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GIS ANALYSIS OF UNIT DRAINAGE DENSITY AND ITS INFLUENCING FACTORS IN THE SOUTH FORK EEL RIVER (NORTHERN CALIFORNIA, U.S.A.)

ABSTRACT: SPAGNOLO M., *GIS analysis of unit drainage density and its influencing factors in the South Fork Eel River (Northern California, U.S.A.)*. (IT ISSN 0391-9838, 2002).

Unit drainage density and its influencing factors in the Eel River South Fork (Northern California) were analysed by means of GIS techniques. The river network was automatically extracted from a digital terrain model (30 m resolution) by applying a contributing area threshold of 0.0225 km^2. The drainage density was evaluated within a constant unit area size of 0.16 km^2 for the entire river basin, obtaining a drainage density spatial distribution characterized by a low auto-correlation. The unit drainage density (UD_d) map reveals higher values of UD_d along major valley axes and lower values predominantly along ridges. With the use of GIS spatial analysis tools rock type, vegetation density and topography (aspect and slope) were quantitatively correlated with unit drainage density. The correlation analysis, tested with the Pearson correlation T-test, shows that the two most important influencing factors on UD_d are aspect and rock type. In particular, UD_d is higher in NW-facing slopes and weaker rock types while it is lower in SE-facing slopes and harder rocks. Finally, no evident relationship was found between drainage density, slope and landcover.

KEY WORDS: GIS, Quantitative geomorphology, Fluvial geomorphology, Drainage density, Eel River (Northern California, U.S.A.).

INTRODUCTION

Drainage density (D_d) is one of the many physiographic properties of basins considered as an index of surface processes. It is still one of the most commonly used indices for the characterization of fluvially dissected landscapes.

In the last fifty years, different methodological approaches have been used to estimate D_d, defined as the ratio between the cumulative length of channels and the area of the drained basin (Horton, 1932). At the beginning, the foremost problem was the measurement of stream length, overcome nowadays by the advent of new technologies (planimeter, GIS, etc.). As a result, the attention of researchers has shifted to another problem: the exact identification of a drainage network. For a long time, the network was extracted from topographic maps, using either the «blue-line» method (Horton, 1945) or the «contour-crenulation» technique (Morisawa, 1957). More recently, the instrumental use of GIS techniques in spatial analysis has prompted many researchers to automatically extract drainage networks from DEMs (Tarboton & *alii*, 1991; Dietrich & alii, 1993; Wharton, 1994; Yin & Wang, 1999).

Numerous studies have been carried out relating D_d to other geomorphic and/or climatic characteristics. Referring to Horton's definition, the drainage density can be interpreted as the degree to which a river basin is dissected by channels. Variation in the drainage density values are related to all factors that, directly or indirectly, influence the degree of slope erosion and the consequent formation of new channels or the modification of old ones. Previous works have demonstrated the sensitivity of drainage density to environmental conditions such as climate, structure and lithology, flood peaks, sediment yields, topography and landcover. The scale at which the analysis is performed is also an important factor in understanding spatial variation of D_d (Morgan, 1973; Dramis & Gentili, 1977). At a continental scale the main control on D_d is exerted by climatic variations, while at larger scales, where the climatic conditions can be considered approximately uniform, the spatial variations of D_d are usually more related to lithology and topography (Abrahams, 1984).

The aim of this work is to consider a new method for evaluating drainage density by using specific GIS tools and to analyse the possible influencing factors on drainage density in a particular area whose digital data are already available. Most of the previous works have evaluated D_d within whole basins with consequent problems in quantitatively correlating drainage density with other factors. In this work a constant unit cell size across the landscape is used to map the spatial distribution of drainage density (thereafter *unit drainage density* or UD_d) making it possi-

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ble to quantify its relationship with other spatial parameters. Particular attention is given to the DEM automatic extraction of the river network and to the choice of the unit area within which the cumulative channel length for the UD_d is calculated.

In the past many studies have been carried out evaluating the influential factors on the spatial variation of drainage density. However, few have taken into consideration the contribution of several different parameters within the same wide area and quantitatively evaluated the correlation among them. The South Fork Eel River basin (Northern California), with its distinct geology, vegetation, aspect and slope properties and with a good availability of digital and remote sensing data, was chosen for this purpose.

THE STUDY AREA

The South Fork of the Eel River, the third largest river system in California, is situated between the Northern Mendocino and Southern Humboldt counties, in Northern California (fig. 1). The South Fork joins the main Eel River branch near Weott, 40 miles from the mouth to the Pacific Ocean. Its basin belongs to the Coastal Range, an area characterized by elongated NNW ridges and valleys controlled largely by underlying geologic structures. The landscape includes gentle grassland areas as well as dense redwood forests. The South Fork Eel River basin covers an area as large as 1,783 km^2 and is drained by one principal stem (flowing NNW) with a large number of tributar-

