A GIS example of Morphometric analysis in tectonic structures of Western Crete, Greece.

MARIA KOULI [(1)], FILIPPOS VALLIANATOS [(1)], PANTELIS SOUPIOS [(1)], DIMITRIS ALEXAKIS [(1)]

[(1)] Department of Natural Resources & Environment,
Technological Educational Institute of Crete
Romanou 3, Halepa, 73133, Chania, Crete
GREECE

Abstract: - In the current work, analysis based on geographic information system (GIS) was carried out in two tectonic structures in the central area of Chania prefecture of Crete Island, Greece. The digital data for deriving geomorphometric parameters were produced from topographical, geological and lithological maps and were updated from Landsat-ETM satellite imagery. Geomorphometric parameters analysis coupled with fractal analysis and statistical analysis of the stream tributaries enabled us to understand the influence of tectonic structures and underlying geotectonics on the drainage basins development and showed that the two structures have undergone severe erosion in the past, and are still susceptible to surface erosion while their development have been significantly affected by geomorphological and lithological factors (i.e. faults, slope, and rock permeability).

Key-Words: - GIS, geomorhometric parameters, tectonic structures, Crete Island.

1 Introduction

The quantification of geotectonic structures was introduced by Horton [9, 10] who studied the origin of river networks. According to Horton [10] many hydrologic measurements are available to quantify the description of river networks and drainage basins. As a result, a series of power-law type of relations, have been extended by others investigators (e.g. [7, 19]). 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 [4, 5, 6, 8, 13, 14, 22].

In the last years, the automated determination of quantitative geoparameters has been proved efficient, timesaving and an ideal application of GIS technology. The present work addresses the following aspects: (1) estimation of morphometric quantities using GIS software, (2) application of ‘‘localized’’ drainage basin- based statistical and fractal measures to characterize the influence of tectonic structures on the evolution of individual drainage basins.

The morphometric parameters of two major tectonic structures (Keritis and Tavronitis) of Chania prefecture, Crete Island, were extracted. The calculated values were mapped and analyzed using statistical approaches and GIS in order to characterize them. Moreover, selected fractal models have been applied. The results that were obtained on the basis of stream and drainage basin analysis and the integration of the geological and tectonic structures, lithology and slope of drainage basins reveal the relationship between stream patterns and geological, and geomorphological factors as well as the role of structural factors in the evolution of streams in the Chania prefecture area.

2 Geo-tectonic Framework of the Study Area

The study area is situated at latitude between 35°19′12′′ and 35°32′05′′ and a longitude between 23°44′54′′ and 24°01′05′′, in the central part of Chania prefecture and comprises the Keritis river basin in the east and the Tavronitis river basin in the west as is shown in Fig. 1.

The surficial geology is composed 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 [12] 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 river basin.

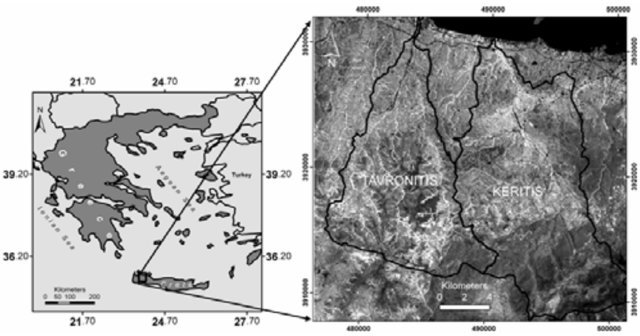

Figure 1. Location map of the studied basins. The 2nd principal component of the Landsat-ETM reveals the drainage network.

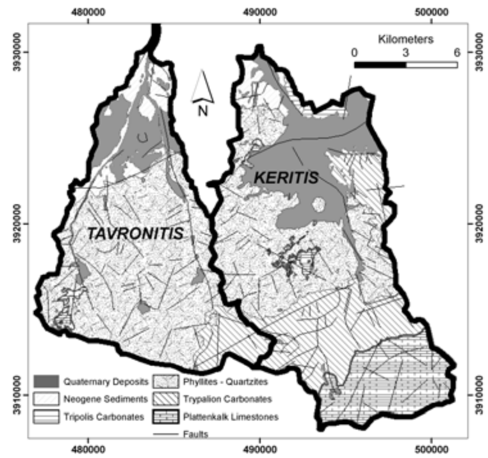

Figure 2. Geotectonic map of the study area.

