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Morphometric Analysis of Drainage Basins in Structurally Controlled Terrain Using GIS

Abstract

A morphometric analysis was carried out to determine the drainage characteristics and the geomorphologic response of the drainage network to an area undergoing active deformation (Thebes Basin, Boeotia, Central Greece) through the use of Geographical Information System (GIS). The landscape of the study area is affected by active normal faults, developing a Basin and Range type topography. It covers an area of ~1500 km^2 and is sub-divided into five drainage basins (Livadostras, Askris, Vathirema, Kalamitis-Kanavari, and Asopos) and a drainage domain (Ritsonas), which range in area from 81 to 711 km^2. The drainage pattern of the study area is mainly dendritic to sub-dendritic with excellent examples of parallel and trellis drainage pattern, with stream orders ranging from IV to VI orders. The morphometric parameters were divided into three categories. The first category includes morphometric parameters (area, perimeter, basin length, stream order, stream length, maximum and minimum heights and slope) that are directly measured from the digital elevation model map and the digitized drainage network of the study area. The other two categories include calculated morphometric parameters of the drainage basins (basin relief, relief ratio, relative basin relief and form factor) and the drainage network (bifurcation ratio, length ratio, fractal dimension, drainage density, stream frequency and ruggedness number), respectively. Additionally, in order to reveal possible patterns of ground tilting in the study area, the Transverse Topographic Symmetry Factor (T) and the Asymmetry Factor (AF) were calculated. Hypsometric relations of drainage basins are also presented, where hypsometric curves identify regions with recent uplift and young topography. The study demonstrates that the calculation of more than one morphometric parameter of drainage networks, using GIS-based approach, is found to be appropriate in regional-scale studies as a reconnaissance tool to identify areas affected by active tectonic deformation, in particular, adjacent to urban areas as well as for planning and management at river basin level.
Keywords: Morphometric analysis, DEM, GIS, drainage network

Introduction

Stream networks are important, both as a control on drainage basin hydrology (Kirkby, 1976) and as indicators of geological processes (Kirchner, 1993). Drainage basins as durable geomorphic features provide insights into the long-term evolution of the landscape (Burbank and Anderson, 2001; Gelabert et al., 2005). Fluvial systems are sensitive to both faulting and regional surface deformation (Keller and Pinter, 2002). Detail analysis of drainage parameters contributes to understanding the influence of drainage morphometry on landforms and their characteristics (Reddy et al., 2004).

In this paper, we present geomorphologic and morphometric, GIS-based analyses of drainage networks in an area undergoing active tectonic deformation. We focused on the Thebes Basin, Beotia area, in Central Greece. In our study, we performed the analysis using a digital elevation model (DEM) of 25 m resolution to calculate the morphometric parameters for drainage networks and drainage basins, in order to extract quantitative clues for an assessment of landscape development.

Geological setting

The study area is located between the Gulf of Corinth and Evia Island, covering an area of approximately ~1500 km^2 (Fig. 1). The ~60 km-long and ~20 km-width Thebes Basin is the most prominent basin in the study area controlled by major WNW and ENE-trending normal faults (Fig. 1). In map view, the Thebes Basin is arcuate in shape and concave to the north. Its major axis trends between ENE, in the western part, and WNW in the eastern part (Fig. 3). The Thebes Basin contains two major intrabasin highs, the Korompilli-Kaparelli range to the west and the Tefmissos-Kirikion range to the east (Fig. 1). Both intrabasin highs are fault controlled (Fig. 1).

