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GIS-BASED MORPHOMETRIC ANALYSIS OF TWO MAJOR WATERSHEDS, WESTERN CRETE, GREECE

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Watershed analysis based on a geographic information system (GIS) was carried out in two agricultural watersheds in the central area of Chania prefecture on the island of Crete, Greece. The digital data for deriving geomorphometric parameters significant for the evaluation of watershed condition were extracted from topographical, geological, hydrological and hydrolithological maps, and were updated by Landsat-ETM satellite imagery. Geomorphometric parameters such as drainage density, stream frequency, hypsometric integrals and hypsometric curves, especially at the sub-basin level, enabled an understanding of the relationships among the different aspects of the drainage patterns and their influence on landform processes, drainage, and land erosion properties. Geomorphometric parameter analysis coupled with fractal analysis and statistical analysis of the stream tributaries revealed that the two watersheds have undergone severe erosion in the past, and are still susceptible to surface erosion, while their development has been significantly affected by geomorphological and lithological factors such as faults, slope, and rock permeability.

INTRODUCTION

The quantification of river networks was introduced by Horton (1932, 1945) who studied the origin of river networks. According to Horton (1945) many hydrologic measurements are available to quantify the description of river networks and drainage basins. As a result, a series of power-law type relations have been extended by other investigators (e.g. Strahler, 1952; Hack, 1957; Gregory and Walling, 1973). These studies have led to the establishment of quantitative fluvial geomorphology. The recent development of fractal theory has provided new horizons to this field of study considering that many kinds of landforms are fractals and multifractals (e.g. Mandelbrot, 1983; Seiler, 1986; Hjemfelt, 1988; Tarboton et al., 1988; La Barbera and Rosso, 1989; Phillips, 1993; Goodchild, 1982; Lavallee et al., 1993; Cheng, 1995; Cheng et al., 1997, 2001). Thus, fractal modeling can be applied to river networks and drainage basin systems with the aim to characterize the evolution of stream systems in terms of geological constraints.

In recent years, the automated determination of drainage basin parameters has been shown to be efficient, timesaving and an ideal application of GIS technology.

The present work addresses the following: (1) estimation of morphometric quantities using GIS software and (2) application of "localized" drainage basin-based statistical and fractal measures to characterize the variance of possible geological constraints on the evolution of individual drainage basins.

The morphometric parameters (area of basins, perimeter of basins, total length of stream channels, basin length, bifurcation ratio, average stream length ratio, drainage density, stream frequency, texture ratio, form factor, elongation ratio and constant of channel maintenance) were extracted for the two major watersheds of Chania prefecture, Crete, the Keritis and Tavronitis watersheds, as well as for the three main sub-basins of the Tavronitis watershed. The calculated values were mapped and analyzed using statistical methods and GIS in order to characterize the stream networks and drainage basin systems. In addition, hypsometric curves and integrals were calculated since they are important indicators of watershed conditions (Ritter, 1986; Awasthi et al., 2002) and selected fractal models have been applied to characterize the stream networks and drainage basins.

The results obtained on the basis of stream and drainage basin analysis provide information for an improved understanding of the hydrological characteristics of the broader Chania area. The integration of the geological and tectonic structures, lithology and slope of drainage basins reveals the relationship between stream patterns and geological and geomorphological factors, as well as the role of geomorphological and geological factors in the evolution of streams in the Chania prefecture.

GEO-TECTONIC AND HYDROLITHOLOGICAL CONTEXT OF THE STUDY AREA

Crete is considered a semi-arid region. The average annual precipitation is estimated to be 900 mm, the potential renewable water resources 2650 mm and the real water used about 485 million m^3/yr (Chartzoulakis et al., 2001). The major water use in Crete is in irrigation for agriculture (84.5% of the total consumption) while domestic use is 12% and other uses 3.5% (Chartzoulakis et al., 2001; Tsagarakis et al., 2004).

The study area is situated at latitudes between $35^o19'12''$ and $35^o32'05''$ and longitudes between $23^o44'54''$ and $24^o01'05''$, in the central part of Chania prefecture. It comprises the

Keritis watershed in the east and the Tavronitis watershed in the west as shown in Figure 1. The Keritis basin lies 4 km west of Chania city and covers 181 km^2 and the Tavronitis basin covers 131 km^2. The watersheds are drained by the two of the most important rivers of the region. The climate is sub-humid Mediterranean with humid and relatively cold winters and dry and warm summers. During winter that starts in November, the weather is unstable due to frequent changes from low to high pressure. The annual rainfall for the broader Chania area has been estimated to be 665 mm (Chartzoulakis et al., 2001). It is estimated that from the total yearly precipitation on the plains about 65% is lost to evapotranspiration, 21% as runoff to sea and only 14% goes to recharging the groundwater (Chartzoulakis et al., 2001). The rainfall is not uniformly distributed throughout the year, and it is mainly concentrated in the winter months, while the drought period is extends over more than six months (May to October) with evaporation values ranging from 140 mm to more than 310 mm in the peak month. As a result, water resources availability is limited due to temporal and spatial variations of precipitation (Tsagarakis et al., 2004). The demand for irrigation water is high, while at the same time only 31.0% of the available agricultural land is irrigated.

The surficial geology consists of Quaternary deposits that form depositional plains oriented from north to south at an elevation of 20-200 m above msl. Miocene to Pliocene sediments crop out in the central and the northwestern part of the study area and carbonates of the Tripolis nappe in the northeastern part. Dissected hills of phyllites and quartzites, a late Carboniferous to late Triassic package of sedimentary rocks composed mostly of quartz-rich siliciclastic sediments, with minor limestone, gypsum, and volcanic rocks (Krahl et al., 1983) cover the central part of the study area. Carbonates of the Trypalion nappe are exposed in the central-eastern and southern part of the Keritis watershed area. Limestones of the Plattenkalk zone are mainly exposed to the most southern part of the Keritis watershed. Regarding permeability, the exposed geological formations can be classified into four hydrolithological units: high permeability rocks which comprise the karstic limestones of the Tripolis and Trypalion nappes, medium permeability rocks which consist of the Quaternary deposits as well as the Miocene to Pliocene conglomerates and marly limestones, low permeability rocks which consist of the Pliocene to Miocene marls, and impervious rocks which consist of the phyllites-quartzites unit.

The tectonic regime of the study area is characterized by faults in NW-SE and E-W directions. These tectonic structures clearly define the boundaries between the existing geological and hydrolithological units (Figures 2 and 3).

METHODOLOGY

In order to create the appropriate information platform upon which to proceed in a systematic way towards determining the morphometric parameters, all available maps were collected (hydrological, hydro-geological, geological, and topographic) and used as the basis for the creation of several GIS thematic layers.

All the data were implemented into a GIS environment and data digitization using ArcGIS software package was performed. The several maps were geo-referenced to the local projection system of Greece (GGRS ‘87 - Greek Geodetic Reference System) so that they could all be tied to the same projection system, together with all future information that may become available. The data manipulation flow chart is shown in Figure 4.

