Assessment of tectonic control on the development of low mountains moderate relief in the Outer Carpathians (Southern Poland)

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Abstract: Inherited tectonic structures, ongoing tectonic deformation, and variations in relative rock uplift rates play an important role in conditioning the processes of relief development. Their influence among other factors, such as climate and lithology, can be quantified using landscape analysis, and geomorphometric indices, in particular. The usage of landscape analysis in recent years is increasing systematically due to the constant improvement of the digital elevation models and GIS software that significantly facilitate this approach. In this study, we aim to recognize the influence of tectonic structures and processes on relief development in the low mountains with moderate relief of the Sola River catchment in the Western Outer Carpathians. To this end, we calculated geomorphometric indices (river longitudinal profile, stream-length gradient index, minimum bulk erosion, relief ratio, circulatory ratio, elongation ratio, and hypsometric integral) for the Sola River and its 47 sub-catchments using a 25-m spatial resolution Digital Terrain Elevation Data Level 2. Additionally, we identified lineaments and knickpoints and correlated the computed results with local and regional fault networks, variations in lithology, and climate fluctuations. Obtained results indicate a significant impact of inherited tectonic structures on the relief development of the Sola River catchment, i.e., directions of principal ridges and valleys follow the orientation of main folds and faults recorded in this area. Anomalously high values of minimum bulk erosion, river gradient, and stream-length gradient index allowed us to define two areas with higher relative uplift rates: 1) the Sola Gorge and 2) the Beskid Żywiecki Mts. Polish Outer Carpathians are generally considered as an area of low strain rate and low seismic activity. However, the possibility of neotectonic processes should be considered in geohazard estimations. Observed bends in the direction of river valleys that do not correspond with changes in lithology could be related to active strike-slip faults. These are probably the reactivated basement structures, copied in the thin-skinned nappe cover, as a result of the accommodation of the Mur-Žilina Fault Zone resulting from the tectonic push of the Alcapa (Alpine-Carpathian-Pannonian) microplate against the European plate. Thus, the role of recent tectonic activity in relief development of the Sola River catchment even though appears to be subsidiary at the most, should not be excluded.

Keywords: Tectonics; Landscape analysis; Relief development; Geomorphometric indices; Digital elevation model; Outer Carpathians
Introduction

Worldwide examples proved the usage of landscape analysis and geomorphometric indices, in particular, to quantify the tectonic deformation and derive variations in relative rock uplift across high strain rate areas, such as the western USA, Taiwan, Himalaya, Andes, forearc of subduction zones, etc. (e.g., Burbank and Anderson 2001; Kirby and Whipple 2001, 2012; Keller and Pinter 2002; Gao et al. 2013; Gaidzik and Ramírez-Herrera 2017; Ramírez-Herrera et al. 2018; Wang et al. 2019; García-Delgado and Velandia 2020), and in low strain rate areas like SE Spain (e.g., Pérez-Peña et al., 2010), the Vienna Basin and central Pannonian Basin (e.g., Ruszkiczay-Rüdiger et al. 2009; Matoš et al. 2013), Sudetes Mts. (e.g., Różycka and Migoń 2017). Extensive and uncomplicated access to digital elevation models and GIS software essentially sustained the worldwide usage of numerous geomorphometric indices to discuss the response of landscapes to ongoing deformation (Keller and Pinter 2002; Font et al. 2010; Kirby and Whipple 2012). Observed anomalies in values of these indices result from tectonic activity, climate conditions, and variations in rock erodibility or changes in base-level (e.g., Burbank and Anderson 2001; Keller and Pinter 2002; Argyriou et al. 2017; Buczek and Górnik 2020).

Low mountains moderate relief of the Outer Carpathians is usually associated with no or low seismic activity. However, seismic events of generally small magnitude with long return periods occur here, as proven by instrumental and historical records (Guterch 2009; Plesiewicz and Wisniewski 2015). Previous studies on relief development in the Outer Carpathians focused mainly on the impact of lithology and climate on mass movements (Margielewski 2006; Wójcik et al. 2006), landslide susceptibility mapping (e.g., Pawluszek and Borkowski 2017), and fluvial processes (Wyżga et al. 2016). Only a few studies suggested the possible influence of neotectonic processes on landscape evolution of the Outer Carpathians using river longitudinal profiles and drainage anomalies (Zuchiewicz 1998; Zuchiewicz et al. 2002, 2009; Placzewska 2014), river terraces (Olszak 2011), palaeomagnetic studies (Tokarski et al. 2016), lithology of Neogene and Quaternary gravels (Tokarski et al. 2012). The Quaternary activity of faults in the Polish part of Carpathians has been proposed based on the analysis of fractured clasts (Tokarski and Świerszewska 2005; Tokarski et al. 2007, 2016; Zuchiewicz et al. 2011). DEM-based quantitative morphometric studies using GIS techniques are still uncommon in the Outer Carpathians (e.g., Vojtko et al. 2012), especially in the western segment. Moreover, the above-mentioned studies focused usually on the possible activity of neotectonic structures itself and not on the response of the landscape to ongoing deformation.

