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Neotectonic control on drainage systems: GIS-based geomorphometric and morphotectonic assessment for Crete, Greece.

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Abstract

Geomorphic indices can be used to examine the geomorphological and tectonic processes responsible for the development of the drainage basins. Such indices can be dependent on tectonics, erosional processes and other factors that control the morphology of the landforms. The inter-relationships between geomorphic indices can determine the influence of regional tectonic activity in the shape development of drainage basins. A Multi-Criteria Decision Analysis (*MCDA*) procedure has been used to perform an integrated cluster analysis that highlights information associated with the dominant regional tectonic activity. Factor Analysis (*FA*) and Analytical Hierarchy Process (*AHP*) were considered within that procedure, producing a representation of the distributed regional tectonic activity of the drainage basins studied. The study area is western Crete, located in the outer fore-arc of the Hellenic subduction zone, one of the world's most tectonically active regions. The results indicate that in the landscape evolution of the study area (especially the western basins) tectonic controls dominate over lithological controls.

1. Introduction

The neotectonic processes that contribute to landscape deformation are difficult to recognize and quantify. That is especially so for regions that are poorly mapped, due to inaccessibility, limited geological survey resources and lack of available datasets. Drainage basin geomorphometry - the quantitative evaluation of drainage networks (Onosemuode, 2010) - can determine the relative importance of tectonic deformation or erosion in landscape evolution (Segura et al., 2007). At a regional scale, analysis of geomorphic indices for stream networks, drainage basin morphology and relief status can be useful in the characterization of basin geomorphometry (Abrahams, 1984; Reddy et al., 2004). Such analyses can provide insights into geomorphological and hydrological processes shaping a given landscape, to quantitatively characterise the geometry, shape, relief, pattern and texture of drainage networks and evaluate whether such features are a result of regional tectonic control (Mesa, 2006; Segura et al., 2007). Information regarding the stream network, or drainage basin relief and shape, can then be used for a quantitative evaluation of drainage basin development against regional tectonic control (Ribolini and Spagnolo, 2008).

To better understand the drainage basin evolution of a given region, it is necessary to examine its topography, the erosion status and drainage pattern development. Building on the drainage morphology studies of Horton (1945), Strahler (1952) and Hack (1957), recent research has produced new insights into the influence of geomorphological or tectonic factors on drainage systems and landscape evolution (e.g. Salvany, 2004; Javed et al., 2011; Aher et al., 2014). Detailed geomorphometric and structural geology analysis can be determined by use of conventional methods (e.g. Horton, 1945; Strahler, 1957; Krishnamurthy et al., 1996) or by Geographic Information System (GIS) processing of satellite remote sensing data, particularly global Digital Elevation Models (DEMs) (e.g. Chorowicz et al, 1999; Ozdemir & Bird, 2009; Bemis et al, 2014).

The use of GIS is particularly helpful in the evaluation and mapping of geomorphic indices for stream networks, drainage basins and relief. Using freely-available DEMs and freeware GIS (e.g. QGIS) is a relatively rapid method and can provide an inexpensive approach to geomorphometric analysis for preliminary identification and analysis of tectonic and geomorphological features in a given drainage basin or fault zone (e.g. Segura et al., 2007; Giorgis et al, 2011; Argyriou et al., 2016a). The spatial relationships among the geomorphic indices of a drainage basin can be easily interpreted through the visualization techniques of GIS, facilitating decision making by analysts evaluating regional tectonic activity.

This study uses geomorphic indices (Table 1) that provide information for evaluating regional tectonic activity. A few studies have examined the distribution of tectonic activity using drainage basin geomorphic indices (e.g. Alipoor et al., 2011; El-Hamdouni et al., 2008; Selim et al., 2013). The latter two studies computed the arithmetic mean of a few morphotectonic indices to determine a classified relative tectonic activity index (*Iat*), representing tectonic activity over a number of drainage basins. For the same indices, Alipoor et al. (2011) considered the *AHP*, instead of the computation of the arithmetic mean: the degree and weight of each index was considered for the representation of the tectonic activity over each drainage basin. The analysis of an even larger number of geomorphic indices, as in this study, can provide more valuable information but can also lead to misleading decisions regarding correlations. Consequently, multivariate classification and clustering of the indices is needed for coherent data analysis (Al-Sulaimi, 1997; Sougnez & Vanacker, 2011).

Multi-Criteria Decision Analysis (*MCDA*) can provide a powerful tool for the integration of the various stages evaluated within this study, leading to grouping of the large number of the indices used, which can provide insights into the tectonic activity within the examined drainage systems. Several spatial decision problems have been examined using GIS-based Multi-Criteria Decision Analysis (*GIS-MCDA*) (e.g. Laaribi et al. 1996; Chakhar & Martel 2003; Chen et al., 2009). Factor analysis (*FA*) and Analytic Hierarchy Process (*AHP*) are used here to group the numerous geomorphic indices and consider the weight of the individual indices by acknowledging specific factors. This study utilises *FA* by reducing the data size and examining the diverse information provided by the geomorphic indices. We also use

AHP procedure by analysing through multiple criteria the degree of control from tectonic processes or other factors, such as hard/soft lithological variations.

The overall aim of this study is to identify which of the 21 examined drainage basins in western Crete, are under a high degree of tectonic control. That has been done by isolating the tectonic information provided by each geomorphic index. The basins with apparently high tectonic control meet the following criteria: i) elongated basin shape; ii) high or low relief (depending on the dominant processes, either tectonic, uplift or tilting) and; iii) hillslope processes and lithological variations dominant in basin development, relative to fluvial processes (Burbank and Anderson, 2001; Sougnez and Vanacher, 2011). That sort of information will be indicated by the various geomorphic indices used in this study.

2. Geology and tectonic setting of the study area

This study considers as a case study the western part of Crete, Greece (Figure 1a). This is a region lying within the emergent outer fore-arc of the Hellenic arc, characterized by high rates of tectonic activity and seismicity (McKenzie, 1978; Shaw et al, 2008; Chatzaras et al, 2013) (Figure 1b). On 21st July of 365 AD, an earthquake (Mw 8.3-8.5) produced co-seismic uplift up to 9 meters on south-western Crete (Thommeret et al., 1981; Stiros, 2001; Pirazzoli, 2005). The geology of the region is complex and is made up of a thrusted sequence of nappes, formed during a Tertiary (~10 Ma) dominantly compressional tectonic regime now inactive associated with the closure of Tethys (Greiling, 1982; Fassoulas, 1999). Limestones and dolomites characterise the south-east part of the study region, while central and south-westerly areas are made up of phyllites and quartzites. Marls, clays, conglomerates, flysch and carbonates are exposed in the north-west part of the study region. The northern coastline is partly made up of Quaternary and Neogene marine deposits (Figure 1c).

The current tectonic regime is producing movements of the following sets of faults: large normal faults with N-S or E-W strikes and smaller normal faults with NNE-SSW or WNW-ESE strikes (Caputo et al., 2010; Mountrakis et al., 2012). This tectonic framework is related to slab rollback at the African margin (compressional forces) as well as arc-parallel extension of the Anatolian micro-plate (extensional forces) (Drooger and Meulenkamp, 1973; Royden, 1993; Wegmann, 2008). However, the complex tectonic evolution of western Crete is not well understood and the location of active fault features is still largely unknown (Papazachos, 1996; Mountrakis et al., 2012). In general, there is a rich archive of background studies regarding the investigation of active faulting outcrops across the coastline of Crete but as we move into the inland the outcrops along active faults are likely to be obscured inherently by products of their activity, e.g. landslides and alluvial deposition making difficult their identification (Mouslopoulou et al., 2001). The normal faults on Crete in their total consist of Mesozoic carbonate bedrock fault scarps juxtaposed against Quaternary alluvial-colluvial sediments (Ganas, 2010; Schneiderwind et al., 2015). In that case, the primary sedimentary structures present at the hanging-wall stratigraphy consist mainly of fissure fills and displaced strata (McCalpin, 2009), with colluvial material that has been eroded and fallen from the footwall mountain above the scarp (Mason, 2016). As a result, only few active fault outcrops are exposed in Crete with the continuous erosion and subsequent degradation of the fault scarp followed by deposition of colluvial material overlying and burying the earlier active faulting phases (Mouslopoulou et al., 2001). Based on this status the investigation of the drainage basins response to active tectonics can provide insights and offer valuable knowledge towards the investigation of active tectonics in the inland of Crete. This is reinforced by the fact that according to Argyriou et al. (2016a), almost half of Crete's dominant formations coverage (~44%) consist of sedimentary rocks of Cenozoic age followed by metamorphic rocks of Mesozoic age. These sedimentary rocks comprise mainly geomorphometric units of coastal lands, alluvial deposits, plains and valleys of low to moderate elevation (Argyriou et al., 2016a). The majority of the examined drainage basins, especially the northern ones, are overlaid in such type of geomorphometric units indicating the importance of evaluating their response to tectonic activity.

Insert Fig. 1.

3. Methodology

3.1 Quantitative analysis of drainage network and drainage basins

Drainage network ordering can provide information regarding the development and the extent of the drainage network within a drainage basin. A few methods have been proposed for the ordering of drainage networks by examining the relation of stream segments (e.g. Horton, 1945; Strahler, 1952). In this study, the drainage network was extracted from the freely-available ASTER G-DEM using the standard spatial analyst hydrological tools found in ArcGIS software. The classification was based on Strahler's (1952) system of stream ordering, with the drainage basins being characterized by stream segments reaching between 3rd order (the lowest) and 6th order (the highest). The quantitative analysis of the drainage networks was initiated using Horton's first law. All the stream orders, stream numbers, stream length and mean stream length for each order are presented in

Table 2. The higher the stream order, the lower the number of expected streams. Disruptions in this descending sequence indicate regional uplift within the studied basin (Chopra et al., 2005).

Insert Table 1.

Insert Table 2.

To better understand the scale of the drainage basins and their extent, some basic morphological features have also been calculated, such as the perimeter of basins (P), the basin length (L_b) and the area of drainage basins (A) (Figure 2). These basic basin morphological characteristics provide inputs for the calculation of the indices used in this study (Table 1).

After the evaluation of the broader scale of drainage basins size, an overall evaluation of the relief within the basins can be helpful for understanding better their physiographic nature. The basin relative relief (R) and relief ratio (R_r) indices enable a rapid assessment of drainage basin relief and whether it has an impact to the drainage network pattern (Table 1 & Figure 2).

Insert Fig. 2.

The next step towards isolating the tectonic signal is to check how the drainage network is developed within the drainage basin. The calculated indices (total number of streams, N_u; total stream length, ΣL_u; stream frequency, F_u; drainage density, D_d; ratio of bifurcation, R_b) concern only stream network features and indicate its complexity, texture and distortion by tectonic disturbances (Table 1 & 2).

The drainage network of each basin was analysed based on Horton's first law (1945): the number of streams decreases as the stream order increases. The graphic logarithmic plots of the stream order against the number of streams were used in order to estimate the values of R_b. This was achieved by calculating the anti-log of the slopes of the linear fit (Maxwell, 1955).

The previous step investigated the stream network using geomorphic indices that can provide information regarding stream network development by neotectonic deformation. The next step to follow is to evaluate the drainage basin as a whole. Several indices (elongation ratio, R_e; form factor, R_f; basin circularity, R_c; drainage basin shape index, *Bs*; hypsometric integral, *HI* and asymmetry factor, *AF*) were used to express the basin geometry, shape, tilting and erosional/incision status (Table 1).

3.2 Multi-criteria decision analysis and modelling of tectonic control

This section examines the classification, ranking and *MCDA* procedure of the geomorphic indices relationships, in order to determine the regional tectonic control of the basins. Each one of the geomorphic indices described above offers some particular information, such as basin geometry, relief, hillslope or fluvial processes. A review of the attribute information of each index, by evaluating the high or low values of each index respectively, is presented in Table (1). Our target is to isolate most of the information from those indices associated with active tectonics and classify the indices for coherent data analysis. That aspect will provide us with better decision-making, regarding the degree of the tectonic influence over the drainage basin development. The type of multivariate analysis applied in this study was Factor Analysis (*FA*), as described by Goddard and Kirby (1976), carried out using the SPSS statistical analysis software. *FA* uses correlation coefficient and covariance-variance matrices, to recognize variables within a set of observed variables that discriminate the pattern of correlations. Usually, it is used in data reduction to highlight a small number of factors that reveal most of the variance observed in a much larger number of variables, as in this study, so those selected for retention can be more meaningful (Yevjevich et.al, 1972; Goddard and Kirby, 1976). Goddard & Kirby (1976) recommended that components with eigenvalues more than 1 should be used. In its final stage, this analysis uses Kaiser's (1958) Varimax technique to rotate the factor axes. This is to reduce the number factors on which the variables under examination have high loadings, as well as to identify distinctive clusters of variables (Davis, 1973; Goddard, & Kirby, 1976). Within *FA*, the Kaiser's function measures the sampling adequacy: it should be greater than 0.5 for a satisfactory *FA* to proceed: in this study it is 0.557. Common applications of *FA* analysis are: i) identification and exploration of patterns in variables and; ii) testing of hypotheses about the structuring of the variables (Jae-On Kim, 1970).