The drainage networks were traced on transparency and digitized as hydrological maps (1:20000) of the study area. The second principal component derived from the processing of a

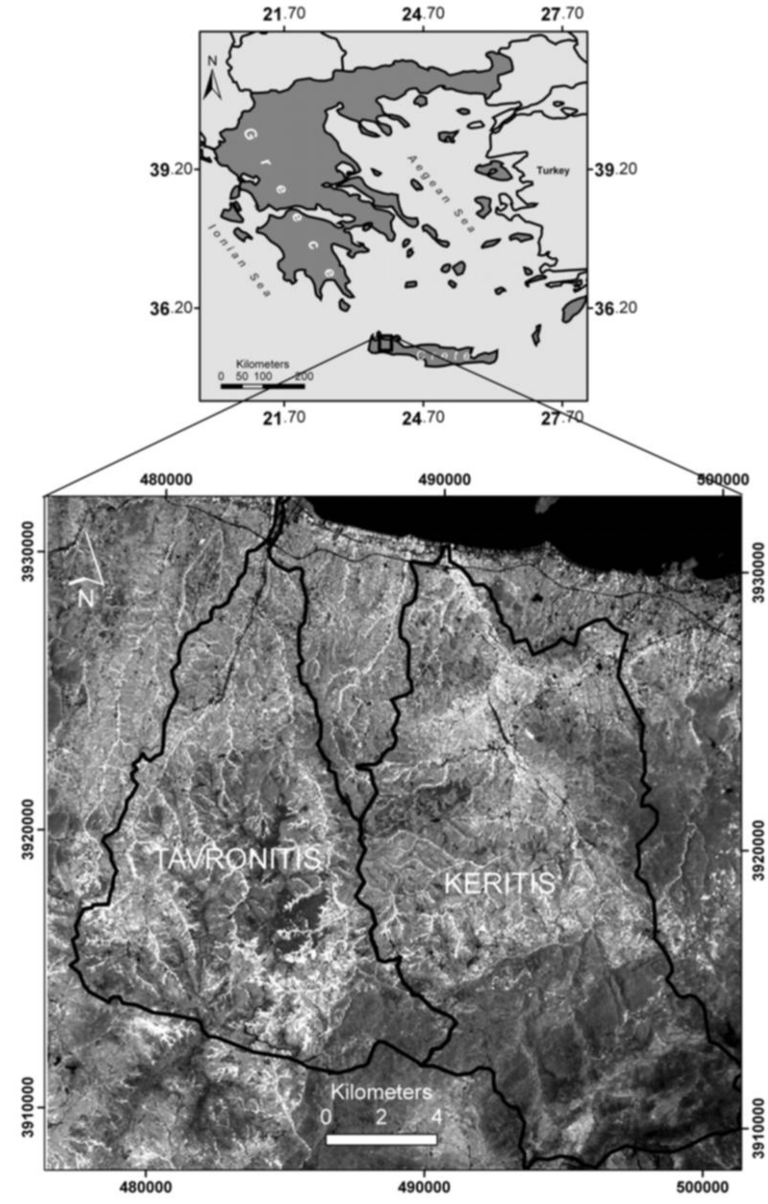

Figure 1. Location of Tavronitis and Keritis watersheds. The second principal component of the Landsat-ETM satellite image reveals the drainage network of the studied watersheds.

Landsat–ETM satellite image of the study area, with a spatial resolution of 30x30 m pixel size for the seven bands of multispectral data, acquired on 30 June 2000, was used for the correction and update of the digitized stream data. The satellite data were also used for the hydrolithological map production through the unsupervised classification with the Isodata algorithm.

The Digital Elevation Model (DEM) of the study area with a cell size of 20 m is a continuous raster layer, in which data values represent elevation. It was generated from the topographic maps (1:20000) of the study area. As a result, significant geomorphological parameters such as slope gradient have been quantified.

The ordering of the digitized streams was performed in GIS according to Strahler's system (Strahler, 1957, 1964). In this classification, streams with no tributaries are defined as first order;

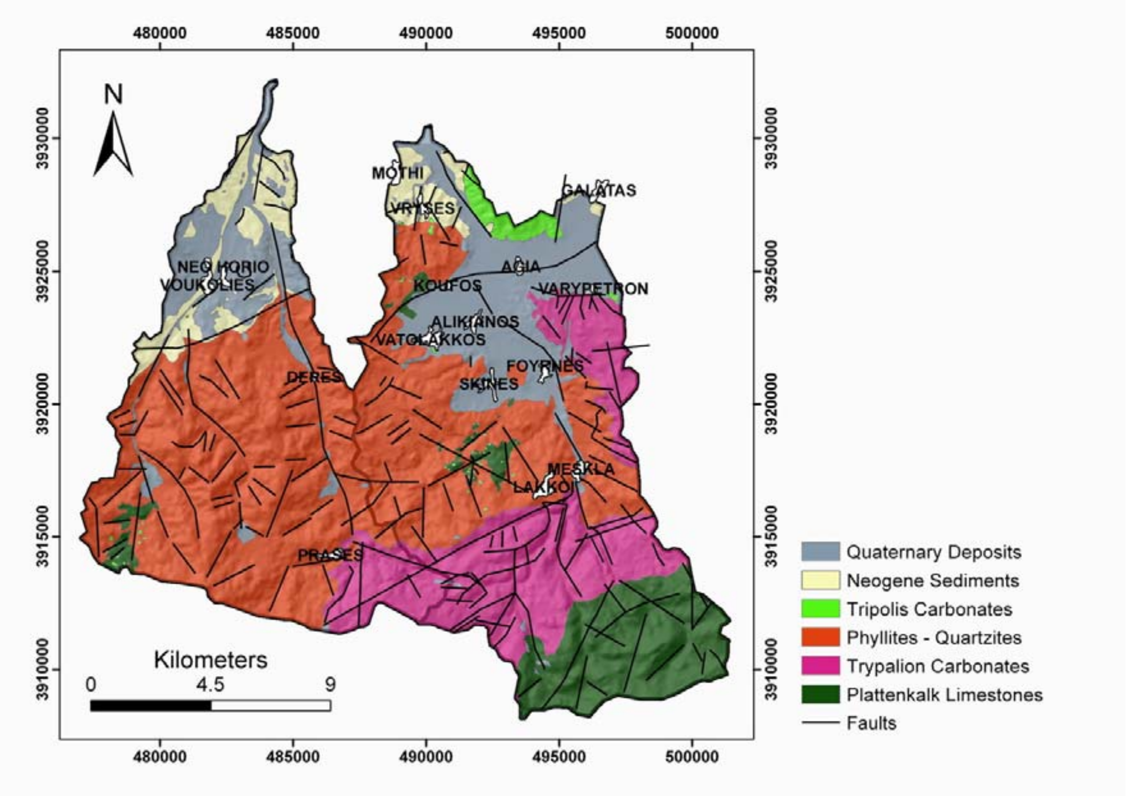

Figure 2. Geological map of Tavronitis and Keritis watersheds. Faults are also given using black thick lines.