In this study, we aimed to recognize the influence of tectonic structures and processes on the morphology and drainage network in the Sola River catchment in the Western Outer Carpathians (Figure 1). Up to date, questions on the tectonic control on the landscape development in this area have not been addressed. Moreover, we attempt to understand the response of landscape to the possible impact of neotectonic structures with a low strain rate by studying the river network, as this is the most sensitive morphological element (e.g., Font et al. 2010; Gaidzik and Ramírez-Herrera 2017). For that, we calculated geomorphometric indices both, along the main rivers and their tributaries and across 47 sub-catchments in the Sola River catchment. Our results indicate a significant impact of inherited tectonic structures and processes on the relief development of the Sola River catchment. Computed values of geomorphometric indices and the results of hydrographic network analysis suggest also the potential influence of neotectonic processes, probably related to tectonic push of the Alcapa microplate against the European Plate that leads to the NNE-oriented compression within the nappes of the Outer Carpathians, and the accommodation of the Mur-Žilina Fault Zone.

1 Study Area

1.1 Location

The Sola River catchment is located in southern Poland, bordering with Slovakia to the south (Figure 1B). It occupies an area of 1365.8 km². Southern and central parts are in the Outer...
Figure 1 Location of the Sola River catchment (C) in the Western Carpathians (B) and Central Europe (A). Topography (C) and slopes (D) of the Sola River catchment.
Carpathians, while the most northern part lies on the Carpathian Foothills. The 90-km long Sola River flowing from south to north is one of the right bank tributaries of the Wisła River, i.e., the longest river of Poland (Figure 1C).

1.2 Relief and climate

Most of the Sola River catchment is characterized by low mountains with moderate local relief of 400-800 m, known as the Beskid Mountains (Figures 1C and 2). In the northern part of the study area, the Sola River incises deeply into the mountain massifs forming the Sola Gorge (Figures 1C and 2A). Only the central (Żywieck Basin; Figure 2) and northernmost (Subcarpathian Basin) parts with lowland landscape at elevations of 200-300 m a.s.l. show low relative relief of < 100 m. The absolute relief in the studied catchment varies from 226 m a.s.l. in the northern part of the catchment at the confluence of the Sola and Wisła Rivers, up to 1542 m a.s.l. in the south-eastern part on the northern peak of the Pilsko Mountain (Figure 1C). Slopes show generally medium gradient of 15°-25°, reaching <5° at the ridges and in the valley floors, and > 35° in steep valleys or

Figure 2 Photographs taken in the northern part of the Beskid Żywiecki Mts. presenting selected features within the study area: A – view to the north on the Beskid Mały Mts., showing the Żywieck Basin, Żywiec Water Reservoir and Sola Gorge; B – view to the west on the Beskid Śląski Mts. and Żywieck Basin with the faceted spurs marking the lineament related to the dip-slip fault.
landslide scarps (Figure 1D). The hydrographic network of the Sola River catchment is predominantly dendritic with trellis in the foothills (Figure 3A). Rivers flow predominantly towards the NNE, i.e. according to the general gradient direction. Also common are straight river segments directed: NW – SE and SW – NE (Figure 3A). The climate of the study area can be described as a warm transitional with significant influence of maritime air masses from the North Atlantic. Climate conditions here are strongly controlled by the elevation, as in any mountainous area. Mean annual precipitation varies between < 750 mm in the northern part of the study area to > 1100 mm in the western, southern, and southeastern parts of the Sola River catchment, which corresponds to the highly elevated parts of the mountains (Figures 1C and 3B). The mean annual temperature ranges between 8° C in the lowest areas and 4° C in the highest parts (Wypych et al. 2018). Early Pleistocene glaciations have reached the northernmost parts of the study area (Carpathian Foothills), thus the majority of the Sola catchment was not involved in glaciations. No evidence for glaciation has been found in the Żywiec Basin or adjacent mountains (Marks 2011).