After the new components of the *FA* are discriminated by clustering and reduction of the initially large number of geomorphic indices, the next step is to check the interrelationship (correlation) of these components. Within each initial component more than one index will probably be found, so it is necessary to rank the indices based on the calculations for each drainage basin. This procedure maintains priority ranking values for the indices, as calculated for the basins, which can be used to acquire one final ranked index for each component. The ranking of the geomorphic indices in this study was based on the procedure adopted by Chaudhary and Sharma (1998) and Biswas et al. (1999). In those studies, the drainage basins in which the index had the highest value were given a rating of 1, the next lowest value was given a rating of 2, and so on; while with shape indices (*Re, Rf, Rc*), the lowest value was given a rating of 1 with the next highest value was given a rating of 2, and so on.

This research study followed the above rating approach, apart from the ensuing ranking procedure: instead of computing the arithmetic mean values of the indices after rating, an *AHP* procedure was used for discriminating basins with higher degrees of tectonic control. A more sophisticated and appropriate separation can be achieved by *AHP* for determining the ranking of the drainage basins and the degree of very high, high, moderate and low levels of regional tectonic control. The *AHP* was introduced by Saaty (1977) and is today still the most widely spread and used theory for decision making (Kremljak and Buchmeister, 2006). *AHP* can calculate the needed weight factors by using a preference matrix which compares all relevant factors against each other in a pair-wise comparison matrix, to find the relative preference among the factors (Saaty, 1980). The comparison consists of a range of values (1 to 9) to describe the intensity of importance (preference/dominance), where each criterion is compared with the other criteria, relative to its importance (Saaty, 1980; Alipoor et al., 2011) (Table 1 in supplementary material).

The classification of the geomorphic indices by *FA* is beneficial in the *AHP* procedure because indices with “equal importance” can easily be determined in each of the components. The values of the pair-wise comparison matrix have to be thoroughly considered and not set arbitrarily. In order to ensure that the comparisons are consistent or not, a single numerical index to check for consistency of the pair-wise comparison matrix, called consistency ratio (*Cr*), was developed by Saaty

(1977). If the ratio has values less than 0.1 (Cr<0.1) then there is a reasonable level of consistency in the pair-wise comparison matrix. A revision of the preference values should be followed if the *Cr* exceeds a value of 0.1 (*Cr*≥ 0.1) (Saaty and Vargas, 1991). The values of the pair-wise comparison matrix are determined with regard to the predominant lithological formations and their permeability. That implies that lithological variations are considered thoroughly, enabling the discrimination of basins that owe their morphology to a high degree of tectonic control. For instance, alternating hard and soft rock strata, or permeable and impermeable bedrock, tends to result in relief being the dominant factor of basin development. A similar approach regarding the consideration of geological conditions during the *AHP* procedure was also used by Alipoor et al. (2011).

The standard method used to calculate the values for the weights from an *AHP* matrix, is to take the eigenvector corresponding to the largest eigenvalues of the matrix and then to normalize the sum of the components to one. The benefit of this approach is that it organizes identifiable and indefinite factors in a systematic way. It is useful in sectors where rationality and irrationality in association with risk and uncertainty can be found (Palcic and Lalic, 2009). Generally, *AHP* consists of hierarchy process, calculation of weights and checking system compatibility (Alipoor et al, 2011).

In order to validate the drainage basin outcome of the final *AHP* procedure, this study draws on the fault type categories produced by the EMERIC project (Sarris et al., 2007; Fassoulas et al., 2007) and used/updated by Mountrakis et al. (2012): active, possibly active or inactive. The method of Argyriou et al. (2016b) is followed, regarding the discrimination of rock strength formations in western Crete, for the construction of the pair-wise matrices within *AHP*. Weak, unconsolidated lithologies provide reduced seismic wave velocities, an increased wave amplitude and increased seismic hazard (Figure 3). This assists with determining whether the main influence on drainage basin development was rock hardness or fault zone tectonic activity.

The methodology used in this study provides a means of mapping neotectonic deformation over drainage basins, based on a multi-disciplinary geomorphic analysis that is not dependent on good/clear outcrops and fault scarps. In many landscapes, such as those of Crete, relative rock hardness and susceptibility to weathering, with ensuing differential erosion, have buried neotectonic fault scarps or other features indicative of neotectonic deformation under limestone/sandstone scree colluvium, making their detection impossible by outcrop mapping and airphoto based geological mapping (Cichanski, 2000). Consequently, the most evident and often-cited active faults in Crete are mainly found in relatively denuded coastal areas that have been stripped of colluvium, with the majority of the previous studies rarely examining inland areas (Mouslopoulou et al., 2001; Mountrakis et al., 2012).

Insert Figure 3.

4. Results and Discussion

4.1 Quantitative analysis of drainage network

The evaluation of the stream segment numbers of the drainage basins reveals some basic characteristics for the stream analysis, as summarized in Table (2). The application of the 1st Horton law revealed useful information regarding the relationship between the number of the stream segments and the ordering of the drainage network. For example, in a few cases (notably basins 3, 5, 7, 13 and 21) the 1st Horton law linear relationship is not followed, with a deviation observed: while stream order increases there is an increase in the number of streams. This is a consequence of variation in relief, which implies that exogenous factors such as tectonics are affecting the drainage network development by influencing the development of the stream order (Chopra et al., 2005) (Table 2).

4.2 Quantitative analysis of drainage basins

The morphological characteristics (*P*, L_b and the *A)* give an indication of the scale and extent of the drainage basins (Table 3). An interesting point is that the range of L_b for most of the basins is around 11-19 km, regardless the basins area size. This indicates that might some basins have an elongated shape, possibly representing tectonically active mountainous areas (Ramirez-Herrera, 1998).

The relief aspects (*R* and R_r) of a drainage basin provide an overview of its morphology and relief. The basins have variable *R* and R_r index values, with the majority of them characterised by a mountainous landscape (Table 3). The stream network aspects (N_u, ΣL_u, F_u, D_d, R_b) are presented in Table (3) and provide information about the extent of the stream network, its complexity, texture and whether drainage pattern is influenced by tectonic structures.

Insert Table 3.

The geomorphic indices (R_e, R_f, R_c, *Bs*, *HI* and *AF*) in Table (4) characterize the geometry and shape of drainage basins, with elongated basins being indicative of tectonic control influencing their development. Information can also be determined about tilting of the drainage basin, its erosional status and relative incision. A quantitative evaluation of the asymmetry of a drainage basin can be examined against the rest of the indices, indicating basins where tectonic control has a higher degree of impact in the landscape evolution.

Drainage basin asymmetry was revealed by the *AF* index, with the results indicating the tilting direction of the drainage basins (Figure 4): the relative degree of tilting is presented, with white arrows show the tilting orientation with regard to the main stream direction. The absolute difference (*AF-50*) and its classification (used to evaluate the highest tectonic tilting of the drainage basins) is presented in Table (4), regarding observed threshold values. The values range from 1 to 35, with 3 classes indicating relative high (Class 1), moderate (Class 2) and low (Class 3) active deformation (Table 4). Higher deviation values (ie, not close to 0) indicate higher tectonic activity within the basin. The *AF* is a powerful index to determine basins characterized by tilting, which implies a tectonic control on stream migration and development of an asymmetry within the basin.

The calculation and classification of *HI* for the drainage basins of the study area is presented in Figure (5). The green-coloured areas represent basins with deep incision and rugged terrain, where tectonic activity is dominant relative to erosion; yellow-coloured areas are basins in the intermediate stage, with dynamic equilibrium landscapes; balanced tectonic and erosional processes (maximum threshold 50%), while the red-coloured basins are in the most severe stage of erosion, with low subdued relief (maximum threshold 35%) (Figure 5).

The basins that have undergone well defined deep incision and rugged terrain are those with high *HI* values and sub-parallel drainage, indicating deformation control by tectonic processes, such as the Pelekaniotis and Sarakiniotis basins. As observed by Willgoose and Hancock (1998) and Hurtrez et al. (1999), small basins generally have a high *HI* percentage (dominance of hillslope processes), whilst larger basins have a low *HI* percentage (dominance of fluvial processes). The Metoxi-Platanos and Milias drainage basins are not in accordance with that theory: they are small basins, characterised by low *HI* percentage and low D_d (Figure 5 and Table 4). For these basins the subdued relief (low *HI*), in conjunction with the lack of uniform drainage network (low D_d), indicate tectonic activity and drainage basin deformation, which can also be associated with the relative tilting observed in the region, as indicated by the *AF* index.

Insert Fig. 4.

Insert Fig. 5.

Insert Table 4.

4.3 Multi-criteria decision analysis and modeling of regional neotectonic control

Initially, a correlation coefficient matrix was composed for all the geomorphic indices (Table 2 in supplementary material). At first sight, the correlation coefficient matrix is in accordance with observations made by Al-Sulaimi (1997) regarding interrelationships of geomorphic indices. Indices such as *A*, L_b, *P*, N_u and ΣL_u have a high positive correlation (≥ 0.8) (Table 2 in supplementary material). The F_u index is highly correlated with D_d, N_u and ΣL_u. The D_d has a strong correlation with F_u and N_u. The strong positive relationship that exists between *A, P,* L_b, N_u and ΣL_u, provides a means of grouping the different basins into distinct groups, based on the identifiable ranges for the different indices, as suggested by Al-Sulaimi (1997). The use of *FA* groups the basins and eliminates statistically irrelevant data, providing easier interpretation of the relations of the various geomorphic indices (Figure 6) through their distinguishing components (Table 3 in supplementary material).

Insert Fig. 6.

In this study four components are recognized with greater eigenvalues than 1 in the *FA*, characterized by almost 87% of variance (Figure 7). The plot in figure 7 shows that the first four components are those containing most of the information (regarding percentage of variance and eigenvalues).

The *FA* shows that the first four components describe 87% of the variance, while the first eight components explain 98% of the variance (Figure 7). After the rotation of data, only the first four components are of significance (Table 3 in supplementary material). The rest of the components (5-16) mainly consist of a single index for each component (Table 3 in supplementary material). Such single individual components do not offer any significant grouping of factors. That aspect coincides with the studies of Goddard & Kirby (1976), as their eigenvalues less than 1 are excluded from further interpretation (Yevjevich et.al, 1972). Each of the final four components is associated with characteristic information that is provided by the contained indices (Table 3 in supplementary material). These revealed overall that:

i) Component-1 contains information regarding basin size and extent;

ii) Component-2 contains information regarding basin shape and geometry;

iii) Component-3 contains information regarding basin relief;

iv) Component-4 contains information regarding hillslope processes or fluvial erosion and tilting.

Given that the aim of this study is to identify which drainage basins are under a high degree of tectonic control, the selected criteria were: (i) the elongated shape of basin; (ii) the high or low relief (tectonic control with ongoing uplift or tilting) and; (iii) hillslope processes and geological controls dominant in basin development, relative to fluvial processes.

Those criteria can be explained only by the extracted components of *FA* numbers 2, 3 and 4 (Table 3 in supplementary material). These components provide useful information about how the *AHP* should be established and about the tectonic control of the drainage basins. Component-1 was excluded from the subsequent *AHP* analysis because it only contained general information regarding the basin size and extent (i.e. minimal information about tectonic control). Although component-1 gives a high percentage of variance (41%), this is mainly because the calculations of the rest of the indices were dependent on the indices consisting of that particular component (Table 1). Such dependency leads to high correlation among the indices (Table 2 in supplementary material), which explains the high percentage of variance.

The *FA* used the geomorphic indices as input variables to distinguish the indices in three final components (Table 3 in supplementary material). The indices within each selected component (2, 3 & 4), were ranked based on Tables 3-4, ordered such that prior values indicate higher elongation, relief and hillslope or tectonic process information (Table 5). These ranked indices were used in the *AHP* procedure to discriminate the basins into four groups with regard to tectonic control on basin development: very high, high, moderate or low.

Insert Fig. 7.

Insert Table 7.

With the *AHP* method, the judgements can be trustworthy if they are not close to randomness. In this study all extracted preference matrices are acceptable ($Cr < 0.1$) and no revision of preference values is needed. The predominant diverse lithological and permeability conditions of the basins were acknowledged within the *AHP* procedure, in conjunction with the indicative information of the geomorphic indices. These conditions are considered in the *AHP* for the representative criteria of weights to be determined by the preference matrix. As soon as the preference matrix is completed for each basin and the criteria of weights are determined, then a final value for each basin is extracted. The lower this value is, the higher the degree of tectonic activity within each basin. This is because the initial ranking took place regarding the highest basin elongation, highest relief and highest degree of hillslope processes. This indicates that basins with the highest final ranked value will represent those associated with neotectonic control.

The western basins of the study area (i.e. 4, 5, 6, 8, 14 and 15) are the ones characterized by regional tectonic control, as indicated by the *AHP* analysis (Figure 8). The basins with red/orange colour in figure 8 (e.g. Arapi, Pelekaniotis) owe their development primarily to neotectonic activity which dominates landscape evolution in the west of the study region. The blue-coloured basins, are indicative of minimal neotectonic activity, which dominates the north-east part of the study area. The yellow-coloured basins, indicating moderate tectonic activity, are mainly observed adjacent to the areas of high neotectonic activity.