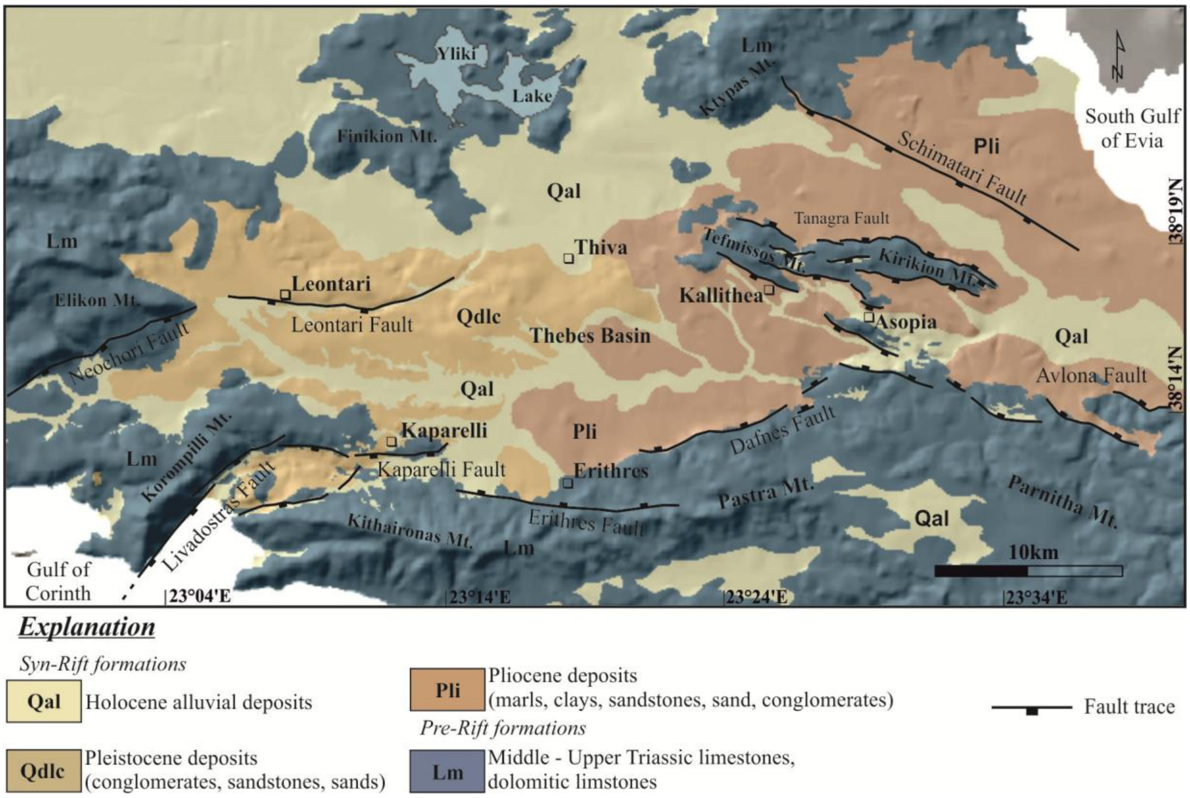

Figure 1. Simplified geological map of the study area (modified from Tsodoulos et al., 2008).

The investigated area is located at the boundary between the Internal and External Hellenides. The pre-rift formations of the study area consist of pre-alpine and alpine formations that belong to the Sub-Pelagonian isopic zone of the Internal Hellenides (Fig. 1). The pre-alpine formations within the Sub-Pelagonian zone are mainly composed of Upper-Palaeozoic shale, sandstones, greywacke, conglomerates, and embedded basic volcanic rocks (Renz, 1955; Dounas, 1971). Alpine formations of the study area consist of Middle-Upper Triassic to Low-Jurassic limestone and dolomitic limestone, deposited in a shallow water environment (Christodoulou, 1969).

The oldest known late to post-orogenic sediments in the Thebes Basin include lacustrine marls and marly limestones, clays, sandstones, and conglomerates of Serravallian age (~ 11.6 Ma) (Mettos et al., 2000) (Fig. 1). On top of the Upper Miocene sediments (and in conformity) a post-Miocene succession composed of fluvial and terrestrial conglomerates, sandstones and sands were deposited (Dounas, 1971). The base of the fluvial and terrestrial deposits consists of massive calcareous breccias. Holocene age alluvial deposits and recent scree compose the youngest sediments of the basin.

