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& CALOGERO SCHILLACI (***)

ANALYSIS OF THE INFLUENCE OF TECTONICS ON THE EVOLUTION OF VALLEY NETWORKS BASED ON SRTM DEM, JEMMA RIVER BASIN, ETHIOPIA

ABSTRACT: KUSÁK M., KROPÁČEK J., VILÍMEK V. & SCHILLACI C., *Analysis of the influence of tectonics on the evolution of valley networks based on SRTM DEM, Jemma River basin, Ethiopia.* (IT ISSN 0391-9838, 2016)

The Ethiopian Highlands are a good example of a high plateau landscape formed by a combination of tectonic uplift and episodic volcanism. Deeply incised gorges indicate active fluvial erosion, which leads to instabilities of over-steepened slopes. In this study we focus on the Jemma River basin, which is a left bank tributary of the Abay - Blue Nile in order to assess the influence of neotectonics on the evolution of its river and valley network. Tectonic lineaments, shape of valley networks, direction of river courses and intensity of fluvial erosion were compared in six *subregions,* which were delineate beforehand by means of morphometric analysis. The influence of tectonics on the valley network is low in the older deep and wide canyons and on the high plateau covered with Tertiary lava flows, whilst in the younger upper part of the canyons it is high. Furthermore, the coincidence of the valley network with the tectonic lineaments differs in the *subregions*. The direction of the fluvial erosion along the main tectonic zones (NE-SW) made it possible for backward erosion to reach far distant areas in the east. This tectonic zone also separates older areas in the west from the youngest landscape evolution *subregions* in the east, next to the Rift Valley.

KEY WORDS: Valley network, Tectonic Lineaments, Jemma River basin, Ethiopian Highlands.

1. INTRODUCTION

Morphostructural analysis is a tool of structural geomorphology, which aims at clarifying the direct and indirect linkage between shapes of the Earth's current surface and the structure of the Earth's crust, whose development and character are currently dependent on the development of the mantle and core (Fairbridge, 1968; Demek, 1987). The observed manifestations of active tectonics and the geological structure can then be used to define basic elementary morphostructures that form a morphologically compact unit. The various methods of morphostructural analysis are based either on field research or a set of morphometric techniques and methods of remote sensing, analyzing interdisciplinary reference charts, aerial or satellite images and digital elevation models (DEMs), most commonly in the environment of geographic information systems (GIS). Several authors deal with morphostructural analysis based on the processing of digital images of remote sensing (RS) and aerial photographs, which allows large areas of territory to be covered, such as Casas et al. (2000), Novak & Soulakellis (2000), Kim & *alii* (2004), Jordan & *alii* (2005), Jordan & Scott (2005), Ekneligoda & Henkel (2006, 2010), Huggett (2007), Arrowsmith & Zielke (2009) and Ozkaymak & Solzbilir (2012). The Shuttle Radar Topography Mapping mission (SRTM) has dramatically improved the availability of consistent high quality relief information in remote areas of the world (Farr & Kobrick, 2000). The size and remoteness of the study area together with the limited availability of detailed topographic information makes this area ideal for the utilization of approaches based on a global DEM.

In order to diversify knowledge of the tectonic structure of the area, part of the morphostructural analysis called a morphotectonic analysis, i.e. analysis of the shape of the

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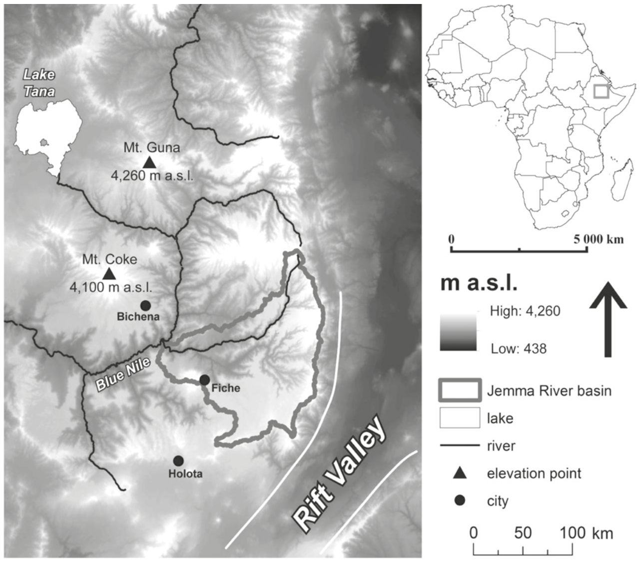

FIG. 1 - Map of study area.

valley network and analysis of linearly arranged elements of relief – lineaments, is used. A valley network can be seen as a result of interaction of geological settings, tectonics and erosion. Analysis of the valley network can therefore give an insight into landscape evolution. The potential of the SRTM DEM dataset for valley network analysis was explored by several authors (De Barolo & *alii*, 2000; Saa & *alii*, 2007) as was lineaments analysis (Kocal & *alii*, 2007; Abdullah & *alii*, 2010; Hubbarde & *alii*, 2012; Muhammad & Awdal, 2012).

In this paper we aim at understanding the landscape evolution and especially the influence of neotectonics on the formation of the valley network in the Jemma River basin. We analyze the relief and valley networks on a regional scale using the SRTM DEM. The main objectives of the work are to:

1) identify areas with the most significant influence of neotectonics on valley network evolution;
2) define *subregions* in the Jemma River basin with similar characteristics;
3) analyze the typology of the valley network within the *subregions*;
4) identify areas with the most dynamic evolution of the valley network;
5) reveal the main morphological processes responsible for the landscape evolution in the study area.

2. THE STUDY AREA: GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The Ethiopian Highlands are among the most tectonically influenced areas in the world and lie in the border zone of three lithospheric plates, the Eurasian, African and Arabian Plate (Beyene & Abdelsalm, 2005). This area has been influenced by sea transgressions, tectonic uplift and episodic volcanism (Kazmin, 1975; Pik & *alii*, 2003; Beyne & Abdelsalam, 2005; Gani & Abdelsalam, 2006; Gani & *alii*, 2007, 2009; Wolela, 2010). The Ethiopian Highlands are not an area of simple structural settings but are a rather complicated structural block divided by the Rift Valley (Yunur & Chorowicz, 1998). The Ethiopian Highlands are characterized by volcanoes and high altitude plains (up to 3,000 m a.s.l.) cut by deep canyons. The flat surface of these blocks is a result of tectonic uplift and piling up of lava flows (Pik & *alii*, 2003). The active uplift of the highlands activated fluvial erosion. We can identify 3 phases from the past 31 million years with increasing incision rates. Furthermore, a significant relationship was found between uplift rates and incision rates which is evidence of tectonically controlled incision (Gani & *alii*, 2009). The Jemma River and its tributaries deeply incised the high elevation plateau west from the Rift Valley by gorges reaching depths of more than 1,300 m (fig. 1).

