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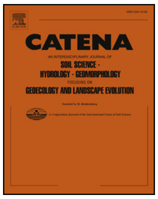

Formulation of the conceptual model for the tectonic geomorphological evolution of an area: Five main rivers of Greece as a case study

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ABSTRACT

This paper associates the tectonic conditions of five rivers (integrated drainage networks) in northwestern Greece, for the purpose of formulating the conceptual model of its tectonic and geomorphological evolution. The applied methodology consisted in the synthesis of elements from the fields of Tectonics and Geomorphology, using suitable software and GIS-techniques, and the correlation of fault and drainage network trends by the use of rose diagrams to reveal the structures and tectonic events affecting the different orders of the branches and its evolution. The relation between morphology, tectonics and the development of the drainage network enabled comparison across different areas, the grouping of rivers and the identification of areas influenced by the same geodynamic regime. In northwestern Greece, two main groups of rivers were distinguished, flowing across areas featuring different tectonic conditions, while a transitional zone between them was defined. The stages of the area's tectonic and geomorphological evolution were identified with highlighting the definitive impact of tectonic structures on the configuration of the river routes, e.g. the Petousi-Souli Fault which forms a natural boundary in the centre of the study area and new elements were added. In view of the aforementioned, northwestern Greece is an independent transitional area in the geodynamic regime of the entire eastern Mediterranean. Notably, the methodology applied to these rivers may also be used in other areas, thus constituting a standard tool for investigating the geodynamic regime and evolution.

1. Introduction

Globally, Morphotectonics links the geomorphological features of an area with its neotectonic activity (Morisawa and Hack, 1985; Keller and Pinter, 2002; Scheidegger, 2004; Kothyari, 2014; Ntokos, 2017d), so that conclusions may be drawn on the evolution of the terrain and the drainage network (Tsodoulos et al., 2008). The geometric characteristics of a drainage network (e.g. change in trends and sharp changes in the inclination of the stream beds) are frequently closely linked with tectonic structures (e.g. faults and folds), whether active or not (Evans, 1980; Prost, 1994; Demoulin et al., 2015). The development of a drainage network is typically related to faults and fault zones and its study contributes to the detailed description of its current geometry, as well as the extraction of data and evidence from the geological past (Burbank and Anderson, 2001; Kothyari et al., 2017). It is evident that an area's geomorphology evolves over time, which results in its transition from an older environment to a different one (Whipple and Tucker, 1999; Burbank and Anderson, 2001). Therefore, the geomorphological conditions of an area are subject to constant, dynamic evolution and geomorphological analysis aims at predicting what this will be (Dehbozorgi et al., 2010). However, there is always a great chance that unforeseen changes may occur, even minor ones, which can throw off any initial predictions about an area's geomorphological evolution.

Scientists keep trying to develop a model on the subject of the processes at work on the surface of the earth and reveal the relationship between a drainage network and tectonics, by employing various methodologies, either creating an index or combining indices and algorithms (Bull and McFadden, 1977; O'Callaghan and Mark, 1984; Rockwell et al., 1984; Merritts and Vincent, 1989; Jones, 2002; Silva et al., 2003; Schoenbohm et al., 2004; El Hamdouni et al., 2008; Pelletier, 2008; Dehbozorgi et al., 2010; Whipple et al., 2013; Kothyari, 2014; Ntokos et al., 2016; Ntokos, 2017c, 2017d), setting certain parameters and producing numerical results, in order to present the local conditions associated with the features of the individual basin that forms the scope of a specific study. Even though the numerical result produced may relate to a natural meaning, analysis should never be restricted to a simple quantitative interpretation, in order to draw the

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right conclusion. Researchers should always strive to keep a critical stance and take further data into account, in order to ensure that the actual conditions are reflected in their conclusions. The attempt to quantify all the related concepts can often result in drawing the study away from the core of their scientific substance, as well as their qualitative and physical significance.

The present paper endeavours to reveal certain concepts which, caused by the great number of indices available to researchers, have been set aside and forgotten. There are actual, useful conclusions to be drawn by the primary observations made in relation to a drainage network (Jones, 2001, 2002). Though the indices may calculate and answer many questions, they can never exceed the power of the human mind, as is also the case with computers, which lack the critical ability to see beyond the mathematical data entered in their system. This paper aims at using older techniques and correlating the tectonic conditions of an area with its drainage networks, by focusing on the orientations of the tectonic structures and branches of a drainage network, expressed by a combined quantitative and qualitative approach, on the basis of the main principles of Geomorphology. River groups and areas featuring the same geodynamic regime, which control the rivers' route through tectonic mega-structures, are identified. This provides a solid ground for forming an opinion regarding the evolution stages of the individual areas and the formulation of the conceptual model of its tectonic and geomorphological evolution. A model, no less, which is even more solid, since it derives from the study of an entire surface, comprising numerous drainage networks, rather than just local features. In the present paper, the aforementioned approach was applied to the tectonic structures and drainage networks of northwestern Greece.