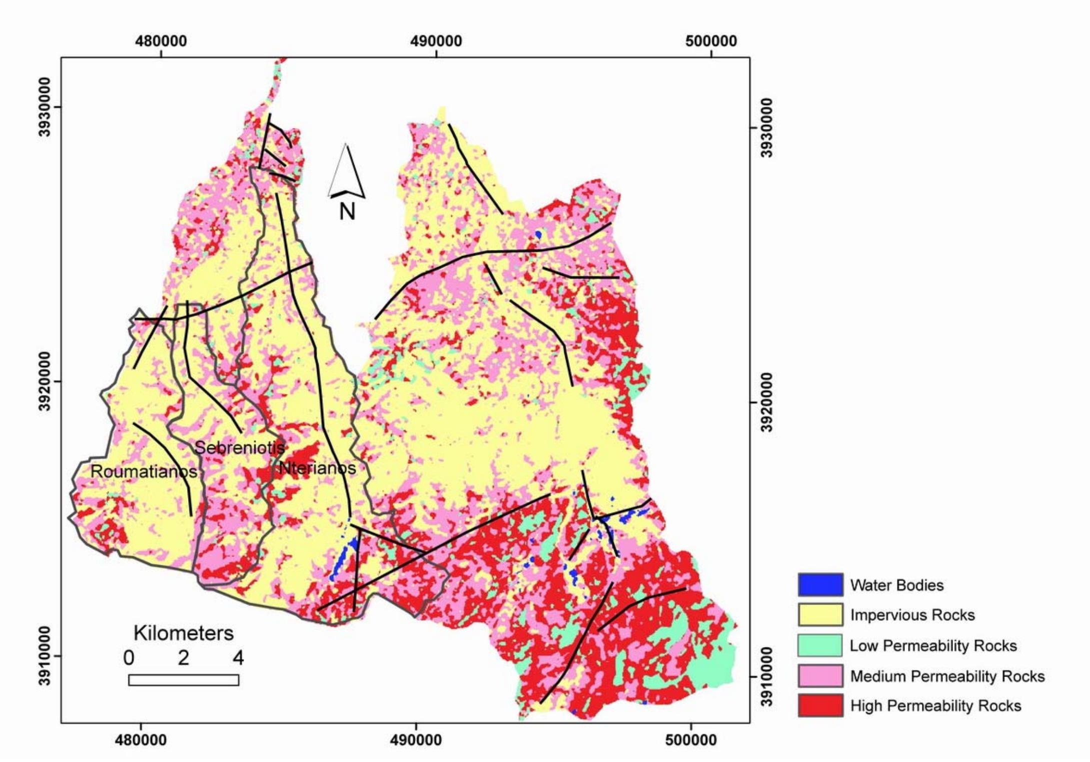

Figure 3. Hydrolithological map of the Tavronitis and Keritis river basins derived after the Landsat-ETM satellite image unsupervised classification. The major faults and the Tavronitis sub-basins borders layers are superimposed to the map.

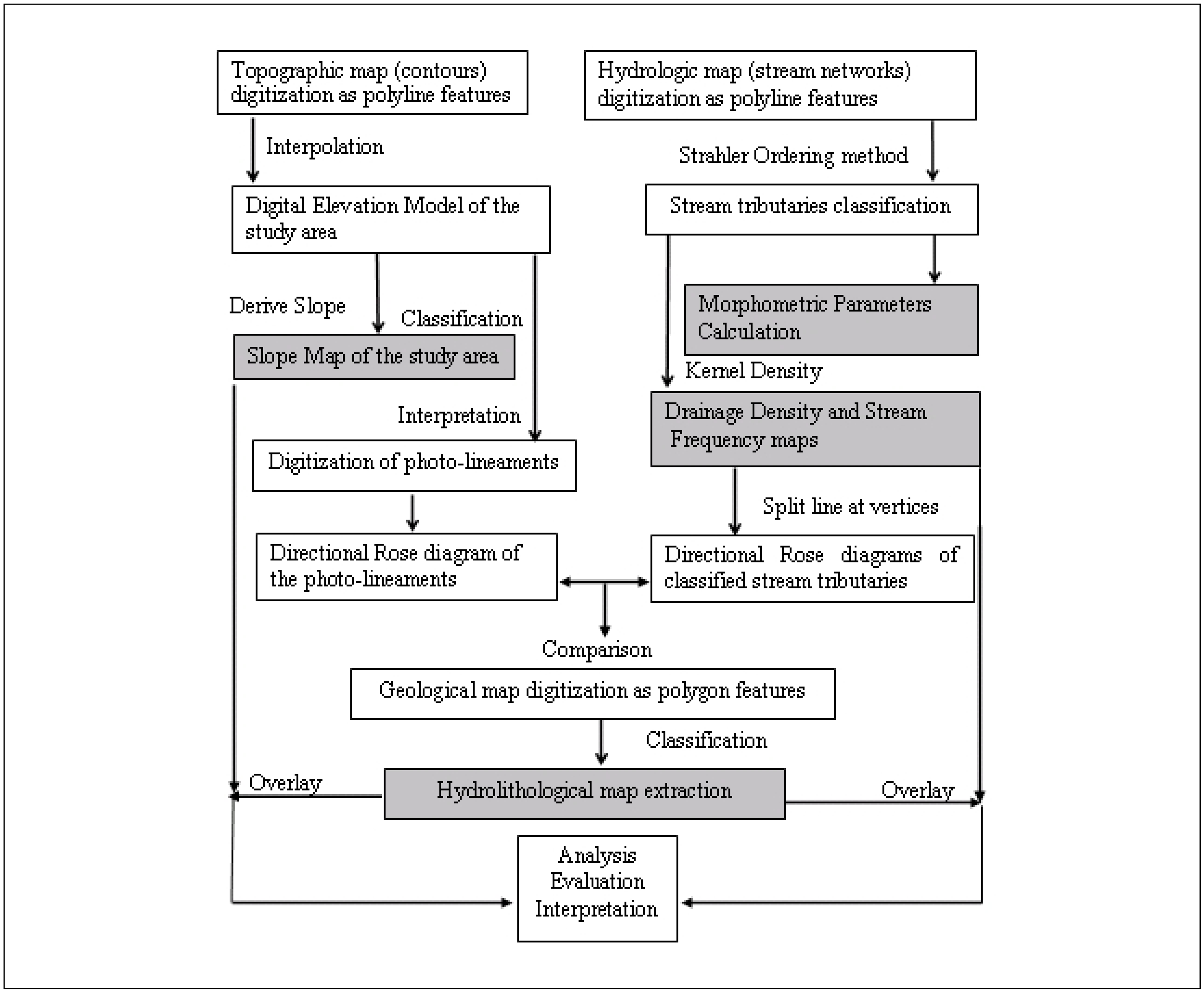

Figure 4. Flow chart showing processes involved in river basins analysis.

two first-order streams join to form a second-order stream, etc. In general, two streams of the same order join to form a stream with a stream order increased by one (Figure 5). The two major watersheds of the study area, the Keritis and Tavronitis watersheds, were found to be of sixth order. For a more detailed morphometric analysis the Tavronitis basin was classified into 3 sub-basins of fifth order; the Sembreniotis, Roumatianos and Derianos sub-basins (Figure 5).

The basic watershed characteristics (basin area, perimeter, cumulative length of streams and basin length) were measured in the GIS environment. Morphometric parameters such as stream frequency, (F_u), drainage density, (D_d), texture ratio, (T), form factor, (R_f), elongation ratio, (R_e) and constant of channel maintenance, (C) were evaluated with mathematical equations (Strahler, 1964). The extracted values are shown in Table 1.

