inflows, sea outlets) in the drainage network and building the catchment for each outlet point from the flow direction grid. Rivers are further ordered according to the Strahler system (Horton, 1945; Strahler, 1952, 1957), which introduces a hierarchy into the river and catchment system. In the current system, the Strahler hierarchy arrives at an order of eight, for example for the Danube and the Rhône while, for example, the Po, Rhine, Ebro, Douro, and Garonne rivers belong to the 7th Strahler order.

A vector database was finally generated from the river network and catchment grids. A further correction was introduced in the case of sub-basins intersecting lakes. These were recalculated so that the outlet of each basin lies along the lake perimeter. Tests in alpine areas showed that the overestimation of sub-catchment areas without this correction could be as large as 10%.

The resulting continental map of river networks together with the major (highest order) drainage basins is shown in Fig. 3. Fig. 4 shows a more detailed view of the river network in southern Germany which illustrates the variability in drainage density.

3. Validation

The resulting drainage density was evaluated with respect to the drainage density of reference data in order to judge the landscape stratification. The accuracy of the river network and catchment boundaries (positioning, length, area) was validated based on reference data in order to judge the geometric qualities of the result. In order to do so, qualitative and quantitative comparisons with a series of independent datasets such as existing digital river datasets, catchment boundaries and information on catchment size were performed. Drainage density and the river network validation analysis was performed on selected areas in Germany, based on a digital river dataset of the German Federal Environment Agency (Umweltbundesamt, UBA) as the reference. For the catchment boundaries, digital reference data was obtained from the Spanish Centro de Estudios Hydrograficos, the Finnish Environment Institute as well as publicly available information on large river basins. Data for Germany, Spain and Finland corresponded to mapping scales of 1:50,000 to 1:100,000. For the validation of catchment size, a large sample was drawn from the EEA Eurowaternet station database and was used in addition to publicly available information on the size of large river basins.

Fig. 3. The derived European river network and large river basins.

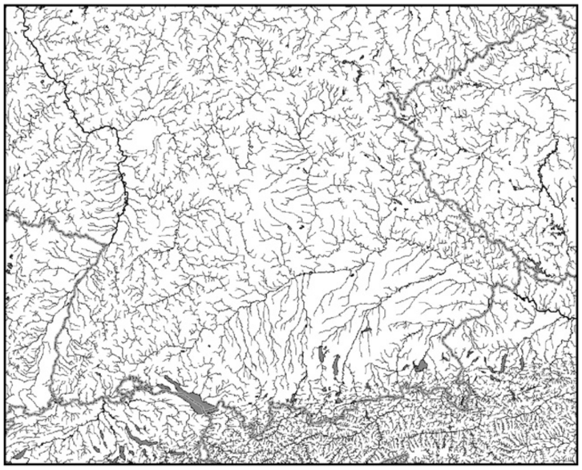

Fig. 4. Example of the derived river network for southern Germany, showing the variation in drainage density according to the landscape classes.

3.1. Drainage density

The drainage densities calculated from the digital river network of Germany (UBA) and from our river network were comparable. Fig. 5 presents the drainage density derived for each class of the landscape stratification in Germany. Due to the difference in scale, the absolute values between the two datasets are different. This difference was expected because drainage density is dependent on the mapping scale. The drainage density from the DEM derived river networks is underestimated with respect to the reference and the magnitude of the relative differences changes across classes. However, the general tendency and their correlation were considered as a qualitative proof that the landscape stratification can reproduce the natural variation in drainage density.

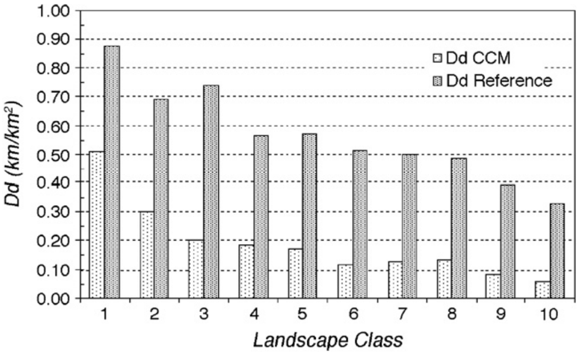

Fig. 5. Comparing the drainage density of the reference dataset to the drainage density of the derived CCM dataset.

3.2. River length and area for large drainage basins

The validation of derived catchment sizes against published catchment sizes is a standard analysis technique for continental and global datasets (Hutchinson and Dowling, 1991; Verdin and Jenson, 1996; Oki and Sud, 1998; Graham et al., 1999; Renssen and Knoop, 2000; Döll and Lehner, 2002). Catchment area and river length were compared to reference values collected from the above-mentioned sources as well as from publications and web pages of local water authorities. For each catchment or river, the error (discrepancy) was computed by subtracting the predicted value from the reference value and dividing by the reference value (catchment area or river length). The comparison between derived catchment area and reference area for 48 large drainage basins showed an average discrepancy of 3.4% (±4.6%).

The validation of the river length was done based on 45 rivers by manually selecting the corresponding headwater cells on the CCM river network and computing the flow length to the sea for each starting node. The extracted flow paths were underestimated with an average error of about 10% (±8.0%) with respect to the official length of the actual river. While the inclusion of estuaries and deltas in the official values can be a source of discrepancy, the main reason for the underestimation is probably due to the generalisation caused by the grid cell size (missing meanders, late starting of headwaters).