The study area of the Ethiopian Highlands has a diverse geological history, e.g. repeated sea transgression and regression, Tertiary and Quaternary volcanism, uplift of the Ethiopian Highlands (in the last 29 million years), and opening of the Main Ethiopian Rift (in the last 18 million years), which has led to the formation of faults and cracks (Kazmin, 1975; Pik & *alii*, 2003; Beyne & Abdelsalam, 2005, 2006; Gani & *alii*, 2007; Gani & *alii*, 2009; Wolela, 2010). The geology of the Ethiopian Highlands has been described by several authors, e.g. Mangesha & alii (1996), Assefa (1979; 1980 and 1981), and Russo & *alii* (1994). Gani & *alii* (2009) distinguished the following three main periods as well as 8 sub-periods: 1) pre-sedimentation phase, including pre-rift peneplanation of the Neoproterozoic basement rocks, possibly during the Palaeozoic era; 2) sedimentation phase, from the Triassic to the Early Cretaceous, including: a) Triassic-Early Jurassic fluvial sedimentation (Lower Sandstone, 300 m thick); b) Early Jurassic marine transgression (glauconitic sandy mudstone, 30 m thick); c) Early-Middle Jurassic deepening of the basin (Lower Limestone, 450 m thick); d) desiccation of the basin and deposition of Early-Middle Jurassic gypsum; e) Middle-Late Jurassic marine transgression (Upper Limestone, 400 m thick); F) Late Jurassic-Early Cretaceous basin-uplift and marine regression (alluvial/fluvial Upper Sandstone, 280 m thick); 3) the post-sedimentation phase, including a) Early-Late Oligocene eruption of 500-2,000 m thick Lower volcanic rocks; including b) relating to Afar Mantle Plume and emplacement of 300 m thick Quaternary Upper volcanic rocks. A more in-depth view reveals one volcanic period in the Tertiary (Hofmann & *alii*, 1997) and another in the Quaternary (Gani & Abdelsalam, 2006). In general, lava flows greatly influenced the valley network because they covered the paleo landscape with ancient drainage and created a new surface over large areas.

The tectonic uplift rate fluctuated in the past and the erosion processes also subsequently changed. Sengor (2001) established an uplift rate of approximately 0.1 mm/year since the Eocene. The rate increased from the Pliocene to the Pleistocene (Wolela, 2010). McDougal & *alii* (1975) assume an average rate of between 0.5 and 1 mm/year. Gani & *alii* (2007) calculated the total uplift for the last 30 million years as being 2.2 km minus 300 m for denudation and 150 m for sediment consolidation, which means a total of 1,750 m. The southern and central openings of the Main Ethiopian Rift are estimated to be 20 million years old (Gani & *alii*, 2009), whereas the northern part of the Rift in the Ethiopian Highlands is 11 million years old based on Ar/Ar geochronology (Wolfendent & *alii*, 2004).

The Jemma River basin consists of a large plateau that has become inclined from the Main Ethiopian Rift to the west. The highest part of the study area is located on the edge of the Main Ethiopian Rift and reaches heights of between 3,401 and 4,252 m a.s.l. The lowest part of the study area (between 765 and 1,245 m a.s.l.) is represented by the confluence of the Jemma River and the Blue Nile (fig. 2a). At present, this platform is cut by a network of deep canyons (fig. 2c). Kieffer & *alii* (2004) describe the overall erosion characteristics of the Ethiopian Highlands – total erosion varies between 0 and 1,600 m. The Blue Nile (Abay River) is the erosion basin for tributaries like the Jemma River.

2. MATERIAL AND METHODS

2.1. *Shuttle Radar Topographic Mission (SRTM) DEM*

The SRTM DEM is an almost globally available digital elevation model (from 60°N to 56°S) which resulted from a single pass interferometric processing of C-band Synthetic Aperture Radar (SAR) data acquired by the Endeavour Shuttle mission in February 2000 (Rabus & *alii*, 2003, Farr &t *alii*, 2007). During the mission, 95% of the target area was covered by at least two acquisitions corresponding to the ascending and descending paths in order to avoid data gaps in radar shadows in areas of rugged terrain. The globally available version of the SRTM, which is in the public domain, features a horizontal resolution of 1 arc seconds, which correspond to approximately 30 m. Its mission specification required a vertical accuracy of below 16 m, which has been achieved (Gorokhovich & Voustianiouk, 2006). Here we use the SRTM 1 Arc-Second Global version, which was released in September 2014. Its vertical accuracy and influence on the hydro-geomorphic products were assessed by (Falorni & alii, 2005) who suggest applying a wavelet filter to suppress noise in the derived drainage network.

Topographic surfaces described as the discrete elevation function f (x,y,z) are of great interest to geoscientists. Variables such as slope inclination and slope aspect derived from elevation data are particularly suitable for the investigation of surface shapes and structures since they reflect the processes that led to their evolution (Kennelly, 2008). First order derivatives include slope inclination (gradient of elevation) and slope aspect (azimuth of the steepest slope) while second order derivatives represent curvature. These variables are computed using operations of the local pixel neighborhood.

Another image layer derived from the DEM that is highly relevant for morphologic interpretation is hill shading. Variations in brightness in the hill shading image are a function of the illumination direction and the orientation of the surface. The brightness value is calculated as the cosine of the incidence angle of the illumination vector. Subtle changes in shades of grey render the terrain with a three-dimensional appearance. Hill shading conveys much stronger three dimensional impressions than a mere visualization of the elevation model in gray tones. Furthermore, it enhances the interpretability of detailed surface structures often completely imperceptible in the DEM visualization. The SRTM DEM has been used by various authors to perform relief analyses such as the assessment of old surfaces (e.g. Martino & *alii*, 2009; Haider & *alii*, 2015)

2.2. *Dataset DEM preprocessing and terrain analysis*

Primary topographic indexes such as Elevation [m a.s.l.] or Slope [°] and hydrological attributes such as Catchment area [m^2] were extracted from the SRTM DEM hydrologic modeling tools implemented in ArcGIS 10.1 (ESRI, 2015). Shaded relief maps with varying directions of illumination were produced using standard tools available in common GIS packages. Various elevation angles of the illumination source (30°, 35°, 40° and 45°) and three different values of illumination azimuth (from N - solar azimuth of 0°; from NE - solar azimuth of 45°; from E - solar azimuth of 90°; and from SE - solar azimuth of 135°) are used in order to assure the independency of the results from the direction of illumination.

The valley network model for the Jemma River basin was extracted from the SRTM DEM in ArcGIS 10.1 (ESRI, 2015). The valley network was identified by analyzing the flow accumulation after a filling procedure was applied to remove sink-like artifacts caused by noise and inaccuracies in the original DEM dataset. The Gravelius order system, which describes the valleys as geomorphological units, was used to perform a basic characterization of the valley network. The Gravelius order system determines the order of the valley networks in the direction from the outfall towards the valley head. The valley network is formed by the main/primary (i.e. the I. order) valley, into which outfalls the subsidiary/secondary (i.e. the II. order) valley, and into this outfalls the tertiary (i.e. the III. order) valley, etc. (Gravelius, 1914). In the study area of the Jemma River basin there are valleys up to the VIII. order (fig. 3 and 4).

According to Křížek & Kusák (2014), the following morphometric characteristics are the most suitable for valley network characterization:

a) the "valley junction angles" is the angle at which the subsidiary valley joins the main valley projected on a horizontal plane.
b) the "number of valleys" n is determined as the number of all valleys of the given order (sensu Gravelius, 1914) in the valley network;
c) the "total lengths of valleys" t is defined as the sum of lengths of all valleys of the give order (sensu Gravelius, 1914) in the valley network, i.e. sum of lengths from the valley heads to the outfalls for each valley;
d) the "valley networks´ density" D is defined by equation (sensu Horton, 1945):

$$D = L / P,$$

where L is the total length of thalwegs and P is the catchment area of the Jemma River basin;

e) the "azimuth of stream channels" A is determined as the orientation of stream channels (i.e. parts of valleys from the valley heads to the first point of valley connection; or parts of valleys between two valley connection points) to the coordinate system. The "azimuth of stream channels" is illustrated by rose diagrams, which are divided into 72 intervals of 5° (360° in total) in a N to E direction. The numbers of stream channels in the rose diagrams are weighted by their length following Belisario & *alii* (1999) and Ciotoli & *alii* (2003).