Other hydrological descriptors such as hypsometric curves and integrals were also calculated for the two major basins and the three sub-basins. The hypsometric curve is an area-elevation relationship curve that plots normalized elevation against normalized area of a watershed (Strahler, 1952) and classifies the watersheds into several levels of geomorphic maturity as influenced by various forcing factors such as tectonics, climate and lithology. The hypsometric integral (HI) can be calculated from the area under the curve, and expresses, as a percentage, the volume of the original basin that remains unweathered.

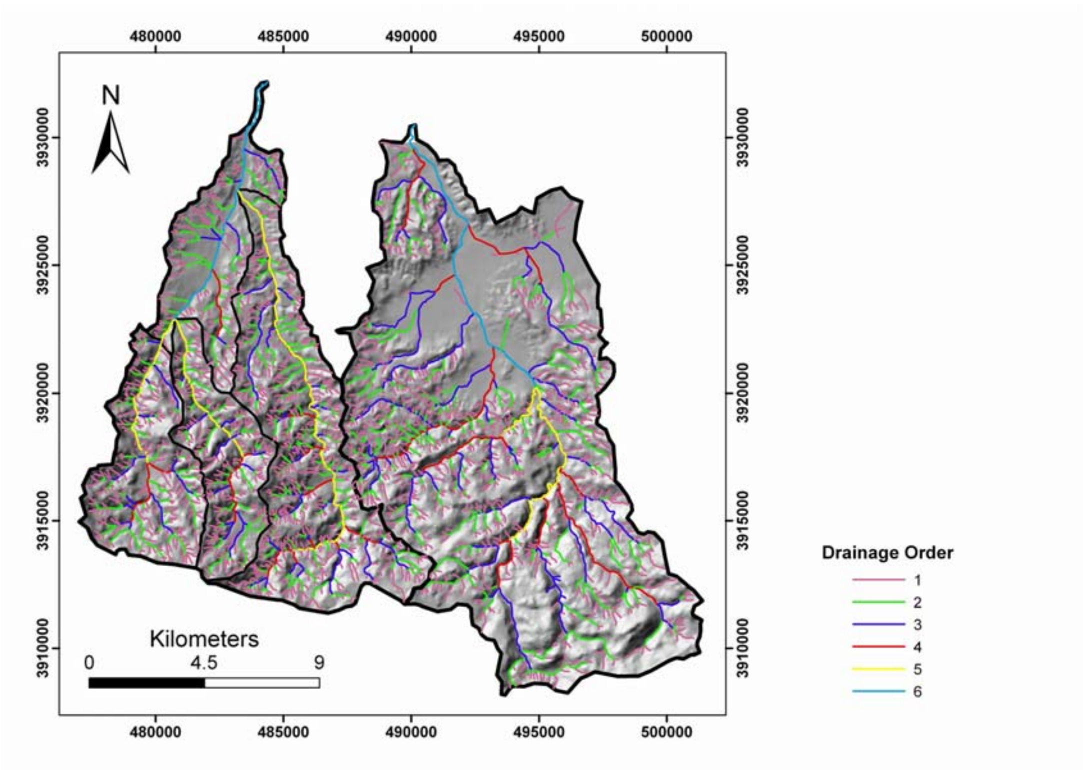

Figure 5. Streams classification map of Tavronitis and Keritis riven basins. The three fifth order sub-basins of Tavronitis are also delineated.

For the identification of the general statistical properties and the probable spatial relationships of stream networks and drainage basins, histogram plots and fractal modeling have been used.

Moreover, directional rose diagrams of the Keritis and Tavronitis classified river tributaries were created in order to compare the development of the drainage networks with the tectonic regime of the area.

The results that were obtained on the basis of stream and drainage basin analysis were integrated with the geological and tectonic structures of the drainage basins is order to reveal the role of

Table 1. Linear and areal relief geomorphometric parameters of Keritis and Tavronitis basins and sub-basins.

Morphometric Parameters	**Keritis**	**Tavronitis**	**Sembreniotis**	**Roumatianos**	**Derianos**
Streams Total Number, N	1783	2312	483	511	1042
Total Stream Length, Σ L (km)	479.27	511.38	92.58	109.26	229.53
Basin Length, Lb	24.87	23.7	11.55	9.95	20.99
Area, A (km^2)	180.62	130.87	22.44	27.78	56.64
Bifurcation Ratio, R_b	2.4	1.99	1.75	1.8	1.68
Average streams-length Ratio, R_L	1.54	1.4	1.45	1.42	1.43
Stream Frequency, Fu	9.87	17.67	21.52	18.394	18.396
Drainage Density, Dd	2.65	3.91	4.13	3.93	4.05
Texture Ratio, T	12.36	18.51	9.4	9.76	10.63
Form Factor, Rf	0.29	0.23	0.17	0.28	0.12
Elongation Ratio, Re	0.61	0.54	0.46	0.6	0.4
Channel maintenance constant, C	0.38	0.26	0.24	0.25	0.25

geomorphological, structural and geological factors in the evolution of the watersheds and streams in the Chania prefecture.

GEOMORPHOMETRIC PARAMETERS CALCULATION

Stream order analysis showed that the two major basins are of sixth order. Three sub-basins (Sembreniotis, Roumatianos and Derianos) of the Tavronitis watershed were identified as fifth order (Figure 5).

Calculation of total stream length (ΣL) showed that the Tavronitis basin has the highest ΣL (511.38 km). The Derianos sub-basin has the highest ΣL (229.53 km) and Sembreniotis the lowest ΣL (92.58 km) among the sub-basins of Tavronitis. For watersheds of the same areal extent, high ΣL may indicate structural complexity, high relief and impervious rocks.

The bifurcation ratio (R_b) was found to be 2.4 for the Keritis and 1.99 for the Tavronitis watersheds. Among the three Tavronitis sub-basins, Roumatianos appears to have the highest (1.8) while Derianos the lowest (1.68) R_b value.

The calculation of drainage density (D_d) is fundamental and reflects geology, hydrolithology, climatic condition, topography and vegetation (Ritter, 1986; Awasthi et al., 2002; Reddy et al., 2004). D_d is significantly higher in the Tavronitis than the Keritis watershed in agreement with the existence of impermeable rocks, sparse vegetation and higher relief. The Keritis basin shows the lowest drainage density among all the studied basins and this fact gives evidence for rocks of higher permeability, lower relief and probably denser vegetation.

High stream frequency (F_u) was calculated for the Tavronitis basin (17.67) and its sub-basins (18.39-21.52). In contrast, the Keritis basin was described by low stream frequency values (F_u=9.87). Moreover, the texture ratio (T) parameter which depends on the underlying geology, infiltration rates of rocks and relief characteristics of the basins, is also high for Tavronitis basin (18.51).

Form factor (R_f) is lower for the Tavronitis than the Keritis watershed, and this fact is probably evidence that the Tavronitis appears to have less side flow for shorter duration and high main flow for longer duration. Among the three Tavronitis sub-basins, Derianos shows the lowest R_f value and Roumatianos the highest R_f value (0.28).

The Keritis watershed shows the higher elongation ratio (R_e) value (0.61), while among the three Tavronitis sub-basins, Roumatianos shows the highest R_e value (0.6) and Derianos the lowest (0.4). This fact may indicate that the Derianos sub-basin has high infiltration and low run off capacity.