1.3 Lithology

The Outer Carpathians are predominantly composed of the Upper Jurassic to Paleogene flysch sediments, including conglomerates, sandstones, claystones, shales, marls and cherts (Rylko and Paul 2013). These are combined in numerous nappe structures extending from west to east, parallel to the deflection of the Carpathians and characterized by different rocks and variations in tectonic structures (Figure 4A). Five of these nappes can be distinguished in the Sola catchment, i.e., from the south to north: 1) Magura, 2) Grybów, 3) Dukla, 4) Silesian and 5) Subsilesian Nappes (Figure 4; e.g., Oszczykpo et al. 2008).
Figure 4A—Tectonic sketch map of the Polish Carpathians (Żytko et al. 1989; Oszczypko et al. 2008; simplified) showing the maximum horizontal stress ($S_{\text{Hmax}}$) distribution constrained by breakout measurements (after Jarosiński 2005, 2006; modified). B—Geology of the Sola River catchment.
The Magura Nappe occurs in the southern and southeastern part of the study area and consists mainly of thick-bedded sandstones, shales and marls. The Grybów and Dukla Nappes are mainly built of shales and thin-bedded sandstones. The Silesian Nappe located in the central, western and northeastern part of the study area can be divided into two units: 1) the Godula Unit in the southern part formed of sandstones and conglomerates with the subsidiary amount of shales, and 2) the Cieszyn Unit in the northern part built of sandstones, shales, marls, limestones and intrusions of alkaline igneous rocks. The Subsilesian Nappe outcrops only in a narrow zone at the forehead of the Silesian Nappe in the northern part of the study area and in the Żywiec tectonic window in the central part of the studied catchment. Shale deposits (like siliceous shales and shales with radiolaria) dominate within this nappe (Książkiewicz 1977; Oszczypko 2004; Nescieruk and Wójcik 2013; Ryłko and Paul 2013).

The youngest deposits in the Sola catchment were deposited in the Late Neogene and Quaternary. Fluvial gravels, sands, and clays fill the valley bottoms. Colluvial deposits represented mainly by clays with rock debris commonly occur on the slopes. Glaciofluvial (gravels, sands) and aeolian (loess) deposits, related to Early Pleistocene glaciations are frequent in the northern part of the Sola catchment in the Carpathian Foothills (Nescieruk and Wójcik 2013).

1.4 Tectonic setting

SW to WSW-trending fold structures, WSW-striking numerous thrusts and reverse faults, together with transverse (i.e., NNW-striking) normal, oblique-slip and strike-slip faults predominate in the Sola catchment (Figure 5). The study area is composed of five nappes, which were overthrusted on each other from the south to the north. The Magura Nappe is the biggest and structurally the highest nappe and consists of four tectonic subunits limited by thrust zones. Inverse landscape, with anticlines producing low areas and synclines forming elevated areas, is characteristic in the area of this nappe. The Grybów and Dukla Nappes are formed as narrow zones of compressional duplexes overthrusted on top of the Silesian Nappe at the forehead of the Magura Nappe. Silesian Nappe consists of two subsidiary folded subunits divided by thrust zones. Formations of this nappe form three distinct monoclinal blocks, clearly seen in the morphology. Two of them are elevated and build mountain ranges, whereas, the third one is lowered and forms the north-western part of the Żywiec Basin. The WSW- to SW-trending fold structures (i.e., parallel to the strike of thrusts and reverse faults) play only a subordinate role here. Subsilesian Nappe is strongly tectonically disrupted and composed of thrust-faulted folds. Rock formations of the Subsilesian, Dukla and Grybów Nappes show a general structure of a mega-breccia (e.g., Książkiewicz 1977; Oszczypko 2004; Oszczypko et al. 2008; Nescieruk and Wójcik 2013; Ryłko and Paul 2013; Detailed Geological Map of Poland 2019). Breakout measurements suggest the NNE–SSW direction of the maximum horizontal stress ($S_{Hmax}$) in the nappes of the Outer Carpathians, rotated to NE–SW in the eastern part (e.g., Jarosiński 1998, 2005, 2006; Figure 4A).

2 Materials and Methods

For landscape analysis of the Sola catchment, we used a 25 m resolution Digital Terrain Elevation Data Level 2 (DTED-2, 2004), acquired from the Military Centre of Geodesy and Remote Sensing of Polish Army. DTED-2 model was prepared in the process of vectorization of contour lines, characteristic points, and skeletal lines from topographic maps on a scale of 1:50 000 (Czajka 2009). Its horizontal accuracy reaches 16 m and vertical – 2-7 m (Kubiak and Stach 2013). For cartographic analysis and the calculation of morphometric indices, we used ArcGIS 10.7.1 (ESRI 2018) and QGIS 3.8 (QGIS Development Team 2019). For statistical analysis, we used the GeoRose software (Yong Technology Inc. 2014). We used precipitation data obtained from the Institute of Meteorology and Water Management – National Research Institute (IMWM – NRI 2020). Calculation of mean annual precipitation was performed for 17 stations for the period 1950-2019 using Python programming language (Van Rossum and Drake 2009). Data were interpolated by applying the ordinary kriging method.