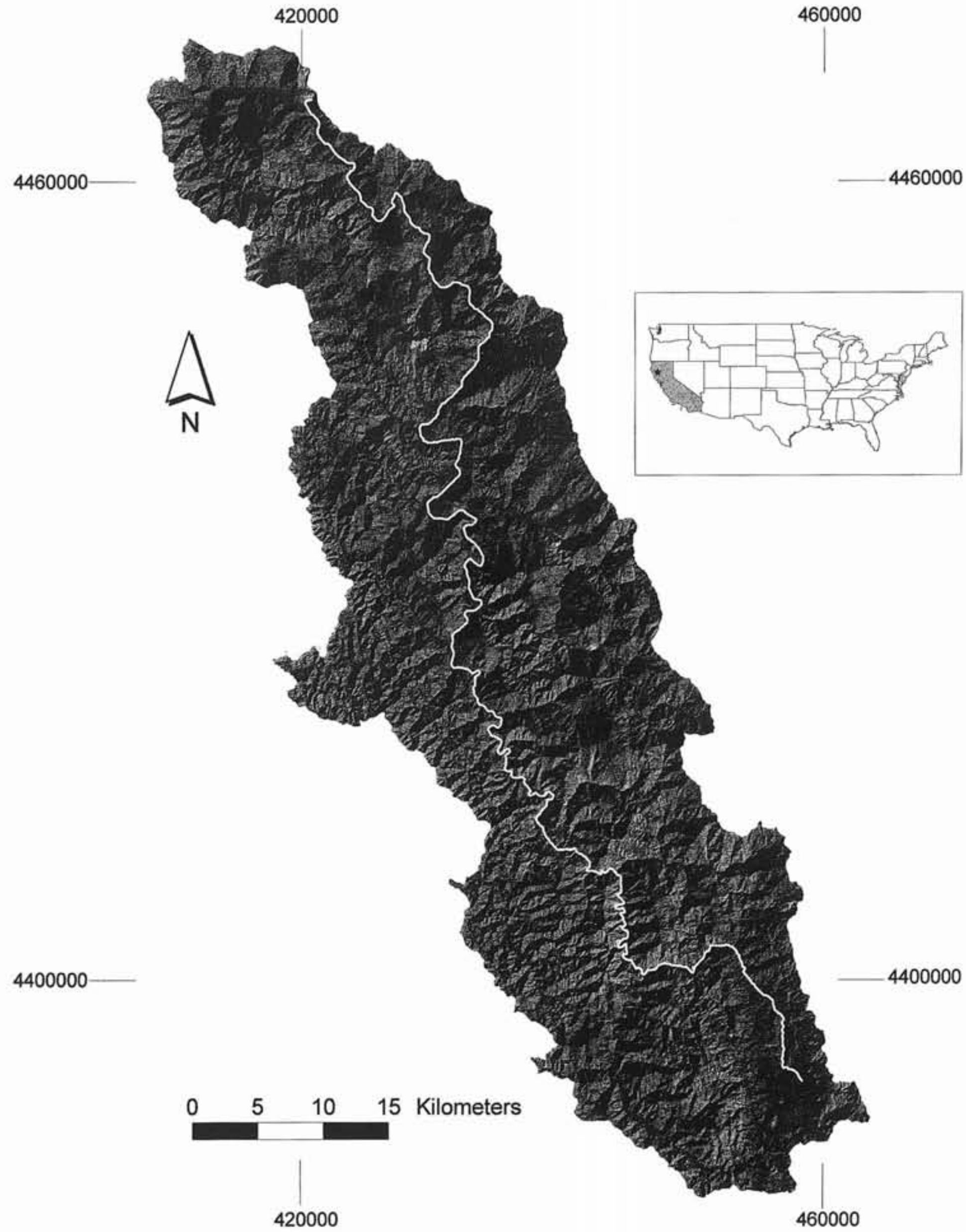

FIG. 1 - The study area with UTM coordinates (in white the main South Fork Eel River stem).

ies, the East Branch being the largest with a drainage area of 197 km². The elevation in the basin ranges from 33 m to 1,497 m (Iron Peak) while the mean slope is around 20°.

The climate of the area is strongly influenced by its proximity to the Pacific Ocean. Even though this area has generally been classified as having a Mediterranean climate (hot summers and heavy winter rainfall), the presence of the ocean with its periodic fog tends to cause cool temperatures even during the summer season. In addition, this particular climatic condition is influenced by the presence of extensive conifer forests with some of the tallest and oldest redwood groves in the world. The Eel River Basin, like the rest of Northern California, is characterized by the highest latitudinal temperature gradient of any area in the Pacific Northwest (Janda & Nolan, 1979), which causes large cyclonic storms lasting several days with a total rainfall of more than 250 mm (Harden & *alii*, 1978). In the Basin, the average monthly precipitation usually ranges from 0 (Summer) to over 254 mm (Winter). Mean annual precipitation generally increases from South to North and from East to West as well as with altitude, ranging from 1,524 mm near Garberville and Laytonville to 2,921 mm in the NW area of the basin (Rantz, 1972). Moreover, because most of the storms and moist air arrive from the Pacific Ocean, precipitation is heavier on the western flank of the Coast Ranges due to the föhn effect (U.S. Department of Commerce, 1977). The temperature, especially in the inner area at high altitudes, can range from very cold in the winter and quite hot in the summer: at Richardson Grove, the mean maximum temperature ranges from about 7°C in January to 22°C in July (U.S. Department of Commerce, 1977).

From a geological point of view, the South Fork Eel River basin belongs to the Coastal Range tectonostratigraphic terrain (Blake & *alii*, 1982) and, in particular, to the Central and Coastal Franciscan belts (Irwin, 1960). The quite active tectonic movement is induced by migration of the nearby Mendocino Triple Junction. On the coast, the general uplift of the area ranges from 0.5 mm/y (SSE) to over 4 mm/y (NNW) (Merritts & Bull, 1989, Merritts & Vincent, 1989; Merritts, 1996).

In the study area, the various lithologies can be grouped into three main different rock types considering their erodibility: hard, soft and intermediate (hard-soft) types (fig. 2).

The soft type rocks (34% of the study area) belong to the Central Franciscan Belt and are characterized by highly tectonically sheared Jurassic-Cretaceous sandstone (minor shale, conglomerate and limestone); in the South Fork Eel River basin they are usually associated with grassland and shrub vegetation. The Quaternary sedimentary deposits (7%) can also be included in the soft rock type.

The hard type rocks (35% of the study area) belong to the Coastal Franciscan Belt and are represented by Cretaceous sandstone and shale (minor conglomerate); in the study area they are generally associated with conifers and hardwood (i.e. oak trees).