The constant of channel maintenance (C) depends on the rock type, permeability, vegetation cover and relief as well as duration of erosion (Schumm, 1956). The very low C value of the Tavronitis watershed (0.26) implies significant structural control. The three sub-basins show the same values, therefore the same dependence upon the local tectonic regime.

The hypsometric curve is related to the volume of the rock in the basin and the amount of erosion that has occurred in a basin compared to what still remains (Hurtrez et al., 1999). The hypsometric integral helps to define the erosion that has taken place over geological time (Bishop et al., 2002). For different basins under the same climatic condition and approximately equal areas, the shape of the hypsometric curves provide relative insights into the past erosional environment of the basins (Awasthi et al., 2002).

Hypsometric curves are usually interpreted as youthful (convex upward curves), mature (S-shaped curves) and peneplain or old age (concave upwards curves) stages of landscape evolution. Convex hypsometric curves are more likely typical of a plateau with little erosion, which can evolve into an S shape, while concave hypsometric curves indicate greater erosion (Hurtrez et al., 1999). The hypsometric curve represents the relative proportions of a watershed area that lies below a given height. For each basin, the range of basin was divided into equal intervals and for each interval the basin area proportion was calculated. The elevation and area values were divided by the relief and the total watershed area to establish a range from 0 to 1.

The hypsometric integral (*HI*) represents the area under the hypsometric curve and corresponds to the percent of original rock mass remaining in the watersheds (Bishop et al., 2002; Awasthi et al., 2002). A hypsometric integral equal to 60% reflects the transition from the youthful to the mature stage, whereas *HI* equal to 30% reflects the transition from the mature to the old age stage (Strahler, 1952, 1957, 1964).

Based on the hypsometric curves and the corresponding hypsometric integrals for the five investigated basins, the Keritis basin seems to be in the old age stage (*HI*=26.21%) of its development whereas the Tavronitis basin is in the mature stage (*HI*=39.32%) of its development. In old age valleys the drainage system becomes very broad and most of the landscape relief has disappeared (i.e. northern Keritis) while in maturity the drainage system becomes more integrated and the extent of the landscape relief is at a maximum. Concerning the Tavronitis sub-basins, they are all in the mature stage with the Sembreniotis basin a little younger (*HI*=36.34%) than the Derianos basin (*HI*=35.63%) and the Roumatianos basin the oldest (*HI*=35.63). The different levels of geomorphic maturity are influenced by various forcing factors such as tectonics.

STATISTICAL ANALYSIS AND FRACTAL MODELLING

In order to identify the statistical properties and the spatial relationships of stream channels and watersheds, histograms were created and fractal modelling was used. Both length histograms of all stream orders (1-6) for the Keritis and Tavronitis watersheds show a lognormal distribution.

Horton's law applies to the number of streams, $n(u)$, which have an average length, $l(u)$, for the u^{th} order (u= 1, 2, . . .), which is the ordering system of Strahler (Horton, 1945; Strahler, 1952). Horton's law shows that the bifurcation ratio (R_b) and the average stream-length ratio (R_L) are two constants given by:

$$R_b = \frac{n(u)}{n(u+1)}, \; R_L = \frac{l(u+1)}{l(u)} \qquad (1)$$

which can be easily related to the fractal dimension of stream networks $D_{\Sigma L}$ (Tarboton et al., 1988; La Barbara and Rosso, 1989; Cheng et al., 1997) as

$$D_{\Sigma L} = \frac{\log R_b}{\log R_L} \qquad (2)$$

Several authors have interpreted the value of $D_{\Sigma L}$ as a possible measure indicating the degree of randomness of the stream network evolution or lack of geological constraint. The extracted values for Keritis ($D^K{}_{\Sigma L}$) and Tavronitis ($D^T{}_{\Sigma L}$) watersheds are almost equal to 2 implying that the stream networks satisfy a space filling property and they are not affected by possible geological constraints. The two sub-basins of the Tavronitis basin, the Sembreniotis and Roumatianos basins, have $D^S_{\Sigma L}$=1.75 and $D^R_{\Sigma L}$=1.8 respectively, whereas the Derianos sub-basin has a $D^D_{\Sigma L}$=1.45. This fact may indicate a local scale geological effect on the river development, which is induced in the Derianos basin.

Moreover, the dependence of the number of streams of various orders on their average length (Turcotte, 1997) for the studied drainage networks is shown in Figure 6. The obtained fractal dimensions are D^K=1.96, D^T=2, D^R=1.7, D^S=1.6, D^D=1.5 and are in a good correlation with the calculated fractal dimensions $D_{\Sigma L}$.

The stream network fractal dimension (D) represents the fractal dimension of the total stream length, ΣL. Mandelbrot (1983) introduced the following relationship between total stream length (ΣL) per basin and drainage basin area (A):

$$\Sigma L \propto A^{D/2} \tag{3}$$

In this case the fractal dimension D, is equal to twice the slope of the straight line formed on the log-log plot of total length versus drainage area (Mandelbrot, 1983; Schuller et al., 2001; Cheng et al., 2001). The calculated average stream network fractal dimension for the studied basins area is equal to 1.72 + 0.08 (Figure 7). This fact shows that although the evolution of stream networks in the study area has a significant degree of randomness, geology also plays an important role. Typical values of D for total stream length vary from 1.5 to 2.0 (Takayasu, 1990; Schuller et al., 2001) with D being greater in areas with greater rainfall.

The perimeter and area of a group of drainage basins have the following power-law relation (Cheng et. al., 2001):

$$P \propto A^{\frac{1}{2} \cdot D_{AL}} \tag{4}$$

where D_{AL} is the fractal dimension and varies between $1 \le D_{AL} \le 2$.

The value of D_{AL} close to 2 indicates that the drainage basins have irregular shapes, whereas the value of D_{AL} close to 1 indicates that drainage basins are regularly shaped. The result obtained for the investigated basins is D_{AL}=1.02+ 0.06 (Figure 7) implying that the basins have regular shapes.

RESULTS AND DISCUSSION

Geomorphometric parameters such as drainage density, stream frequency, hypsometric integrals and hypsometric curves especially at the sub-basin level reveal the relationships among the different aspects of the drainage patterns and their influence on landform processes, drainage, and land erosion properties.