Lineaments are substantially linearly arranged elements of relief, for example linear sections of a valley or straight sections of slopes, and should be considered as a potential zone of brittle fracture of bedrock with an influence on the geomorphological evolution of the area (Hobbs 1904 in Abdullah et al. 2010). Most lineaments have been shown to represent fractures (Tuschida & Yamaguchi, 1996). The concept of lineaments was developed in the context of geological mapping from aerial photographs. They can be simply defined as a liner structure identifiable from RS data that reflects a sub-surface phenomenon (O'Leary, 1976). According to Minár & Sládek (2009), lineaments are surface discontinuities probably tectonic in origin and are named on the map according to the method of their construction as follows: 1) photolineaments are linear boundaries identified from aerial or satellite images; 2) topolineaments are linear boundaries identified from topographic maps; 3) morpholineaments are linear boundaries determined solely from the properties of the relief (now mostly using a digital model). An analysis of lineaments can therefore give an insight into landscape evolution and the study of lineaments thus allows us to obtain information about tectonic activity over large areas or over areas where there is no access to the field (Ehlen, 2004).

Lineaments were identified in the series of hill shading images as straight linear structures appearing in the image under different conditions of illumination (from N - solar azimuth of 0°; from NE - solar azimuth of 45°; from E - solar azimuth of 90°; and from SE - solar azimuth of 135°) (*sensu* Sarp, 2005; Kocal & *alii*, 2007; Abdullah & *alii*, 2010; Hubbarde & *alii,* 2012; Muhammad & Awdal, 2012). In most cases these structures represent the lower part of scarps enhanced in the image as a sharp transition of grey tone. In some cases distinctly straight parts of streams were also identified as lineaments.

The azimuth of lineaments is determined as the orientation of lineaments to the coordinate system. The azimuth of lineaments is illustrated by rose diagrams, which are divided into 72 intervals of 5° (360° in total) in a N to E direction. The numbers of lineaments in the rose diagrams are weighted by their length.

The following areas of potential erosion were plotted based on SRTM DEM: 1) "erosion from 1 side", i.e. the places on the border of the erosion - mainly the valley heads – where the backward erosion is active; 2) "erosion from 2 sides"; and 3) "erosion from 3 and more sides", i.e. the butte-temoins and divided ridges which are eroded by more than one valley from several sides. The backward erosion can be identified quite easily from the DEM and some locations were also checked during the field trips.

3. RESULTS

3.1. *Mophometry of the Jemma River basin*

3.1.1. *Analysis of the morphometry of the valley network*

We defined a drainage network consisting of 3,647 streams organized into 8 orders. The study area is drained by the Jemma River, which flows through a I. order valley for a length of 278.40 km (table 1; fig. 2). The number of valleys decreases with increasing length (fig. 2a). A total of 1,437 (39.4%) valleys are less than or equal to one kilometer in length. The difference in the "average length of valleys" between valleys of the I. and II. orders is 97.84%. This is due to the "number of valleys" of both orders i.e. only one valley is in the I. order and 251 valleys are in the II. order (table 1 and fig. 2b). The "number of valleys" and the "total length of valleys" of various orders increase with increasing order until the IV. order; then both the "number of valleys" and the "total length of valleys" begin to decrease (table 1; fig. 2b). The "average length of valleys" decreases with increasing order (table 1; fig. 3b).

TABLE 1 - The "number of valleys", the "total length of valleys" and the "average length of valleys" of various orders in the Jemma River basin (according to the Gravelius order system of valley networks)

Valley order	**"Number of valleys"**	**"Total length of valley" [km]**	**"Average length of valley" [km]**
I. order	1	278.40	278.40
II. order	251	1,509.25	6.01
III. order	713	2,820.59	3.96
IV. order	1137	3,163.03	2.78
V. order	1007	2,047.09	2.03
VI. order	435	767.06	1.76
VII. order	84	175.04	1.48
VIII. order	19	21.18	1.11

In the study area of the Jemma River basin the "valley junction angles" reached an average value of 77.71 and the "valley network density" reached a value of 0.7 km/km^2. If the *subregions* are considered then there are significant differences, which reflect the internal variations in the landscape morphology (comp. also Chapter 4.2.).

3.1.2. *Analysis of azimuths of lineaments and valleys in the Jemma River basin*

A total of 408 lineaments were mapped in the Jemma River basin and its close surroundings with a total length of 5,248.42 km. This part of the Ethiopian Highlands was influenced by tectonic processes associated with the formation of the Rift Valley. The lineaments have a main NE-SW azimuth, which is consistent with the orientation

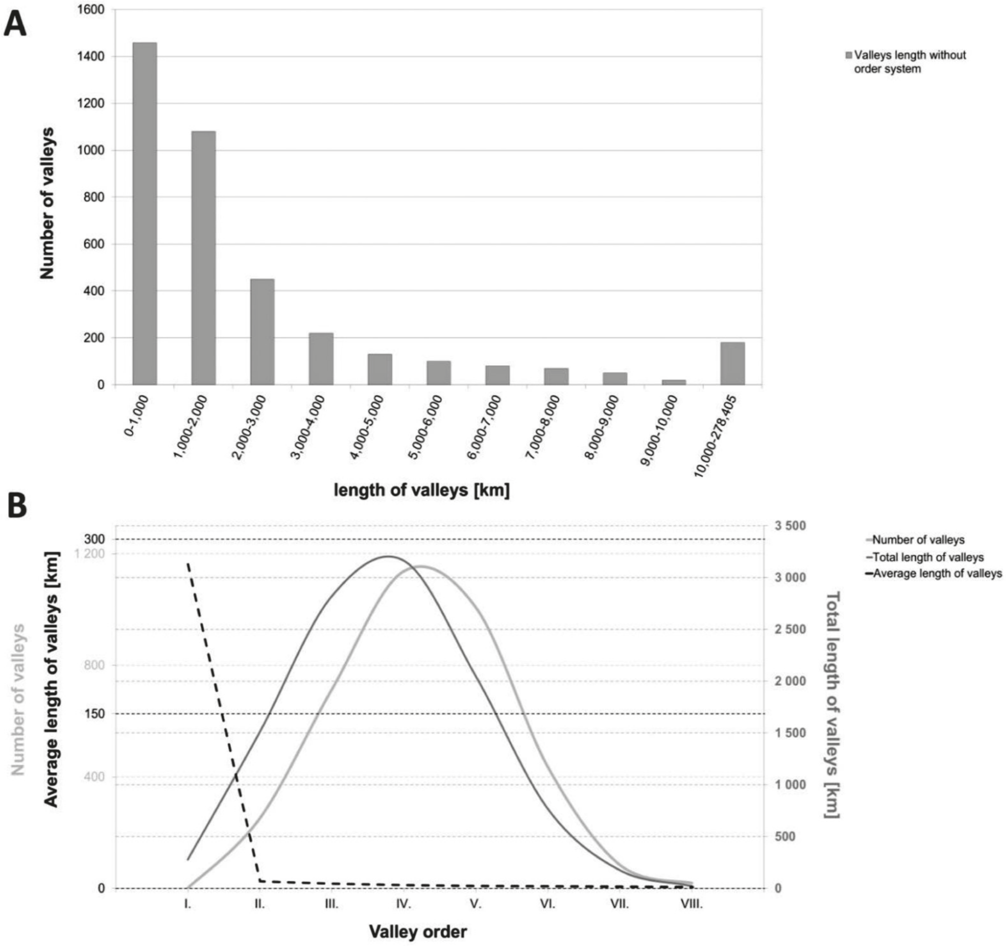

FIG. 2 - The number of all of the valleys in the Jemma River basin without using the Gravelius order system (a). The "number of valleys", the "total length of valleys" and the "average length of valleys" of various orders in the Jemma River basin (according to the Gravelius order system of valley networks) (b).

FIG. 3 - Map of lineaments (a). Azimuth of lineaments in the Jemma River basin and its surroundings (b). NOTE: The numbers of lineaments in the rose diagrams are weighted by their length.

of the rift (fig. 3). If the *subregions* are considered then there are significant differences, which reflect the internal variations in landscape morphology – the local topography and the prevailing trends may be different in such small *subregions* (Chapter 4.2.).

Trellis valley networks are dominant in the Jemma River basin, where the stream channels of valleys copy two sets of tectonic directions (fig. 7a): 1) NE-SW azimuth (consistent with the orientation of the Rift Valley) and a perpendicular NW-SE azimuth; and 2) N-S and W-E azimuths.