The intermediate soft-hard type rocks (24% of the study area), also part of the Coastal Franciscan Belt, are

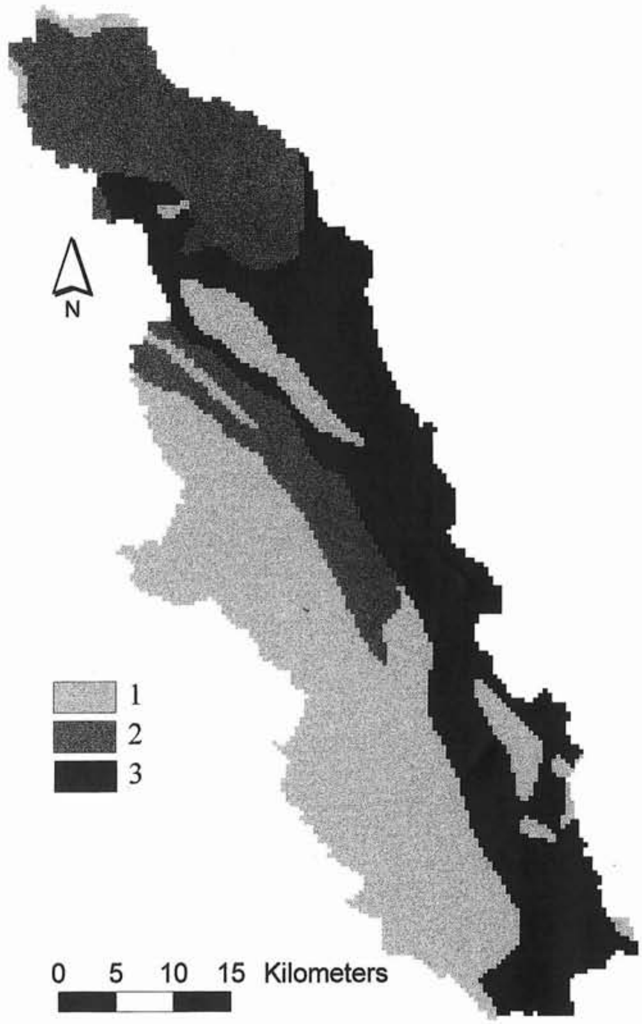

FIG. 2 - The rock type map (1: hard; 2: soft-hard; 3: soft).

characterized by tectonically uplifted Paleocene sandstone, shale and conglomerate.

Both soft-hard type and (even more) soft type rocks experience deep-seated landslides, which are the most important outflow process of masses in the area. Landslides, often induced by human activities, have been estimated to account for 25% of the total volume of the sediment yearly transported by the river (US Department of Agriculture, Soil Conservation Service, 1970). The Eel River is referred to as one of the highest sediment transporting rivers in the US, carrying fifteen times as much sediment as the Mississippi River (Brown & Ritter, 1971). In particular, the estimated South Fork basin-wide rate of sediment production is currently 700 t/km²/y (Lisle, 1990; Stillwater Sciences, 1999).

DATA SOURCE

The USGS DEM, with a resolution of 30 m, was used both for the topographic information (slope and aspect)

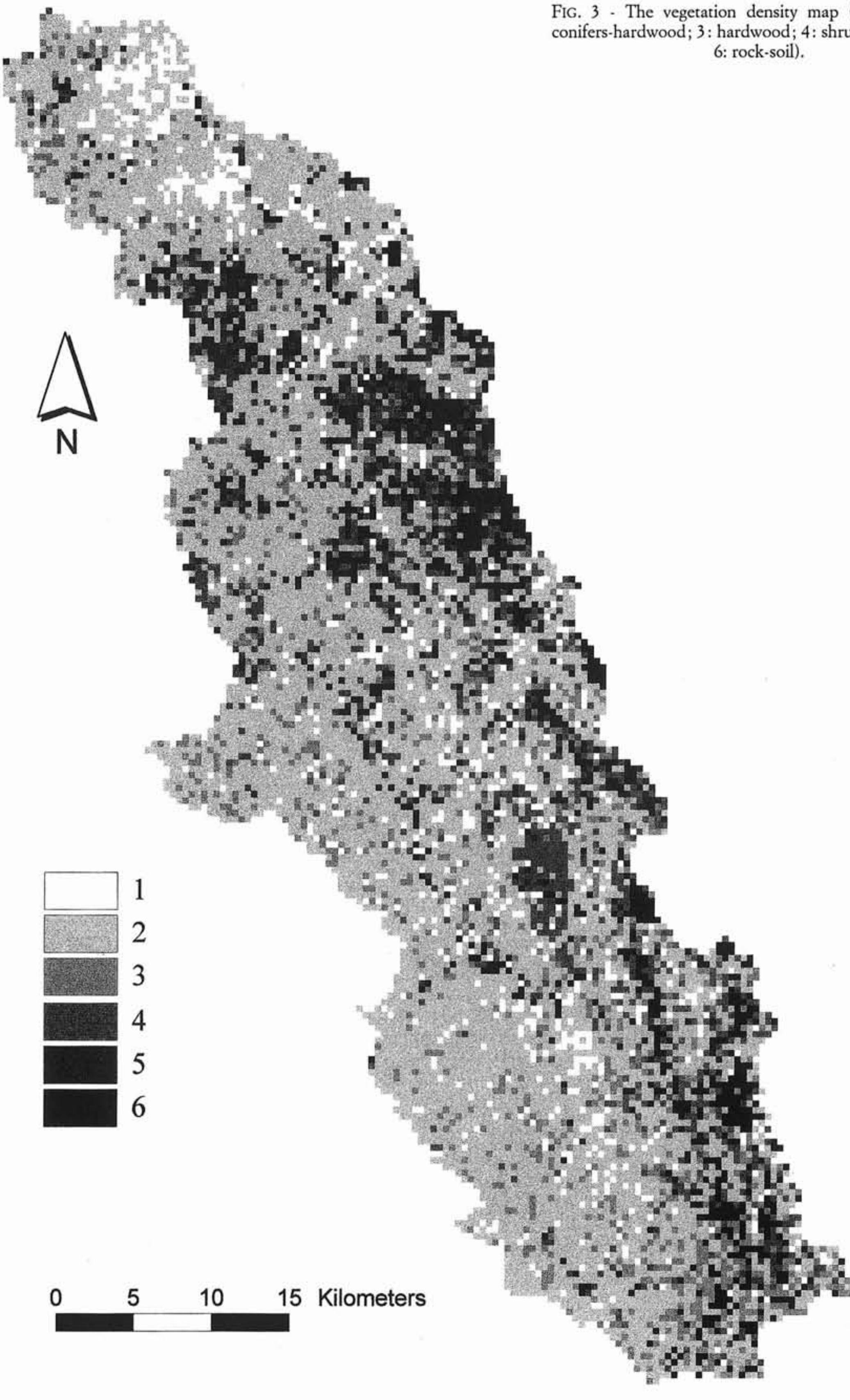

FIG. 3 - The vegetation density map (1: conifers; 2: conifers-hardwood; 3: hardwood; 4: shrubs; 5: grassland; 6: rock-soil).