The drainage density (D_d) morphometric parameter appears significantly higher in the Tavronitis watershed implying the existence of impermeable rocks and high relief (Ritter, 1986; Awasthi et al., 2002; Reddy et al., 2004). High D_d values correspond to dissected terrains while low D_d values to long hill slopes (Berger and Entekhabi, 2001; Awasthi et al., 2002). Stream frequency (F_u) values are also high for the Tavronitis basin (17.67) and its sub-basins (18.39-21.52). In contrast, the Keritis basin shows low stream frequency (F_u=9.87) indicating relatively permeable geology and low relief. The overlay of the drainage density (Figure 8) and stream frequency (Figure 8) maps on the hydrolithological/tectonic map, in the GIS environment, shows that areas marked with high

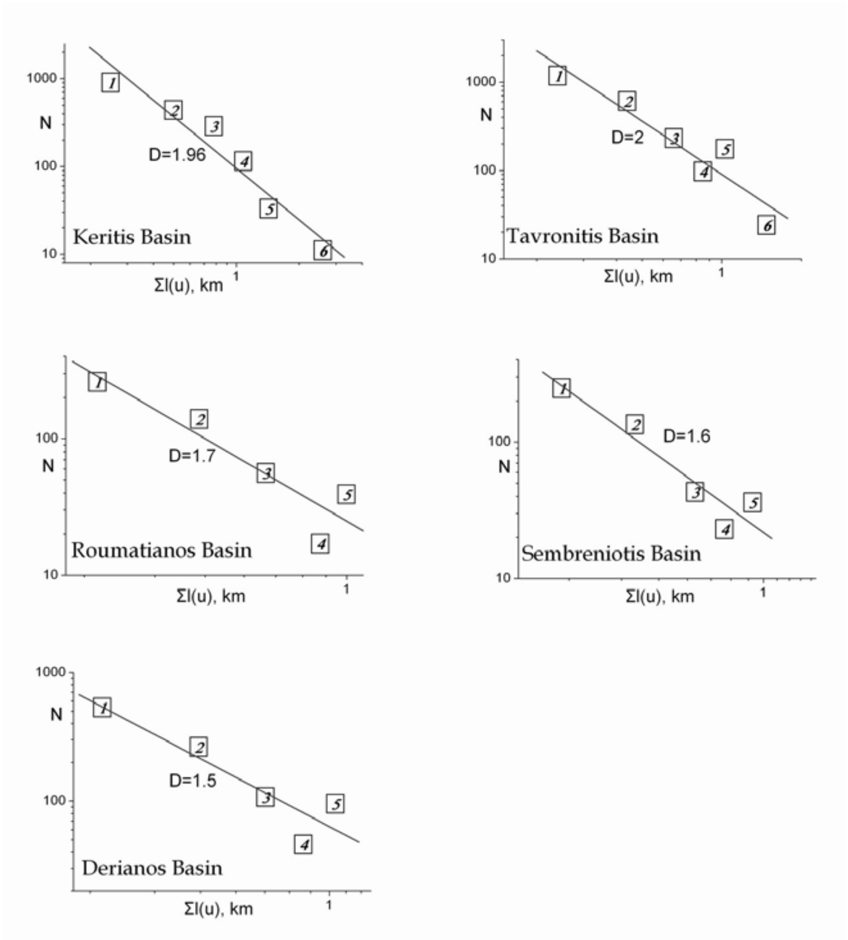

Figure 6. Dependence of the number of streams, N, of various orders 1-6 on their average length, L_u, for the studied watersheds.

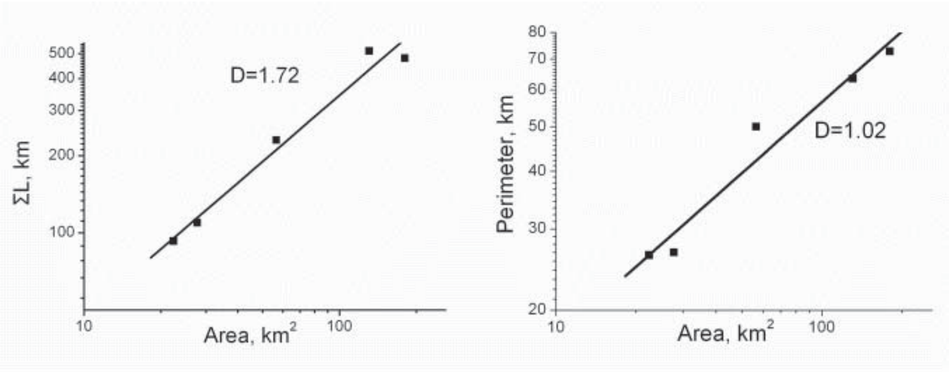

Figure 7. Relationship between total length of streams and area of drainage basins as well as between perimeter and area of drainage basins.

drainage density and high stream frequency correspond mainly to impervious rocks. Domains of high surface permeability typically have low drainage density and stream frequency. High stream frequency values are exhibited in almost linear patterns, parallel or sub-parallel to the major tectonic lineaments in both the Tavronitis and Keritis basins (Figure 8) showing that the stream networks have been developed under tectonic influence. High drainage density and stream frequency appear locally also on rocks of medium permeability. These rocks are Neogene sediments intersected by major faults (Figures 2 and 3).

The areas of highest drainage density are associated with very gentle slopes (1-3%). The lowest drainage density values are related with rocks of high permeability. Even in areas with a small exposure of such rocks the decrease of D_d is significant (i.e. the central part of the Keritis watershed) (Figure 8).

The relationship between drainage density and slope angle (drainage density increases from mountains to valley portions, i.e. negative correlation with slope angle) was found to be similar to the Type 2 basins of Lin and Oguchi (2004) related to enhancement of channelization as erosion progresses.

Basins with low bifurcation ratio, high stream frequency and high drainage density reflect the highest flooding probability and the lowest groundwater potential.

Texture ratio (T) was found to be much higher for the Tavronitis (18.51) compared to the Keritis (12.36), further showing that the Tavronitis is under severe erosion (Reddy et al., 2004).

The fact that the form factor (R_f) parameter is lower in the Tavronitis than in the Keritis basin indicates that the Tavronitis has less side flow for shorter duration and high main flow for longer duration than the Keritis basin. Among the three Tavronitis sub-basins, Derianos shows the lowest R_f value whereas Roumatianos the highest R_f value (0.28).

The calculated elongation ratios (R_e) of the Keritis basin (0.61) and the Roumatianos sub-basin (0.6) imply high infiltration capacity and low runoff capacity in comparison with the other basins. At the opposite end, the Derianos sub-basin exhibits the lowest elongation ratio and consequently, lower infiltration capacity and higher runoff capacity. This observation perhaps indicates that the Derianos is more susceptible to erosion and sedimentation than the other basins.

Finally, the low constant of channel maintenance (C) of the Tavronitis watershed implies that the basin is under significant structural control, has steep to very steep slopes and high surface runoff due to rocks of low permeability (Schumm, 1956). The above implication is enhanced by the fact that the 47% of the total Tavronitis watershed area is steep slopes (15–30%), 32% is moderate and moderately steep slopes (5-15%) and only 1.5 per cent is flat or almost flat slopes (0-1%) while at the same time, 38.5% of Keritis area is steep slopes, 30% is moderate and moderately steep slopes and 5% is flat to almost flat slopes (Figure 9).

The fractal dimension of stream networks, $D_{\Sigma L}$ in both the Keritis and Tavronitis watersheds is approximately 2. This implies that the stream networks in the area can be considered statistically as space-filling, or free of geological constraints. On the contrary, the estimated $D_{\Sigma L}$ for the Tavronitis sub-basins is smaller (1.75, 1.8 and 1.45 for Sembreniotis, Roumatianos and Derianos, respectively). This fact, coupled with the morphometric parameters evaluation, as well as with the resulting average stream network fractal dimension (1.72) and the D_{AL} fractal dimension (1.02) derived from the perimeter-area relation, indicates a local scale geological effect on river development, which is induced in the Derianos basin ($D_{\Sigma L}$=1.45).