Methodology

The geomorphologic and morphometric analyses of the study area were carried out on GIS environment using the ArcGIS 10.4 software. A data flow diagram for these analyses is shown in Fig. 2. In order to calculate the morphometric parameters of the drainage network of the study area, two data sets were used: a Digital Elevation Model (DEM) and an automatically extracted drainage network. A 25 m-resolution with vertical accuracy ±7 m-RMSE DEM (EU-DEM v1.1) was downloaded from the https://land.copernicus.eu internet site of the European Union's Earth Observation Programme (Copernicus). The EU-DEM is based on SRTM and ASTER GDEM data fused by a weighted averaging approach into a single, consistent and homogeneous elevation dataset (Copernicus, 2017). The EU-DEM was used for the hydrologic analysis functions in order to model the movement of water across the surface of the study area and key terms regarding drainage systems.

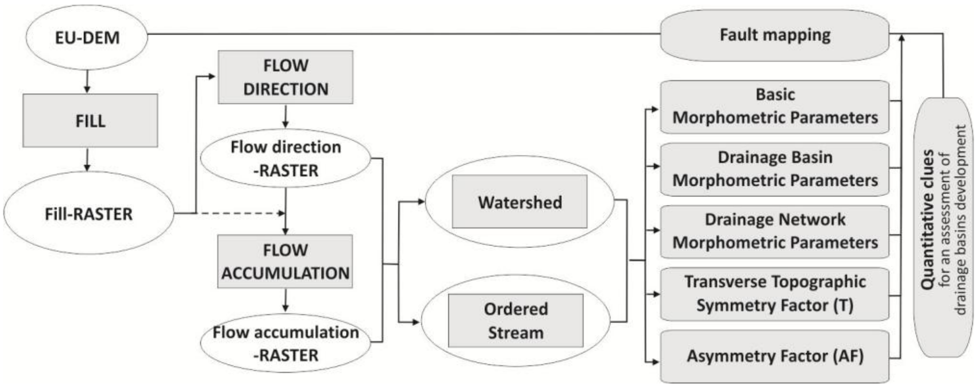

Figure 2. Simplified flow diagram for calculation of parameters associated with morphometric and geomorphic analyses.

Hydrologic information was extracted from the EU-DEM using the Hydrology toolset in the ArcGIS Spatial Analyst extension toolbox. Drainage networks were created and watershed boundaries were delineated from the EU-DEM, using the output from the flow accumulation function. Errors such as sinks, spikes or peaks removed before attempting to derive automatically any other surface information. Visual interpretation techniques have been followed to reform streams based on their imprints on satellite images from the Google Earth. Then, drainage channels were classified automated in different order class according to Strahler's classification (Strahler, 1964). Feature geometry, drainage network length and drainage basin area, calculated in order to establish mathematical equations of the morphometric parameters.

The morphometric parameters, for drainage basins and drainage networks, were divided into three categories: basic parameters, calculated parameters of the drainage basins and calculated parameters of the drainage networks. The first category includes morphometric parameters that are directly measured from the DEM of the study area and for the studied drainage basins includes area, perimeter, lowest and highest point of the basin and basin length. The basic morphometric parameters for the drainage networks include stream order and stream length. Those of the second category includes calculated parameters of the drainage basins which are basin relief (B_h), relief ratio (R_h), relative basin relief (R_{hp}), form factor (R_f), hypsometric curve and hypsometric integral (H_i) (Table 1).

Table 1: Calculated morphometric parameters of drainage basins

Morphometric parameter	Formula	Reference
Basin relief (B_h)	$B_h = h_{max} - h_{min}$	Gregory and Walling (1983)
Relief ratio (R_h)	$R_h = B_h / L$	Schumm (1956)
Relative basin relief (R_{hp})	$R_{hp} = B_h / P$	Gregory and Walling (1983)
Form factor (R_f)	$R_F = A/L^2$	Horton (1932)
Hypsometric integral (H_i)	$Hi = (h_{mid} - h_{min})/(h_{max} - h_{min})$	Strahler (1952)

Those of the third category includes calculated morphometric parameters of the drainage network which are bifurcation ratio (R_B), length ratio (R_L), fractal dimension (D_n), drainage density (D_d), stream frequency (F_s) and ruggedness number (R_n) (Table 2).