3.1.3. *Analysis of landscape features and potential erosion in the Jemma River basin*

The border of erosion (black line in fig. 4a) separates younger parts of the landscape with a lower altitude and steep valley slopes from older parts of the landscape with a higher altitude and gentle valley slopes (fig. 4; 5). A rather sharp boundary (zone) (yellow line in fig. 4a) runs across the Jemma River basin in a SSW-NNE direction, which is in agreement with the orientation of faults on the geology map compiled by the Geology Survey of Ethiopia (Mangesh et al., 1996), and which is in agreement with the analysis of lineaments (comp. also Chapter 4.1.2.; fig. 3b). The boundary (zone) divides the trellis valley networks into the older part in the west and younger parts in the east.

Fig. 4b shows the potential for erosion, which is greater in the area adjacent to the border of the Rift Valley in the eastern part of the analyzed area, while there are only a few watershed crests remaining in the western part of the basin. The erosion progresses along the young tectonic discontinuities in the eastern part and the valleys are extended by erosion towards the Rift Valley at the expense of the old platforms.

A total of 1,220 places of potential erosion were mapped in the Jemma River basin with a total area of 775.53 km^2 (table 2). The largest number of places with a potential for erosion is from "erosion from 1 side", i.e. places on the border of erosion – mainly the valley heads – where back erosion could be active. The largest area of places with a potential for erosion is from "erosion from 3 and more sides", i.e. butte-temoins and divided ridges, which are eroded by multiple valleys from several sides. After the destruction of these places (erosion from 3 and more sides) river capture will occur.

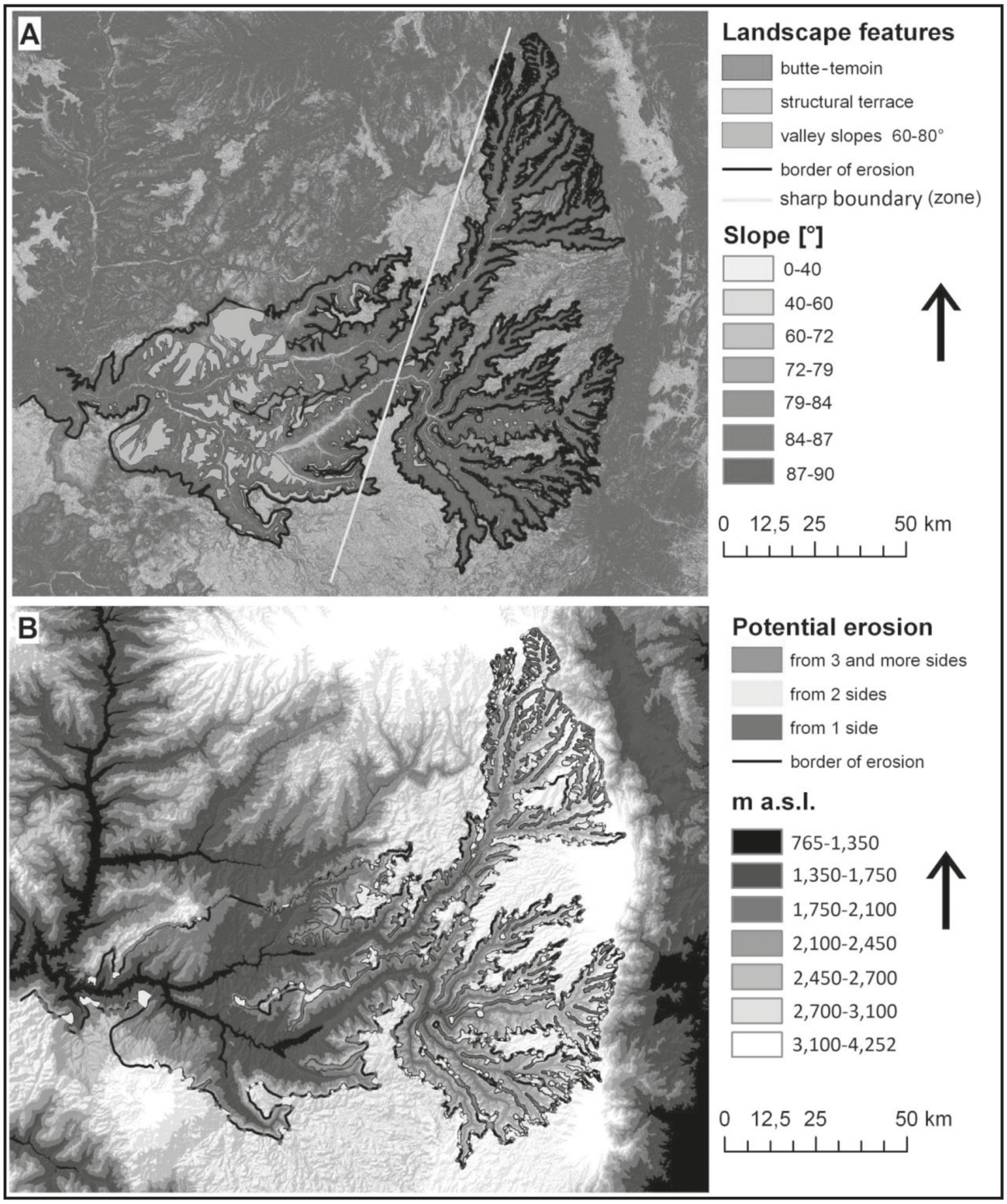

FIG. 4 - Landscape features (a). Erosion potential in the Jemma River basin (b).

