Geogr. Fis. Dinam. Quat.
26 (2003), 87-96, 5 figg., 3 tabb., 1 c.

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MORPHOMETRIC ANALYSIS OF THE DRAINAGE NETWORK IN THE MODENA AND REGGIO EMILIA APENNINES (NORTHERN ITALY)

ABSTRACT: BARBIERI M. & MARCHETTI M., *Morphometric analysis of the drainage network in the Modena and Reggio Emilia Apennines (Northern Italy).* (IT ISSN 1724-4757, 2003).

This paper provides quantitative geomorphic analysis in the catchment basins of the rivers Secchia and Panaro, in the Modena and Reggio Emilia Apennines (northern Italy).

The research is based on established methods applied in several Apennine basins of central Italy. The aim of the research is to carry out a preliminary morphometric characterisation of the Emilia basins that, if supported by sample monitoring, should allow the correct management of these fluvial basins.

A Digital Elevation Model (DEM), based on contour line interpolation of the Regional Technical Maps at a 1:25,000 scale is used to calculate and extract landscape metrics. The DEM provide an objective means through which the drainage network was defined. The DEM is linked to a cartographic database, that spatially coordinates the calculation of metrics including: Frequency of channels (F), Length of channels (L), Area of catchment basins (A), Ratio between area and length, Drainage density (D). From these basic metrics the following ratios and indexes have been derived: Mean bifurcation ratio (Rb), Direct mean bifurcation ratio (Rbd), Bifurcation index (R), Hierarchic anomaly (Ga), Hierarchic anomaly density (ga), Hierarchic anomaly index (Δa), Extension ratio (Re), and Circularity ratio (Rc). Subsequently, hypsometric analysis was carried out and finally, on the basis of established empirical relationships, the annual unitary stream load (Tu) has been assessed.

The various parameters extracted have been compared with the lithological, structural and slope characteristics of the area, in the attempt to define the different role that the latter have played in relation to the morphodynamic evolution of the hydrographic network within the study area. The DEM has provided us with information on the type of geomorphological evolution of the basins in relation to both the structural and lithological characteristics of the area and the distribution of the prevailing modelling processes. The assessment of stream load is consistent with the scanty data experimentally measured along the main watercourses in the pre-war period.

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We wish to thank the anonymous referees for the valuable comments and suggestions. The research was supported by MIUR «COFIN 2001», Local Coordinator prof. S. Piacente and MIUR «COFIN 2002», Local Coordinator prof. M. Soldati.

KEY WORDS: Quantitative Geomorphology, Fluvial Dynamics, GIS, Modena and Reggio Emilia Apennines, Italy.

RIASSUNTO: BARBIERI M. & MARCHETTI M., *Analisi morfometrica della rete di drenaggio nell'Appennino modenese e reggiano (Italia settentrionale).* (IT ISSN 1724-4757, 2003).

Il presente lavoro tratta dell'analisi geomorfica quantitativa nell'area dell'Appennino modenese e reggiano caratterizzata dalla presenza dei bacini dei Fiumi Secchia e Panaro.

La ricerca si fonda su metodologie ampiamente validate in bacini appenninici soprattutto nelle aree dell'Italia centrale. Lo scopo della ricerca è pertanto quello di fornire una prima caratterizzazione morfometrica dei bacini emiliani, che, se supportate da monitoraggi a campione nei differenti bacini fluviali, consentono una corretta gestione degli stessi.

Attraverso algoritmi di calcolo che si basano su modelli ampiamente descritti in letteratura sono stati elaborati i dati numerici di elevazione (DEM), derivati dall'interpolazione delle curve di livello della Cartografia Tecnica Regionale alla scala 1:25,000, al fine di estrarre in modo automatico la rete di drenaggio ed i relativi bacini di competenza, dell'area appenninica afferente alle province di Modena e Reggio Emilia.

Le singole aste fluviali ed i relativi bacini sono stati indicizzati in modo univoco. Lo sviluppo di una banca dati cartografica relazionale ha permesso di estrarre, attraverso operazioni di analisi spaziale i parametri idrologici più comunemente impiegati in letteratura: Frequenza dei canali (F), Lunghezza delle aste fluviali (L), Area dei bacini (A), Rapporto tra aree e lunghezze, Densità di drenaggio (D). Da questi sono stati ricavati i più comuni rapporti e indici derivati: Rapporto di biforcazione medio (Rb), Rapporto di biforcazione diretto medio (Rbd), Indice di Biforcazione (R), Anomalia gerarchica (Ga), Densità di anomalia gerarchica (ga), Indice di anomalia gerarchica (Δa), Rapporto di allungamento (Re), Rapporto di circolarità (Rc). Successivamente è stata svolta l'Analisi Ipsometrica ed infine è stato stimato, sulla base di equazioni empiriche note in letteratura, il trasporto torbido unitario annuo (Tu).

I diversi parametri estratti sono stati confrontati con le caratteristiche litologiche, strutturali e di acclività dell'area, nel tentativo di definire il differente ruolo che queste hanno avuto nei confronti dell'evoluzione morfodinamica della rete idrografica del territorio considerato. Il DEM ha fornito indicazioni sul tipo di evoluzione geomorfologica dei bacini in relazione sia con le caratteristiche strutturali e litologiche dell'area che con la distribuzione dei processi di modellamento prevalenti. La stima del trasporto torbido risulta in linea con gli scarsi dati misurati sperimentalmente lungo le aste principali nel periodo pre-bellico.

TERMINI CHIAVE: Geomorfologia quantitativa, Dinamica Fluviale, Sistemi Informativi Territoriali, Province di Modena e Reggio Emilia.