and the drainage network extraction (10 m and 2 m DEMs were also available but only for sub-sample areas). Two different grids of the same extension and with equal resolutions were acquired, one for the lithology and another one for the landcover. The lithological data was derived from the geological map of California (Blake & *alii*, 1982), while the landcover data was obtained by processing a Landsat satellite image of the area (Klamath Bioregional Assessment Project, 1998). The geology grid acquired was eventually classified into the three erodibility classes (previously defined), numerically expressed by 1 to 3 values: 1=hard; 2=hard-soft; 3=soft rock types (fig. 2). Similarly, the landcover grid was classified into six different units (1=conifer, 2=conifer-hardwood, 3=hardwood, 4=shrubs, 5=grassland, 6=rock, soil) on the basis of the vegetation density, expected to be the landcover factor most influencing drainage density (fig. 3). The slope grid derived from the DEM was expressed in degrees (fig. 4). Finally, also

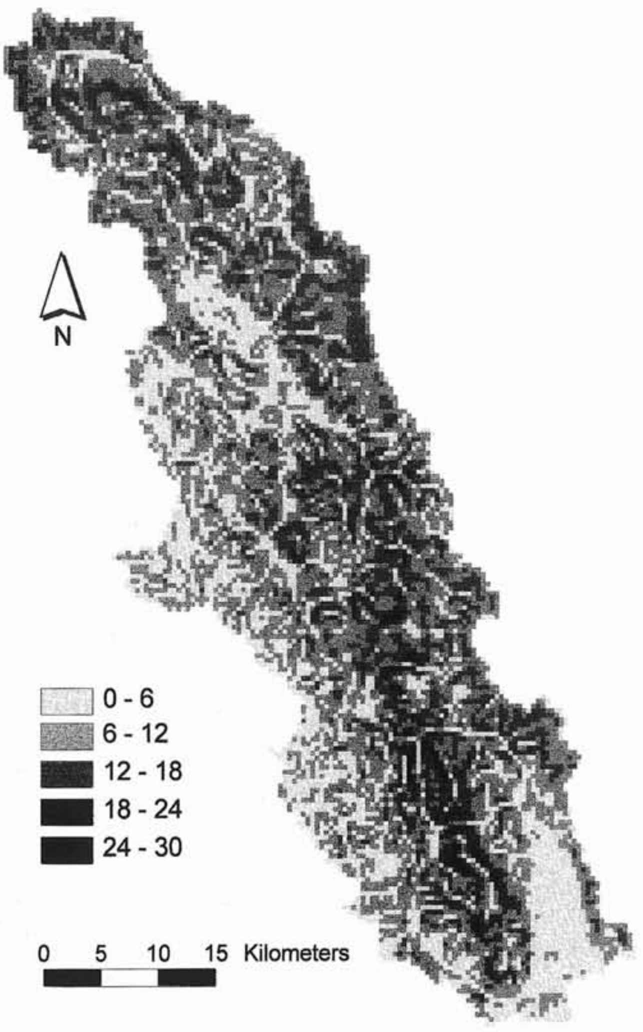

FIG. 4 - The slope map (slope classes in degrees).

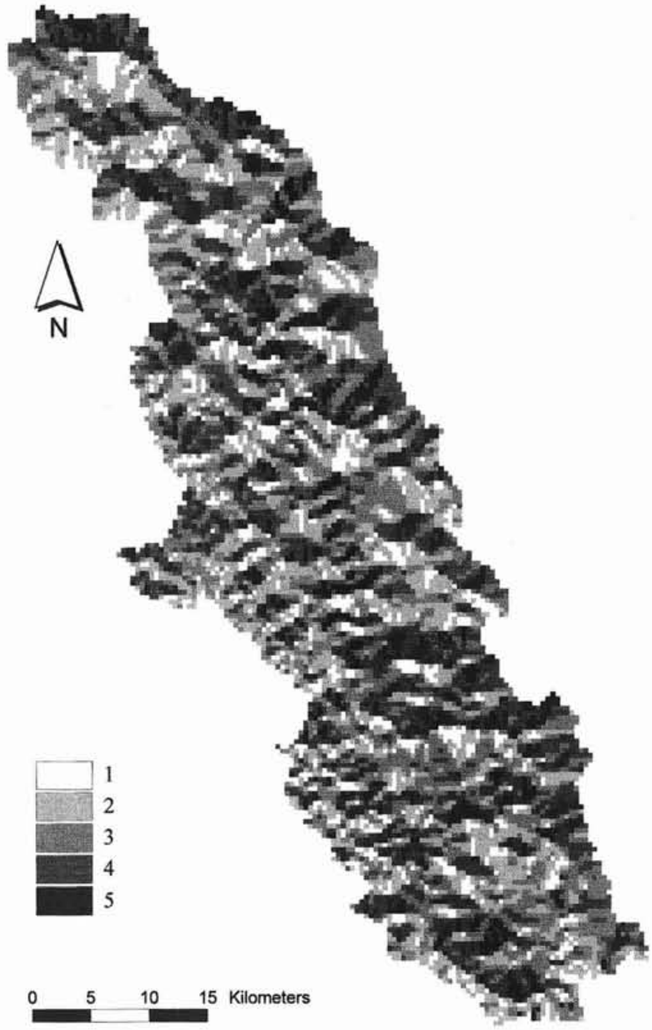

FIG. 5 - The aspect (S-N trend) map (1: N; 2: NE and NW; 3: E and W; 4: SE and SW; 5: S).

the aspect grid was considered in terms of numerical trends: a S-N (1=S; 2=SW and SE; 3=W and E; 4=NW and NE; 5=N; see fig. 5), E-W, SW-NE and SE-NW trends were chosen and four new correspondent grids were created. In this way, for example, in the case of a positive correlation between UD_d and the S-N grid, UD_d is expected to be higher in northern slopes and lower UD_d in southern slopes.