With the aim to further investigate the relationship between the stream tributary directions and the local tectonic regime, the stream channels of the Keritis and Tavronitis basins were grouped according to their order (1-6) and six rose diagrams were created for each basin (Figure 10). In the Keritis watershed, the streams of first, second and third order show a major N-S direction as well

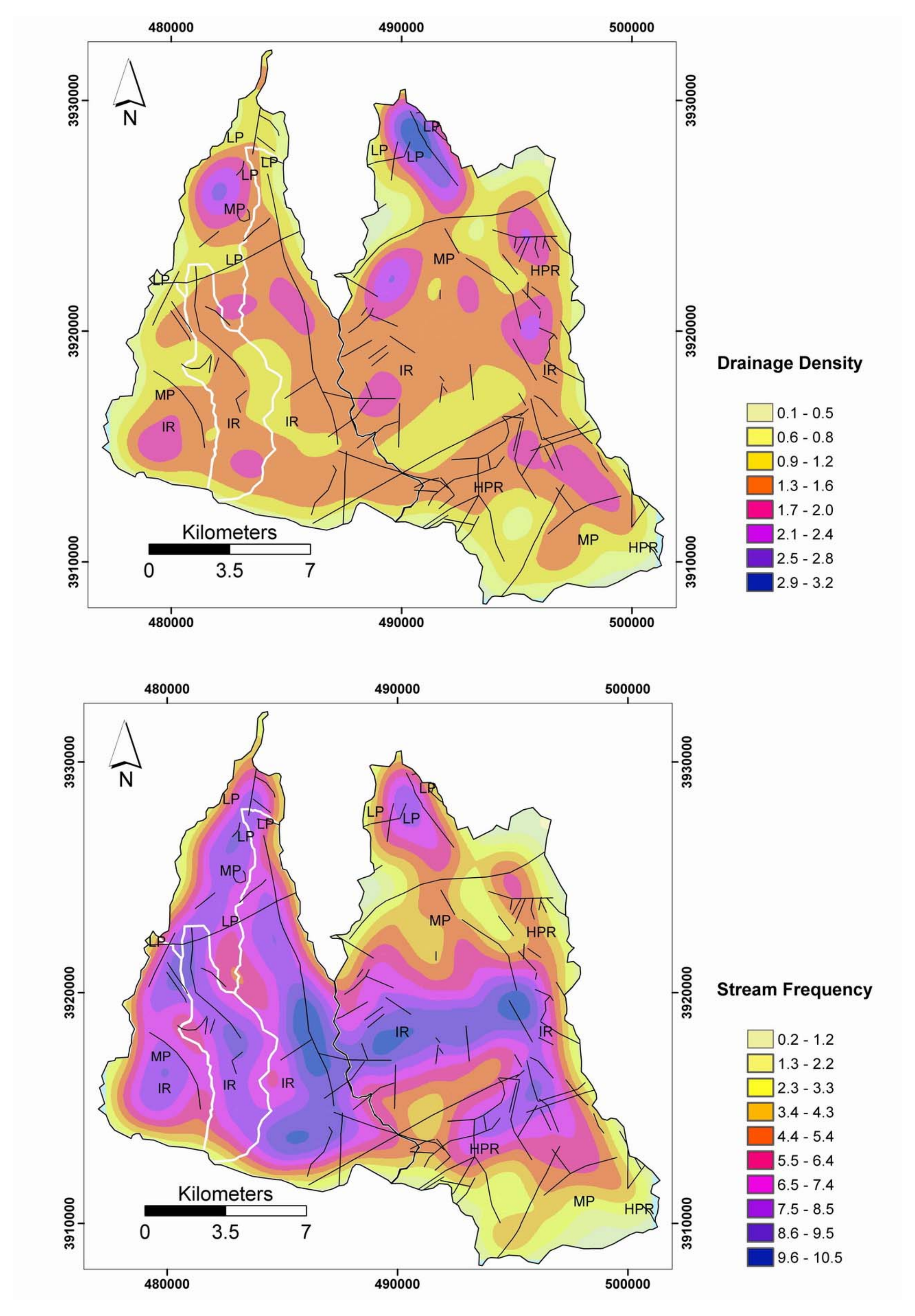

Figure 8. Hydrolithological map with drainage density map and faults overlay for the studied watersheds (upper figure) and with stream frequency map and faults overlay for the studied watersheds (lower figure).

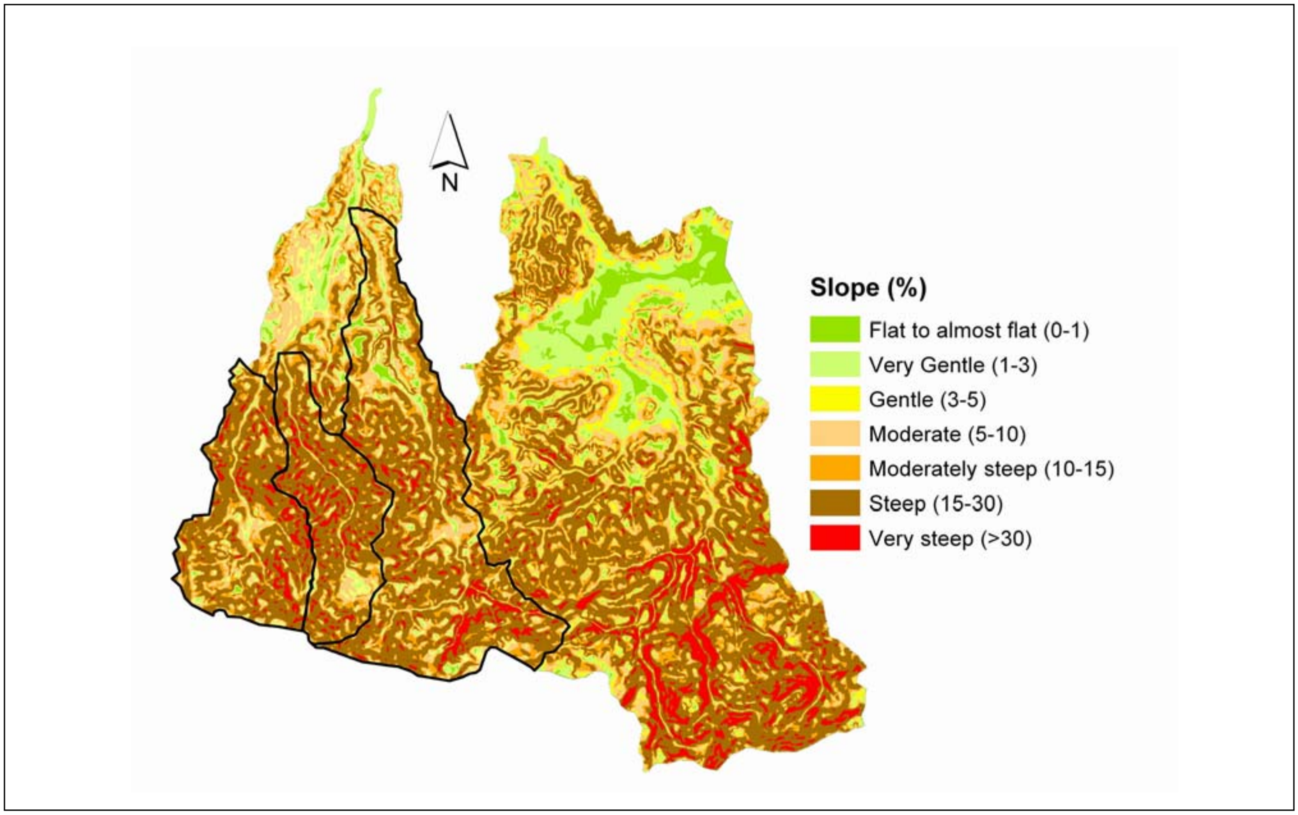

Figure 9. Slope map of the Keritis and Tavronitis watersheds.

as a NW-SE direction (especially the streams of third order). The stream segments of fourth order show a ENE-WSW major direction with a secondary N-S, while the streams of fifth order are directed N-S and finally the sixth order streams show a NW-SE direction.