INTRODUCTION

This paper aims to characterise the drainage network of the Modena and Reggio Emilia Apennines (northern Italy) by means of quantitative geomorphic analysis. This research procedure will allow the relationships between drainage pattern, climatic conditions and geo-structural characteristics to be assessed. This study, which was carried out by applying widely adopted research methods (Avena & Lupia Palmieri, 1969; Ciccacci & *alii*, 1981, 1988; Lupia Palmieri & *alii*, 1995, 1998, 2001), is finalised to better characterise the study area by using established empirical relationship for assessing the amount of erosional processes. These equations were proposed and repeatedly tested in the central and centre-southern Apennines by the Geomorphology researchers of the Roman school (Ciccacci & *alii*, 1981, 1983, 1987, 1988, 1992; Lupia Palmieri & *alii*, 1995, 1998, 2001). The use of this method will permit the assessment of the mean annual unit stream load. This quantity should also be calculated empirically by means of measurement gauges installed along the watercourses. We intend this study to be the first step in enterprising, in agreement with local authorities, a thorough monitoring of rivers' solid transport which might have significant improvement in the future management of the territory.

For this purpose, it should be remembered that the whole hydrographic network of the Modena and Reggio Emilia Provinces is subject to considerable erosional processes. Particularly serious is the situation in the hill areas where the deepening of the network has caused serious stability problems to the river banks and transversal hydraulic works (Pellegrini, 1969a; Bonazzi, 1998; Marchetti, 2002). For example, between 1960-1980, many bridges were damaged or destroyed (Roveri, 1960; Pellegrini, 1969a). These include the collapse of the Busana, Gatta, Rubiera and Vignola bridges and damage to the Sassuolo, Spilamberto, Falanello, Marano, San Donnino and San Damaso bridges on the Secchia and Panaro rivers. The rapid incision of the bedrock channels of these rivers was caused by widespread excavation of gravel and sand for the aggregate industry (Rossetti, 1970; Pellegrini & *alii*, 1979; Natale & Savi, 1990). Given that this industry has largely ceased quarrying operations in river channel bottoms, we have a narrow window of opportunity to study and document the anticipated changes in river channel morphology.

This research has made use of recent in-depth geological, geomorphological and geo-structural investigations resulting from collaboration between the Department of Earth Sciences of Modena and Reggio Emilia University and the Administrations of Modena and Reggio Emilia Provinces (Castaldini & *alii*, 2000; Panizza & *alii*, 2001). Our ultimate goal is to apply the data we derive here, in cooperation with local and regional authorities, to help guide the future management of the watersheds.

GENERAL SETTING OF THE STUDY AREA

The study area is located in the northern Apennines, mainly in the Provinces of Modena and Reggio Emilia (fig. 1). The southern boundary of the study area is marked by the Tuscan-Emilia watershed, whereas the northern boundary lies along the foot of the hills on the upper Po Plain.

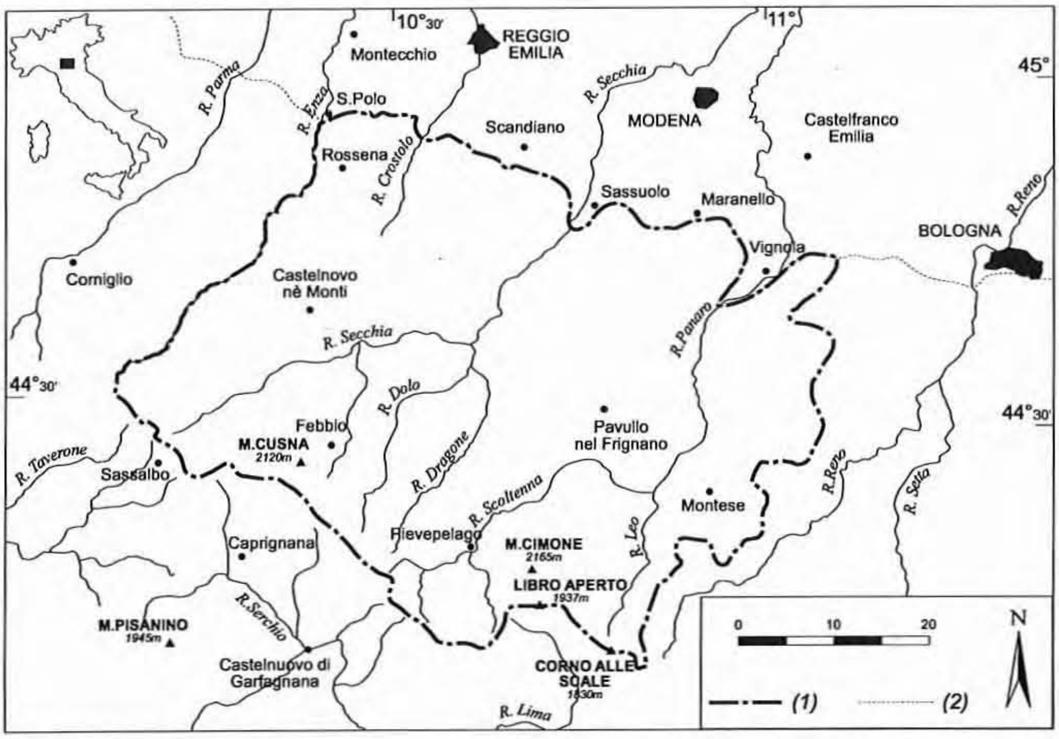

FIG. 1 - Location of the study area. 1) Boundary of the study area; 2) Boundary of the plain.

Some smaller tributaries of the R. Panaro, the torrents Rio delle Pozze and Rio Motte, are included in the Province of Pistoia whereas the Torrent Dardagna is located in the Province of Bologna.

The northern limit was imposed because it was impossible to recognise a completely natural hydrographic network in the plain areas. In fact, in the plain areas there is a high artificial component in the hydrographic networks due to man's activities dating from the early human settlements in the Po Plain. The intense works of territorial planning carried out in the Roman Period and, especially, in the Imperial Period (Cremaschi & *alii*, 1980, Pasquinucci & Settis, 1983) have left many evidence of the centurial pattern (Manicardi, 1991). Other, not less persistent traces are to be ascribed to land reclamation activities carried out by Benedictine monks in the Middle Ages and, much later, to the more intense and larger hydraulic works of the Napoleonic Period and the period following Italian Unification up to the post-war period (Castaldini, 1987). The northern boundary of the area investigated is ideally represented by the alignment of large inhabited centres which have expanded considerably since the end of World War 2: Vignola, Maranello, Sassuolo, Scandiano and San Polo d'Enza.