Limits of the Sola River catchment were delineated using hydrological tools in the ArcGIS software based on the digital elevation model. A similar approach was used to delineate the boundaries of 47 sub-catchments of the Sola River’s main tributaries. Four geomorphometric
Figure 5 A - Spatial distribution and rose diagrams of tectonic structures in the Sola River catchment (according to Detailed Geological Map of Poland 2019) divided into: normal faults (B), reverse faults, and thrusts (C), and fold axes (D). Rose diagram in Figure 5A shows the distribution of strikes of the normal faults and thrusts.
on the river longitudinal profiles and SL-index charts. Knickpoint can be defined as a place in the river longitudinal profile, where a sudden increase in river bed gradient occurs caused by tectonic, lithological, or climatic factors (Galay 1983). Lineaments in the Sola catchment were interpreted based on the shaded relief and slope maps (Figure 1D). Directions of lineaments were summarized at rose diagrams using azimuth interval of 5 degrees.

3 Results

3.1 Distribution of lineaments and faults

Detailed analysis of the digital elevation model allowed us to detect lineaments that were categorized into four groups, i.e., lineaments related to 1) nappes structures, 2) strike-slip faults, 3) dip-slip faults, and 4) lineaments in the Quaternary deposits (Figure 6). Lineaments related to nappes, sub-parallel to these regional tectonic structures, show a relatively uniform distribution in the mountainous areas of the central and southern part of the studied catchment (Figure 6B). Their spatial orientation varies insignificantly ranging from WSW-ENE to SW-NE (Figure 6B), perpendicularly to the orientation of normal faults (see Figures 5B and 6B). These are generally relatively short features, usually not exceeding 5 km. Straight segments of river valleys are commonly developed parallel to lineaments related to nappes (Figure 7D). On the other hand, latitudinal lineaments that could be related to strike-slip faults are usually transverse or diagonal to hydrographic network, causing river deflections

### Table 1 Geomorphometric indices calculated for 47 catchments located within the study area.

| Index name       | Definition                                                                 | Equation                                                                 | Interpretation                                                                 |
|------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Relief ratio     | The ratio of maximal difference of height in the catchment to its length   | \[ R_\text{rel} = \frac{H_{\text{max}} - H_{\text{min}}}{L} \]             | High \( R_\text{rel} \) values indicate a high medium slope in a catchment and suggest a presence of high relative uplift (Różycka and Migoń 2017) |
| Circulatory ratio| Compares the area of a catchment with an area of a circle, which has a perimeter equal to a perimeter of the catchment (Miller 1953) | \[ R_c = \frac{4\pi A}{P^2} \]                                           | High \( R_c \) values suggest the more circular shape of a catchment, i.e. shapes similar to circle occur in tectonically stable areas (Miller 1953) |
| Elongation ratio | The ratio of a diameter of a circle, which area is equal to an area of a catchment, to the maximal length of a catchment (Eagleson 1970) | \[ R_e = \frac{\sqrt{A}}{L} \]                                           | \( R_e \) values vary from 0 to 1. Values close to 0 indicate highly elongated catchment suggesting increased tectonic activity (Bull and McFadden 1977) |
| Hypsometric integral | The ratio of a difference between medium and minimal height to the difference of minimal and maximal height in a catchment (Pike and Wilson 1971) | \[ HI = \frac{H_{\text{avg}} - H_{\text{min}}}{H_{\text{max}} - H_{\text{min}}} \] | The higher \( HI \) values, the higher intensity of ongoing erosional processes in the catchment. High \( HI \) values occur mainly in tectonically active areas (Panek 2004) |
or offsets (Figures 6D and 7B). Lineaments related to dip-slip faults were defined based on the triangular facets distribution, i.e. limiting the Żywiec Basin (Figures 2B, 6E, and 7C). The last group of lineaments was distinguished based on the youngest deposits (i.e., Quaternary river terraces), which these features crosscut. These predominantly longitudinal features were observed in basins in the central part of the Sola catchment and foothills located in the northern section (Figure 6C). Their spatial orientation shows a clear correlation with the river network in the Żywiec Basin and mountain foothills (Figures 3A and 6C). It also corresponds to thrusts, and reverse faults, which might suggest that these structures could have been reactivated in the Quaternary (Figures 5 and 6C).