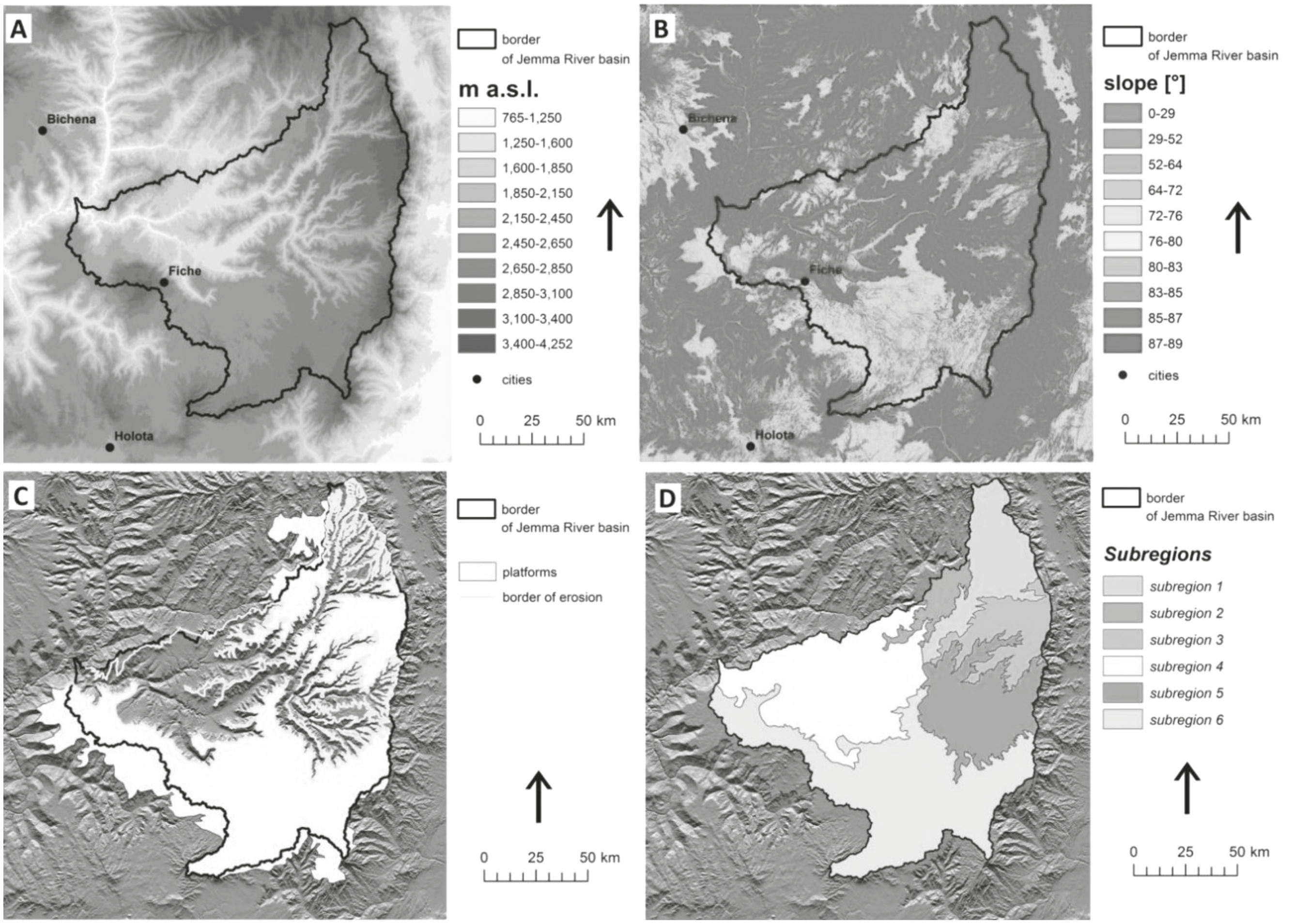

FIG. 5 - Characteristics of the landscape and determination of the *subregions*: Elevation of the Jemma River basin [m a.s.l.] (a); Slopes of the Jemma River basin [°] (b); Platforms and border of erosion, i.e. the boundaries dividing the old platforms and deep canyons, which are cutting into these old platforms, in the Jemma River basin (c); and Determination of the six *subregions* in the Jemma River basin (d).

TABLE 2 - Landscape features

Landscape features	Number	Total [km^2]	Minimum size [km^2]	Maximum size [km^2]
Valley slopes 60-80°	39	661.78	0.54	130.52
Structural terraces	179	290.16	0.06	22.13
Butte-temoins	170	163.21	0.01	20.01
Erosion from 3 and more sides	291	333.55	0.04	22.91
Erosion from 2 sides	428	315.53	0.02	9.64
Erosion from 1 side	501	126.45	0.01	2.50

3.2. *Identification and analysis of* subregions *based on the morphometry of the landscape*

Six separate *subregions* were identified in the Jemma River basin (area of 15,357.54 km^2) based on the properties of the landscape defined by the terrain analysis (fig. 5d, table 3).

Subregion 1 and *subregion 5* are located on the eastern boundary of the Jemma River basin adjacent to the Ethiopian Rift. They are formed by deep canyons that cut into the old platform. The prevalent slope inclination varies between 83 and 89° and the difference between the highest and lowest parts can be up to 3,007 m for *subregion 1* and 2,156 m for *subregion 5,* respectively.

Subregion 2, *subregion 3* and *subregion 6* are fragments from the old platform of the Ethiopian Highlands. This old platform has been divided into the following three parts

TABLE 3 - Summary table of the morphometric characteristics and landscape properties of *subregions* in the Jemma River basin

SUBRGION 1		
Characterization of landscape		
Area [km²]	1,770	**Characterization: 1)** location on the eastern boundary of the Jemma River basin; **2)** dominate deep canyons that cut into the old platform; **3)** slopes of deeply cut valleys are 84-90° due to the young tectonic discontinuities; 4) only 5.59% of the structural terraces have evolved here.
Prevalent slope inclination [°]	85-89	
Gain of height [m]	3,007	
Morphometry of valley network		
Shape of valley network	trellis	**Characterization: 1)** interval average values of 85-90° of the "valley junction angles" were reached by 72.27%; **2)** a "valley junction angles" value of about 90° is typical for trellis shaped valley networks; **3)** trellis are typical for areas with a dominant influence of continuous tectonic deformations (folds, faults); 4) emergence of tectonic deformations facilitates the effects of erosion and explains the high values of the "valley network density".
"Valley junction angles" [°]	83.17	
"Valley network density" [km/km²]	1.33	
Analysis of azimuth		
Azimuth of lineaments	NE–SW	**Characterization: 1)** azimuth of lineaments is in accordance with the orientation of the Rift Valley; **2)** strong tectonic uplift in the easternmost part of the Ethiopian Highlands demonstrates slightly more variability i.e. range in azimuth between N20°E and N60°E; **3)** there is a rather strong influence of tectonics; however, this is not significantly reflected by the azimuth of stream channels.
Azimuth of stream channels	N-S, W-E, NE-SW, NW-SE	
SUBREGION 2		
Characterization of landscape		
Area [km²]	540	**Characterization: 1)** fragment from the old platform of the Ethiopian Highlands; **2)** divided and isolated by intensive erosion of the rivers; **3)** area is too small to perform an analysis of the morphometry of the valley network and analysis of lineaments; **4)** shape of network is described as being undefined.
Prevalent slope inclination [°]	52-83	
Gain of height [m]	426	
SUBREGION 3		
Characterization of landscape		
Area [km²]	1,330	**Characterization: 1)** fragment from the old platform of the Ethiopian Highlands; **2)** divided and isolated by intensive erosion of the rivers; **3)** erosion progresses along the young tectonic discontinuities; **4)** valleys are extended by erosion towards the Rift Valley at the expense of the old platforms.
Prevalent slope inclination [°]	52-83	
Gain of height [m]	1,813	
Morphometry of valley network		
Shape of valley network	parallel	**Characterization: 1)** reaches the lowest average value of "valley junction angles"; **2)** a "valley junction angles" value of about 30° is typical for parallel shaped valley networks; **3)** parallels are often formed in areas with a considerable inclination of slopes or by the aggregation of large rivers.
"Valley junction angles" [°]	36.55	
"Valley network density" [km/km²]	0.57	
Analysis of azimuth		
Azimuth of lineaments	ENE-WSW	**Characterization: 1)** azimuth of lineaments is in loose parallelism with the Rift Valley and may be a sign of the slightly different evolution of this "block"; **2)** structure of a trellis valley network, which changes its upstream flow direction from W-E (N-S and W-E azimuths) to NE-SW (NE-SW and NW-SE azimuths); **3)** this relation is stronger here than the parallelism with the direction of lineaments.
Azimuth of stream channels	N-S, W-E, NE-SW, NW-SE	
SUBREGION 4		
Characterization of landscape		
Area [km²]	4,090	**Characterization: 1)** located in the lower part of the Jemma River basin; **2)** consists of older valley networks; **3)** it has been reactivated by recent erosion; **4)** it is represented by wide valleys with larger valley bottoms; 5) there have evolved 62.57% of the structural terraces.
Prevalent slope inclination [°]	64-89	
Gain of height [m]	1,674	