In the west of the study area, drainage basins 4 to 8, are characterized by high to very high regional tectonic activity, as shown by many previous geological and seismological studies (e.g. Mouslopoulou et al., 2001; Bohnhoff et al., 2005; Chatzaras et al., 2013). It seems that these basins owe their elongated shape to the presence of the Rodopos and Keras active faults, extending along basin 8 with a N-S to NE-SW orientation, and the Platanos active fault extending along basin 4 with a NE-SW strike (Figure 3b). The nearby to Platanos fault, the main active fault zone “Western Crete”, has a N-S strike, controlling the morphology of the western coast and basins 1 to 3, and responsible for the tectonic scree found in older terraces and eroded/reworked debris in more recent terraces (Mountrakis et al., 2012). Moreover, it is essential to consider for these basins the presence of the Topolia fault zone, cutting through basins 5 to 8 in an E-W direction (Figure 3b). Such a complex tectonically active status characterizing basins 4 to 8, in association with the majority of these basins being mostly covered by Neogene and Quaternary deposits, supports the findings of this study. Based on the study of Mouslopoulou et al. (2001) and Mountrakis et al. (2012), the Keras fault has a NE-SW strike and dip to NW: that supports the *AF* tilting analysis in this study (Figure 4) for basins 7 and 8. The high degree of tectonic activity for the basins 14 and 15 is a result of the Paleochora major fault zone, where the highest recorded neotectonic uplift in Crete is found, with 9 m of uplift on the western margins of those basins (Pirazzoli, 2005) (Figure 3b). The area of Paleochora has been shown to be tectonically active by many other studies, with a fault- bounded sequence of coastal notches and caves, as well as the presence of an en-echelon ENE–WSW fault set, with both normal and reverse slips (Thommeret et al., 1981; Tiberti et al., 2014; Argyriou et al., 2016b).

Some discussion is essential regarding tectonic control versus lithological control. This research takes into account lithological influences, even where a strong tectonic signal occurs (e.g. Mouslopoulou et al., 2001; Caputo et al., 2010; Tiberti et al., 2014). Several types of drainage network characteristics (e.g. basin shape, basin elongation) can be used as indicators of active tectonics or lithological influences controlling the morphological development of drainage basins (Summerfield, 2000). In this study, the majority of the faults where neotectonic activity was indicated were mostly located in homogeneous lithologies: i.e. the mapped lineaments were not due to lithological boundaries (Figure 3). Moreover, the majority of basins 4 to 8, characterized by high tectonic activity, are sedimentary basins with wet/saturated ground that would be severely affected by seismic waves and tilting (Mountrakis et al., 2012; Argyriou et al., 2016b).

Insert Fig.8.

5. Conclusions

This study has examined interrelations between drainage basin development and regional tectonic activity in Crete. Various geomorphic indices were calculated: these provided insights into the processes shaping the study basins. The indices used evaluations of the relationships between the geomorphology and lithology, via factors such as basin relief, basin geometry, dominant processes (i.e. hillslope deposits, tectonic deformation or fluvial erosion) and tilting of basins.

A key feature was the selection of particular indices for drainage basin morphometry evaluation. Assemblages of geomorphic indices can offer valuable information on regional tectonic control processes occurring within a basin. To clarify the interrelationships of the geomorphic indices, a multivariate *FA* analysis was applied, to group the indices and rank them. The derived *FA* components were particularly useful because they were used in the *AHP* procedure that enabled the criteria of weights to be extracted. As a result, the *AHP* stage was more coherent because knowledge of the related indices, provided by the *FA*, provided more representative weighted criteria for the final discrimination of drainage basins neotectonic activity. This issue, along with the lithological characteristics of each basin during the criteria of weights determination, highlighted basins dominated by high degrees of tectonic activity.

The western basins (e.g. 4, 5, 6, 8, 14, and 15) are deformed in ways that indicate a high degree of tectonic control, a finding that is in agreement with many other publications on the geology of the study area. A unique aspect of this study into neotectonic features and landscape evolution is that does not focus on coastal investigations; nor outcrops and fault scarps, nor regional seismological data analyses. Instead, this methodology examines drainage basin morphological evolution, highlighting areas of enhanced neotectonic landscape deformation, through a low-cost GIS-based multi-disciplinary approach, which can be used in advance of fieldwork to target locations for ground investigation.

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References

Abrahams, A.D., 1984. Channel networks: a geomorphological perspective. Water Resour. Res. 20, 161–188.

Aher, P.D., Adinarayana, J., Gorantiwar, S.D., 2014. Quantification of morphometric characterization and prioritization for management planning in semi-arid tropics of India: a remote sensing and GIS approach. J. Hydrol. 511, 850–860.

Alipoor, R., Poorkermani, M., Zare, M., El-Hamdouni, R., 2011. Active tectonic assessment around Rudbar Lorestan dam site, High Zagros Belt (SW of Iran). Geomorphology 128, 1–14.

Al-Sulaimi, J., Khalaf, F.J., Mukhopadhyay, A., 1997. Geomorphological analysis of paleo drainage systems and their environmental implications in the desert of Kuwait. Environmental Geology 29 (1/2), 94-111.

Argyriou, A.V., Sarris, A., Teeuw, R.M., 2016a. Using geoinformatics and geomorphometrics to quantify the geodiversity of Crete, Greece. International Journal of Applied Earth Observation and Geoinformation, 51, 47-59.

Argyriou, A.V., Teeuw, R.M., Rust, D., Sarris, A., 2016b. GIS multi-criteria decision analysis for assessment and mapping of neotectonic landscape deformation: a case study from Crete. Geomorphology, 253, 262–274.

Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S.T., Bangash, H-A., 2014. Ground-based and UAV-Based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology. Journal of Structural Geology, vol. 69, Part A, 163-178.

Biswas, S., Sudhakar, S. and Desai, V.R., 1999. Prioritization of subwatersheds based on morphometric analysis of drainage basin- a remote sensing and GIS approach. J. of Ind. Soc. Of Rem. Sens., 27(3), 155-166.

Bohnhoff, M., Harjes, H.-P., Meier, T., 2005. Deformation and stress regimes in the Hellenic subduction zone from focal mechanisms. J. Seismol., 9 (2005), pp. 341-366.

Burbank, D.W. and Anderson, R.S., 2001. Tectonic geomorphology. Blackwell Science, Malden, Massachusetts, 274.

Caputo, R., Catalano, S., Monaco, C., Romagnoli, G., Tortorici, G., Tortorici, L., 2010. Active faulting on the island of Crete (Greece). Geophysical Journal International 183, 111-126.

Chakhar, S. and Martel, J.M., 2003. Enhancing geographical information systems capabilities with multi-criteria evaluation functions. J. Geogr. Inf. Decis. Anal. 7, 47–71.

Chatzaras, V., Xypolias, P., Kokkalas, S., koukouvelas, I., 2013. Tectonic evolution of a crustal-scale oblique ramp, Hellenides thrust belt, Greece. Journal of Structural Geology, vol. 57, 16-37.

Chaudhary, R.S. and Sharma, P.D., 1998. Erosion hazard assessment and treatment prioritisation of Giri River catchment in north western Himalayas. Indian J. Soil Conservation, 26 (1), 6–11.

Chen, Y., Khan, S., Paydar, Z., 2009.To retire or expand? A fuzzy GIS-based spatial multi-criteria evaluation framework for irrigated agriculture. Irrig. Drain. 59 (2), 174–188.

Chopra, R., Deep Dhiman, R. & Sharma, P.K., 2005. Morphometric analysis of sub-watersheds in Gurdaspur district, Punjab using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, Volume 33 (4), 531-539.

Chorowicz, J., Dhont, D., Gundogdu, N., 1999. Neotectonics in the eastern North Anatolian fault region (Turkey) advocates crustal extension: mapping from SAR ERS imagery and Digital Elevation Model. Journal of Structural Geology, vol. 21, Issue 5, 511-532.

Cichanski, M., 2000. Low-angle, range-flank faults in the Panamint, Inyo and Slate ranges, California: Implications for recent tectonics of the Death Valley region. Geological Society of America Bulletin, vol. 112, 871-883.

Davis, J.C., 1973. Statistics and data analysis in geology. New York, John Wiley & Sons, Inc. 550 pp.

Drooger, C.W. and Meulenkamp, J.E., 1973. Stratigraphic contributions to geodynamics in the Mediterranean area: Crete as a case history. Bulletin of the Geological Society of Greece 10, 193–200.

El-Hamdouni, R., Irigaray, C., Fernández, T., Chacón, J., Keller, E.A., 2008. Assessment of relative active tectonics, southwest border of the Sierra Nevada (southern Spain). Geomorphology 96, 150–173.

Fassoulas, C., 1999. The structural evolution of central Crete] insight into the tectonic evolution of the south Aegean (Greece). Geodynamics 27, 23-43.

Fassoulas, Ch., Georgila, K., Sarris, A., Kokkinaki, M., 2007. Geohazard risk assessment based on the evaluation of Cretan faults, Crete-Greece. In: The 6th International Symposium on Eastern Mediterranean Geology & The 9th International Conference of Jordanian Geologists Association, Amman, Jordan.

Ganas, A., Palyvos, N., Mavrikas, G., Kollias, S., Tsimi, C. 2010. Geomorphological and geological observations at the coast of Tripiti hill (Heraklion harbour, Crete), in relation to reported active faulting. Scientific Annals, School of Geology, Proceedings of the XIX CBGA Congress, vol. 99, 11-20.

Giorgis, S., Weber, J., Hojnowski, J., Pierce, W., Rodriguez, A., 2011. Using orthographic projection with geographic information system (GIS) data to constrain the kinematics the Central Range Fault zone, Trinidad. Journal of Structural Geology, vol. 33, Issue 8, 1254-1264.

Goddard, J. and Kirby, A., 1976. An introduction to Factor Analysis. Norwich, GeoAbstracts Ltd, Concepts and Techniques in Modern Geography (7), 39.

Greiling, R., 1982. The metamorphic and structural evolution of the Phyllite-Quartzite Nappe of western Crete. Journal of Structural Geology, vol. 4, Issue 3, 291-297.

Hack, J.T., 1957. Studies of longitudinal profiles in Virginia and Maryland: U.S. Geological Survey Professional Paper 294-B, 45–97.

Horton, R.E., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56, 275–370.

Hurtrez, J.E., Sol, C. & Lucazeau, F., 1999. Effect of drainage area on hypsometry from an analysis of small-scale drainage basin in the Siwalik Hills (Central Nepal). Earth Surface Processes and Landforms 24, 799–808.

Jae-On Kim, 1970. Cited in factor analysis, selected topics from SPSS. IInd Edition. Norman et al. Mc Graw-Hill Book Co., 485 – 500.

Javed, A., Khanday, M.Y. & Rais, S., 2011. Watershed prioritization using morphometric and land use/land cover parameters: A remote sensing and GIS based approach. Journal Geological Society of India 78, 63-75.

Kaiser, H.F., 1958. The varimax criterion for analytic rotation in factor analysis. Psychometrika, 23, 187-200.

Kremljak, Z. & Buchmeister, B., 2006. Uncertainty and development of capabilities. DAAAM International Publishing Vienna, 2006.

Krishnamurthy, J., Srinivas, G., Jayaram, V., Chandrasekhar, M.G., 1996. Influence of rock types and structures in the development of drainage networks in typical hardrock terrain. ITC Journal 3–4, 252–259.

Laaribi, A., Chevallier, J.J., Martel, J.M., 1996. A spatial decision aid: a multicriterion evaluation approach. Computers and Urban Systems 20, 351–366.

Mason, J., 2016. Active fault investigations in the western Peloponnese and eastern Crete, Greece. PhD Thesis. Faculty of Georesources and Materials Engineering at RWTH Aachen University, 1-221.

Maxwell, J.C., 1955. The Bifurcation Ratio in Horton's Law of Stream Numbers, Trans. Am.Geophys. V. 34, 520.

McCalpin, J.P., 2009. Paleoseismology, 2nd edition, Elsevier, vol. 95, 1-629.

Mesa, L.M., 2006. Morphometric analysis of a subtropical Andean basin (Tucuman, Argentina). Environ. Geol. 50, 1235–1242.

McKenzie, D.P., 1978. Some remarks on the development of sedimentary basins. Earth Panet. Sci. Lett. 40, 23-32.

Mountrakis, D., Kilias, A., Pavlaki, A., Fassoulas, C., Thomaidou, E., Papazachos, C., Papaioannou, C., Roumelioti, Z., et al, 2012. Neotectonic study of Western Crete and implications for seismic hazard assessment. In: (Eds.) Emmanuel Skourtsos and Gordon S. Lister, *Journal of the Virtual Explorer*, volume 42, paper 2, 1-35.

Mouslopoulou, V., Andreou, C., Atakan, K. & Fountoulis, I., 2001. Paleoseismological investigations along the Kera fault zone, western Crete: implications for seismic hazard assessment, Bull. Soc. Geol. Greece, 34, 1531–1537.

Onosemuode, C. Adetimirin, O.I. and Aboderin, S.O., 2010. Hydrological Analysis of Onitsha North East Drainage Basin Using Geoinformatic Techniques. World Applied Sciences Journal 11 (10), 1297-1302.

Ozdemir, H. and Bird, D., 2009. Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point offloods. Environ. Geol. 56, 1405–1415.

Palcic, I. and Lalic, B., 2009. Analytical hierarchy process as a tool for selecting and evaluating projects. International Journal of Simulation Model 8 (8), 16-26.

Papazachos, B.C., 1996. Large seismic faults in the Hellenic arc: Annali di Geofisica, v. 39, 891-903.

Pirazzoli, P.A., 2005. A review of possible eustatic: isostatic and tectonic contributions in eight late-holocene relative sea-level histories from the Mediterranean area. Quat. Sci. Rev. 24, 1989–2001.