Table 2: Calculated morphometric parameters of drainage networks

Morphometric parameter	Formula	Reference
Bifurcation ratio (R_B)	$R_B = N(\omega)/N(\omega+1)$	Horton (1945)
Length ratio (R_L)	$R_L = L(\omega)/L(\omega+1)$	Horton (1945)
Fractal dimension (D_n)	$D_n = ln(R_B)/ln(R_L)$	Tarboton et al. (1988)
Drainage density (D_d)	$D_d = L_T/A$	Horton (1932, 1945)
Stream frequency (F_s)	$Fs = Ns/A$	Horton (1932, 1945)
Ruggedness number (R_n)	$R_n = B_h * D_d$	Gregory and Walling (1983)

To reveal possible patterns of ground tilting in the study area we used two quantitative morphometric methods. These are the Transverse Topographic Symmetry Factor (T) following the basic technique presented in Cox (1994) and the Asymmetry Factor (AF) which is described in Keller and Pinter (2002).

Drainage pattern analysis

The study area is divided into six main drainage basins and one domain (Fig. 3) (Tsodoulos et al., 2008). The drainage basins are Livadostras, Askris, Vathirema, Kalamitis-Kanavari and Asopos (Fig. 3, drainage basins 1-5). The Ritsonas drainage domain is defined as the area where the stream catchments that are broadly consistent in character, in terms of dimensions and their predominant direction of flow (Fig. 3, drainage domain).