3.2 Geomorphometric indices for catchments

The selected 47 sub-catchments within the study area (Figure 8) present high variability in values of their geomorphometric parameters (see Tables 2 and 3). The smallest sub-catchments cover an area of < 5 km² (Pisarzówka – 3.44, Przyborowiec – 3.51, Trzebinka – 4.52, Mał Puszcza – 4.9), whereas, the largest > 50 km² (Łękawka – 55.2, Żylica – 52.95) (Table 2). The average area equals 18.9 km² (Table 3). The elevation changes significantly from < 300 m a.s.l. (Żarnówka Mała, Domaczka) to > 1500 m a.s.l. (Glinne), with an average of 660 m a.s.l. (Tables 2 and 3).

Values of relief ratio (R_h) vary in a range between 41.72 and 167.7 m, with an average of c. 90 m (see Tables 4 and 5). Most of the studied catchments (> 30) show a moderate or low relief ratio, i.e., <100 m. The highest values were computed for relatively small catchments located adjacent to the Sola Gorge (Żarnówka Mała – 167.70, Mał Puszcza – 148.35), and the ones in highly elevated mountain ranges (Glinne – 136.51,
Low values are observed in catchments located partially on mountain foothills (Pisarzówka – 57.37, Domaczka – 88.60), and in the area of the Żywiec Basin (Moszczanica – 47.55, Kalna – 56.93) (Table 4, Figures 8 and 9A). Also, catchments located in the NE (Łękawka – 44.86, Kocierzanka – 46.36), and SW (Slanica – 57.14, Rycerski Potok – 62.95) parts of the study area show low values of this ratio (Table 4, Figs. 8 and 9A). It appears to be related to both, relatively low values of maximum height in each catchment, and their high length.

Circulatory ratio ($R_k$) values calculated for 47 sub-catchments in the study area vary moderately from 0.19 to 0.46 (see Tables 4 and 5), suggesting predominance of non-circular shapes of these features. The highest values of this ratio associated with catchments of nearly circular shape are located in the surrounding of the Sola Gorge (Żarnówka Duża – 0.45, Roztoka – 0.41), and in the central-eastern and central-western (Glinne – 0.4, Bystra I – 0.4) parts of the study area, whereas these with the lowest $R_k$ values occupy an area adjacent to the Żywiec Basin (Leśnianka – 0.23, Przybęźda – 0.20) (Table 4, Figures 8 and 9B).

Elongation ratio ($R_e$) values for 47 studied catchments range between 0.4 and 0.94 (see Tables 4 and 5). The highest values are observed in catchments located in the NW (Wieśnić – 0.94), SW (Niedłedwianka – 0.84, Rycerski Potok – 0.73), and E (Pewlica – 0.76, Łękawka – 0.73) parts of the Sola River catchment, as well as in the area adjacent to the Sola Gorge (Isepnica – 0.74, Mała Puszcza – 0.71) (Table 4, Figures 8 and 9C). The lowest $R_e$ values occur in catchments partially located within the Żywiec Basin and foothills.

Figure 7 Relations between hydrographic network, lineaments, and faults: A – location of detailed maps shown in Figure 7B-D; B – river deflections probably related to a strike-slip fault; C – faceted spurs at the border of mountain massif related to normal faults; D – straight segment of rivers developed parallel to lineaments related to nappe structures.
The occurrence of the highest values of the hypsometric integral (HI) range from 0.2 to 0.51 (see Tables 4 and 5), with most catchments placed within a narrow range of 0.35-0.45. The occurrence of the highest values of this index is associated with the presence of steep-
incised valleys (e.g., Żarnówka Mała – 0.51, Wielka Puszcza – 0.47), and highly elevated massifs, i.e., Skrzyczne Massif (Leśnianka – 0.47), Romanka Massif (Sopotnia Wielka – 0.5), Muńceł Massif (Danielka – 0.46) (Table 4, Figures 8 and 9D). Relatively high values are noted also for catchments located in the W, S, and SE parts of the Sola River catchment (Bystra I – 0.41, Rycerki – 0.44, Przyborowiec – 0.40) (Table 4, Figures 8 and 9D). The lowest HI values are usually computed for areas of low elevation (e.g., Pisarzówka – 0.24, Moszczanica– 0.23, Łękawka– 0.3, Janoszka– 0.32) (Table 4, Figures 8 and 9D).

3.3 Longitudinal profiles, stream length-gradient index and knickpoints

Most of the longitudinal river profiles generated for rivers with catchment areas > 15 km² presents close to equilibrium concave shape (e.g., Janoszka, Pisarzówka, Sopotnia Wielka) (Figure 10). Similar concave pattern, with well-marked knickpoints, is also demonstrated in the Sola and Kozarawa profiles, i.e., the main river and its principal longest tributary (Figure 10). Generally, the shortest rivers show the largest disturbances of profile concavity (e.g., Bystra III, Glinka, Pewlica), however, some larger rivers also present transient profiles (e.g., Kocierzanka, Czerna) (Figures 8 and 10).