Ramírez-Herrera, M.T., 1998. Geomorphic assessment of active tectonics in the Acambay Graben, Mexican volcanic belt. Earth Surf. Process. Landf. 23, 317–332.

Reddy, G.P.O., Maji, A.K., Gajbhiye, K.S., 2004. Drainage morphometry and its influence on landform characteristics in a basaltic terrain: central India—a remote sensing and GIS approach. Int. J. Appl. Earth Obs. Geoinf. 6, 1–16.

Ribolini, A. and Spagnolo, M., 2008. Drainage network geometry versus tectonics in the Argentera Massif (French–Italian Alps). Geomorphology 93, 253–266.

Royden, L.H., 1993. Evolution of retreating subduction boundaries formed during during continental collision. Tectonics 12, 629-638.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15, 231–281.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw Hill International, 287.

Saaty, T.L., Vargas, L.G., 1991. Prediction, Projection and Forecasting. Kluwer Academic, Boston 254 pp

Salvany, J.M., 2004. Tilting neotectonics of the Guadiamar drainage basin, SW Spain. Earth Surf. Process. Landforms 29, 145–160.

Sarris, A., 2007. Management of landscape & natural resources through remote sensing & GIS. Int. Soc. Opt. Eng., SPIE Newsroom.

Schneiderwind, S., Mason, J., Wiatr, T., Grützner, C., Pallikarakis, A., Reicherter, K., 2015. Innovative trenching investigations on active normal faults: A combination of experience, remote sensing applications and geophysics. INQUA Focus Group on Paleoseismology and Active Tectonics, 431-435.

Segura, F.S., Pardo-Pascual, J.E., Rosselló, V.M., Fornós, J.J. and Gelabert, B., 2007. Morphometric indices as indicators of tectonic, fluvial and karst processes in calcareous drainage basins, South Menorca Island, Spain. Earth Surf. Process. Landforms 32, 1928–1946.

Selim, H.H., 2013. Tectonics of the buried Kirklareli Fault, Thrace Region, NW Turkey. Quat. Int. 312, 120–131.

Shaw, B., Ambraseys, N.N., England, P.C., Floyd, M.A., Gorman, G.J., Higham, T.F.G., Jackson, J.A., Nocquet, J.M., Pain, C.C., Piggott, M.D., 2008. Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake. Nature Geoscience 1, 268–276.

Sougnez, N. and Vanacker, V., 2011. The topographic signature of Quaternary tectonic uplift in the Ardennes massif (Western Europe). Hydrology and Earth System Sciences, 15, 1095–1107.

Strahler, A.N., 1952. Hypsometric (area–altitude) analysis of erosional topography. Geol. Soc. Am. Bull. 63, 1117–1142.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology, Transaction of American Geophysical Union 38, 913-920.

Stiros, S.C., 2001. The AD 365 Crete earthquake and possible seismic clustering during the fourth to sixth centuries AD in the Eastern Mediterranean: a review of historical and archaeological data. Journal of Structural Geology, Volume 23, Issues 2–3, 545-562.

Summerfield, M.A., 2000. Geomorphology and Global Tectonics. John Wiley & Sons, 1-386.

Thommeret, Y., Thommeret, Y., Laborel, J., Montaggioni, L., Pirazzoli., P., 1981. Late Holocene shoreline changes and seismotectonic displacements in western Crete (Greece). Zeitschift fur Geomorphologie 40, 127–149.

Tiberti, M.M., Basili, R., Vannoli P., 2014. Ups and downs in western Crete (Hellenic subduction zone). Nature, Scientific reports, 4:5677,1-7.

Wegmann, K.W., 2008. Tectonic Geomorphology above Mediterranean Subduction Zones: Northeastern Apennines of Italy and Crete, Greece. PhD thesis, Dept. Earth and Environmental Sciences, Lehigh University.

Willgoose, G. and Hancock, G., 1998. Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment. Earth Surface Processes and Landforms 23, 611–623.

Yevjevich, V., 1972. Stochastic processes in hydrology, Water Resources Publications, Colorado.

Parameters	*Group*	*Formula/Description*	*Values range*	*References*
Basin Length, L_b (km)	Drainage basins	L_b , the length of the main stream order, plus the length of the extension between the end of the main stream order until the longer point of the basin, parallel to the main stream order		Gregory and Walling, 1973
Area, A (km^2)		A, the entire area that is comprised by the drainage basin boundary		
Perimeter, P (km)		P, the total length of the drainage basin boundary		
Basin relative relief, R(m)	Relief structure	R= h_{max}-h_{min}, the difference between the maximum and the minimum elevation points of the basin. The index helps to understand the relation between drainage formation and surface.	High values indicate low infiltration, high runoff conditions and high physiographic mountainous structure and vice versa.	Reddy et al., 2004; Mesa, 2006; Al-Sulaimi, 1997
Relief ratio, R_r (km/km)		R_r= R/L_b, the ratio of the basin relief to the basin length. Its values may reveal the degree of the rock resistance	High values are characteristic of hilly regions and resistant rocks, while low values are characteristic of flat regions and valleys with less resistant rocks.	Sudheer 1986; Sreedevi 1999; Mesa, 2006; Schumm, 1963
Bifurcation Ratio, R_b		R_b= N_u/ N(u+1), the ratio of the number of streams of any order to the number of streams with an increased by one order. The R_b index describes the degree of the structural complexity of the basin and the influence of geological structure on the drainage network development.	When R_b ranges from 3 to 5 indicates natural drainage system characteristics and minimum influence of geological structures in drainage networks. Within that range (3-5), lower values can be considered to refer to less structural disturbances without drainage pattern distortion, while higher values can be indicative of high structural complexity and low permeability. Abnormal values of R_b either less than 3 or more than 5 are encountered in areas where geological control is dominant.	Chow, 1964; Verstappen, 1983; Kale and Gupta, 2001; Ozdemir and Bird, 2009; Horton, 1945; Reddy et al., 2004; Kinthada et al., 2013; Mekel, 1970; Raghavan et al., 1983
Stream Frequency, F_u (km^{-2})		F_u= N/A, the ratio of the total number of stream segments to the area of the basin. The values of *Fu* indicate the degree of slope steepness, rock permeability and surface runoff.	High *Fu* values range (>5) are associated with impermeable subsurface material, high relief and low infiltration capacity, while low values imply high permeability geology, low relief and high infiltration capacity.	Al-Sulaimi, 1997; Reddy et al. 2004; Shaban et al.2005; Ozdemir & Bird, 2009; Bagyaraj & Gurugnanam, 2011
Drainage Density, D_d (km^{-1})		D_d= ΣL/A, the ratio of the total stream length to the area of the basin. The *Dd* reveals information regarding surface runoff potential, ground surface steepness, the degree of landscape dissection, rock permeability and resistance to erosion.	*Dd* values less than 5 are associated with a coarse drainage network and subsurface material being permeable. *Dd* is controlled by factors such as slope gradient and relative relief. A low value of *Dd* is associated with low relief within the basin and permeable materials, while a high *Dd* value provides a high relief and impermeable rocks.	Verstappen, 1983; Sreedevi, 2005, 2009; Strahler, 1964; Gardiner, 1995

Stream Total Number, N	Stream network	N_u, the number of streams in each order. Number of streams VS the number of order, can examine whether Horton's first law observation is confirmed (see below). If it is not confirmed, then tectonic control is a factor influencing the drainage network disturbance.		Al-Sulaimi, 1997; Chopra et al., 2005; Paraschou, 2005
Total Stream Length, ΣL (km)		ΣLu, the sum of all stream lengths of the basin. Stream length can be useful to check Horton's second law, which describes the relation of the average stream length to the stream orders. The basin stream length is supposed to decrease as the order increases, but any deviation observed implies to variation in relief.		Horton, 1945; Al-Sulaimi, 1997; Sreedevi, 2005
Asymmetry Factor, AF		AF = 100*(A_r / A_t), the ratio of the area, in the basin, on the right of the main stream (downstream) to the area of the basin multiplied with the percentage. A_r is the percent of the area in the basin that is found on the right of the main stream. A_t is the total area of the basin. Meander belt midline is the long axis of the mainstream if stable settings of a drainage network formation were taking place. This index identifies tectonic tilting of a drainage basin and characterizes its asymmetry or symmetry, as it is sensitive to rotations vertical to the axis of the main stream.	Under stable settings of a drainage network formation, the index will be equal to 50%. In any other case, calculation of the *AF* index will reveal either *AF*> 50% (tilting left downstream) or *AF*< 50% (tilting right downstream). Values of absolute difference (*AF-50*) close to 0 indicate low tectonic activity while values away from 0 indicate higher tectonic activity.	Hare and Gardner, 1985
Drainage basin shape index, Bs		Bs= Bl / Bw, the ratio of the length of the basin measured from the mouth to the most distant drainage divide, to the width of the basin at its widest point. Elongated basin shapes indicate high active tectonic processes while more circular basins less active tectonic processes.	High index values imply elongated basins with areas of continuing rapid uplift and tectonic activity presence. Low values are associated with more circular basins.	Cannon, 1976; Bull and McFadden, 1977
Hypsometric Integrals, HI		$HI = \frac{mean - minimum}{maximum - minimum}$,the ratio of the difference between mean elevation and minimum elevation, to the difference of maximum elevation minimum elevation. A powerful technique that reveals the degree of disequilibrium in the balance of erosive and tectonic forces	High values indicate zones with high relief and deeply incised valleys with minimal upland (plateau) erosion. Conversely, lower values reveal more dissected drainage basins, being highly eroded with less impact from recent active tectonics. Three stages of erosion: i) areas representing basins with deep incision and rugged terrain (*HI*>0.5); ii) areas with approximate equilibrium between erosional and tectonic processes (0.4<*HI*<0.5) and; iii) basins characterized by low subdued relief and severe erosion (*HI*<0.4).	Strahler, 1952; Keller and Pinter, 2002; El-Hamdouni et.al, 2008
Form Factor, R_f		R_f= $A/(L_b)^2$, the ratio of the basin area to the square of the basin length. This index is related to the peak discharge and flow	Lower values, imply the presence of elongated basins with less side flow for shorter duration and high main flow for longer duration takes place,	Gregory and Walling, 1973; Reddy et al., 2004; Kouli et

	Morpho-tectonics	intensity of the drainage network.	resulting in low peak flows for longer duration. That can imply to exogenous procedures taking place within the basin, preventing the proper development of a homogeneous drainage network (e.g. dendritic). On the other hand, high *Rf* exists in circular basins with high side flow for longer duration and low main flow for shorter duration, causing high peak flows in a shorter duration.	al, 2007; Javed et al., 2011
Elongation Ratio, R_e		$R_e=D/L_b=2A/\pi/L_b= 1.128*A^{1/2}/L_b$, the ratio of the diameter of the circle of the area of the basin to the basin length. This ratio gives the proportion of the basin that has been elongated mainly by tectonic activity control and slightly by lithology, while more circular basins indicate less active tectonic processes. It is a proxy indicator of recent tectonic activity.	Values of the *Re* index less than 0.5 indicate tectonically active regions, values between 0.5 to 0.75 moderate active regions and values larger than 0.75 inactive ones.	Schumm, 1956; Bhatt et al., 2007; Kale and Shejwalkar 2008
Basin Circularity, R_c		$R_c= 4\pi A/ P^2$, the ratio of the basin area to the area of a circle with the same perimeter as the basin. Characterizes the current stage of maturity of the basin segments and the degree of circularity.	Strongly elongated basins have *Rc* between 0.40 and 0.50, with quadrangular basins having values close to 0.8.	Miller, 1953

Table 1. Geomorphic indices associated with the morphological characteristics of the drainage basins; relief structure; stream network aspects; regional drainage basin morphotectonics.