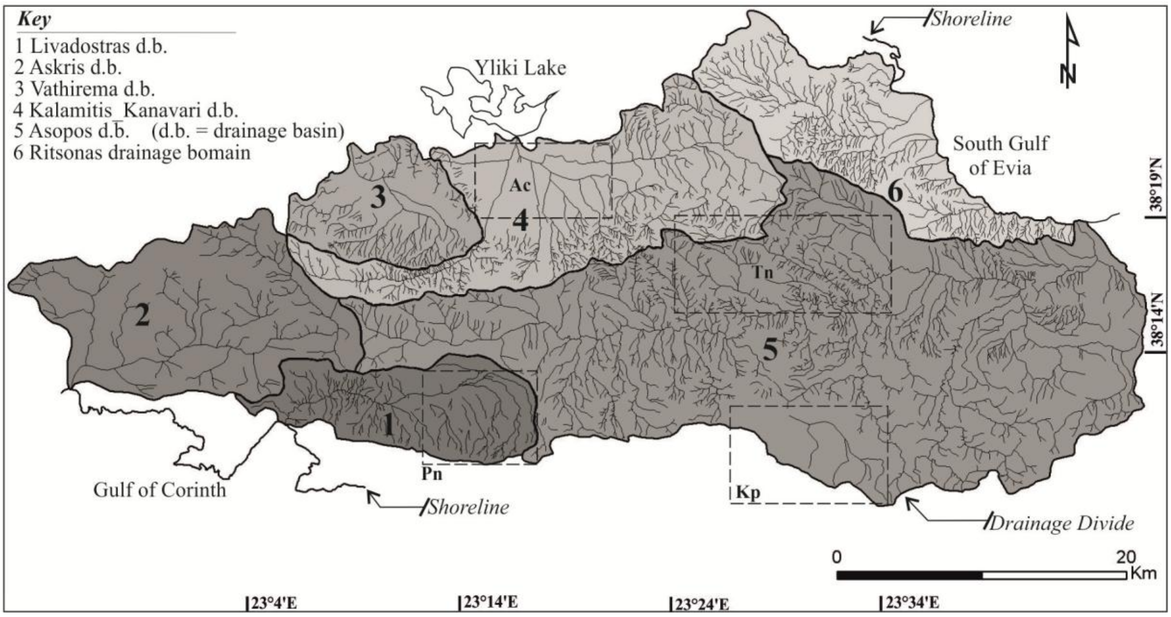

Figure 3. Drainage map of the study area showing the divides between of the six major drainage basins and domain (modified from Tsodoulos et al., 2008). Ac: Artificial channels; Kp: Karstic plain; Pn: Parallel network; Tn: Trellis network.

The Livadostras drainage is located in the southwest part of the study area and drains the southwesternmost part of the Thiva Basin (Fig. 3). The Livadostras River arises on the northern side of Kithaironas Mt. between villages of Plataies and Erithres and flows roughly in an east-west direction, to its mouth at the head of the Alkyonides Bay. Drainage pattern for the lower to the middle part of the basin is dendritic and becomes parallel to the upper part of the basin, probably affected by the tectonic activity. The Askris River characterized by a dendritic network which drains the south flanks of Elikon Mountain feeds drainage basin and is located in the western sector of the Thebes Basin (Fig. 3). Vathirema drainage comprises a parallel drainage pattern (Fig. 3). Drainage in the southern side of this basin is characterized by a system of long, incised, sub-parallel streams that run northwards on the gentle slope of the uplifted footwall of the Leontari normal fault (Goldsworthy and Jackson, 2000). The Vathirema River drains at its middle and lower part the basin of a former strand of the Kopais palaeolake. Kalamitis-Kanavaris drainage exhibits a more complex pattern (Fig. 3). Kalamitis River is fed by a dendritic network, which drains the northeastern part of the basin. It flows to an east-west direction and reaches Yliki Lake. Kanavari River mainly runs parallel to the Leontari fault up to the confluence with the Kalamitis River. It is fed by a sub-parallel system of rivers that run down the dipping slope of the Leontari fault footwall block. Kalamitis-Kanavaris drainage basin at its lower part is at present modified by a system of irrigation channels (Ac in Fig. 3). The Asopos drainage is the largest drainage basin within the study area and is strongly influenced by the relief and tectonic gradients produced by a series of normal faults (Figs. 1 and 3). Both axial (E-W trending) and lateral (N-S trending) drainage systems are developed (Fig. 3). Axial drainage is dominated by the Asopos River and is fed by a dendritic network that drains almost the entire southern part of the Thebes Basin. Drainage throughout the basin is predominantly dendritic, although clear examples of trellis drainage networks are found to the north of the basin (Tn in Fig. 3), within the uplifted Kallithea-Asopia Fault zone. In contrast, to the lateral and axial drainage systems throughout the major part of the basin, a discrete area of drainage located in the southern part of the basin drains a karstic plain (Kp in Fig. 3). Finally, the Ritsonas drainage domain (Fig. 3) includes several small drainage basins one of which is the Ritsonas River drainage basin. The Ritsonas River drainage basin is the largest drainage basin within the domain. The reason that we found it useful to define this domain is the common drainage basin characteristics of all the rivers included in this domain. In the central part of this domain, the drainage occurs on a dipping surface that gently descends to the NE. This slope and its superimposed drainage directions are the results of the action of the SW dipping Schimatari normal fault. Drainage pattern throughout this domain is mainly dendritic, except some places that exhibit a parallel character.

Morphometric analysis

The total drainage area of the five drainage basins (Livadostras, Askris, Vathirema, Kalamitis-Kanavari, and Asopos) and the drainage domain (Ritsonas) is 1473 km^2. The largest drainage basin is that of the Asopos River (711 km^2), whereas, the smallest is the drainage basin of the Vathirema River (81 km^2). Based on the stream order analysis the drainage basins of the Asopos and Kalamitis-Kanavari designated as 6^{th} order class, the Ritsonas drainage domain as 5^{th} order class, while the rest of the drainage basins (Livadostras, Askris, and Vathyrema) as 4^{th} order class. The basic morphometric parameters of the drainage basins are given in Table 3.