Stream length-gradient index values vary between 140 and 250 for rivers flowing through areas of relatively low local relief (e.g., Czerna, Słanica), and reach up to 450-500 for rivers draining the highly elevated areas (e.g., Ryderski Potok, Sopotnia Wielka, Glinne) (Figure 10). The highest SL values obtained for Koszara (1000) and Sola (6000) rivers are probably related to the significant length of these two rivers. In general, high SL values correspond well with considerable breaks in river longitudinal profiles, corroborating their location. In total 53 knickpoints were identified along the Sola River and its 24 main tributaries, based on the river longitudinal profiles and variations in SL index (Figure 11). The number of distinguished knickpoints varies from 0 (Kalonka and Pisarzówka) to 5 (Glinka) (Figure 10). Detected knickpoints appear to cluster in two main elevation ranges: 1) 570 – 620 m a.s.l. (15 knickpoints), and 2) 620 – 670 m a.s.l. (7 knickpoints) (Figure 11A). 4 knickpoints located in the S and W part of the

| Table 4 | Values of four geomorphometric indices calculated for 47 sub-catchments (for location see Figure 8). |
|---------|------------------------------------------------------------------------------------------|
| No      | Name of the catchment |
|---------|------------------------|
| 1       | Pisarzówka             |
| 2       | Żarnówka Mała          |
| 3       | Żarnówka Duża          |
| 4       | Ponikiew               |
| 5       | Roztoka                |
| 6       | Wiśnik                 |
| 7       | Żylica                 |
| 8       | Kalonka                |
| 9       | Kalna                  |
| 10      | Leśnianka              |
| 11      | Wieńnik               |
| 12      | Przybężda              |
| 13      | Bystra I               |
| 14      | Janoszka               |
| 15      | Nieledwianka           |
| 16      | Czerna                 |
| 17      | Słanica                |
| 18      | Ryderski Potok         |
| 19      | Ryderski               |
| 20      | Danielka               |
| 21      | Cicha                  |
| 22      | Glinka                 |
| 23      | Bystra II              |
| 24      | Nickulina              |
| 25      | Salamonka              |
| 26      | Zabnicka               |
| 27      | Ciężkina               |
| 28      | Juszczynka             |
| 29      | Trzebiniec             |
| 30      | Przyłęckowka           |
| 31      | Sopotnia Mała          |
| 32      | Sopotnia Wielka        |
| 33      | Glinne                 |
| 34      | Krzyżówka              |
| 35      | Przyborowiec           |
| 36      | Przybyłka              |
| 37      | Bystra III             |
| 38      | Górna Koszarawa        |
| 39      | Pewlica                |
| 40      | Ryderski II            |
| 41      | Moszczanica            |
| 42      | Łękawka                |
| 43      | Kocierzanka            |
| 44      | Isepinka               |
| 45      | Mała Puszcza           |
| 46      | Wielka Puszcza         |
| 47      | Domaczka               |

| Table 5 | Statistical characteristics of geomorphometric indices calculated for 47 sub-catchments in the Sola River catchment. |
|---------|--------------------------------------------------------------------------------------------------------------------------|
| Statistical characteristics | Rₘ | Rₖ | Rₑ | HI |
| Minimum | 41.72 | 0.19 | 0.40 | 0.20 |
| Maximum | 167.7 | 0.46 | 0.94 | 0.51 |
| Average | 89.11 | 0.34 | 0.65 | 0.39 |

**Note:** relief ratio (Rₘ), circularity ratio (Rₖ), elongation ratio (Rₑ), and hypsometric integral (HI).
Figure 9 Spatial variation in values of relief ratio (A), circulatory ratio (B), elongation ratio (C), and hypsometric integral (D) calculated for 47 sub-catchments within the Sola River catchment.
Figure 10 Longitudinal profiles of the Sola River and its longest tributary – Koszarawa River, as well as the other 24 main tributaries with area > 15 km². Numbering as in Figure 8, and Tables 2 and 4. (-To be continued-)
study area occur on the contact of resistant sandstones with more erodible shales (Figures 4 and 10A). A group of 18 knickpoints appears to be related to mass movement processes, as these are located adjacent to the landslide features reaching the valley floor (Figure 11A). Some of the knickpoints are associated with detected faults network, i.e., 12 knickpoints situated < 200 m to the nearest transverse or diagonal fault zone (e.g., Rycerski Potok, Glinka, Wielka Puszcza; Figure 11B). However, in most of the cases, the distance between knickpoint and the nearest fault exceeds 500 m (Figure 11B). Two knickpoints located in the central part of the Sola River course refer to man-made water reservoirs and dams (Figures 10 and 11).