		Morphometry of valley network
Shape of valley network	trellis	**Characterization: 1)** interval average values of 85-90° of the "valley junction angles" were reached by 59.95%; **2)** a "valley junction angles" value of about 90° is typical for trellis shaped valley networks; 3) trellis are typical for areas with a dominant influence of continuous tectonic deformations (folds, faults); 4) emergence of tectonic deformations facilitates the effects of erosion and it explains the high values of the "valley network density".
"Valley junction angles" [°]	81.34	
"Valley network density" [km/km^2]	0.61	
		Analysis of azimuth
Azimuth of lineaments	NE–SW	**Characterization: 1)** azimuth of lineaments of N55°E is in accordance with the orientation of the Rift Valley; **2)** tectonic predisposition of the central part of the Jemma River basin is clear; **3)** structure of a trellis valley network, which changes its upstream flow direction from W-E (N-S and W-E azimuths) to NE-SW (NE-SW and NW-SE azimuths); **4)** this relation is stronger here than the parallelism with the direction of lineaments.
Azimuth of stream channels	N-S, W-E, NE-SW, NW-SE	
		SUBREGION 5
		Characterization of landscape
Area [km^2]	2,350	**Characterization: 1)** located on the eastern boundary of the Jemma River basin; **2)** dominated by deep canyons that cut into the old platform; **3)** slopes of deeply cut valleys are 84-90° due to the young tectonic discontinuities; **4)** 31.84% of the structural terraces have evolved here.
Prevalent slope inclination [°]	83-89	
Gain of height [m]	2,156	
		Morphometry of valley network
Shape of valley network	trellis	**Characterization: 1)** interval of average values of 85-90° for "valley junction angles" was reached in 74.91% of cases; **2)** a "valley junction angles" value of about 90° is typical for trellis shaped valley networks; 3) trellis are typical for areas with a dominant influence of continuous tectonic deformations (folds, faults); 4) emergence of tectonic deformations facilitates the effects of erosion and it explains the high values of the "valley network density".
"Valley junction angles" [°]	84.44	
"Valley network density" [km/km^2]	0.84	
		Analysis of azimuth
Azimuth of lineaments	NE–SW	**Characterization: 1)** azimuth of lineaments is in accordance with the orientation of the Rift Valley; **2)** strong tectonic uplift in the easternmost part of the Ethiopian Highlands demonstrates slightly more variability i.e. range in azimuth of between N20°E and N60°E; **3)** the best parallelism between the directions of stream channels and lineaments is identified; 4) also parallelism with the dominant direction of the Rift Valley systems.
Azimuth of stream channels	NE–SW	
		SUBREGION 6
		Characterization of landscape
Area [km^2]	5,280	**Characterization: 1)** fragment from the old platform of the Ethiopian Highlands; **2)** divided and isolated by intensive erosion of the rivers; **3)** erosion progresses along the young tectonic discontinuities; **4)** valleys are extended by erosion towards the Rift Valley at the expense of the old platforms.
Prevalent slope inclination [°]	52-83	
Gain of height [m]	1,813	
		Morphometry of valley network
Shape of valley network	dendritic	**Characterization: 1)** reach a low average value for "valley junction angles"; **2)** a "valley junction angles" value of about 60° is typical for dendritic shaped valley networks; **3)** dendritic valley networks are often formed in areas with a low vertical division without the influence of structures.
"Valley junction angles" [°]	63.13	
"Valley network density" [km/km^2]	0.55	
		Analysis of azimuth
Azimuth of lineaments	NE–SW	**Characterization: 1)** the perpendicular direction has the same significance (much older type of landscape); 2) the best parallelism between azimuth of lineaments and the directions of stream channels is also identified here.
Azimuth of stream channels	NE–SW	

by intensive erosion of the Jemma River and its tributaries. The prevalent inclination is 52-83° and the differences between the highest and lowest areas in these *subregions* are estimated to be 426 m for *subregion 2*, and 1,813 m for *subregions 3* and *6,* respectively.

Subregion 4 is located in the lower part of the Jemma River basin and consists of older valley networks than in *subregions 1* and *5*. The prevalent inclination of valley slopes is 89°, but the large valley bottom tends to incline only by about 64°. The difference between the highest and lowest area is estimated to be 1,674 m. This area is significantly older; however, it has been reactivated by recent erosion.

3.2.1. *Analysis of the morphometry of the valley network in the* subregions

The highest average values for “valley junction angles” are reached in *subregions 1* and *5* (table 3). In addition, the interval average values of 85-90° of the “valley junction angles” were reached by 72.27% for *subregion 1* and 74.91% for *subregion 5,* respectively. In *subregion 4* the “valley junction angles” also reach high values, but in the interval of average values of 85-90° only 59.95% was reached. According to Křížek & Kusák (2014), the value of about 90° of “valley junction angles” is typical for trellis and rectangular shaped valley networks, as can be seen in *subregions 1*, *4* and *5* in the Jemma River basin (fig. 6d). Folds are typical in areas with a dominant influence of continuous tectonic deformations but in areas with discontinuous tectonic deformations faults are most commonly encountered (Howard, 1967; Fairbridge, 1968; Demek, 1987; Babar, 2005; Huggett, 2007). The emergence of tectonic deformations facilitates the effects of erosion and could explain the high values of the “valley network density” in *subregions 1*, *4* and *5* (table 3).

Compared to values of *subregions 1*, *4* and *5*, the average value for “valley junction angles” in *subregion 6* reaches only 63.13° and in *subregion 3* it reach the lowest average value of 36.55°. According to Křížek & Kusák (2014), a value of approximately 60° for “valley junction angles” is typical for dendritic shaped valley networks (as can be seen in *subregion 6*; fig. 6d), which are often formed in areas with a low vertical division without the influence of structures, and the values of about 30° were typical for parallels shapes of valley networks (as can be seen in *subregions 3*; fig. 6d), which are often formed in areas with a considerable inclination of slopes or by the aggradation of large rivers (Howard, 1967; Fairbridge, 1968; Demek, 1987; Babar, 2005; Huggett, 2007). The area of *subregion 2* is too small to perform an analysis of the morphometry of the valley network so the shape of the network in *subregion 2* should be described as being undefined (fig. 6d).

3.2.2. *Analysis of lineaments in* subregions

Subregions 1, *4* and *5* appear to be similar in terms of the lineament analysis – rose diagrams showing the azimuth of lineaments weighted by their length (fig. 7a, c, d), whereby most of the lines stretch in a NE-SW direction i.e. in accordance with the Rift Valley. Moreover, *subregions 1* and *5*, which are on the border of the Rift Valley, coincide even more and the NE-SW direction (fig. 7a, d) is not so apparent (the azimuth varies between N20°E and N60°E, compared to N55°E in *subregion 4,* fig. 7c). The tectonic predisposition of the central part of the Jemma River basin is clear while the strong tectonic uplift in the easternmost part of the Ethiopian Highlands demonstrates slightly more variability i.e. the azimuth varies between N20°E and N60°E.

In *subregion 3* the lineaments are less frequent and follow an ENE-WSW direction (fig. 7b), which is in loose parallelism with the Rift Valley and may be a sign of the slightly different evolution of this “block” – also the erosion rate is diverse here (smaller). *Subregion 6* is different to *subregions 1*, *4* and *5,* whereby the tectonic predisposition is clear (NE-SW lineaments; fig. 7e); however, the perpendicular direction has the same significance (much older type of landscape).