The study area stretches over a surface of some 3000 km^2; the highest peak is Mt. Cimone (2165 m a.s.l.) which is also the highest mountain of the entire Northern Apennines. The catchment basins involved are the Enza, Crostolo, Secchia basins with its main tributary Fossa (di Spezzano) and Panaro with its main tributaries Tiepido and Guerro (fig. 2).

From the structural and stratigraphic standpoint, the Apennine territory between the provinces of Modena and Reggio Emilia, is made up of 4 main units (Bettelli & *alii*, 1989):

- Tuscan Units, made up of Tertiary siliciclastic turbidites cropping out along the axis of the chain commonly known as Upper Apennines.
- Ligurian Units made up of shallow sea sediments with Jurassic ophiolite fragments overlain by a thin sequence (Cretaceous to Eocene) of terrigenous or calcareous turbidites cropping out in the mid-Apennine area.
- Epi-Ligurian sequence made up of mainly terrigenous units deposited during the evolutional phase of the Ligurian Units.
- Plio-Pleistocene terrigenous marine Units cropping out in the northernmost portion of the Apennines facing the Po Plain.

From the lithological viewpoint (cf. Lithological Map enclosed) the study area can be schematically subdivided into three belts parallel to the direction of formation of this mountain chain. The southernmost part is underlain by indurated sandstone-rich units. The central belt of the Apennines is underlain by interbedded, poorly indurated claystone and sandstone. The northernmost sector is underlain by unlithified clay, sand silt, with lesser amounts of gravel.

The above mentioned units are covered by deposits of varying extent of glacial origin in the Upper Apennines,

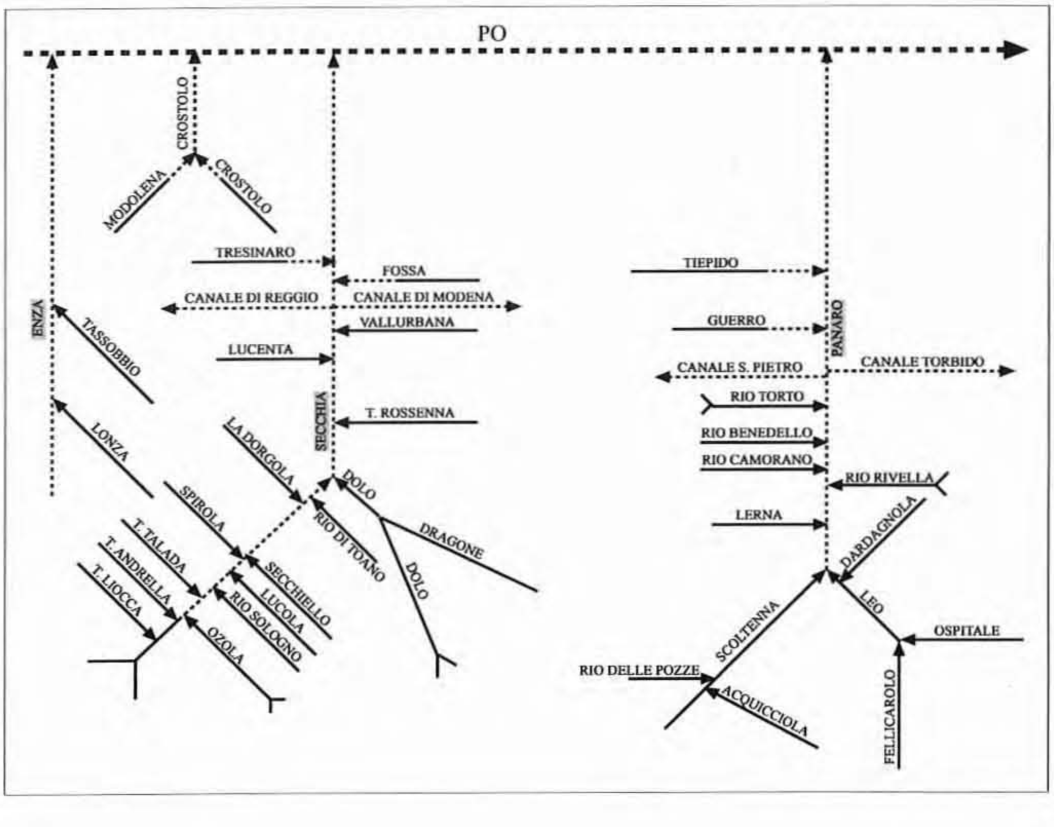

FIG. 2 - Simplified sketch of the hydrographic network of the study area. Unbroken lines show the networks of the basins studied, whereas dotted lines refer to networks not considered in this research.

fluvial origin in the main valley floors and slopes and, in some rare cases, lacustrine origin. This sector of the Apennines is characterised by a high incidence of landslides (Bertolini & Pellegrini, 2001) consistent with steep slopes and the prevailing underlying structural fabric. A recent inventory carried out by the Emilia-Romagna Region (Regione Emilia-Romagna, 1996, 1999) has identified some 32,000 landslides all over the Region's territory; among these, some 9,500 are located in the Apennine sector of the Modena and Reggio Emilia provinces.

The hydrographic networks found in the study area are in most cases exorheic, with run-off towards the River Po and, eventually, to the sea. Exceptions are found only in some small areas. The most important exception is found along a stretch of the R. Secchia some 10 km long, where the Triassic evaporites crop out. In this portion of territory some minor watercourses are confined within an endorheic basin, from which they disappear underground, owing to the karst nature of these rocks, and eventually reappear from the natural springs which feed the main watercourse.