### 3.4 Minimum bulk erosion

Values of minimum bulk erosion calculated for the Sola River catchment vary significantly from 0 m on mountain ranges bordering the catchment limits to >500 m in two areas characterized by a deeply incised principal river valley, i.e., 1) to the

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**Figure 10** Longitudinal profiles of the Sola River and its longest tributary – Koszarawa River, as well as the other 24 main tributaries with area > 15 km². Numbering as in Figure 8, and Tables 2 and 4.

**Figure 11** Spatial distribution of detected knickpoints in the Sola River catchment; A – knickpoints classified according to their elevation a.s.l.; B – knickpoints categorized based on their distance to the adjacent faults.
south of the Żywiec Basin, where the Sola River flows between highly elevated massifs of Beskid Śląski and Beskid Żywiecki Mts., and 2) the Sola Gorge, to the north of the Żywiec Basin (Figure 12A). Recorded low values (< 100 m) mainly refer to the ridges and areas with low relative relief like basins and foothills, especially in the NW part of the Żywiec Basin and in the northern section of the study area (Figure 12A). In general, high values of this index are associated with deeply incised valleys bordered by high mountain ridges, while low values relate to wide, flat valleys surrounded by low ridges.

The minimum bulk erosion calculated for each of the 47 sub-catchments separately shows high values for catchments with rivers flowing in SW-NE direction (Sopotnia Wielka ~ 460, Żylica ~ 400, Leśnianka ~ 350), and in places of river confluences (e.g., in Rycerski Potok, Glimne, Bystra II catchments) (Figures 8 and 12B). Low values, on the other hand, refers to wide valleys (e.g., Czerna, Pewlica), those surrounded by low ridges (e.g., Janoszka, Górska Koszarawa) and the smallest sub-catchments, as these present the lowest local relief (Roztoka ~ 200, Nieledwianka ~ 250) (Figures 8 and 12B).

4 Discussion

4.1 Passive tectonic control on the relief development

Results of our landscape analysis, including lineaments and faults detection and their spatial distribution analysis, together with geomorphometric and hydrographic network analysis, show the importance of inherited tectonic structures in relief development of the Sola River catchment. The main principle direction of river flow, i.e., towards the NNE, in general, follows the topographic gradient
of the Beskidy Mts. (Figure 3A). However, in some areas deviations from this general trend can be observed, especially in the southern and northern parts of the study area, caused by the influence of fault structures (Figures 5B and C). These are usually normal or reverse faults, with occasional strike-slip structures. Large valleys commonly coincide with the traces of NW-striking normal faults (Figures 5B and 7D). Similarly-oriented fault structures were observed also bordering large depressions and basins, i.e., Żywiec Basin (Figures 2B, 5B, and 7C). The predominant direction of fault and lineaments structures related to nappes (i.e., WSW- to SW-striking; Figures 5C and 6B) corresponds with the trace of fold structures (Oszczypko et al. 2008; Ryłko and Paul 2013; Figure 5D) and is commonly used by the Sola River tributaries (Figures 3A and 7D). Most of the mountain ridges and lineaments in this area also follow this principle structural direction (Figures 1D and 6). The location of the intra-mountainous depressions and basins is often conditioned by the presence of narrow nappe zones developed as strongly disrupted tectonic mélanges, with significant susceptibility to erosional processes, i.e., the mélangé outcrops of Grybów and Dukla Nappes (Figures 1C and 4B; see also Oszczypko 2004; Jankowski and Margielewski 2014).

4.2 Geomorphometric indices

Values of geomorphometric indices, i.e., relief ratio, circulatory ratio, elongation ratio, and hypsometric integral, calculated for 47 sub-catchments show the significant variety, which does not correlate with changes in lithology or climate variations (Table 4, and Figures 3B, 4B and 9). According to obtained values, the most elongated catchments with significant variability in local relief are located in the southern and eastern part of the study area (within the Beskid Żywiecki Mts.) and to the north of the Żywiec Basin, adjacent to the Sola Gorge (Figure 9). Previous studies proved that such catchments are indicative of high relative uplift rates (Table S1; e.g., Miller 1953; Bull and McFadden 1977; Schumm et al. 2000; Burbank and Anderson 2001; Keller and Pinter 2002; Ruszkiczay-Rüdiger et al. 2009; Pérez-Peña et al., 2010; Giaconia et al. 2012; Matoš et al. 2013; Różycka and Migoń, 2017; Gaidzik and Ramirez-Herrera 2017; Ramirez-Herrera et al. 2018), also in areas of low tectonic activity (e.g., Badura et al. 2003; Pánek 2004; Wołosiewicz 2018). For example, landscape analysis using similar geomorphometric indices suggested tectonic activity along the Sudetic Marginal Fault in the Sudetes (Badura et al. 2003). This conclusion was later corroborated by paleoseismological trenching (Štěpančíková et al. 2010), and geophysical studies (Štěpančíková et al. 2011). Moreover, detected areas of high relative rock uplift correspond to axes of neotectonic elevations delineated by Zuchiewicz (1998).