In the sense of permeability the exposed geological formations can be classified into four hydrolithological units: high permeability rocks which comprise the karstic limestones of 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 consists of the Pliocene to Miocene marles and impervious rocks which consist of the phyllites – quartzites unit. The tectonic regime of the study area is characterizing by faults of NW-SE and E-W directions. These tectonic structures clearly define the boundaries between the existing geological and hydrolithological units (Fig. 2).

3 Methodology

All the collected data (hydrological, hydro-geological, geological, and topographic maps) were implemented into a GIS environment and then 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 fused to the same projection system, together with all kinds of future information that may rise.

The drainage networks were traced on transparency and digitized as on hydrological maps (1:20000) of the study area. The second principal component derived from the processing of a Landsat–ETM satellite image of the study area, with a spatial resolution of 30x30 m pixel size for the seven bands of multi-spectral data, acquired on 30 June 2000 and was used for the correction and update of the digitized stream data (Fig. 1).

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 [20]. In this classification, streams with no tributaries are defined as first order, 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 (Fig. 3).

The basics river basins characteristics (*basin area, perimeter, cumulative length of streams and basin length*) were measured in GIS environment. Morphometric parameters such as *Stream Frequency, (Fu), Drainage Density, (Dd), Texture Ratio, (T), Form Factor, (Rf), Elongation Ratio, (Re)* and *Constant of channel maintenance, (C)* were evaluated with mathematical equations [20]. The extracted values are shown in Fig. 4. Other geotectonic morphometric parameters such as hypsometric curves and integrals were also calculated. The hypsometric curve is an area-elevation relationship curve that plots normalized elevation against normalized area of a watershed [19] 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) expresses, as a percentage, the volume of the original basin that remains unweathered.

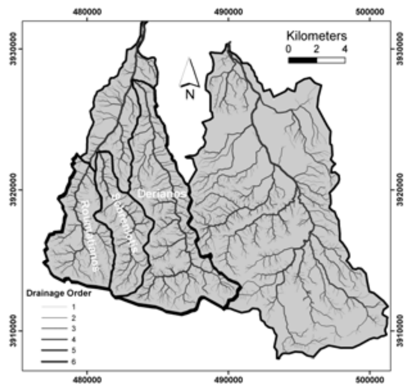

Figure 3. Streams classification map of Tavronitis and Keritis basins with sub-basins delineation.

For the identification of the probable spatial relationships of stream networks and drainage basins, histogram plots and fractal modelling have been used. 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 structural and geological factors in the evolution of the river basins and streams of the study areas.

Morphometric Parameters	*Keritis*	*Tavronitis*	*Sembreniotis*	*Roumatianos*	*Derianos*
Streams Total Number, N	1783	2312	483	511	1042
Total Stream Length, ΣL (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
Constant of channel maintenance, C	0.38	0.26	0.24	0.25	0.25

Figure 4. The calculated parameters.

4 Geomorphometric Parameters

The two major structures of the study area, Keritis and Tavronitis basins, were found to be of sixth order. For a more detailed analysis the Tavronitis basin was classified into 3 sub-basins of fifth order, the Sembreniotis, Roumatianos and Derianos sub-basins (Fig. 3). Calculation of Total Stream Length (ΣL) showed that Tavronitis basin has the highest ΣL (511.38 km), whereas 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 drainage basins of the same area extent, high ΣL may indicate structural complexity, high relief and impervious rocks. The bifurcation ratio (R_b) was found to be 2.4 for Keritis and 1.99 for Tavronitis water basin. 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 [1, 15, 16]. D_d is significantly higher to Tavronitis than to Keritis watershed in agreement with the existence of impermeable rocks, sparse vegetation and higher relief. Keritis basin shows the lowest D_d 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 Tavronitis basin (17.67) and its sub-basins (18.39-21.52). In contrast, Keritis basin was described by low F_u value (9.87). Moreover, 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 Tavronitis than Keritis basin, and this fact is probably an evidence that Tavronitis appears 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 (0.12) whereas Roumatianos the highest (0.28). Keritis shows higher Elongation ratio 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 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 [18]. The low C value of Tavronitis (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 had occurred in a basin vs. what still remains [11]. The hypsometric integral helps to define the erosion that has taken place during the geological time [3]. The Hypsometric Integral (HI) represents the area under the hypsometric curve and corresponds to the per cent of original rock mass remaining in the watersheds [1, 3]. HI 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 [19, 20]. According to the HI calculation, Keritis basin is in the old age stage (HI=26.21%) of its development whereas 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 maximum. Concerning the Tavronitis sub-basins, they are all in the mature stage with Sembreniotis basin to be a little younger (HI=36.34%) than Derianos basin (HI=35.63%) and Roumatianos basin to be the oldest one (HI=35.63). The different levels of geomorphic maturity are influenced by various forcing factors such as tectonics.