Another belt, similar to the previous one, although of much smaller extent, is found along the Apennine margin between Borzano di Albinea (village located SW of Scandiano) and the Torrent Crostolo where, due to the presence of a Messinian gypsum formation, drainage patterns similar to those previously described are observed.

On the calcarenite plateau of Pavullo (Modena Province), flowing waters disappear underground owing to pseudo-karst infiltration and reappear as springs at the boundary between calcarenites and the underlying clayey formations.

Feeding of the Emilia Apennine watercourses takes place mainly through precipitation, with a regime characterised by two flow rate peaks: in the springtime and in the autumn (fig. 3). In these periods, the monthly flows of these watercourses can be up to 20% of the total annual flows. Usually there are two low-water periods: the most pronounced one is found in July-August, when monthly flows can be as low as 0.1% of total annual flows; the second one is found in the winter months (especially in January) when precipitation is very scarce and, in the upper part of the Apennines, mainly snowy. Besides scarce precipitation, summer low-water periods are accentuated also by considerable evapotranspiration which, is far less important during the winter.

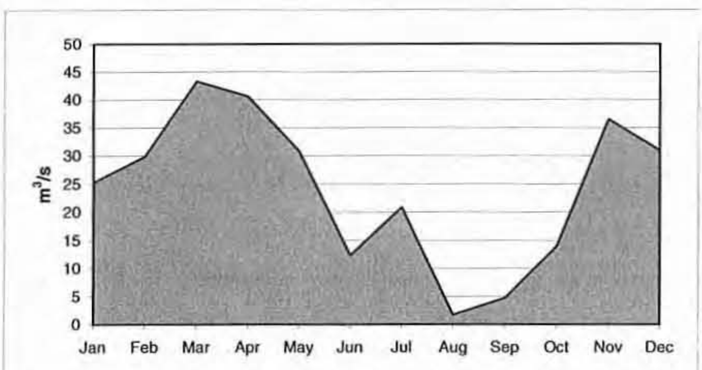

FIG. 3 - Mean monthly discharge of the Secchia River based on data collected at Ponte Bacchello from 1923 to 1970 (Ministero dei Lavori Pubblici, 1992).

A few meteorological stations, installed in the basins of the rivers Secchia and Panaro, allow their pluviometric regimes to be determined. Mean annual precipitation, calculated over the 1921-1950 period, ranges from 2078 mm in the highest areas along the Apennine crest to 599 mm in the plain (Ministero dei Lavori Pubblici, 1959), with nearly continuous variation (tab. 1).

According to Monti & Rubbianesi (1983), the flow coefficient, calculated for the R. Secchia at Ponte Bacchello (21.47 m a.s.l.) outside of the investigated area and for the R. Panaro in Bomporto (19.43 m a.s.l.) outside of the investigated area, is 0.47 and 0.48, respectively. Therefore, nearly half of the total precipitation contributes to their stream flow rates. From flow rate measurements desumed from the annual Reports of the R. Po Hydrographic Office - recorded at the same meteorological stations - maximum flow rates for a 10-year recurrence interval of 720 and 710 m^3/s, respectively, have been calculated, whereas for a 100-year return time the values are 1060 and 1040 m^3/s, respectively (Ministero Lavori Pubblici, 1988, 1992).

As regards stream load, the R. Po Hydrographic Office has carried out turbidity measurements in the R. Secchia at Ponte Bacchello, recording, for the 1924-1925 and 1927-

TABLE 1 - Main thermo-pluviometric gauges of Modena Province, with indication of altitude (m a.s.l.) and mean annual precipitation (M.A.P.) in mm in the 1921-1950 period (Ministero dei Lavori Pubblici, 1959)

Gauge	Elevation (m)	M.A.P. (mm)
Plain area between Secchia and Panaro		
S. Felice s/P	19	599
Plain area between Crostolo and Secchia		
Carpi	28	670
Crostolo basin		
Reggio Emilia	60	704
Regnano	415	708
Casina	500	945
Secchia basin		
Sassuolo	121	941
Pavullo	682	951
Castelnovo né Monti	730	1120
Civago	1024	1854
Panaro basin		
Modena	35	631
Montese	841	956
Fiumalbo	943	1045
Sestola	1020	1267
Tagliole	1150	2078

1935 periods, a unit turbidity flow of 510 $t \cdot km^{-2} \cdot y^{-1}$. The R. Panaro shows turbidity characteristics quite similar to or slightly higher than the values measured in the R. Secchia. Indeed, the unit turbidity rate, measured in Bomporto in the 1923-1965 period (Pellegrini, 1969b), is 756 $t \cdot km^{-2} \cdot y^{-1}$.

GIS AS A SUPPORT TO QUANTITATIVE GEOMORPHIC ANALYSIS

Traditionally, the study of relief forms on a quantitative basis is considered to have started with quantitative geomorphology investigations on fluvial networks in the second half of the 20th century and, in particular, by Horton (1945). From the conceptual viewpoint, this discipline attained further developments by Strahler (1950, 1952a, 1952b, 1954, 1956, 1958, 1963, 1975) who dealt with the linear properties of hydrographic networks and areal properties of catchment basins, introducing statistical methods.

The recent development of investigation systems applied to mapping and spatial analysis, commonly known as Geographic Information Systems or, more simply, GIS, has given new momentum to the research carried out in the field of quantitative geomorphology. By means of numerical models, and more and more refined calculation algorithms, it is possible to apply the above mentioned technologies for describing the various components of the landscape. For example, in Italy the papers by Onorati & *alii* (1992) and Guzzetti & Reichenbach (1994) should be quoted.

As for the study of fluvial networks, automatic tracing systems of networks have been developed, besides the possibility of extracting the most common hydrological parameters. O'Callaghan & Mark (1984) developed one of the first mathematical models for automatic tracing of hydrographic networks, known in literature as D8. This system defines for each cell the stream flow direction on the basis of the maximum difference in altitude by considering the 8 adjacent cells (fig. 4a). The model by O'Callaghan & Mark (1984) has been successfully applied by numerous authors (Jenson & Domingue, 1988; Tarboton & *alii*, 1988).