Table 3: Measured morphometric parameters of drainage basins

Drainage basin	Area A (Km^2)	Perimeter P (Km)	Basin Length L (Km)	Maximum Elevation h_{max} (m)	Minimum Elevation h_{min} (m)
Livadostras	100	53	17,5	1400	0
Askris	197	70	21	1520	0
Vathirema	81	40	11	564	100
Kalamitis-Kanavari	233	103	19,5	772	80
Asopos	711	163	56,5	1400	0
Ritsonas	151	76	17	1018	0

The basin relief (B_h) is an important factor in understanding drainage development, surface and sub-surface water flow, permeability, landform development and erosion properties of the basin (Reddy et al., 2004). The basin relief in the study area range between 464 and 1520 (Table 4). High values of the basin relief suggest lesser infiltration and greater runoff due to lower surface rock permeability (Rao, 2016). The calculated relief ratio (R_h) for the five drainage basins and the drainage domain is range between 0.02 and 0.08 (Table 4) and indicates the overall steepness of the basin (Schumm, 1956). According to Hadley and Schumm (1961), sediment transport capacity of the basin increases exponentially in relation to the increase in the value of the relief ratio. The relative basin relief (R_{hp}) index has been used to describe rock permeability (Gregory and Walling, 1983) similar to the relief ratio. High values of relative basin relief indicate steep slopes and low rock surface permeability (Rao, 2016). The relative basin relief for the studied basins ranges between 0.007 and 0.03 (Table 4). Horton (1932) proposed the form factor (R_f) to describe the shape of the basin. The form factor shows an inverse relationship with the square of the axial length and direct relation with peak discharge. Thus, elongated basins have low values of form factor have less side flow for shorter duration and high main flow for a longer duration. The form factor values range between 0.22 and 0.63 (Table 4). The hypsometric analysis is a useful tool for differentiating tectonically active from tectonically inactive regions (Keller and Pinter, 2002).

The hypsometric curve describes the distributions of elevations across an area. The hypsometric integral (H_i) corresponds to the area below the hypsometric curve and therefore is correlated with the shape of this curve. A convex curve is associated to a relatively young and weakly eroded region; an S-shaped curve characterizes a moderately eroded region, and a concave curve characterizes a relatively old and highly eroded region (Ohmori, 1993). Hypsometric integral values above 0.6 indicate a youthful stage of evolution, those between 0.35 and 0.6 indicate a mature stage, and those below 0.35 are characteristic of a monadnock stage (Strahler, 1952). The hypsometric integral values range between 0.25 and 0.63 (Table 4).

Table 4: Morphometric parameters of drainage basins

Drainage basin	Basin relief (B_h)	Relief ratio (R_h)	Relative basin relief (R_{hp})	Form factor (R_f)	Hypsometric integral (H_i)
Livadostras	1400	0,08	0,03	0,32	0,63
Askris	1520	0,07	0,02	0,46	0,44
Vathirema	464	0,04	0,01	0,63	0,39
Kalamitis-Kanavari	692	0,03	0,007	0,61	0,25(0,59)
Asopos	1400	0,02	0,009	0,22	0,53
Ritsonas	1018	0,06	0,01	0,52	0,32

The calculated morphometric parameters of the studied drainage network are given in Table 5. The bifurcation ratio (R_B) is an index of relief and landscape dissection (Horton, 1945). Values of bifurcation ratio more than 5.0 indicate a structural control, while values less than 3.0 indicate the absence of structural control (Strahler, 1964). The bifurcation ratio values range between 3.55 and 5.62 (Table 5). The length ratio (R_L) reflects the relationship between the surface flow discharge and the erosion stage of the basin (Horton, 1945). The values of length ratio in naturally developed networks range between 1.5 and 3.5 (Rodriguez-Iturbe and Rinaldo, 1997).