5 Fractal modelling

Fig. 5 shows the length-histograms of all stream orders (1-6) for Keritis and Tavronitis basins. Both histograms show a lognormal distribution.

The ‘‘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 [10, 19]. 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 could be easily related to the fractal dimension of stream networks $D_{\Sigma L}$ [5, 13, 22] 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 ($D^T_{\Sigma L}$) basins are almost equal to 2 implying that the stream networks satisfy a space filling property and they are not affected by possible geological constraints.

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 [6, 14, 17].

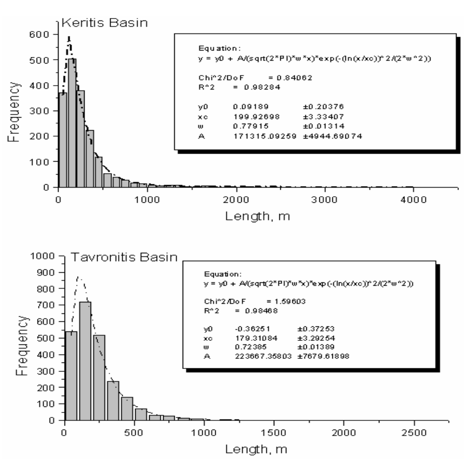

Figure 5. Frequency histograms for the Keritis and Tavronitis streams.

The two sub-basins of the Tavronitis basin, Sembreniotis, Roumatianos basins, have $D^S_{\Sigma L}$=1.75 and $D^R_{\Sigma L}$=1.8 respectively whereas the Derianos sub-basin gives $D^D_{\Sigma L}$=1.45 indicating a local scale geological effect on the rivers development. Moreover, the dependence of the number of streams of various orders on their average length [23] for the studied drainage networks is shown in Fig. 7. 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, [14] introduced the following relationship between total stream length (ΣL) per basin and drainage basin area (A):

$$\Sigma L \propto A^{D/2} \qquad (3)$$

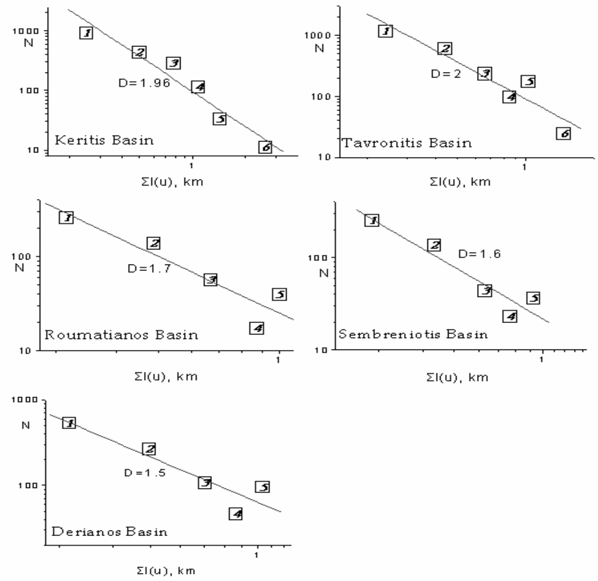

Figure 6. Dependence of the number of streams (N) of orders 1-6 on their average length (Lu).

The calculated average stream network fractal dimension for the studied basins area is equal to 1.72 $\pm$ 0.08 (Fig. 7). This fact shows that although the evolution of stream networks in the study area has a significant degree of randomness, geology plays also an important role. Typical values of D for total stream length vary from 1.5 to 2.0 [17, 21] 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 [6]:

$$P \propto A^{\frac{1}{2} \cdot D_{AL}} \qquad (4)$$

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 under investigation basins is D_{AL}=1.02$\pm$ 0.06 (Fig. 7) implying that the studied basins have regular shapes.