METHOD

Drainage network extraction

The method of automatically detecting the drainage network from a DEM was chosen in consideration of the wide extent of the study area. All pits present in the 30 m

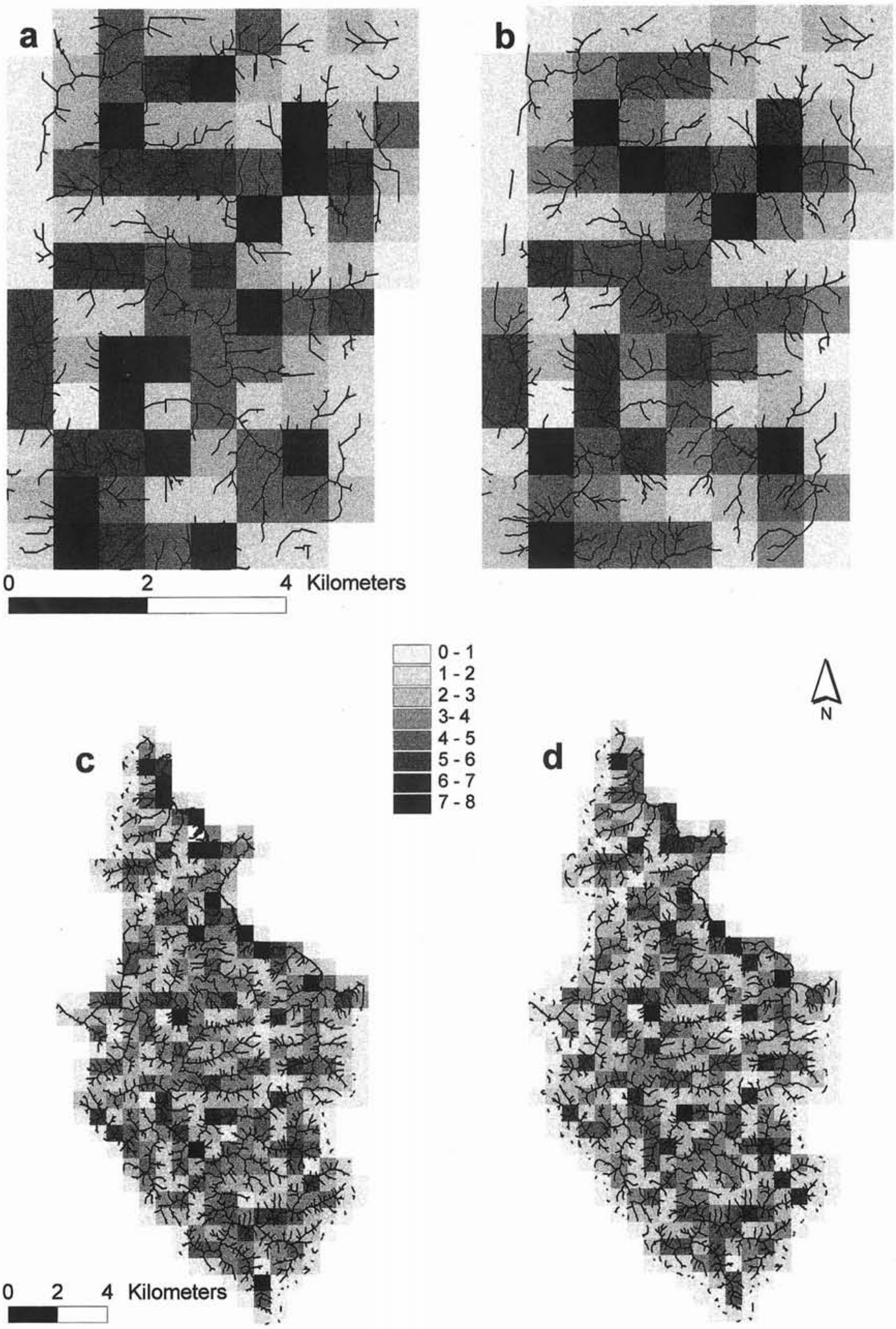

FIG. 6 - The comparison between drainage density maps obtained from DEMs at different resolution (a and c: UD_d from 30 m DEM; b: UD_d from 2 m DEM; d: UD_d from 10 m DEM); the black lines represent the drainage network; the UD_d classes are expressed in 1/km.