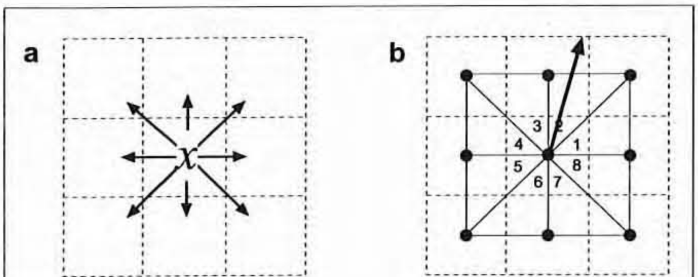

FIG. 4 - (a) D8 model (O'Callaghan & Mark, 1984) where flow directions are discretised according to 8 possible directions. (b) Model D∞ (Tarboton, 1997), in which flow direction is calculated between 0 and 360°.

In the attempt to overcome the constraints imposed by model D8, resulting from the discretisation of stream flow directions, several changes to this method were proposed (Quinn & *alii*, 1991; Freeman, 1991; Lea, 1992; Costa-Cabral & Burges, 1992). A recent method developed by Tarboton (1997), is considered the most realistic for the description of a natural network (Alberico & *alii*, 2001). This procedure, known as D∞ is based on the assignment of a stream flow direction, between 0 and 360°, after having analysed the maximum dips in each of the eight faces centred on the cell under investigation (fig. 4b).

Method for the extraction of the drainage network

The problem of accuracy and resolution of Digital Elevation Models in the development of hydrological models was emphasised in the past by several Authors (Zhang & Montgomery, 1994; Wolock & Price, 1994; Kenward & *alii*, 2000). Nevertheless, because of very high costs, it is nearly always impossible to make use of sufficiently accurate DEM, resulting from specific aerial photographic surveys or GPS campaigns.

In this study the Digital Elevation Model was calculated by means of digitising the 25 metres contour lines of the Regional Technical Map at a 1:25,000 scale of the Emilia-Romagna Region and subsequent linear interpolation using the Borgefors method (Borgefors, 1996) implemented in the ILWIS software package. By taking into account the size of the area considered and the technical time necessary for the elaboration of the data contained in the DEM, a pixel dimension of 25 m was fixed for all the raster elaborations which were then referenced according to the UTM co-ordinates system, presently in use for all computer-based regional mapping.

The tracing of hydrographic networks and their relative basins was obtained through the elaboration of numerical elevation data by using a calculation algorithm which is an extension of the commercial ArcView package.

The procedure here applied, which by now has been used by numerous Authors (Jenson & Dominigue, 1988; Donker, 1992), is preliminarily based on the creation of a depressionless elevation data DEM. The removal of these elevation anomalies, identified as unit cells surrounded by cells with a higher value, was carried out by means of an automated procedure based on the reassignment of the anomalous pixel value, on the basis of the lowermost value recorded in the adjacent cells.

In correspondence with the widest valley floors, where the contour lines used for obtaining the DEM are more distanced between one another and where, as a consequence, greater approximations have been necessary in the DEM elaboration phase, the mathematical extraction of the hydrographic network is less related to reality. In order to overcome this considerable shortcoming in studies concerning a whole hydrographic complex, DEM values have been modified in correspondence with the riverbeds (previously digitised from the CTR). This change was obtained by assigning lower elevations in the pixels occupied by the network itself and in the adjacent ones according to an empirically identified algorithm.

Once a DEM suitable for mathematical extraction of the hydrographic network was elaborated, a preliminary map of stream flow direction was created according to the already quoted D∞ method and, subsequently, a map of flow accumulation was calculated. The latter is defined as the flow amount accumulated in each pixel resulting from the sum of the accumulations calculated along maximum inclination directions.

The hydrographic network was eventually traced by constructing a vectorial net of the map of flow accumulations, fixing a minimum threshold value from which the tracing of the hydrographic network started. The choice of the threshold value was derived from the compared analysis of the networks extracted by means of the mathematical algorithm, by using different threshold values and comparing the results with those shown on the official maps in particular sample areas. The cell flow accumulation threshold values which minimized the difference in fluvial network shape is 50.

The hydrographic network thus obtained (see «Drainage network and basins map» in the attached map) was then ordered according to Strahler (1952b). By making use of the maps describing the stream flow characteristics calculated from the DEM, the polygons representing the hydrographic basins from the 2^{nd} order upwards were extracted. Each basin was assigned an entire identification number and, on the basis of the basins of higher order including the basin considered, a relational database was created. Through spatial analysis operations, this system allowed the most commonly used hydrological parameters to be extracted all over the territory considered. They are: Frequency of the channels (F), Length of fluvial courses (L), Area of basins (A), Ratio between areas and lengths, drainage density (D). From these parameters the most common ratios and indexes were derived: Mean Bifurcation Ratio (R_b), Mean Direct Bifurcation Ratio (R_{bd}), Bifurcation Index (R), Hierarchic Anomaly (G_a), Density of Hierarchic Anomaly (g_a), Index of Hierarchic Anomaly (Δ_a), Extension Ratio (R_e), Circularity Ratio (R_c). Finally, Hypsometric Analysis was carried out for each basin higher than the 5^{th} order and for the two main basins of the rivers Secchia and Panaro.

ANALYSIS OF SURFACE HYDROGRAPHY

Hierarchisation of the network

The hydrographic network was hierarchised by using the techniques previously described. The values considered, relative only to the 5^{th} and 6^{th} order basins, are summarised in tab. 2.

Analysis of data shows that 5^{th} and 6^{th} order basins have a fair degree of network organisation, demonstrated by the tendentially low values of parameters *ga* and Δ_a if they are compared with other studies carried out on Italian areas (Lupia Palmieri & *alii*, 2001). From a more detailed analysis of the parameters calculated, relatively higher values can be observed in the basins of T. Tresinaro (ID.62 of tab. 2), Rio Torto (ID 46) and T. Scoltenna (ID 65). Also the *Bifurcation Index (R)*, which best summarises the geometrical characteristics of the networks, also defined as the *Mean Bifurcation Ratio (Rb)* minus the *Direct Mean Bifurcation Ratio (Rbd)*, shows values of 0.3 to 1.4 in all the basins considered, which are typical of basins with a discrete hierarchic organisation.