2. Methodology

Geology and tectonics help us understand the evolution of the terrain and the drainage network. Different tectonic events affect different orders of its branches (Mayer, 1986; Scheidegger, 2004). This approach enables the comparison between individual areas, the grouping of rivers and the identification of areas affected by the same geodynamic regime, which will lead to the synthesis of morphological and tectonic elements and the features of drainage networks and ultimately to the formulation of the conceptual model of the area's tectonic and geomorphological evolution.

The applied methodology is based on GIS techniques and consists -among other things- in the processing and correlation of rose diagrams - plots of the trends of tectonic structures and the branches of drainage networks with the quantitative analysis of the displacement of the main bed of the drainage basins of such drainage networks, by use of the asymmetry factor A_F. More specifically, the aim of this study is to improve the method of developing a quantitative, geomorphic analysis of tectonic activity, by combining its results with the conclusions deriving from the fieldwork data of the qualitative analysis.

More specifically, the methodology applied in the formulation of the conceptual model of the area's tectonic and geomorphological evolution, consisted in the steps and technical processes listed hereunder:

A. Determination and classification of the tectonic structures by fieldwork and illustration and classification of drainage networks. The data relating to tectonic structures were gathered from extensive fieldwork (neotectonic mapping). The branches of the drainage networks were initially classified by applying the numbering according to Strahler (1954), which is the standard and most widely applied numbering system.

B. Quantitative analysis of the displacement of the main bed of the drainage basins of such drainage networks, by use of the asymmetry factor A_F (Hare and Gardner, 1985; Pérez-Peña et al., 2010), which is used for the identification of the tectonic origin of the slope or the rotation of drainage basins. This index constitutes a fundamental criterion for the determination of tectonic influence (Hare and Gardner, 1985; Salvany, 2004; Harkins et al., 2005; Ntokos et al., 2016; Ntokos, 2017c). It provides an indication, which is why accurate tectonic data from the area should always be considered, in order to verify the area's kinematic activity and evolution. It expresses (%) the ratio of the area of the basin section, extending to the right (downstream) of the main river, to the total area of the river's drainage basin (Hare and Gardner, 1985).

C. Quantitative analysis of the orientations of tectonic structures and branches of the drainage networks, through the processing - composition of rose diagrams - plots, by combining its results with the observations deriving from fieldwork data and morphology of the qualitative analysis. For the purposes of quantifying the tectonic structures and branches of drainage networks, rose diagrams -a widely used technique for representing orientations - were composed, on the orientation of the tectonic and folded structures, as well as the direction of the branches of drainage networks, on a circular diagram (360°). By comparing these diagrams, conclusions were drawn on the correlation between the drainage network and tectonics and the identification of the tectonic structures, affecting the development and evolution of drainage networks. The rose diagrams of tectonic structures demonstrate their orientation and determine the geodynamic regime that caused them. The rose diagrams of the branch trends of all orders show their distribution and aim at identifying the fault structures controlling and determining the development and evolution of the respective orders.

D. Overall review of the impact of neotectonics on the configuration of the drainage network and synthesis of morphological and tectonic elements and features of the drainage networks, for the purpose of formulating the conceptual model of the area's tectonic and geomorphological evolution. The current configuration of drainage networks was definitively affected by the movements of active and potentially active tectonic structures. These tectonic structures cause the selective orientations and sharp bends in the branches of the drainage networks and in many cases they are the cause of their one-sided development. The overall analysis and association, between drainage networks and tectonics, can lead to useful conclusions, regarding the activity of faults and their impact on the drainage network. This helps achieve comparison between different areas, grouping of rivers according to their distinguishing features and identification of areas affected by the same geodynamic regime.

It is noted that:

- Tectonic structures were classified as active (created or reactivated, with documented displacements, from the Upper Pleistocene until present), potentially active (created or reactivated during the Upper Pliocene until the Upper Pleistocene) and non-active (have not been activated since the Lower Pliocene and therefore present no chance of activation), according to their activation age.
- For the production of the drainage network, Landsat data extracted from topographic maps of Hellenic Military Geographical Service, on a scale of 1:50,000, and NASA's DEM on a resolution of 25 m (Source: earthdata.nasa.gov), using ArcGIS 10.3 (Source: www.esri.com), were used. The software selected for the analysis and processing of the DEM and the calculation of the drainage network was the ArcMap 10.3 by the ArcGIS extension, "Spatial Analyst" (Hydrology; Source: www.esri.com).
- For the A_F calculation, the following mathematical Eq. (1) was used, which was formulated by Pérez-Peña et al. (2010):

$$A_F = \left| 50 - \frac{A_r \times 100}{A} \right| \qquad (1)$$

where, A_F: is the asymmetry factor (%), A_r: is the area of the basin section, extending to the right (downstream) (km^2), and A: is the area of the drainage basin (km^2).

A_F values were grouped into four classes: 1 - symmetrical basins with A_F values between 0.00 and 5.00%, 2 - low asymmetry basins with A_F values ranging from 5.01 to 10.00%, 3 - average asymmetry basins