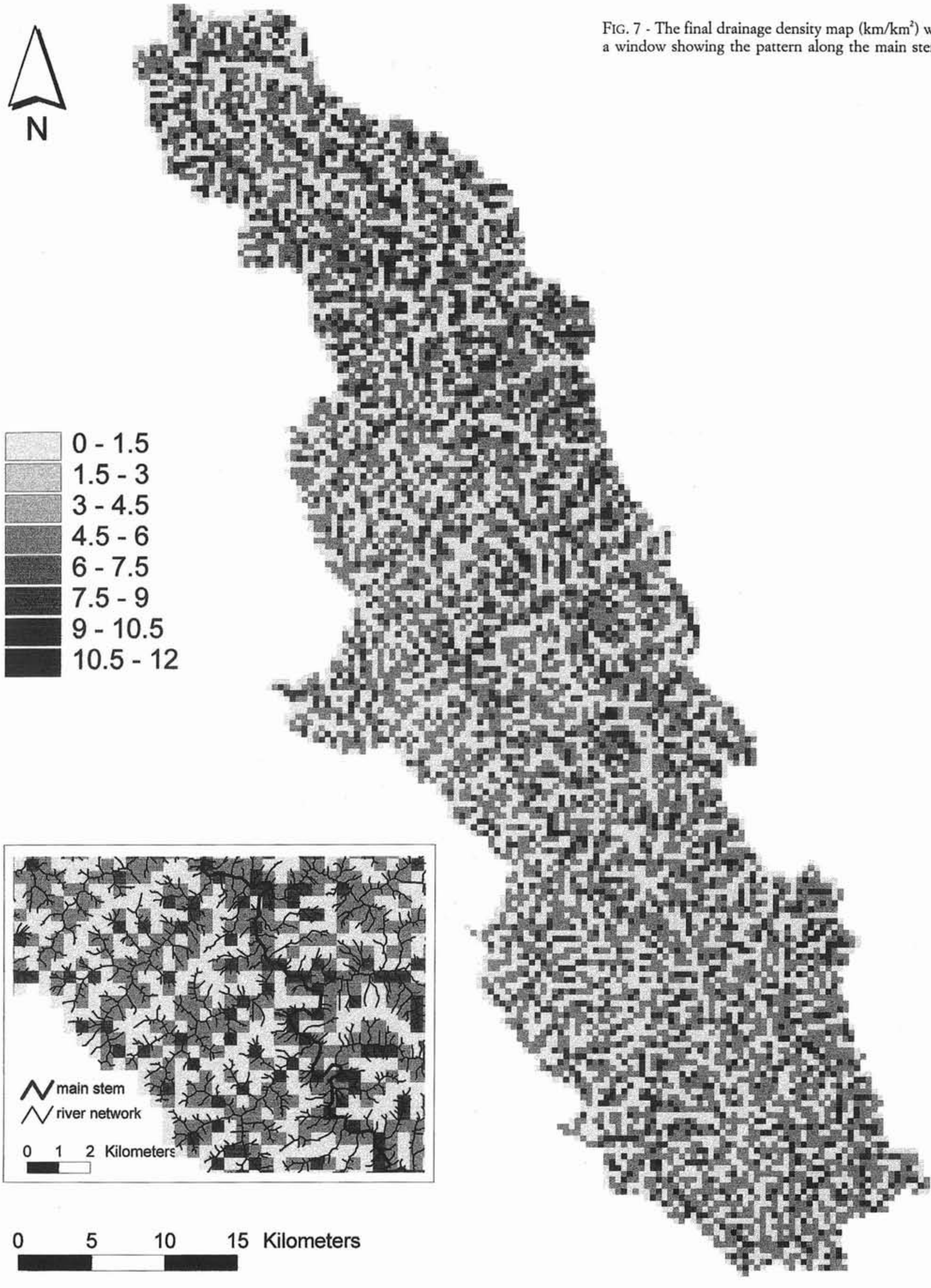

FIG. 7 - The final drainage density map (km/km²) with a window showing the pattern along the main stems.

DEM (related either to data error and/or sampling effects) were first removed by raising them to a level where they overflow or flood. Afterwards, the flow direction and accumulated area matrixes were calculated so that each grid cell value represented the upstream drainage area. Following the most common method (Mark & O'Callaghan, 1984) of identifying channels on a DEM as all points with a certain upstream contributing area above them («flow-accumulation» or «contributing-area» method), four different thresholds (20-25-30-35 pixels) were applied in the South Fork Eel River basin. For four sub-sample areas of various aspect, slope and elevation, the networks obtained from the DEM were compared with the one obtained manually by using the contour crenulation method. Even though some errors were encountered in the low gradient areas (eventually removed), the network obtained from the DEM with a 25-pixels threshold (0.0225 km^2 of minimum accumulated flow area) was found as the closest approximation to the contour crenulation one. For the aim of this study, although the relatively low definition of the data source (30 m DEM) and the consequent lack of part of the uphill first order channels, the network obtained in this way is considered as a good approximation of the real channel network of the area.

Using the same contributing-area threshold on better resolution DEMs (10 m or 2 m) enabled us to obtain a more precise river network. Nevertheless, the final UD_d maps obtained from different DEMs and evaluated within the same unit area of 0.16 km^2 show a very similar trend (fig. 6). In particular, the correlation coefficient among these different UD_d series is of about 0.8 (Pearson's r). This means that, for the purpose of correctly evaluating spatial variation of UD_d at such a unit area threshold, there is no need for a higher resolution DEM than the 30 m ones available for the whole South Fork Eel River.

Calculation of drainage density

With the use of the «flow-direction» and «flow-accumulation» GIS functions, after having specified the 0.0225 km^2 threshold, a grid network was obtained from the original 30 m DEM. Eventually, the grid network was converted into a vector file with a simple raster-to-vector GIS tool. Finally, using a specific script, the unit drainage density (as the cumulative network length per given unit area) was evaluated. The result is expressed by a UD_d grid file (fig. 7), where the attribute value of each cell is the cumulative length of the channel portions within the cell (km) divided by the area of the cell itself (km^2).

The UD_d is evaluated from a river network automatically extracted on the basis of an accumulated area threshold. Moreover, in a space filling perspective, a constant drainage area threshold will tend to minimize drainage density spatial variation over large areas. For these reasons, the choice of the unit area (the final UD_d grid cell size), by which unit drainage density is measured, is a crucial methodological point. For the work presented here, we applied a rational and objective criterion, based both on the cumulative channel length and the autocorrelation of the final drainage density distribution.

For the cumulative channel length, the idea was to obtain a final UD_d where in each cell the channel length is significantly greater than the cell side. Considering that the network obtained has a total length of 6,573 km, the drainage density of the South Fork Eel River basin (1,783 km^2), on average, is $D \simeq 3.8$ km/km^2. In this case, a squared cell with a side of 0.2 km would have on average a too low cumulative channel length (0.152 km), while with a side of 0.3 km the cumulative length (0.342 km) is slightly greater than the cell side itself. Finally, at a cell side of 0.4 km, the cumulative channel length (0.608 km) is significantly greater than the cell side itself.