Morphometry of the hydrographic basins

In order to express quantitatively the shapes of the drainage basins studied, the main parameters have been considered, they are: *Extension ratio (Re)* (Schumm, 1956), *Circularity ratio (Rc)* (Strahler, 1958), *area of basin (A)* (tab. 2).

Particularly low values of these ratios were recorded in the following basins: Torrent Modolena (ID 51), T. Guerro (ID 57), T. Fossa (ID 58), T. Tiepido (ID 41), T. Secchiello (ID 45), T. Tresinaro (ID 62), T. Scoltenna (ID 65).

The close relationship exerted by the geological-structural conditions on the development of the hydrographic network, has been stressed by several authors (Papani, 1971; Barbieri & Rossi, 2001). The vergence of the geological structures consequent to Northern Apennine orogenesis has resulted in the preferential SW-NE orientation of the catchment basins. This direction is perpendicular to the direction of the main structures (see Map of the linear disjunctive structures in the annexed sheet). Along the SE-NW lineation a secondary extension of the basins, characterising the minor watercourses is observable.

In order to further understand the single factors which have controlled the development and shape of the single basins, with the identification of the structures responsible, more detailed investigations should be carried out.

Surface drainage

One of the most significant parameters for assessing the erosional intensity of the drainage basins is *drainage density (D)* (Horton, 1945). This parameter takes into account the characteristics of a given basin and its hydrographic network, thus correlating a linear property with an areal one. Drainage density, as was widely recognised in literature (Schumm, 1977; Thorna, 1982; Lupia Palmieri & *alii*, 2001), usually reflects a direct proportionality with both precipitation intensity and slope acclivity. This parameter is strongly influenced also by the lithological characteristics of the area, respecting direct proportionality with erodibility and inverse proportionality with the permeability of the soils. Also the type and density of the vegetation cover have strong effects on drainage density, with the lowermost values recorded where vegetation is most developed.

In the study area drainage density ranges from 3.2 km/km^2 to 4.4 km/km^2, that is within the boundaries of mean values with respect to those calculated all over Italy (Avena & Lupia Palmieri, 1969; Lupia Palmieri & *alii*, 1995, 1998, 2001). The lowest values are found in the basins of the following streams: Modolena (ID 51), Guerro

TABLE 2 - Main morphometric and organisation parameters of the hydrographic networks extracted: O) Hierarchic order; Rb) Mean bifurcation ratio; Rbd) Mean direct bifurcation ratio; R) Bifurcation index; Ga) Hierarchic anomaly; ga) Density of Hierarchic anomaly; Δ_a) Hierarchic anomaly index, Re) Extension ratio; Rc) Circularity ratio; A) Area (km^2), D) Drainage density (km/km^2), Tu[1]) Unitary stream load calculated by means of equation 1 ($t \cdot km^{-2} \cdot y^{-1}$); Tu[2]) Unitary stream load calculated by means of equation 2 ($t \cdot km^{-2} \cdot y^{-1}$); (T[1]) Total stream load calculated by means of equation 1 ($t \cdot y^{-1}$)

ID	NAME	O	Rb	Rbd	R	Ga	ga	Δ_a	Re	Rc	A	D	Tu[1]	Tu[2]	T[1]
1	Dolo	6	5,4	4,4	1,0	2940	10,8	0,7	0,7	0,5	273,1	4,4	817	953	223012
40	Vallurbana	5	3,2	2,6	0,6	104	9,4	1,2	0,9	0,5	11,1	3,7	571	595	6333
41	Tiepido	5	4,7	3,3	1,4	454	10,7	1,3	0,6	0,5	42,5	3,8	639	648	27159
42	Talada	5	3,0	2,7	0,3	37	2,2	0,5	0,9	0,6	8,7	4,1	603	745	5244
43	Spirola	5	3,7	3,0	0,7	151	7,6	1,0	1,1	0,4	19,7	3,8	573	628	11293
44	Rio di Toano	5	3,1	2,7	0,4	53	5,4	0,6	1,0	0,5	9,9	4,4	788	943	7797
45	Secchiello	5	4,9	3,6	1,3	808	11,1	1,5	0,6	0,5	72,9	4,3	1010	963	73641
46	Rio Torto	5	4,2	2,7	1,4	585	18,4	2,1	0,7	0,4	31,7	3,9	922	761	29237
47	Rio Sologno	5	3,1	2,3	0,8	125	11,5	1,5	0,6	0,5	10,9	3,9	742	714	8089
48	Rio Rivella	5	4,3	3,2	1,1	399	8,5	1,2	1,0	0,4	39,7	3,9	666	691	26428
49	Rio Camorano	5	3,4	2,6	0,9	169	12,4	1,5	0,7	0,6	13,6	3,9	742	714	10093
50	Rio Benedello	5	4,1	2,9	1,1	310	16,8	2,1	0,7	0,5	18,5	3,6	732	608	13540
51	Modolena	5	3,8	2,8	1,0	261	11,4	1,6	0,5	0,4	22,9	3,2	449	427	10273
52	Lucola	5	3,9	3,0	0,9	229	9,5	1,3	0,7	0,5	24,1	4,1	805	812	19408
53	Lucenta	5	4,0	2,9	1,1	374	13,1	1,7	0,7	0,5	28,5	3,9	798	729	22740
54	Liocca	5	3,9	3,1	0,8	179	7,9	1,0	0,9	0,6	22,6	3,9	619	677	13993
55	Lerna	5	3,6	2,8	0,8	172	10,7	1,4	0,9	0,5	16,1	3,6	568	564	9144
56	La Dorgola	5	3,3	2,8	0,5	85	7,0	0,8	0,9	0,2	12,1	3,8	533	615	6451
57	Guerro	5	4,3	2,8	1,5	436	13,4	1,8	0,5	0,4	32,4	3,4	563	507	18232
58	Fossa	5	4,5	3,8	0,7	274	7,8	1,0	0,5	0,4	35,2	3,5	455	502	16012
59	Dorgola	5	3,4	2,7	0,8	181	11,5	1,5	1,1	0,6	15,7	3,6	589	570	9246
60	Dardagnola	5	3,7	2,9	0,8	276	11,9	1,5	0,8	0,7	23,1	4,3	1010	963	23335
61	Andrella	5	3,2	2,7	0,5	203	16,8	2,2	0,9	0,6	12,1	4,0	1033	829	12499
62	Tresinaro	6	4,2	3,0	1,2	2999	20,0	2,5	0,7	0,3	150,1	3,7	914	684	137160
63	Tassobbio	6	4,0	3,0	1,0	1597	15,8	1,9	1,0	0,4	101,3	3,6	681	595	68957
64	Secchia	6	3,4	2,8	0,9	1220	14,8	1,8	0,9	0,6	82,0	4,0	894	794	73277
65	Scoltenna	6	4,7	3,5	1,2	5002	17,6	2,2	0,6	0,5	283,7	4,2	1205	963	341903
66	Rossenna	6	4,4	3,3	1,1	2872	15,4	1,9	0,8	0,4	187,1	3,9	858	745	160502
67	Ozola	6	3,7	2,9	0,8	1018	15,9	1,8	0,9	0,5	64,0	4,2	1043	922	66726
68	Leo	6	3,9	2,8	1,1	1632	15,1	1,9	0,8	0,6	90,1	4,3	1168	1005	105208
69	Lonza	6	3,6	3,0	0,6	631	10,0	1,3	1,1	0,5	63,1	4,0	746	753	47046
70	Crostolo	6	3,9	2,7	1,2	1436	16,3	2,1	1,0	0,5	88,2	3,5	678	564	59762
Average			*3,9*	*3,0*	*0,9*	*850*	*12,1*	*1,5*	*0,8*	*0,5*	*59,6*	*3,9*	*763*	*724*	*51992*