Table 5: Morphometric parameters of the drainage network

Drainage basin	Bifurcation ratio (R_B)	Length ratio (R_L)	Fractal dimension (D_n)	Drainage density (D_d)	Stream frequency (F_s)	Ruggedness number (R_n)
Livadostras	5,62	2,95	1.60	1,77	2,1	2,48
Askris	4,9	2,63	1.64	0,97	0,73	1,47
Vathirema	5,25	2,97	1.52	1,93	2,64	0,89
Kalamitis-Kanavari	3,55	1,66	2,10	2,02	3,2	1,40
Asopos	4,17	2,09	1.93	1,75	2,04	2,45
Ritsonas	4,57	2,09	2,05	2,37	3,87	2,41

The length ratio values for the studied basins range between 1.66 and 2.97 (Table 5). Tarboton et al. (1988) have shown that drainage networks tend to cover the space within which they develop (i.e. the boundaries of the catchment area) showing a fractal distribution with their fractal dimension (D_n) approach a value close to 2. The fractal dimension values range between 1.52 and 2.10 (Table 5). The drainage density (D_d) is a measure of the degree of drainage basin dissection from the channel network (Horton, 1932; 1945). The drainage density values of the studied drainage basins range between 0.97 km/km^2 and 2.37 km/km^2 (Table 5). The stream frequency (F_s) reflects topographic texture with high values indicating steeper slopes. The stream frequency values range between 0.73 and 3.2 (Table 5). The ruggedness number (R_n) indicates the structural complexity of the basin (Gregory and Walling, 1983). High values of ruggedness number reflect high basin relief, steep slopes, and less resistant rocks. The ruggedness number values of the studied drainage basins range between 0.89 and 2.48 (Table 5).

The Asymmetry Factor (AF) can detect tectonic tilting on drainage basin scales or large areas and is sensitive to tilting perpendicular to the direction of the trunk stream. Values of AF greater or less than 50 may suggest tilt (Fig. 4). The Transverse Topographic Symmetry Factor (T) is also another quantitative morphometric index used to reveal possible patterns of ground tilting. For a symmetrical drainage basin, the stream is in the middle of its drainage basin and T=0. In the case that the stream migrates laterally, away from the center of the basin, toward to one of the two margins, the value of T increases and approaches 1 (Fig. 4). Rivers controlled completely by faults are strongly asymmetrical, i.e. Leontari Fault that appears to control the Kanavari River (Fig. 4). Stronger asymmetry is due to large isolated faults. The position of the fault within the basin is also important. For example, the Erithres and Dafnes Faults cross in the middle the Asopos basin (Fig. 4). In this case, the basin river appears symmetric although it is obvious that the river was captured by the fault.