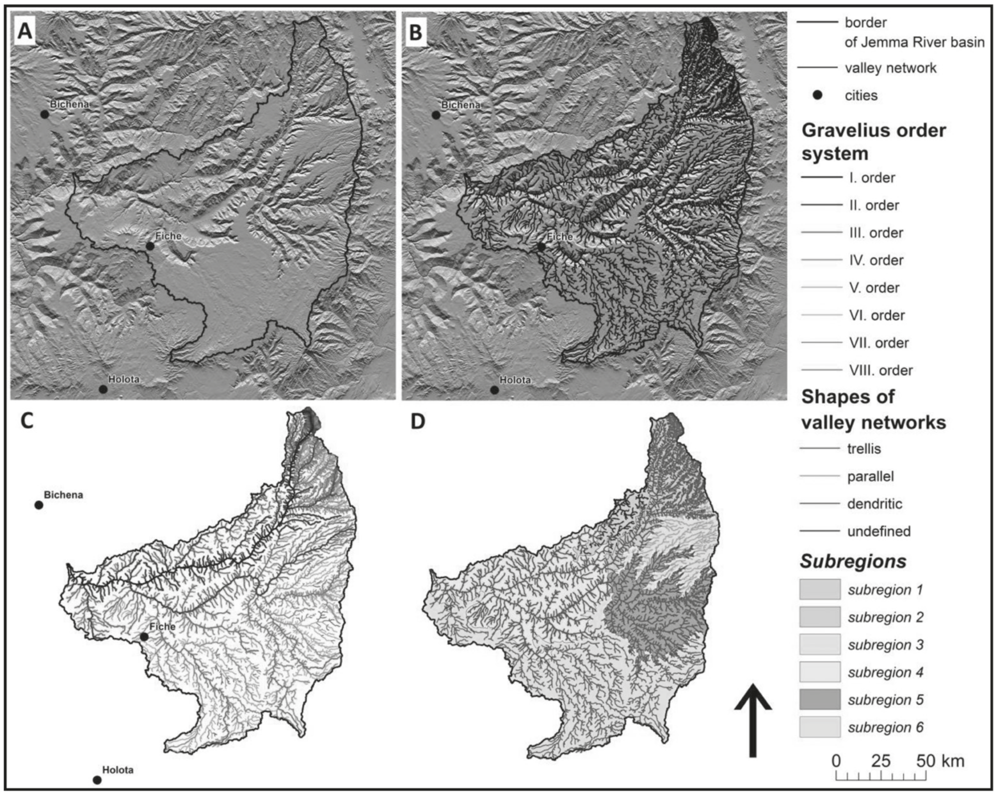

FIG. 6 - Procedural steps for creating a digital model of valley networks: Digital images from the SRTM DEM (a); Thalwegs created in ArcGIS 10 (b); Definition of valley network orders according to the Gravelius order system (c); Shapes of valley networks in the *subregions* of the Jemma River basin according to Křížek & Kusák (2014) (d).

3.2.3. *Analysis of the azimuths of stream channels in* subregions

A detailed analysis of the azimuths of stream channels was performed on the individual *subregions* (fig. 8) in accordance to Chapter 4.3., in order to compare with the diagrams for the lineaments (see fig. 7). The analysis revealed that certain *subregions* (e.g. *subregion 4*) follow the structure of a trellis valley network, which changes its upstream flow direction from W-E (N-S and W-E azimuths of stream channels) to NE-SW (NE-SW and NW-SE azimuths of stream channels). This relation is stronger here than the parallelism with the direction of lineaments. A similar situation can be seen in *subregion 3*; however, the total number of items on the graph is lower (fig. 8c).

The best parallelism between the directions of stream channels and lineaments was identified in *subregions 5* and *6*. *Subregion 6* is typically characterized by a gently modulated landscape on the surface of volcanic lava flows, which is rather old (Tertiary) and is without recent erosion (see also Chapter 5. Discussion). The parallelism in *subregion 5* between the directions of stream channels and lineaments is also clear and in this case also with the dominant direction of the Rift Valley systems. The most interesting interpretation could be linked with *subregion 1*, where there is also a rather strong influence of tectonics; however, this is not significantly reflected by the direction of water courses (!). If we compare graphs 7A and 8B there is no strong parallelism visible; however, the backward erosion has used the tectonic zones to reach rather distant areas (see also fig. 4b).

3.2.4. *Analysis of landscape features and potential erosion in* subregions

From fig. 4a, 4b or 5c it is possible to reveal the intensity of erosion in various *subregions* - *subregions 1*, *4* and *5* are characterized as younger parts of the landscape with a lower altitude and steep valley slopes compared to *subregions 2*, *3* and *6,* which are older parts of the landscape with a higher altitude and gentle valley slopes. The boundary (zone) (yellow line in fig. 4a) divides trellis valley networks into the older part in the west – *subregion 4* and younger parts in the east – *subregions 1* and *5*. The western part (*subregion 4*) is represented by wide valleys with larger valley bottoms and gentle valley slopes of 60-80°, having a total area of 661.78 km^2 (table 4). Moreover, 62.57% of the structural terraces in the Jemma River basin are located there. On the contrary, deeply cut valleys with slopes of approximately 84-90° dominate in the eastern part (*subregions 1* and *5*) due to the young tectonic discontinuities. Only a few structural terraces have evolved in these erosionally influenced regions (fig. 8a) (5.59% of the terraces are in *subregion 1* and 31.84% in *subregion 5*; table 4). The potential for erosion is greater in the area adjacent to the border of the Rift Valley in *subregions 1* and *5*; while there are only a few watershed crests remaining in *subregion 4*. The erosion progresses along the young tectonic discontinuities of *subregions 1* and *5* and the valleys are extended by erosion towards the Rift Valley at the expense of *subregions 3* and *6* (old platforms).

4. DISCUSSION

4.1. *Used methods*

The Gravelius order system, which describes the valleys as geomorphological units, was used to perform a basic characterization of the valley network. The Gravelius order system can be used to determine the number of valleys, length of valleys, and also to analyze longitudinal profiles and knick points in valleys (Gani & *alii*, 2007; Kusák, 2014). On the contrary, the order systems of Horton (1945), Strahler (1957) and Shreve (1966) only describe the network as segments and not the entire length of the valley. The drainage pattern is described in a direction from the river springs to the estuary – I. order watercourses are parts of the watercourse from the river springs to the first node, i.e. the confluence of watercourses in the network. So while using the order systems of Horton (1945), Strahler (1957) and Shreve (1966) the valleys cannot be described as units.

The value for the "total lengths of valleys" t was defined as the sum of the lengths of all of the valleys of the given order (sensu Gravelius, 1914) in the valley network, i.e. the sum of the lengths from the valley heads to the outfalls of each valley. Previously, during extraction of valley networks from topographic maps, the shapes of valley networks were made up of 1D lines transferred onto a 2D plane - the lengths of the valleys were not accurate (Davis, 1889, 1899, 1906 in Gaudie & *alii*, 2004; Horton, 1945; Howard, 1967; Fairbridge, 1968, Demek, 1987; etc.). In this article, the value for the "total lengths of valleys" is calculated automatically in ArcGIS 10.1 (ESRI, 2015) from SRTM (3D), so the results are more accurate.

4.2. *Future perspectives*

It would be of great benefit for the presented research to be supplemented by detailed geomorphological field research at the "hot spots" we identified using the presented methodology with general field experience of selected areas (around Fiche, Dessie, Andit Tid etc.). These hot spots could be considered as areas with the most dynamic landscape evolution, like *subregion 1* (see Chapter 6. Conclusion). The other candidate would be *subregion 3*, which has not yet been influenced by the most recent fluvial erosion.

Using the scale of our research, the fluvial erosion seems to be the leading process in landscape evolution, also considering the depth of several canyons; however, using a more detailed scale the slope processes (e.g. landslides, rock falls) and weathering start to play a more important role (e.g. Zvelebil & *alii*, 2010; Vařilová & *alii*, 2015).

The analysis of *subregion 6* suggests that it is not influenced by young tectonics because a dendritic network has evolved. However, the parallelism between the direction of lineaments and the water courses is contrary to this statement. We have to take into consideration that the number of lineaments in this *subregion* was rather low compared to the others and this could probably have a negative influence on the accuracy of the parallelism between the direction of the lineaments and the water courses. In this case the river network analysis (dendritic network) appears to be more plausible.