Furthermore, the Modelling Efficiency (ME) (Nash and Sutcliffe, 1970) was calculated in order to quantify the degree of correspondence between derived rivers and catchments and the reference datasets. The ME was found to be 0.99 for both the river lengths and catchment areas, indicating a good fit to the 1:1 line.

3.3. Catchment boundaries

Kenward et al. (2000), using a high resolution DEM, pointed out that despite similar drainage areas, catchment boundaries may differ considerably between reference and DEM-derived data. For this reason an overlay analysis was carried out for Spain and Finland in order to quantify the effect of possible catchment boundary differences (over- and under-estimation) that can cancel each other out. In order not to consider errors generated by mis-registration, differences within a buffer of 500 m along the catchment boundaries were not considered. This comparison provided a more realistic measure of the spatial discrepancy between the boundaries of the reference catchments and the CCM catchments. This validation was done for Finland, a country with low relief energy and a complex drainage system with many lakes, and for Spain, a country characterised by more accentuated relief. The discrepancy in the catchment boundaries (measured as the deviation in area along the catchment perimeter) was found to be of a magnitude of 10% (±6.1%) for Finland and of 5% (±3%) for Spain.

3.4. Comparison with Eurowaternet catchment areas

Finally, data from the Eurowaternet station network (EWN) of the European Environment Agency were used to validate the size of the derived catchments.

A total of 1944 river stations were available for validation purposes and for each station, information on its position (co-ordinates) as well as a series of attributes, including the drainage area, was available (Nixon et al., 1998; Boschet et al., 2000). For each station, which could be positioned on the CCM River network, the corresponding catchment was delineated and its size compared to the official size as reported in the EWN database. Fig. 6 presents the results for 1600 stations. The average difference resulting from this comparison was 3.3% (±3.9%), and the ME was found to be 0.99.

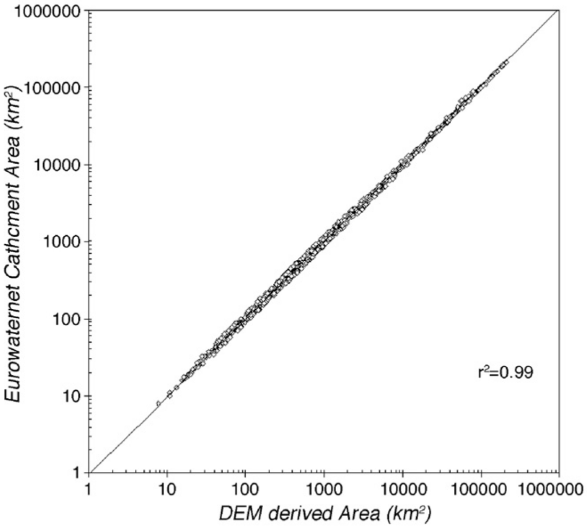

Fig. 6. Comparison between the derived catchment areas (CCM) with the reported catchment areas for 1600 Eurowaternet stations.

4. Discussion and conclusions

The methodology presented in this paper enables the analysis of large areas and the automatic derivation of river networks from medium resolution DEMs. It led to the derivation of a high quality pan-European dataset of river networks and associated catchments, useful in supporting hydrological analyses from medium to small scales. The presented database serves the immediate needs of the European Commission's Joint Research Centre and of the European Environment Agency for their European-wide monitoring and modelling activities. Currently, the database is used for research in modelling nitrate loads in rivers as well as for flood forecasting across Europe.

The development and use of a landscape stratification for drainage density is a major improvement for the modelling of river networks in areas with non uniform drainage densities. In order to produce such a landscape stratification, we applied a simple method based on a linear combination of the environmental factors that control (or have controlled) the degree of landscape dissection by running water. However, the use of scores based on expert knowledge implies subjective judgement and it is difficult to evaluate the interaction between different factors. This approach was applied for the first time in the context of drainage density at the continental scale and therefore should be considered as a first attempt, requiring further testing and development. The subsequent analysis of the local slope–contributing drainage area relationship for each landscape class enabled the definition of a variable critical contributing drainage area that reflects the natural variability in drainage density between different landscape types. The main drawback of this analysis lies in the uncertainty to define the absolute position of the breakpoints of contributing drainage area and to associate them with a physical meaning.

The fast processing of the extended DEM was possible due to the implementation of algorithms based on the concepts of morphological image analysis and piecewise correction of the resulting river network was implemented through an adaptive burning algorithm, avoiding the typical problems of double streams due to misalignment of DEM and reference networks.

Comparisons between the derived channel network and catchment boundaries with a series of independent reference data showed that river lengths were generally under-estimated with respect to their actual length, and catchment areas could differ from actual values up to about 10% in flat and complex areas.

The positioning of channel heads was limited by the grid-cell resolution of our DEM. As a consequence, our analysis led to relatively large CDA thresholds and, therefore, channel heads were placed relatively low inside the valley. Another limitation was the exact location of rivers in extended flat areas especially when no digital reference network was available for adaptive drainage enforcement. These problems will partly be overcome in the near future with the derivation of a second version of the CCM database, based on the Space Shuttle Radar Topography (SRTM) elevation data (http://srtm.usgs.gov). With these elevation data it will be possible to resolve finer details and to position channel heads more accurately. The analysis of the European-wide coverage of Landsat Thematic Mapper Images available from the Image2000 project (http://image2000.jrc.it) will provide an independent and accurate reference river network in flat areas, where the SRTM DEM is not expected to yield satisfactory results.

Version 1.0 of the CCM pan-European dataset of river networks and catchment boundaries is available at the URL http://agrienv.jrc.it/activities/catchments/ccm.html together with ancillary information on the above described methodologies.

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