			Stream Order						
Basins Name	**Basin ID**	**Parameters***	**1^{st}**	**2^{nd}**	**3^{rd}**	**4^{th}**	**5^{th}**	**6^{th}**	**Comment**
Ag.Eirini	17	NS	567	279	126	87	39	6	The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	142.85	77.617	37.441	23.654	10.682	1.823	
		MSL	0.251	0.278	0.297	0.271	0.273	0.303	
Kakodikianos	16	NS	344	165	57	45	17	**29**	Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 5^{th} to 6^{th} order is observed.
		SL	109.37	56.86	17.264	14.099	5.3	11.66	
		MSL	0.317	0.344	0.302	0.313	0.311	0.402	
Kalami	12	NS	736	319	171	127	68	6	The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	175.61	86.254	50.374	30.369	21.167	3.405	
		MSL	0.238	0.27	0.294	0.239	0.311	0.567	
Keritis	10	NS	900	438	287	114	33	1	The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	227.69	111.06	81.53	34.67	11.43	12.87	
		MSL	0.252	0.253	0.284	0.304	0.346	1.17	
Tauronitis	9	NS	1176	608	232	97	**175**	24	Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 4^{th} to 5^{th} order is observed.
		SL	277.45	121.97	51.458	18.588	31.2	10.697	
		MSL	0.235	0.2	0.221	0.191	0.178	0.445	
Tiflos	7	NS	355	153	71	44	**53**	11	Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 4^{th} to 5^{th} order is observed.
		SL	101.89	50.087	24.712	10.903	15.572	6.068	
		MSL	0.287	0.327	0.348	0.247	0.293	0.551	
Therisiano Gorge	11	NS	350	171	86	51	21	1	The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	77.475	39.302	23.429	17.536	13.188	1.308	
		MSL	0.221	0.229	0.272	0.343	0.628	1.308	
Kasteli	5	NS	137	68	26	18	**22**		Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 4^{th} to 5^{th} order is observed.
		SL	39.755	19.763	11.109	7.434	9.113		
		MSL	0.29	0.29	0.427	0.413	0.414		
Pelekaniotis	14	NS	166	68	34	22	**26**		Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 4^{th} to 5^{th} order is observed.
		SL	46.774	22.145	12.458	6.06	9.919		
		MSL	0.281	0.325	0.366	0.275	0.381		
Samaria Gorge	18	NS	191	96	36	15	**29**		Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 4^{th} to 5^{th} order is observed.
		SL	63.91	32.112	12.021	5.149	8.095		
		MSL	0.334	0.334	0.333	0.343	0.279		
Xsiropotamos	13	NS	139	59	26	**37**	15		Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3^{rd} to 4^{th} order is observed.
		SL	49.405	16.445	8.523	9.783	4.06		
		MSL	0.355	0.278	0.327	0.264	0.27		
Aradaina	20	NS	34	19	11	5			The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	15.661	13.449	6.556	6.743			
		MSL	0.46	0.707	0.596	1.348			
Arapi	8	NS	170	77	31	**43**			Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3^{rd} to 4^{th} order is observed.
		SL	53.803	24.105	11.841	17.473			
		MSL	0.316	0.313	0.381	0.406			
Magagistra	4	NS	91	38	32	16			The higher the order the lower number of streams is expected. This basin follows Horton's first law.
		SL	29.07	12.339	12.375	5.66			
		MSL	0.319	0.324	0.386	0.353			

Mesa Rema	3	NS SL MSL	52 15.636 0.3	30 9.7 0.323	3 1.021 0.34	**16** 4.153 0.259			Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3rd to 4th order is observed.
Metoxi-Platanos	1	NS SL MSL	20 7.161 0.358	10 4.988 0.498	6 2.073 0.345	1 1.234 1.234			The higher the order the lower number of streams is expected. This basin follows Horton's first law.
Milias	6	NS SL MSL	70 22.242 0.317	33 8.521 0.258	19 6.365 0.335	10 5.781 0.578			The higher the order the lower number of streams is expected. This basin follows Horton's first law.
Potamos	19	NS SL MSL	97 30.02 0.309	35 12.964 0.37	14 3.728 0.266	**35** 10.791 0.308			Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3rd to 4th order is observed.
Sarakiniotis	15	NS SL MSL	144 31.737 0.22	59 15 0.254	34 7.113 0.209	**45** 13.782 0.306			Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3rd to 4th order is observed.
Sfakiano Gorge	21	NS SL MSL	50 21.741 0.434	21 12.039 0.573	5 2.188 0.437	**20** 7.153 0.357			Any disruptions in descending order sequence (raise in number of streams for higher ordering) indicates structural control and regional uplift within the basin. Raised stream number from 3rd to 4th order is observed.
Balsamakia	2	NS SL MSL	22 8.639 0.392	11 2.17 0.197	7 2.454 0.35				The higher the order the lower number of streams is expected. This basin follows Horton's first law.

*NS: Number of streams, SL: Stream length and MSL: Mean stream length

Table 2. The stream analysis for the study area drainage basins. The order stream where a deviation is observed in the linear regression indicates a lower number of streams than the higher order which follows. This is not in accordance with Horton's first law, indicating that the deviation observed is a result of variation in relief (that issue implies that exogenous factors such as tectonic might be influencing the drainage network development).

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Basin ID	Basin names	Area (km^2)	Perimeter (km)	L_b (km)	Basin relative relief (h_{max}-h_{min}) (m)	Basin relief ratio (km)	N_u	ΣL_u	Dd	Fu	Rb
1	Metoxi	6.86	14.48	5.37	830	0.154	37	15.45	***2.25***	**5.39**	2.59
2	Balsamakia	4.77	11.17	3.67	908	**0.247**	40	13.26	2.78	**8.38**	1.77
3	Mesa Rema	10.68	14.44	5.78	912	0.157	101	30.51	2.85	**9.45**	1.79
4	Magagistra	22.52	24.07	10.94	903	0.082	**177**	59.44	2.64	**7.86**	1.71
5	Kastelli	31.7	32.86	14.81	1041	0.070	**271**	87.25	2.75	**8.54**	**1.65**
6	Milias	15.34	23.94	11.35	794	0.069	132	42.91	2.8	**8.60**	1.89
7	Tiflos	76.06	48.36	19.48	1143	***0.058***	**687**	209.24	2.75	**9.03**	1.82
8	Arapi	41.51	42.04	20.25	923	***0.046***	**321**	107.22	2.58	**7.73**	**1.65**
9	Tauronitis	128.47	62.78	23.7	1294	***0.052***	2312	511.38	**3.91**	**17.67**	1.99
10	Keritis	177.9	72.98	24.87	2106	0.089	1783	479.27	2.65	**9.87**	2.40
11	Therisiano Gorge	57.46	47.69	19.49	2067	0.106	680	172.24	**2.99**	**11.83**	2.81
12	Kalami	129.61	52.44	19.98	2187	0.109	1427	367.18	2.83	**11.00**	2.29
13	Xsiropotamos	35.36	25.8	8.65	1199	0.139	276	86.43	2.44	**7.80**	1.64
14	Pelekaniotis	40.42	32.82	14.53	1152	0.139	316	96.03	2.37	**7.81**	**1.62**

15	Sarakiniotis	23.31	30.86	15.05	922	0.061	**282**	67.63	**2.9**	**12.09**	**1.50**
16	Kakodikianos	77.43	51.59	19.55	1458	0.075	**656**	213.42	2.75	**8.47**	1.74
17	Agia Eirini	98.33	45.92	14.99	1981	0.132	1104	294.07	2.99	**11.23**	2.29
18	Samaria Gorge	51.56	33.92	11.84	2130	**0.180**	367	124.29	2.41	**7.12**	1.76
19	Potamos	27.82	30.96	12.76	**2398**	**0.188**	**181**	57.5	***2.06***	**6.50**	**1.49**
20	Aradaina Gorge	27.79	25.86	11.88	**2342**	**0.197**	69	42.46	***1.52***	***2.48***	1.88
21	Sfakiano Gorge	28.5	34.56	13.4	2183	0.163	**96**	43.12	***1.51***	***3.37***	**1.52**
Comments					Bold values indicate the high values. High values apply to hilly regions and resistant rocks. Such characteristic basins are Aradaina Gorge and Potamos basins, which overly in moderate resistant rock formation but the presence of high permeability reinforces the validity of the high values of *Rr* index. There are basins in	Bold values indicate the high values while italic grey values the low values. High *R* values are characteristic of hilly regions and resistant rocks, while low values are characteristic	Bold values indicate an increase of stream length which is observed in some stream orders with regard the next highest order, implying variation in relief to be significant. This shows that some of the		Bold values indicate the high values while italic grey values the low values. Low *Dd* shows a high coarse drainage texture, while high *Dd* a fine drainage texture (less coarse) (Strahler, 1964). The lowest *Dd* values are expected to characterize regions with highly resistant	Bold values indicate the high values (>5), associated with impermeable subsurface material, high relief and low infiltration capacity, while italic grey values the low values (<5). In comparison with the Dd outcomes, similar basins have lower *Fu* values as well as low *Dd* values, indicating a low frequency of stream segments. Considering the relative highly relief and the fact of not quite resistant presence of rocks within these basins,	Bold values indicate significant low values of *Rb* (1.49<*Rb*<1.65), where the highest degree of disturbance is observed. Values less than 3 for all the basins, indicating that geological structures are disturbing the drainage pattern within all the basins. This issue is in accordance with Mekel (1970) who first showed that

					western part of study region that are characterized by moderately resistant impermeable rock types (e.g. the Phyllites-Quartzites of the Balsamakia and Pelekaniotis basin). In such impermeable regions fluvial processes were expected to provide lower values of the *Rr* index, but instead high values are predominant. That reinforces the implication that their high relief is a result of ongoing uplift and not due to lithological control.	of flat regions and valleys with less resistant rocks.	basins are not in accordance with Horton's first law.		material, low relief and not a consistent fine drainage network development (i.e. dendritic drainage). Basins 19, 20 and 21 do not fulfil the expected observations as they are characterized by significantly high relief. Those basins have evolved in moderately permeable resistant material, preventing uniform drainage network development and as a result the relative relief remains close to 2000m.	an explanation that can be given for their development is due to ongoing uplift in those basins. This leads to a lack of a uniform drainage network development, with the drainage dominated by long length stream segments. In few cases basins with >5 values supposedly provide a finer drainage pattern (e.g. dendritic). This is not in accordance in few drainage basins, where although the drainage network is flowing over impermeable Phyllite-Quartzites and Neogene deposits, justifying the index's values, instead of an expected dendritic pattern, there are trellis and long linear length stream patterns. Low values (<5) are implying high permeability geology and high infiltration capacity which is confirmed by the presence of permeable karst formation of Plattenkalk nappe.	abnormal values of *Rb* less than 3 are indicative of dominant geological control. The range of values being less that 3 is in accordance also with Kouli et al (2007) study, who calculated *Rb* for two of the basins within the study area revealing similar low *Rb* values.

Table 3. Morphological characteristics of the drainage basins, geomorphic indices associated with the relief structure and stream network aspects of the drainage basins.

Basin ID	Re	Rc	Rf	Bs	HI %	AF				
						Ar (km^2)	At (km^2)	AF (km^2)	AF-50	Class
1	0.55	0.41	0.23	2.17	28.0	1.71	6.86	24.92	-25.07	1
2	0.67	0.48	0.35	1.58	**51.8**	3.281	4.77	68.78	18.78	2
3	0.63	0.64	0.32	1.51	48.1	5.996	10.68	56.14	6.14	3
4	0.49	0.49	0.19	2.75	39.9	4.31	22.52	19.14	-30.86	1
5	**0.43**	0.37	**0.14**	2.42	45.9	15.13	31.7	47.72	-2.27	3
6	**0.39**	**0.33**	**0.12**	**4.64**	33.9	4.87	15.34	31.74	-18.25	2
7	0.51	0.41	0.21	1.83	39.6	51.66	76.06	67.92	17.92	2
8	**0.36**	**0.29**	**0.11**	**3.85**	42.9	22.59	41.51	54.42	4.42	3
9	0.54	0.41	0.23	1.47	32.8	19.62	130.87	14.99	-35.01	1
10	0.61	0.43	0.29	2	26.7	72.24	180.62	39.99	-10	2
11	**0.43**	**0.31**	**0.15**	2.78	24.9	27.81	57.46	48.40	-1.592	3
12	0.64	0.59	0.32	1.3	27.9	43.59	129.61	33.63	-16.36	2
13	0.77	0.66	0.47	0.96	46.6	26.40	35.36	74.68	24.68	1
14	0.49	0.47	0.19	2.39	**51.14**	22.43	40.42	55.49	5.49	3

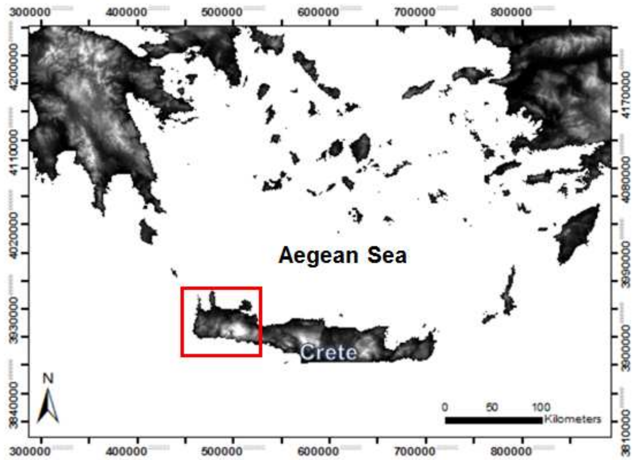
15	**0.36**	**0.3**	**0.1**	**3.53**	**55.8**	14.2	23.31	60.91	10.918	2
16	0.5	0.36	0.2	1.59	37.9	38.89	77.43	50.22	0.226	3
17	0.74	0.58	0.43	1	39.9	63.51	98.33	64.59	14.59	2
18	0.68	0.56	0.36	1.31	**51.6**	32.77	51.56	63.56	13.567	2
19	0.46	0.36	0.17	**2.91**	**64.0**	9.01	27.82	32.38	-17.61	2
20	0.51	0.52	0.19	1.95	49.0	21.22	27.79	76.37	26.376	1
21	0.45	**0.3**	0.16	2.84	**58.5**	14.88	28.5	52.20	2.207	3
Comments	Based on the study by Bhatt et al (2007) about the ranges of *Re* values, circular basins 12, 13 and 17 are tectonically inactive regions; with basins 4, 7, 14 and 16 characterised as moderately active regions because *Re* values range between 0.5 to 0.75; while elongated basins 5, 6, 8, 11 and 15 imply *Re* values lower than 0.5, indicating drainage basins influenced by tectonic activity.	Low *Rc* values characterized basins 6, 8, 11, 15 and 21, reflecting their strongly elongated shape, with more quadrangular basins indicated by higher values of the index, such as basins 13, 3, 12 and 17.	The *Rf* lower values were observed in basins 5, 6, 8, 11 and 15, indicating elongated basins with less side flow for shorter durations and high main flow for longer durations, resulting in low peak flows for longer duration. That can be associated with less circular drainage basins and minimal development of a uniform drainage network (e.g. dendritic). In comparison with the *Rc* and *Bs* indices, that relates to the elongated nature of those basins, in particular basins 6, 8 and 15. High values of *Rf* index were determined for basins 2, 12, 13, 17 and 18, characterizing circular basins with high side flow for longer duration and low main flow for shorter duration, causing high peak flows in a shorter duration.	Highest values of the *Bs* index, reveals that basins 6, 8, 15 and 19 are indicative of high elongation shape, formed by continuing rapid uplift and tectonic activity deformation.	*HI* implies to high rates of tectonic activity and provides high relief when the index exceeds 0,5 values, such as basins 2, 14, 15, 18, 19 and 21. Lower values of *HI* (<0.35) characterise basins 1, 6, 9, 10, 11 and 12, indicating their old stage with low relief and undergoing severe soil/regolith erosion.	With *AF*>50%, there is tilting to the left downstream, while with *AF*<50%, there is tilting to the right towards the downstream. The basins with the higher degree of tilting were basins 1, 4, 9, 20, 13, 6 and 7. There are other basins with moderate asymmetry which in relation with other indices (such as *HI*) can also be associated with potential tectonic activity.				