(ID 57), Fossa (ID 58), Crostolo (ID 70), Tassobbio (ID 63), Dorgola (ID 59), Lerna (ID 55) and Rio Benedello (ID 50), that is in those areas located at the boundary between the Apennines and the Po Plain, where acclivity decreases considerably.

Relatively higher values of drainage density (*D>4*) are found in the higher Apennine areas, where slopes are steeper, such as in the valleys of the following streams: Dolo (ID 1), Rio di Toano (ID 44), Secchiello (ID 45), Dardagnola (ID 60), Leo (ID 68), Scoltenna (ID 65), Ozola (ID 67), Talada (ID 42), Lucola (ID 52).

As for this parameter, though, it should be noticed that since the algorithm used for tracing the hydrographic network is the same for the whole study area, just like the previous *cell flow accumulation threshold* value , the drainage density values extracted are tendentially smoothed in all the area considered. Particular situations, such as the presence of badlands, show a number of 1st order networks tendentially lower than those actually present in nature.

Hypsometric analysis

In order to further characterise the catchment basins studied, we proceeded to calculate the hypsometric integral and the construction of the relative curves for each basin of the study area (see «Hypsometric curves» in the attached map). Hypsometric curves (shown in the annexed sheet) represent the areal distribution of elevations within the basin. Their pattern usually reflects the present denudation processes acting on the basin (Masek & *alii*, 1994; Willgoose & Hancock, 1998; Hurtrez & Lucareau, 1999).

To assess this parameter, considering the size of the study area and the calculation time, classes of difference in elevation of 100 m have been fixed. The corresponding curves show some typical trends that can be summarised in three different types: nearly rectilinear curves, concave curves and convex curves.

Among the former, it can be noticed that some of them are characterised by steep inclination, as in the case of T.

Dolo (ID 1). On the other hand, other curves show an average inclination witnessing a uniform distribution at different elevations of the basins, as in the cases of T. Scoltenna (ID 65) and La Dorgola (ID 56).

Among the basins showing marked convex curves, typical is the case of Rio Rivella (48), whereas concave curves characterise the T. Lonza (ID 69) and T. Secchiello (ID 45). The trend of curves is often interpreted as the measurement of the evolution degree of a basin, from convex, more immature basins to concave ones, showing a more pronounced level of evolution. In fact, as pinpointed by various Authors (Lupia Palmieri & *alii*, 1995, 1998, 2001), in the light of present-day knowledge, these definitions are often misleading since hypsometric curves are representative not only of the evolutional stage of a basin but also of its evolution patterns which, in turn, are constrained by numerous factors, among which the most important ones are lithological-structural factors.

Finally, it should be noticed that if we consider the general hypsometric curves of the two main watercourses, the rivers Secchia and Panaro (fig. 5), they both bound areas of about 40%, with similar curve patterns: concave for the R. Panaro and concave-convex for the R. Secchia. They also show uniform distribution of the areas in function of elevations.

Assessment of stream load

On the basis of morphometric data from 14 Italian basins equipped with stream load measurement gauges, Ciccacci & *alii* (1981) proposed some equations for assessing the annual mean unitary stream load (*Tu*). Among these, the equations which take into account parameters D, Δ_a and g_a:

$$log\ Tu[1] = 0.33479\ D + 0.15733\ \Delta_a + 1.32888 \quad \text{(eq. 1)}$$

$$log\ Tu[2] = 1.82818\ log\ D + 0.01769\ g_a + 1.53034 \quad \text{(eq. 2)}$$

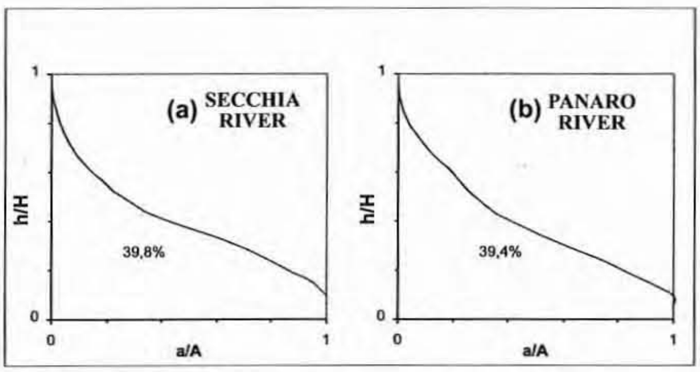

FIG. 5 - Hypsometric curves of the River Secchia basin from its closing point near Sassuolo (a), and the River Panaro basin from its closing point near Marano sul Panaro (b).