In order to obtain a significant spatial variation of UD_d and to avoid an excessively high autocorrelation, following a similar statistical approach to Tucker & *alii* (2001), the auto-correlation of the drainage density spatial distribution at different unit areas was evaluated (fig. 8). The autocorrelation for a unit area of 0.16 km^2 (0.4 km x 0.4 km) is very low ($\simeq$ 0,05), which means a strong spatial variation of D. Smaller unit areas show a very low spatial variation (high auto-correlation values), each positive D value being correspondent to a small portion of only one channel (and each null value correspondent to the ridges between channels). On the other hand, a drainage density obtained with a larger unit area, even though acceptable in terms of autocorrelation, would have caused an excessively large approximation of the other spatial parameters that need to be correlated with UD_d.

Concluding, a cell size of 0.16 km^2 seems to satisfy both criteria and was chosen for this analysis. Moreover, it has not to be forgotten that also the lithological, vegetation and topographic parameters could have an auto-correlation problem depending on the choice of unit area. In this case, with a unit area of 0.16 km^2, the parameters taken into account show an almost null auto-correlation.

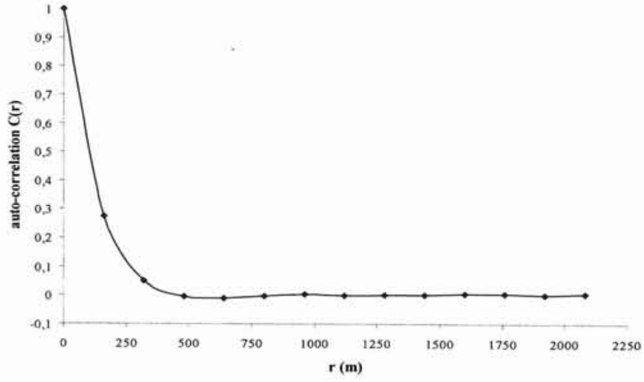

FIG. 8 - The autocorrelation plot (auto-correlation C(r) vs unit area size; r is the side – in meters – of the squared unit area).

Correlation

With the use of specific GIS extensions, the spatial correlation between UD_d, lithology, landcover, aspect and slope was evaluated. For this purpose all the parameters needed to be expressed numerically and with an equivalent grid cell size. Every grid theme (lithology, landcover and the original DEM) was then converted into a grid theme with a cell size of 500 m. At this cell size the total study area is represented by 11,107 cells. Slope and aspect were derived automatically from the new DEM.

The correlation obtained between the different variables is expressed in terms of correlation coefficient (Pearson's r):

$$r = (\text{covariance}(x, y) / (\sigma(x) * \sigma(y))$$

with σ being the standard deviation and x,y the two series taken into account. The results were statistically tested with the t test for Pearson's correlation where t is defined as follows (Lane, 2001):

$t = r / s_r$

with s_r being the standard error of r and equal to $s_r = [(1-r^2) / (N-2)]^{0.5}$

where N is the sample size (in this case always 11,107).

The null hypothesis (H_0) considered in this analysis states that two variables are independent (Pearson correlation coefficient equals zero). Results were considered significant if the probability, p, to be H_0 wrong was <5%. When this probability exceeded 5% ($p>0.05$), the correlation was considered non-significant. With such a significance level (5%), the consequent t minimum value for a significant result was t = 1.983.

RESULTS

The rock type map (fig. 2) shows that the basin can be lithologically distinct in three main geographic sectors: a WSW sector characterized by hard rocks, an ESE sector with soft rocks and a N sector with intermediate soft-hard rocks. Part of the main stem of the river, as well as some of the secondary branches, runs along the contact between different rock type units, often following the main structural direction of SSE-NNW.

In the vegetation density map (fig. 3) the most representative class is the one characterized by a mixed vegetation of conifers and hardwood (60%), uniformly distributed in the whole basin, especially in the central and western sectors. On the contrary, the least represented class is the one characterized by absence of vegetation (1%). The other four classes each occupy about 10% of the basin area, with conifers mainly located in the central and northern sectors, grasslands in the eastern sector and shrubs and hardwood in the central sector of the basin.

The slope map (fig. 4) shows higher values (max 26.8°) along the main valley in the northern sector, while in the central sector they are usually located East of the main valley. Flat or very gentle areas characterize the western part of the basin.

All the possible aspects (fig. 5) are uniformly distributed within the basin, even though the North and South slopes are less common (together, 22% of the whole area) than the other three classes.

The UD_d map (fig. 7) shows a general pattern with higher values along the main stems of the river network and lower values on the top of the hills or along ridges dividing consecutive channels. Similar research carried out in a mountainous area in the Italian Alps with both small and large basins (Spagnolo, 2002) does not show a higher UD_d along the main stems of the river networks as in the Eel River South Fork. This suggests that the result found here has little to do with the method but rather could be more probably related to the morphological condition of the basin analysed. Although on the basis of this preliminary results it is not possible to reach any general conclusion, it can be hypothesized that in well-developed big rivers and in relatively low relief basins the lateral erosion of the main stems causes steepening of lateral valley-sides and creates the condition for the elongation and formation of new small lateral tributaries (and consequently higher UD_d). This is actually the case of the Eel River basin where at the valley thalwegs the main stems collect all the incoming tributaries, resulting in a higher UD_d. One of the possible reasons for an increment of the main stems' erosive power could be local base level lowering, due either to eustatic changes or, more likely in the study area, to active tectonic movement.

The relationships between rock type, vegetation density, slope and aspect

Before analysing their correlation with UD_d, all the other spatial parameters were compared to one another. The results show that vegetation density is well correlated with rock type and aspect (N to S trend); rock type is also correlated with slope. The direct relationships between lithology and vegetation density (r = 0.303) and between aspect and landcover (r = 0.168) mean that denser vegetation (conifers, hardwoods) is associated with northern (more humid) slopes and harder rocks (Coastal Franciscan Belt) while sparse (shrubs, grassland) or null vegetation with southern (and drier) slopes and softer rocks (Central Franciscan Belt). The positive, although lower, correlation between slope and lithology (r = 0.109), suggesting harder rocks associated with less steep slopes and softer rocks with steeper slopes, may be interpreted in a tectonic key. In fact, by looking at the rock type distribution it can be easily verified that harder rocks occupy most of the western portion of the study area, which is also the one that likely experienced the highest tectonic uplift, it being closer to the Mendocino Triple Junction.