Table 4. Geomorphic indices associated with regional drainage basin aspects for the basins as a whole, in order to determine regional tectonic control.

ID basin	Component 3				Component 2				Component 4				
	ID Rr	ID R	ID Fu	ID Dd	ID Bs	ID Re	ID Rf	ID Rc	ID HI	ID Rb	ID AF	Mean compound ranking	AHP analysis ranking
1	7	20	19	18	10	14	13	11	18	20	4	14	14.051
2	1	18	12	8	15	18	18	14	4	11	6	11.363	10.823
3	6	17	7	5	16	16	16	20	8	12	15	12.545	12.626
4	14	19	13	13	7	8	8	15	13	8	2	10.9	9.505
5	16	14	10	9	8	4	4	8	10	6	18	9.727	9.48
6	17	21	9	7	1	3	3	5	16	15	7	9.454	7.789
7	19	13	8	10	13	10	11	10	14	13	8	11.727	11.127
8	21	15	16	14	2	1	1	1	11	7	17	9.636	8.213
9	20	10	1	1	17	13	14	9	17	16	1	10.818	10.784
10	13	6	6	12	11	15	15	12	20	19	14	13	14.956
11	12	7	3	2	6	5	5	4	21	21	20	9.636	14.524
12	11	3	5	6	19	17	17	19	19	17	10	13	14.696
13	9	11	15	15	21	21	21	21	9	5	5	13.909	13.13
14	8	12	14	17	9	9	9	13	6	4	16	10.636	9.641
15	18	16	2	4	3	2	2	3	3	2	13	6.18	4.499
16	15	9	11	11	14	11	12	6	15	9	21	12.181	12.71
17	10	8	4	3	20	20	20	18	12	18	11	13.09	13.683
18	4	5	17	16	18	19	19	17	5	10	12	12.909	12.125
19	3	1	18	19	4	7	7	7	1	1	9	7	5.77
20	2	2	21	20	12	12	10	16	7	14	3	10.818	10.195
21	5	4	20	21	5	6	6	2	2	3	19	8.454	8.129

Table 5. Ranking of indices within each factor analysis component, with mean compound ranking of the indices compared to the improved AHP ranking analysis.

(a)



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Aegean Sea
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50
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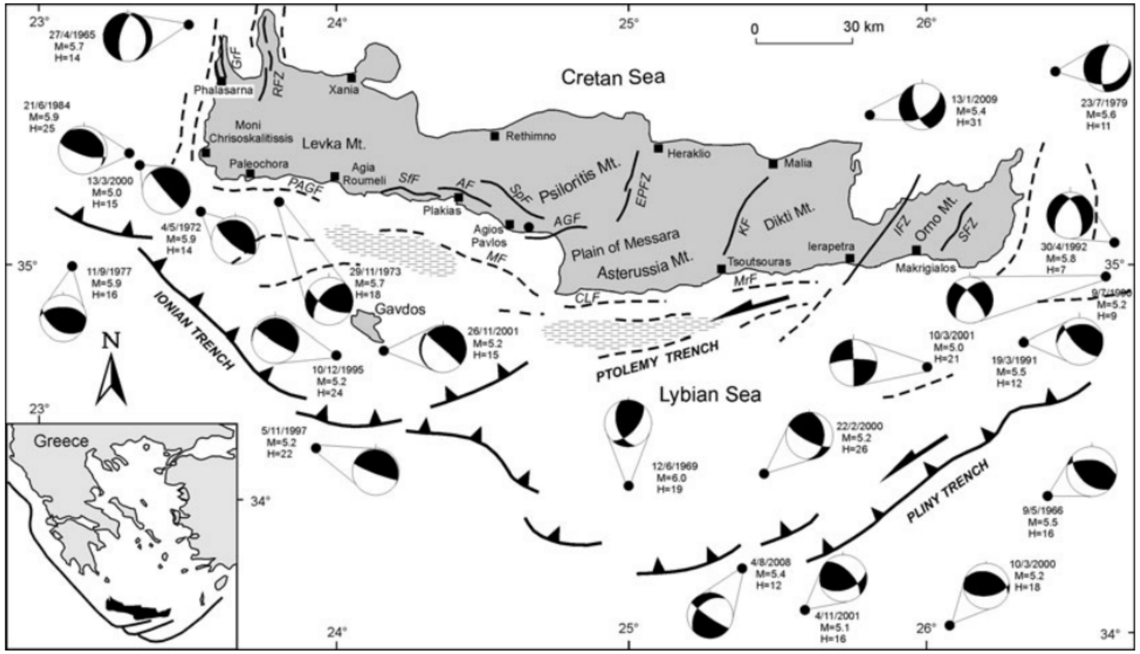
(b)


Cretan Sea
Lybian Sea
IONIAN TRENCH
PTOLEMY TRENCH
PLINY TRENCH
Phalasarna
Xania
Moni Chrisoskalitissis
Levka Mt.
Paleochora
Agia Roumeli
Plakias
Rethimno
Psiloritis Mt.
Heraklio
Malia
Agios Pavlos
Plain of Messara
Asterussia Mt.
Dikti Mt.
Tsoutsouras
Ierapetra
Makrigialos
Orno Mt.
Gavdos
Greece
0 30 km
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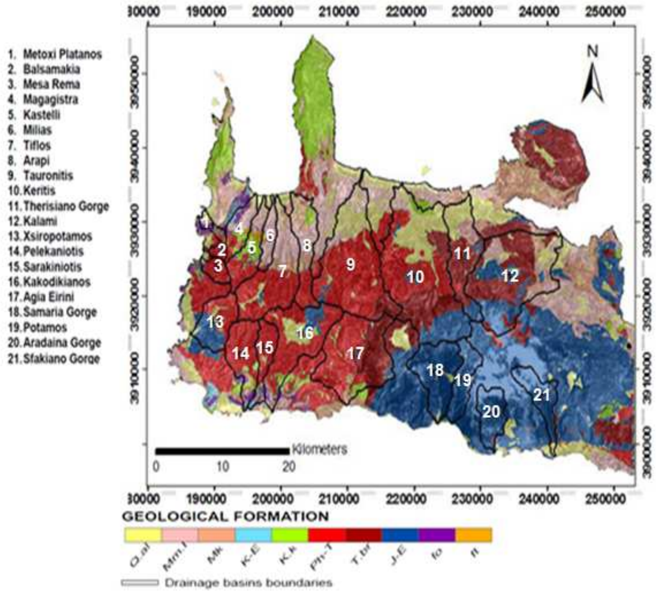
(c)



Symbol	Geological formation	Rock Type	Rock strength
Q.al	Quaternary	Sedimentary rocks (alluvial deposits)	Weak
Mm.l	Neogene	Sedimentary rocks	Weak
Mk	Neogene		Weak
K-E	Carbonate Pindos zone tectonic nappe	A class of sedimentary rocks composed primarily of carbonate minerals	Extremely strong
K.k	Carbonate Tripolis zone tectonic nappe		Extremely strong
Ph-T	Phyllite-Quartzite series	Hard metamorphic rocks	Medium strong
T.br	Carbonate Tripali zone tectonic nappe	A class of sedimentary rocks composed primarily of carbonate minerals	Extremely strong
J-E	Plattenkalk nappe		Medium strong
fo	Flysch Pindos zone tectonic nappe	A sequence of sedimentary rocks that is deposited in a deep marine facies in the foreland basin of a developing orogen.	Weak
ft	Flysch Tripolis zone tectonic nappe		Weak

Figure 1: (**a)** Aegean region. The red box indicates the study region; (b) Seismotectonic map of Crete island (modified from Caputo et. al., 2010 and references therein). (SfF: Sfakia Fault; AF: Asomatos Fault; SpF: Spili Fault; AGF: Agia Galini Fault; PAGF: Paleochora-Agia Roumeli Fault; MF: Messara Fault; CLF: Cape Lithino Fault; MrF: Mirto Fault; SFZ: Sitia Fault Zone; IFZ: Ierapetra Fault Zone; KF: Kastelli Fault; EPFZ: Eastern Psiloritis Fault Zone; RFZ: Rodopos Fault Zone; GrF: Gramvousa Fault); (c) geological formations of the study area and the 21 examined drainage basins are shown by solid black line;

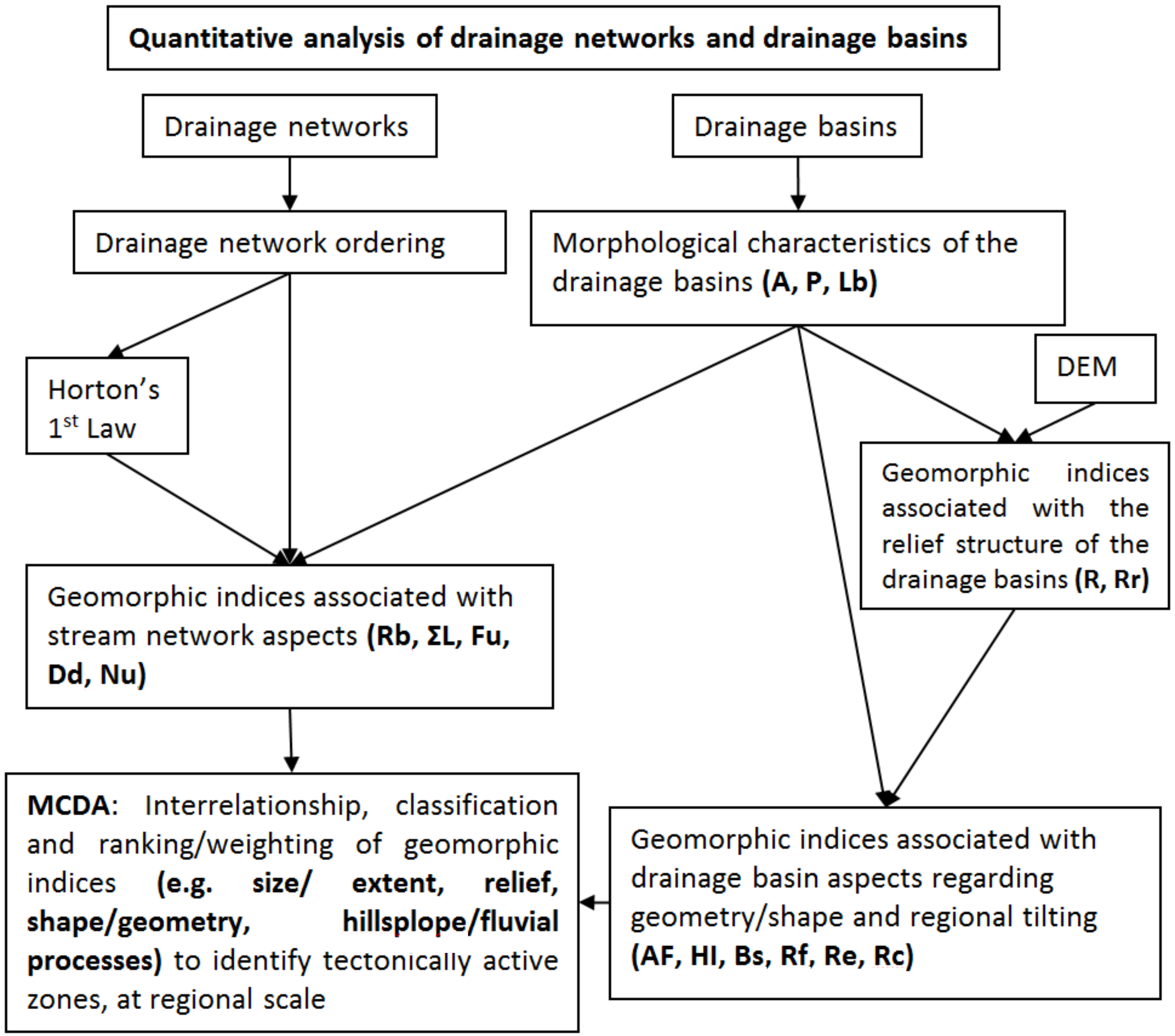
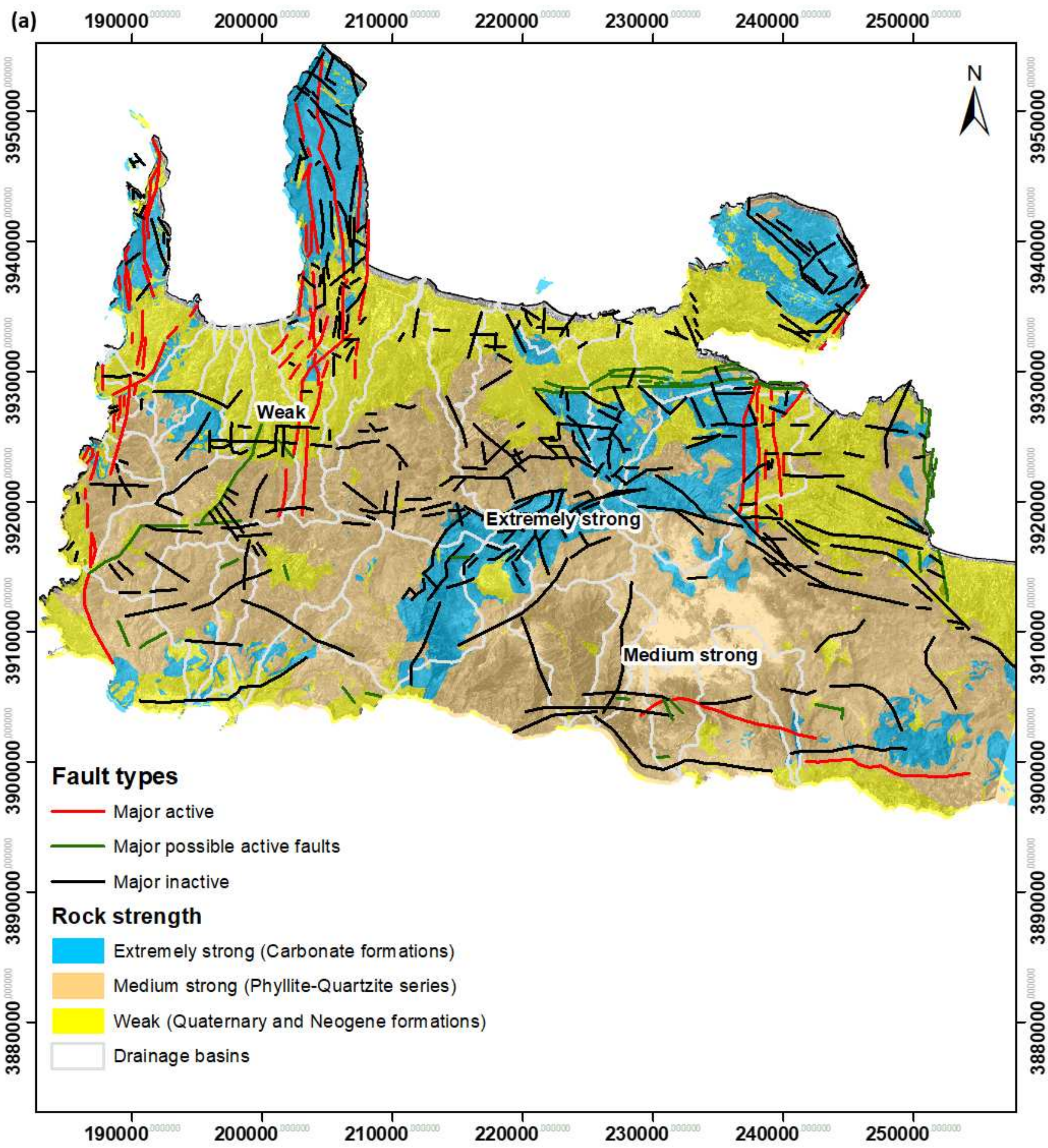