TABLE 3 - Main morphometric parameters of the catchment basins of the northern side of the Northern Apennines calculated after Cicacci & *alii*, 1981. Tu[1]) Unitary stream load calculated by means of equation 1 ($t{\cdot}km^{-2}{\cdot}y^{-1}$), D) Drainage density ($km/km^2$), Δ_a) Hierarchic anomaly index, ga) Density of Hierarchic anomaly, A) Area (km^2), h_{AV}) mean elevation (m), Ga) Hierarchic anomaly

NAME	Tu	D	Δ_a	ga	A	h_{AV}	Ga
Trebbia	1523	4.90	1.59	19.35	226	953	4373
Idice	2397	5.61	0.86	30.27	397	430	12017
Senio	857	4.17	1.32	15.12	269	438	4067

are commonly utilised in literature for studies relative to Italian basins.

Since these equations have been obtained from basins with very different characteristics among them, located in very distant areas, the above quoted equations have been recalculated on the basis of data from Ciccacci & *alii* (1981) for the only basins of the northern slope of the Northern Apennines (tab. 3), that are the Trebbia, Idice and Senio basins. The equations thus obtained:

$$log\ Tu[3] = 0.32497\ D + 0.04625\ \Delta_a + 1.51679 \quad \text{(eq. 3)}$$

$$log\ Tu[4] = 3.8088\ log\ D - 0.00281\ g_a + 0.61138 \quad \text{(eq. 4)}$$

do not have proved statistical validity, nevertheless they produce values fairly similar to those obtained by means of the previous equations. In particular, this is true for the equation taking into account parameters D and Δ_a. The reference values obtained by means of equations 1 and 3 are shown in tab. 2. Although these equations produce values of *Tu* showing differences up to 230 $t{\cdot}km^{-2}{\cdot}y^{-1}$, they nevertheless show similar maxima and minima.

The values of parameter *Tu[1]* have been grouped into five classes, graphically represented in the Map of the Erosion Index (attached map). The highest values of this parameter have been recorded in the basins of T. Scoltenna (ID 65) and T. Leo (ID 68) which in their southernmost parts are characterised by particularly high acclivity intervals and by a lithological situation corresponding prevalently to flysch and sandstone rock types. Also in other basins located at higher altitudes such as the Ozola (ID 67), Andrella (ID 61), Dardagnola (ID 60) and Secchiello (ID 45) basins; in fact, in these basins *Tu* exceeds 1000 $t{\cdot}km^{-2}{\cdot}y^{-1}$. The lowermost values of annual mean unitary stream load are found in the basins located in the lowermost part of the Northern Apennines, where *Tu* values are less than 500 $t{\cdot}km^{-2}{\cdot}y^{-1}$. Paradoxically, the least competent rock types crop out in these basins, but erosion is primarily influenced by slope acclivity (see «Slope map» in annexed sheet) rather than by lithology. Among these higher basins, particularly significant are the T. Modolena (ID 51) and T. Fossa (ID 58) basins.

FINAL REMARKS

This paper has defined the main morphometric characteristics of the catchment basins included in the Apennine sector of the Modena and Reggio Emilia provinces. The research carried out so far has led us to acquiring important numerical data useful for a first definition of the drainage characteristics and the amount of denudation processes taking place in the area considered. The relationships thus identified show a fair similitude with the data obtained from adjacent areas and central Italy basins.

Mean annual stream load was assessed by means of the equation proposed by Cicacci & *alii* (1981) which provided us with a first indication on the fluvial stream load potential in the basins analysed. This approach should stimulate the implementation of experimental measurement campaigns in order to calibrate the equations proposed in this paper. The lack of periodic measurements of suspended load and bed load is a serious shortcoming for knowing the fluvial dynamics of the two main watercourses as well as for planning and implementing hydraulic works capable to mitigate the serious erosional processes occurring along the rivers Secchia and Panaro.

The amount assessed by using Cicacci & *alii* (1981) equation shows values that in the higher order basins are compatible with the experimental values measured in the period between the two world wars. Considering that at present stream load might be lower with respect to previous measurement campaigns, due to considerable waterbed erosion problems, the general morphometry of the basin might reflect conditions of fluvial dynamics that are no longer active.

For this reason, it is really necessary to proceed with great care in monitoring the morphometric evolution of these basins and measuring stream load.

Nevertheless, from this study it can be concluded that the basins investigated show morphometric characteristics indicating a rather high degree of evolution. The basins show considerable differences due to the different outcropping rock types, which are more competent in proximity of the Tuscan-Emilia watershed and highly erodible in the mid-Apennines.

In addition, owing to the widespread presence of clayey, easily erodible rock types, the mid-Apennines are characterised by the frequent occurrence of landslides in the form of earth flows and rotational slides which, in many cases, are particularly vast.

The morphometric evolution of these basins results therefore from the sum of contrasting evolutional trends. High erodibility favours the development of mature morphometries, especially in the mid-lower Apennines, whereas neotectonic activity producing the general uplift of this chain generates opposite effects, thus causing a partial rejuvenation of the basins. Finally it should be pinpointed that intense anthropogenetic activities produce effects which are not always univocal on the morphometric features of the basins examined.

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(Ms. received 15 April 2003; accepted 15 October 2003)