In the Tavronitis watershed the dominant direction for first and second order streams is E-W, for the streams of third order the direction is ENE-SWS, while for the segments classified in the remaining three orders the main directions are N-S (fourth order), NE-SW and N-S (fifth order) and N-S and NE-SW (sixth order).

The comparison of the rose diagrams of both watersheds shows a temporal relationship between the Tavronitis and Keritis watersheds. The sixth order direction of Keritis is the same as the fifth order direction of Tavronitis, the fifth order of Keritis is the same as the fourth order of Tavronitis, and the fourth order of Keritis is the same as the third order of Tavronitis. This fact implies a development for both watersheds under the same tectonic regime which is dominated by ENE-WSW and NW-SE trending faults (Figure 10). Moreover the second and first order tributaries of the Tavronitis appear to have a main direction (E-W) perpendicular to the main direction of second and first order tributaries of the Keritis basin (N-S). This direction of Tavronitis younger streams may be due to their development perpendicular to the major NW-SE trending faults which are located in the eastern part of the Tavronitis basin, in the Derianos sub-basin (Figure 8). This fault seems to control the development of Derianos streams and this is further consistent with the calculated fractal dimension $D_{\Sigma L}$ of 1.45.

The significant difference of hypsometric integrals can be explained by a probable more rapid development of the Keritis watershed in an area of lower relief and consequently of faster erosional processes which led to the past movement of significant soil amounts.

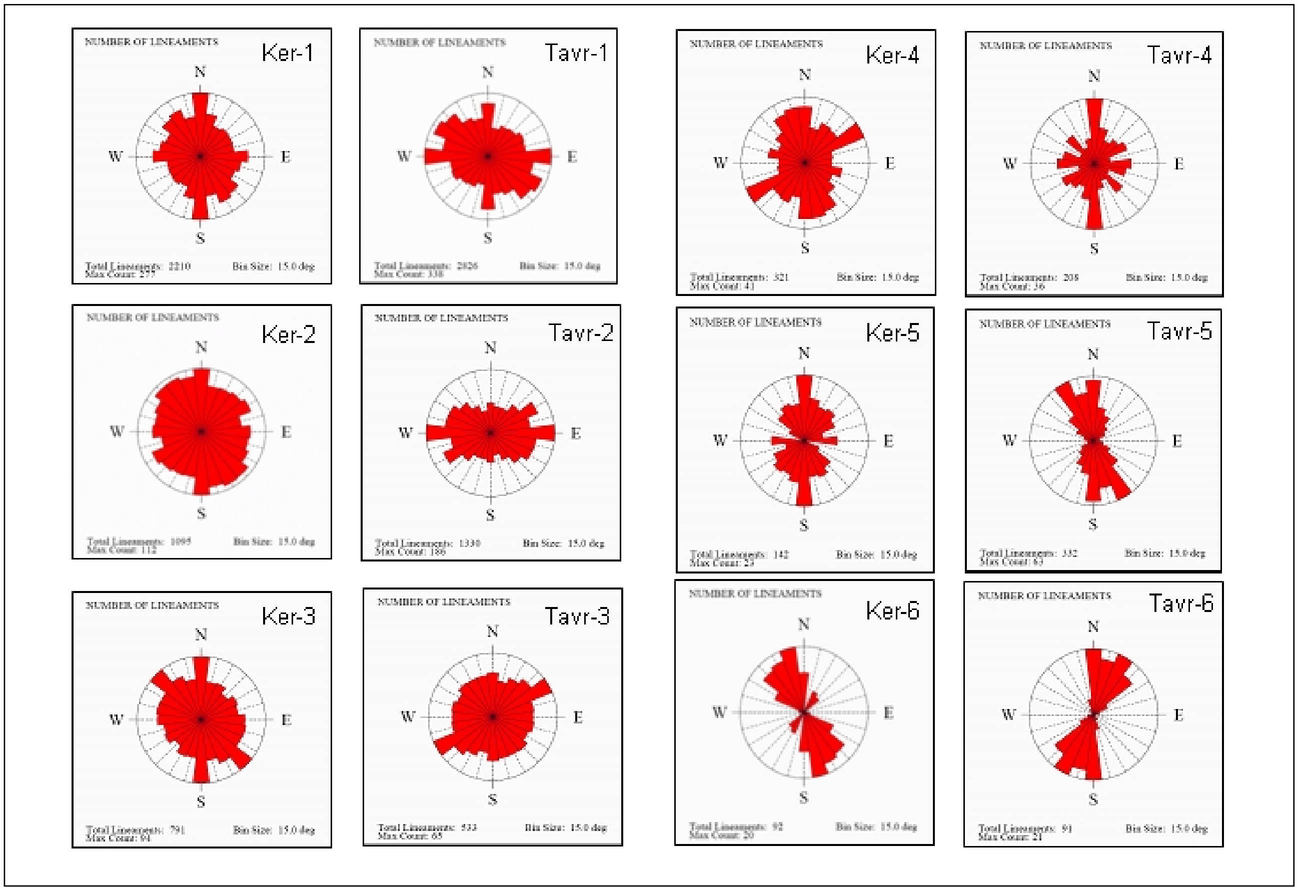

Figure 10. Rose diagrams for the classified channel segments of Keritis (Ker) and Tavronitis (Tavr) river network.

CONCLUSIONS

The stream patterns generated in this study show that the two major drainage basins of the Chania prefecture have been significantly affected by geomorphological and lithological factors (i.e. faults, slope, and rock permeability). These patterns, singly or in combination, can be used as GIS layers in integrated geological and hydrological interpretations of the watersheds under investigation.

Although the fractal dimension obtained for the Keritis and Tavronitis watersheds was equal to 2 implying freedom of geological constraints on drainage network development, the quantitative morphometric analysis at the sub-basin level provided an understanding of the relationships among the different aspects of the drainage patterns and their influence on landform processes, drainage, and land erosion properties. The results from the analysis of morphometric parameters indicate structural complexity, high relief and impermeable rocks mainly for the Tavronitis watershed and the Derianos sub-basin.

The results reveal that the types of morphometry, underlying geology and slope factors have great influence on landform evolution processes.

Having constructed the several thematic layers (in the GIS sense) it is our intent as a future work to estimate the soil loss equations for the study area to better understand the spatial distribution of soil characteristics and status of land erosion for soil management decisions at the watershed level. This would be of great interest, especially for Chania prefecture, since agricultural activities in the highlands appear to be in danger due the phenomenon of desertification.

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