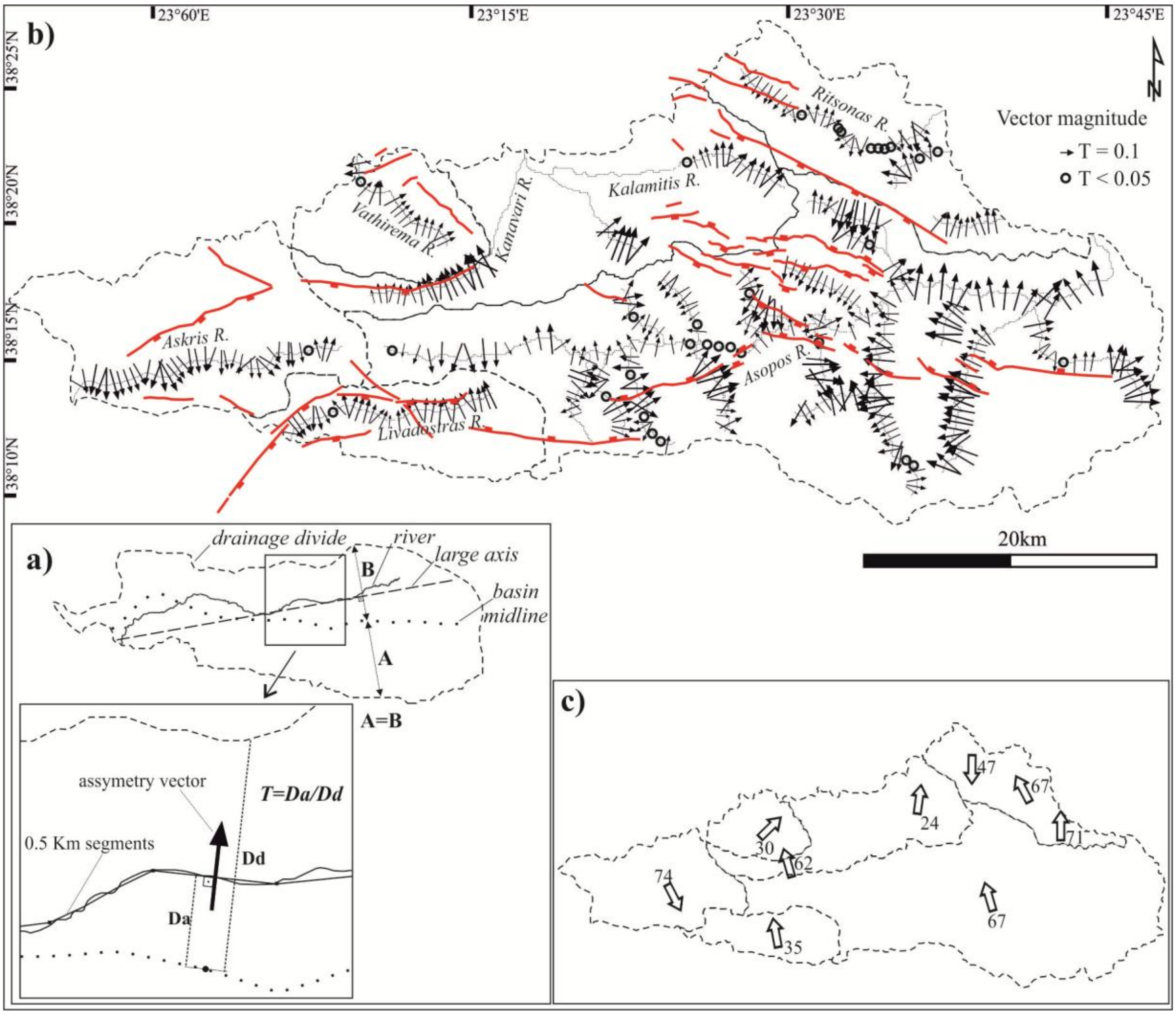

Figure 4. (a) The Transverse Topographic Symmetry Factor. (b) The basin asymmetry vectors within the investigated area. (c) Asymmetry Factor values and direction of tilt for the studied drainage basins (modified from Tsodoulos et al., 2008).

Conclusions

The qualitative and quantitative analysis of the hydrographic network of the study area showed that the evolution of the river basins is significantly influenced by the activity of individual fault zones, as well as the position of the fault within the basin, and to a lesser extent on local geological and hydrogeological conditions in the area.

The analysis of one geomorphic parameter typically exhibits limitations or even contradicting results due to lithological differentiations or the location of the fault within the studied basin. Our analysis is based on the application of more than one parameter in the study area and leads to more meaningful results than of those a single parameter analysis would provide.

GIS-based analysis using free available and accessible data from Copernicus services is a precise, fast, and an inexpensive way to evaluate morphometric parameters of river basins at regional scale.

The study demonstrates that the calculation of more than one morphometric parameter of drainage networks is found to be appropriate in regional-scale studies as a reconnaissance tool to identify areas affected by active tectonic deformation, in particular, adjacent to urban areas as well as for planning and management at river basin level.

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