The relationship between unit drainage density and the other parameters

The correlation analysis between UD_d and the other spatial parameters taken into account generally shows very

TABLE 1 - Matrix showing correlation values for the variables analysed

	Drainage density	Rock type	Landcover	Slope	Aspect (N to S)	Aspect (E to W)	Aspect (NW to SE)	Aspect (NE to SW)
Drainage density	1,000	0,087	–0,034	0,032	–0,100	0,143	–0,182	0,028
Rock type	0,087	1,000	0,303	0,109	0,009	0,048	–0,032	0,039
Landcover	–0,034	0,303	1,000	–0,086	0,168	0,003	0,113	0,119
Slope	0,032	0,109	–0,086	1,000	–0,003	0,066	–0,047	0,042
Aspect (N to S)	–0,100	0,009	0,168	–0,003	1,000	0,057	0,639	0,680
Aspect (E to W)	0,143	0,048	0,003	0,066	0,057	1,000	–0,657	0,691
Aspect (NW to SE)	–0,182	–0,032	0,113	–0,047	0,639	–0,657	1,000	–0,023
Aspect (NE to SW)	0,028	0,039	0,119	0,042	0,680	0,691	–0,023	1,000

TABLE 2 - The t-test of Pearson's correlation matrix, showing t values (related to correlation values of tab. 1) for the variables analysed (significant values, $p < 0.05$, when $t > 2$)

	Drainage density	Rock type	Landcover	Slope	Aspect (N to S)	Aspect (E to W)	Aspect (NW to SE)	Aspect (NE to SW)
Drainage density		9,217	–3,588	3,354	–10,564	15,243	–19,505	2,913
Rock type	9,217		33,446	11,528	0,915	5,093	–3,329	4,139
Landcover	–3,588	33,446		–9,056	18,012	0,264	12,016	12,612
Slope	3,354	11,528	–9,056		–0,269	6,968	–4,924	4,459
Aspect (N to S)	–10,564	0,915	18,012	–0,269		5,981	87,433	97,603
Aspect (E to W)	15,243	5,093	0,264	6,968	5,981		–91,842	100,851
Aspect (NW to SE)	–19,505	–3,329	12,016	–4,924	87,433	–91,842		–2,411
Aspect (NE to SW)	2,913	4,139	12,612	4,459	97,603	100,851	–2,411	

low values of correlation (tab. 1). Nevertheless, with such a big amount of data, most of the values found have to be considered as significant (tab. 2).

In the study area the UD_d seems to be influenced mainly by aspect and secondarily by rock type. Its relationship with vegetation density and slope is too low ($r = 0.03$ in both cases) to be considered relevant, it being very close to the significant limit.

The relatively strong inverse relationship between UD_d and the NW-SE aspect trend ($r = -0.18$) means that drainage density is higher in NW slopes while it is lower in SE ones. This could be only partly explained by the micro-climatic trend of drier conditions moving inward and southward in the study area, because south-eastern areas do not necessarily have SE slopes. It is more likely related to the combination of two more factors, both resulting in a relative higher humidity of the NW slopes: the lower sun radiation experienced on northern slopes and the higher precipitation of western slopes directly facing the sea, from where most of the humid air masses come. A higher humidity, in this case of NW slopes, is likely to cause a more rapid and easier formation and development of water channels, resulting in a higher drainage density (Gregory & Gardiner, 1975; Abrahams & Ponczynski, 1984) .

The direct relationship ($r = 0.087$) with lithology (higher D with softer rocks), as already suggested by many authors (Tanaka, 1957; Strahler, 1964; Wilson, 1971; Tandon, 1974; Ciccacci & alii, 1988; Lupia Palmieri & *alii*, 1998), is a consequence of the higher erodibility of weaker rocks that allows the formation of well-developed channel networks.

CONCLUSION

The method of measuring drainage density within a constant unit cell size makes it possible to quantitatively evaluate the relationship between this and any other spatial variable. In this study the unit drainage density was derived from a digital river network automatically extracted from a 30 m DEM. Both choices of contributing area threshold (for the river network extraction) and unit area within which the UD_d was calculated were crucial methodological points. This is particularly because a drainage density derived from an automatically extracted river network tends to have a high autocorrelation which is not good for future analysis. The network obtained from the DEM with a 0.0225 km^2 contributing area threshold was found as the closest approximation to the one obtainable with the contour crenulation method. A drainage density unit area of 0.16 km^2 was chosen considering both the cumulative channel length and the low auto-correlation of the resulting UD_d spatial distribution (auto-correlation $\simeq 0.05$).

The use of GIS tools and digital data enabled us to take into account a river basin (the South Fork Eel River basin) as wide as 1,783 km^2. With the constant unit area of 0.16 km^2, the drainage density pattern obtained for the Eel River South Fork shows a general increment along the main stems where big water channels usually collect incoming tributaries and small channels of recent formation. The correlation analysis between slope, aspect, rock type and vegetation density highlights a strong relationship between rock type, vegetation density and aspect due to the obvious direct dependence of vegetation on micro-climatic and lithological conditions.

Less strong, although in some cases still significant, was the correlation between UD_d and the other spatial parameters analysed. This is likely a consequence of the fact that there are several different influencing factors that take part in the development of a river network. Nevertheless, for the study area both aspect (SE-NW trend) and rock type (harder to weaker trend) showed a positive and significant correlation with UD_d. Lithology influences drainage density in terms of rock erodibility and consequent landscape dissection by water channels. The aspect of an area is strictly related to its microclimatic condition. In the study area, NW slopes are usually the more humid ones and a higher humidity results in the elongation of old channels and formation of new ones.

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