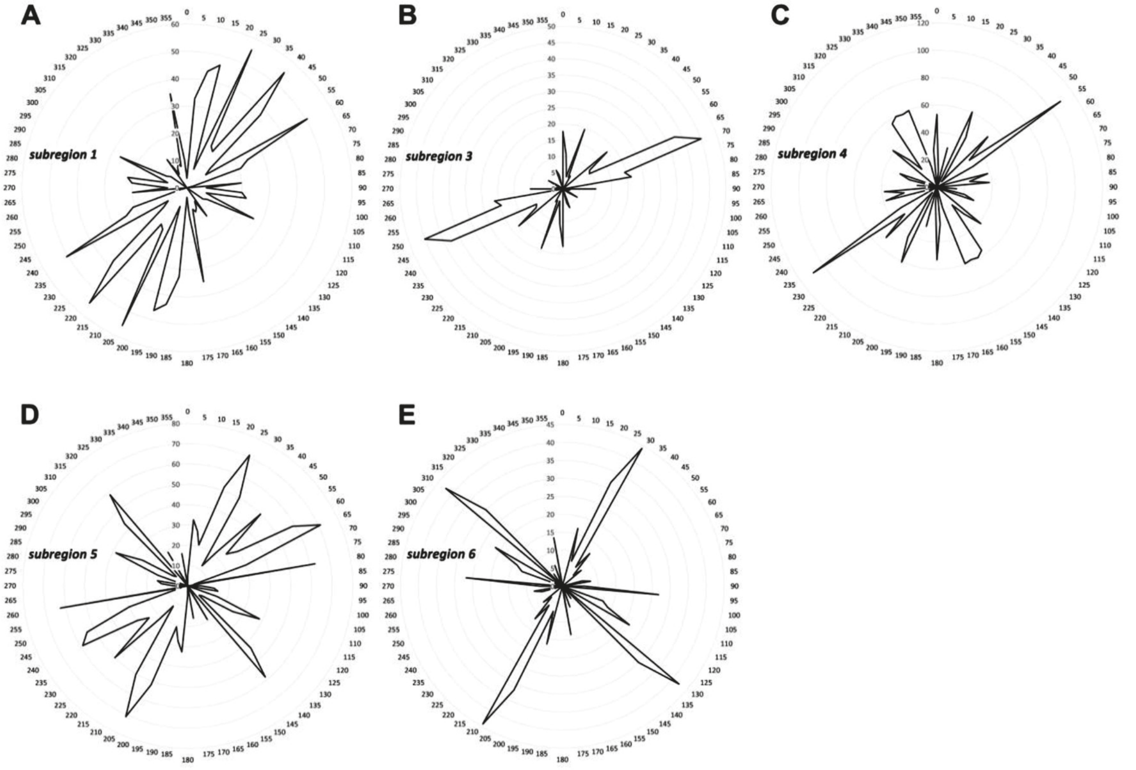

FIG. 7 - The azimuth of lineaments in the Jemma River basin; for *subregion 1* (a); for *subregion 3* (b); for *subregion 4* (c); for *subregion 5* (d); for *subregion 6* (e). Note: *Subregion 2* was not analyzed due to its small area and the presence of only two lineaments.

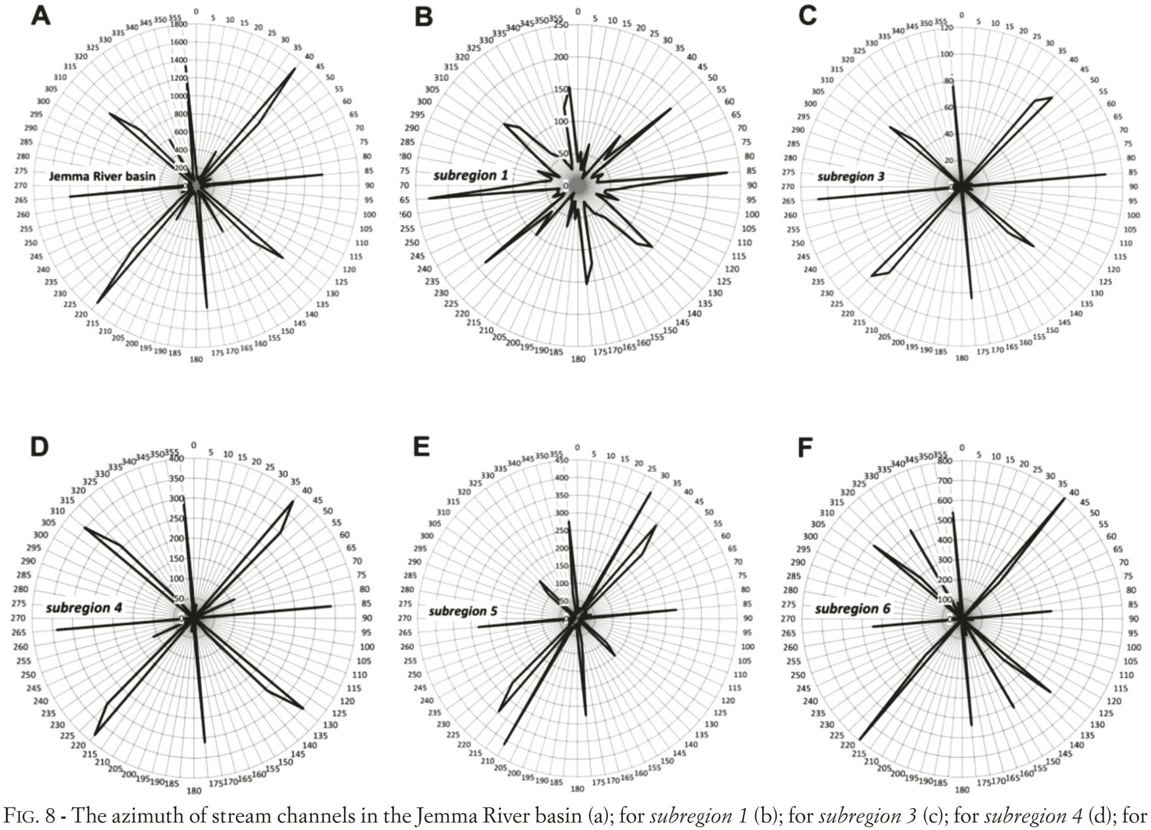

FIG. 8 - The azimuth of stream channels in the Jemma River basin (a); for *subregion 1* (b); for *subregion 3* (c); for *subregion 4* (d); for *subregion 5* (e); for *subregion 6* (f). Note: *Subregion 2* was not analyzed due to its small area.

CONCLUSION

The presented study demonstrated a high SRTM DEM value for terrain analysis as well as the influence of neotectonics on landscape evolution of the Jemma River basin in the Ethiopian Highlands at a regional scale. A set of morphometric variables allowed us to define different *subregions*, what helped us later in the interpretation phase because the *subregions* are rather homogenous from the point of view of the character of the river network.

Nevertheless, several specifics were indentified when we analyzed the *subregions* separately. Among the areas influenced by recent tectonics we can distinguish *subregion 4* – where the middle part of long valleys is dominant with more gentle slopes and the main valleys are wider. The most recent tectonic influence took place over a border area of the Rift Valley (*subregions 1*, *3* and *5*), where the upper parts of the valleys are usually located. However, certain differences could also be seen among these last three *subregions*. In the area of *subregions 1* and *5* trellis networks were created due to intensive erosion along the faults and fault zones, while the area of *subregion 3* was uplifted (inclined towards the west) and "only" a parallel network evolved. The most recent erosion through backward erosion has not reached this area yet (see also the part about lineaments). In addition, the analysis of lineaments showed that the central part of the Jemma River basin (*subregion 4*) was influenced (predisposed) by tectonic movements, whereas the eastern areas (*subregions 1* and *5*) which are also under the influence of neotectonics expressed larger variability. The eastern part of the Jemma River basin (next to the Rift Valley) is more affected by potential erosion – not only the head scarps but also the lateral sides of valleys. Moreover, the deeply cut valleys in this area with slopes of around 84-90° are signs of the influence of young tectonics.

The novelty of the paper is in the characterization of the *subregions* (in terms of the valley network structure, tectonics and erosion in an un-biased way) as well as in the overall description of the differences in the relationship between neotectonics and long-term landscape evolution. The evaluation of the river network is predisposed both by volcanic lava flows and tectonics, whereas the river network evolution generally predominates the fluvial erosion and slope processes in the long term. Analysis of the derived parameters resulted in a deeper insight in the landscape evolution in this part of the Ethiopian Highlands.

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