Figure 2: Schematic table showing the sequence and contribution of calculated geomorphic indices to evaluate and isolate tectonically active zones, at regional scale of study.


(a)
190000
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3940000
3930000
3920000
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3900000
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3880000
N
Weak
Extremely strong
Medium strong
Fault types
Major active
Major possible active faults
Major inactive
Rock strength
Extremely strong (Carbonate formations)
Medium strong (Phyllite-Quartzite series)
Weak (Quaternary and Neogene formations)
Drainage basins

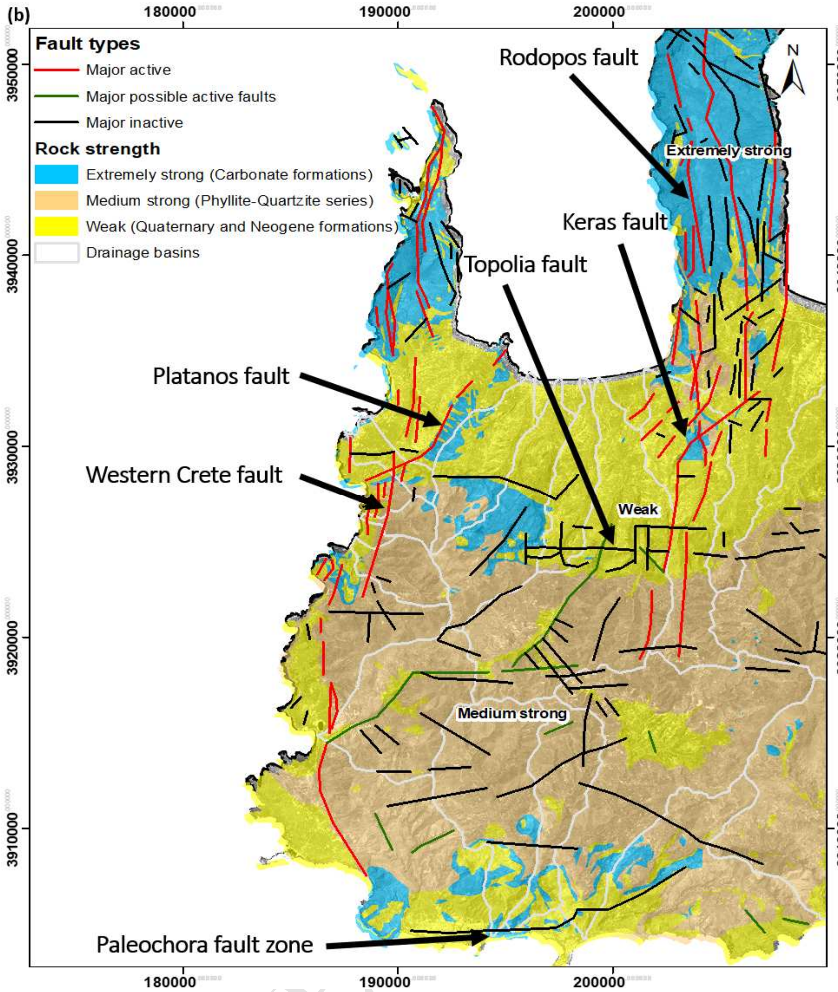


Figure 3: a) Fault types and major rock strengthness of geological formations; **b)** Zoom in on western drainage basins with the major representative faults.

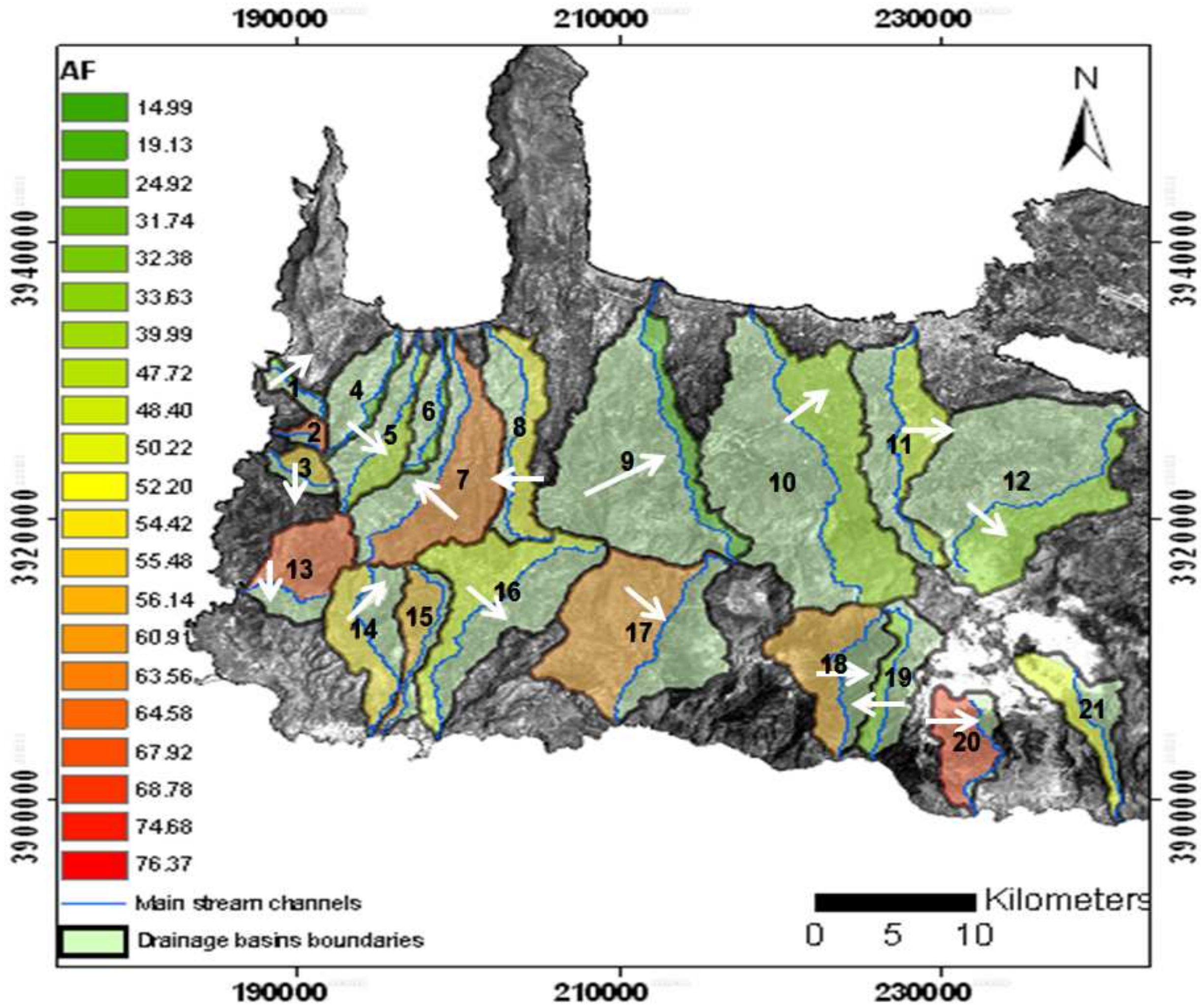


Figure 4: The AF (%) index, with the values indicating the level of tilting. It is notable that drainage basins with westward tilting are surrounded by basins with eastwards tilting (basins 7, 8, 19), indicating zones of high structural control. White arrows show the tilting orientation with regard to the mainstream direction.

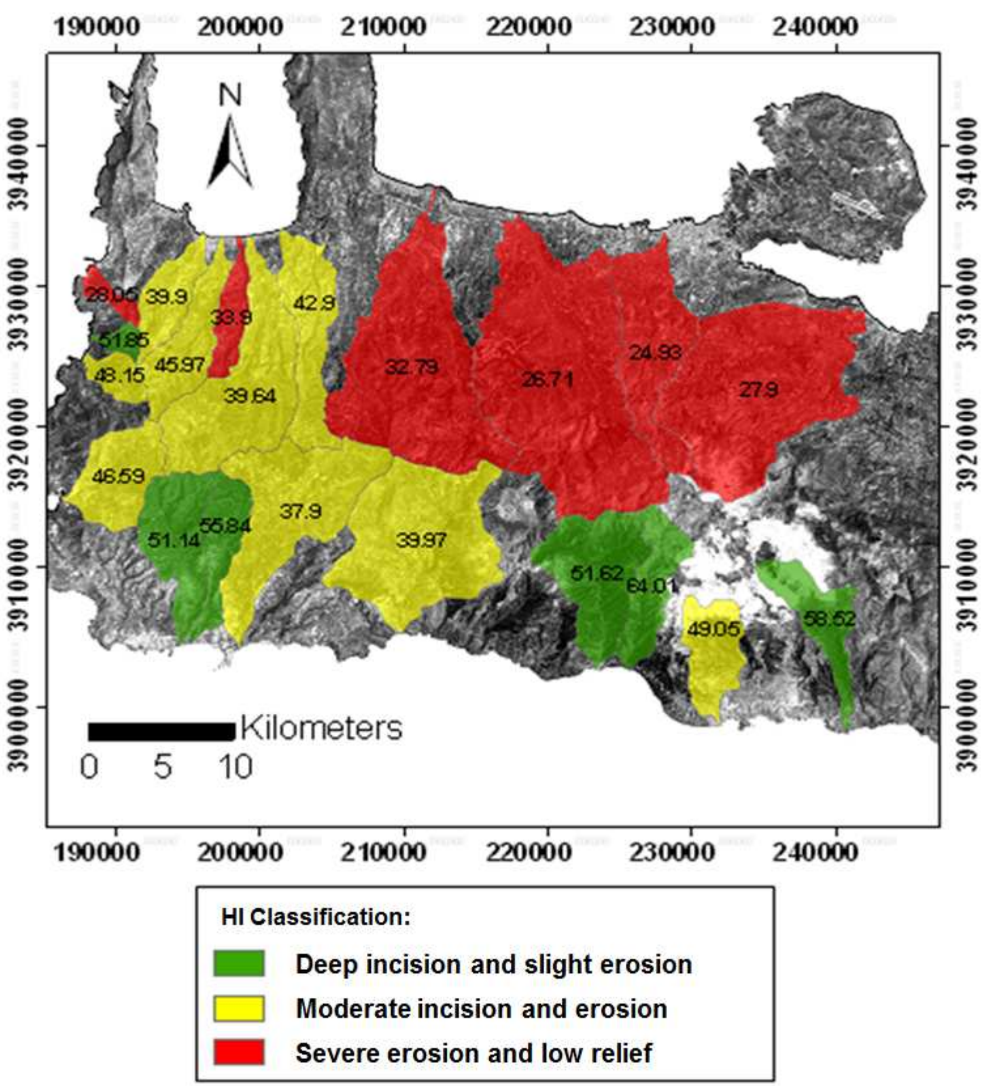


Figure 5: Hypsometric integral evaluation. The areas of well-defined deep incision and slight erosion in basin as a whole are the drainage basins that are associated with higher tectonic activity (due to erosion not being the underlying, principle factor).