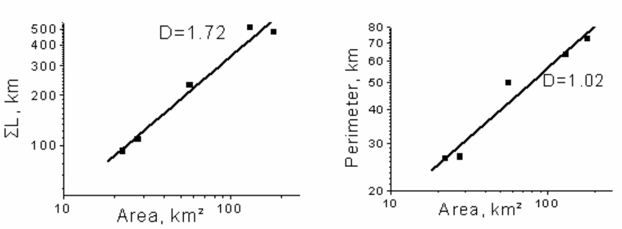

Figure 7. Relationship between total length of streams and area of drainage basins as well as between perimeter and area of drainage basins.

6 Discussion and Conclusions

The Drainage density (D_d) morphometric parameter appears significantly higher to Tavronitis watershed implying the existence of impermeable rocks and high relief [1, 15, 16]. High D_d values correspond to dissected terrains while low D_d to long hill slopes [1, 2]. Stream frequency (F_u) values are also high for Tavronitis basin (17.67) and its sub-basins (18.39-21.52). In contrast, Keritis basin shows low stream frequency (F_u=9.87) indicating relatively permeable geology and low relief. The overlay of the drainage density (Fig. 8) and stream frequency (Fig. 9) maps on the hydrolithological/tectonic map, in the GIS environment, shows that areas marked with high D_d and F_u correspond mainly to impervious rocks. High F_u values are exhibited in almost linear patterns, parallel or sub-parallel to the major tectonic lineaments in both Tavronitis and Keritis basins (Fig. 9) showing that the stream networks have been developed under tectonic influence. Texture ratio (T) was found to be much higher for Tavronitis (18.51) than for Keritis (12.36) further advocating that Tavronitis is under severe erosion [15]. The calculated Elongation ratios (R_e) of Keritis basin (0.61) and Roumatianos sub-basin (0.6) imply high infiltration capacity and low run off capacity in comparison with the other studied basins. At the opposite hand, Derianos sub-basin exhibits the lowest R_e and this fact, indicates that Derianos is more susceptible to erosion and sedimentation than the other basins.

Moreover, the low constant of channel maintenance (C) of Tavronitis watershed implies significant structural control, steep to very steep slopes and high surface runoff while it exposes rocks of low permeability [18]. The above implications are enhanced by the fact that the 47% of the total Tavronitis watershed area is under steep slopes (15–30%), the 32% under moderate and moderately steep slopes (5-15%) and only the 1.5 per cent flat or almost flat slopes (0-1%) while at the same time, 38.5% of Keritis area is under steep slopes, 30% is under moderate and moderately steep slopes and the 5% under flat to almost flat slopes.

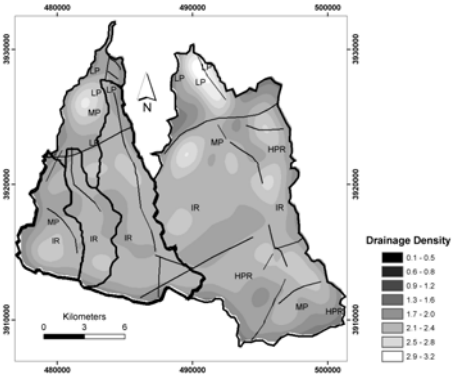

Figure 8. Drainage density map with faults overlay.

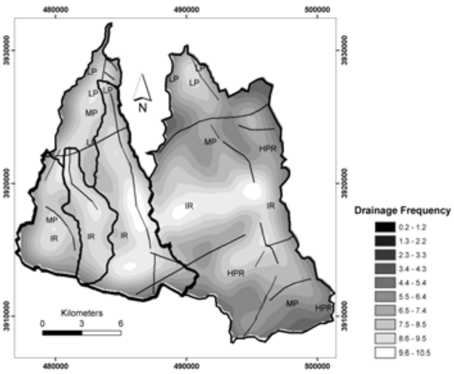

Figure 9. Stream frequency map with faults overlay.

Finally, although the fractal dimension obtained for the Keritis and Tavronitis basins, was equal to 2 implying a free of geological constraints drainage network development, the estimated $D_{\Sigma L}$ for Tavronitis sub-basins is rather 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 resulted average stream network fractal dimension (1.72) and the D_{AL} fractal dimension (1.02) derived from the perimeter-area relation, indicates structural complexity, high relief and impermeable rocks mainly for Tavronitis basin and a local scale geotectonic effect on the rivers development, which is induced in the Derianos sub-basin ($D_{\Sigma L}$=1.45).

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