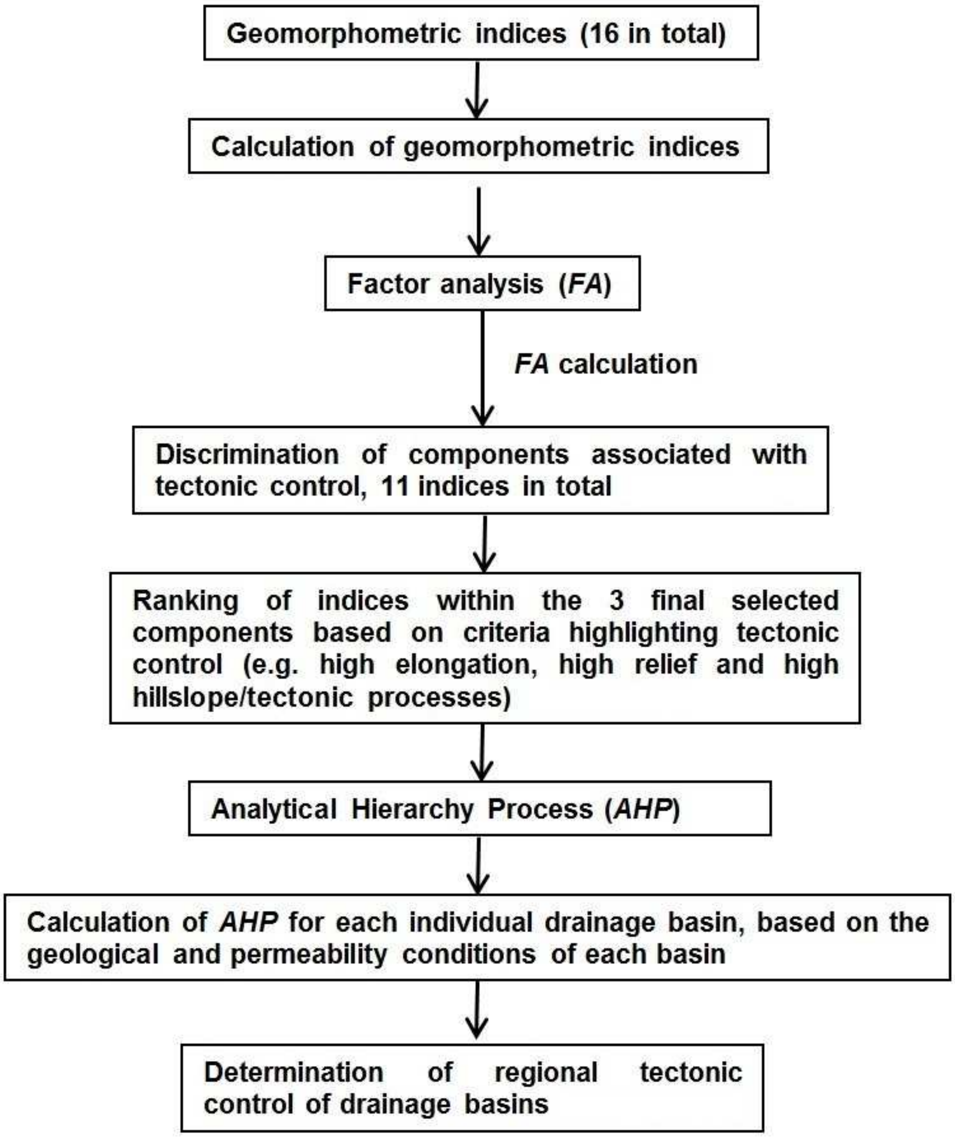
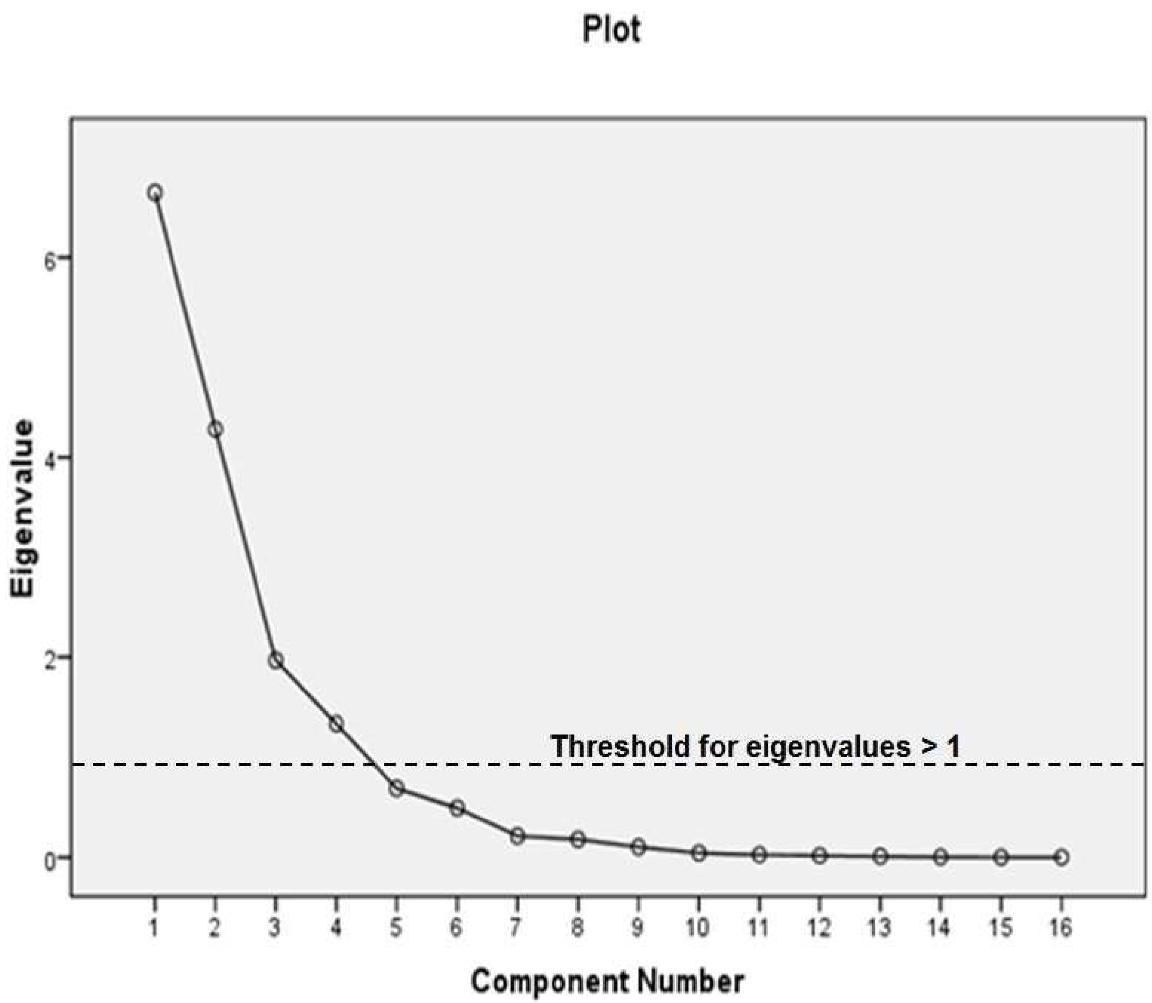


Figure 6: Schematic diagram, showing how regional tectonic control of the drainage basins is determined from an initial number of geomorphometric indices, by using *FA* and *AHP* procedures.



	Initial Eigenvalues	
Component	Total	% of Variance
1	6.648	41.548
2	4.281	26.756
3	1.968	12.301
4	1.335	8.344
5	.687	4.294
6	.492	3.076
7	.212	1.323
8	.178	1.114
9	.102	.640
10	.043	.268
11	.026	.160
12	.016	.102
13	.009	.056
14	.003	.017
15	.000	.003
16	.000	.001

Figure 7: The plot shows that the first four components are those containing most of the information (total of eigenvalue >1) and those are expected to be retained in final stage of factor analysis.

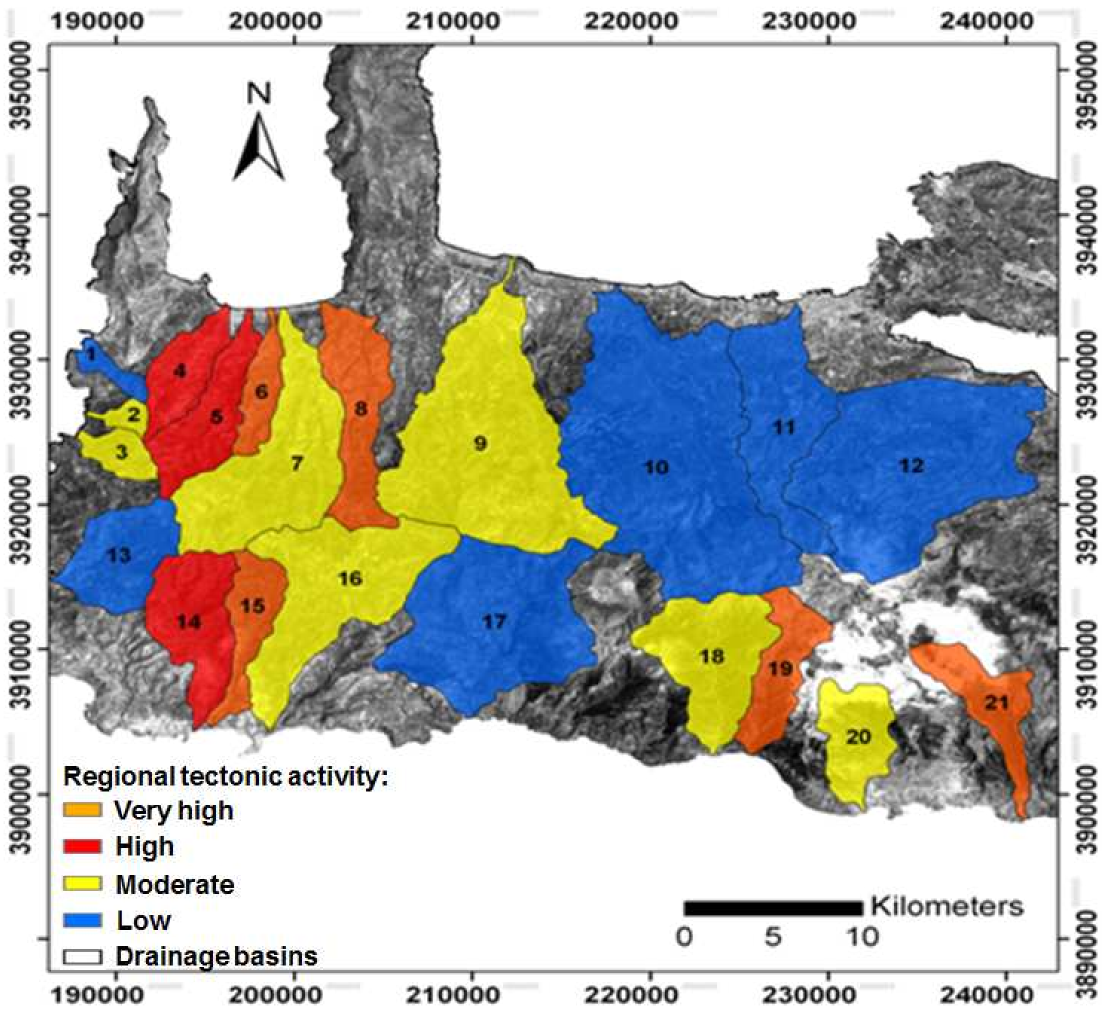


Figure 8: The AHP procedure applied in this research regarding the determination of regional tectonic control showed that the basins in: i) orange-coloured owe their development in highest tectonic activity; ii) red-coloured owe their development in high tectonic activity; iii) yellow-coloured in moderate tectonic activity and; iv) blue-coloured in minimal tectonic activity.

Highlights:

- A geomorphometric and morphotectonic approach has been used to assess and map the neotectonic activity of the drainage basins.

- A Multi-Criteria Decision Analysis (MCDA) procedure is applied to determine the neotectonic deformation of drainage systems.

- This methodology, using geoinformatics, is a useful tool to decision making regarding seismic hazard assessment.