Spatial variations in the minimum bulk erosion in the Sola River catchment does not appear to be related to changes in lithological and climatic conditions (Figures 3B, 4B, and 12). Differences in lithology between areas of high and low values of minimum bulk erosion are not significant (compare Figures 4B and 12A). These variations are usually local and include only changes in proportions between sandstones and shales that cannot explain observed anomalies in this index. Also variations in climatic conditions are inconsiderable as the climate of the entire study area is similar and is conditioned mainly by the elevation a.s.l. Areas with high and low values of mean annual precipitation do not correlate with areas of maximum and minimum values of minimum bulk erosion (Figures 3B and 12A). A similar lack of correlation between lithology, climate, and minimum bulk erosion values was observed by Giaconia et al. (2012), and by Gaidzik and Ramirez-Herrera (2017). Thus, recorded variations in the minimum bulk erosion may reflect changes in relative rock uplift. Both areas of high erosion, i.e., high relative rock uplift, 1) to the south of the Żywiec Basin, with deeply incised Sola River valley between highly elevated massifs of Beskid Śląski Mts. and Beskid Żywiecki Mts., and 2) the Sola Gorge, to the north of the Żywiec Basin (Figures 2A and 12A) correlate with mentioned earlier areas distinguished based on relief ratio, circulatory ratio, elongation ratio, and hypsometric integral, as well as zones of anomalous values of river channel gradient (Zuchiewicz 1998).

4.3 Knickpoints and longitudinal profiles

The majority of the analyzed river longitudinal
profiles show shape similar to the line of equilibrium (Figure 10), suggesting recent relative stability of the Soła River catchment and corroborate low tectonic activity in this area. Transient long profiles obtained for short rivers can be related to the low intensity of the erosive force of this type of rivers (Schumm et al. 2000). Observed breaks in long profile lines could be related to local acceleration in tectonic activity (an active crustal fault with long recurrence period), as well as local variations in lithologic or climatic conditions (e.g., Schumm et al. 2000; Kirby and Whipple 2012; Gaidzik and Ramírez-Herrera 2017; Ramírez-Herrera et al. 2018).

We distinguished 53 knickpoints along the Soła River and its 24 main tributaries that reflect the interactions between lithologic, climatic, and tectonic factors (Figure 11). About half of them are located <500 m from the nearest fault, and c. 80% if we include also interpreted lineament pattern, suggesting their possible relation to the stated fault network (Figure 11B). Especially the development of 12 knickpoints located < 200 m to the nearest fault could be associated with their presence, either as passive or active control (e.g., Giaconia et al. 2012; Gaidzik and Ramírez-Herrera 2017). Moreover, these knickpoints occur mainly in the Beskid Żywiecki Mts. and adjacent to the Soła Gorge (Figure 11B), thus areas with higher relative tectonic activity based on previously presented geomorphometric indices. Knickpoints clustering at a similar elevation a.s.l. might have been produced by changes in the base-level of the entire Soła River catchment that could be related to climatic or tectonic factors. However, in areas of low tectonic strain, considerable variations in base-level caused by tectonic activity are not likely. On the other hand, climatically driven changes in base-level took place a few times during the Quaternary as a result of the ice cap migration in the northern part of the study area during glacial/interglacial cycles (Marks 2011). Such changes in base-level can be transmitted to the river profiles of the main river and its tributaries resulting in a set of knickpoints at comparable elevations (e.g., Kirby and Whipple 2012; Gaidzik and Ramírez-Herrera 2017). Using the spatial distribution of recorded knickpoints, river longitudinal profiles, and SL values, we identified one transient wave (15 knickpoints at elevations ranging between 570 and 620 m a.s.l.) of incision propagating through the system that could denote the occurrence of such an event related to this process (Figure 11A). The second group including only 7 knickpoints (620 – 670 m a.s.l.) is too small to make reliable conclusions on their nature using variations in a base-level (Figure 11A).

4.4. Potential neotectonic activity

We found a few examples of offset channels in the Soła River catchment (Figure 13) that in the areas of high tectonic activity are usually interpreted as the evidence of strike-slip fault displacements (e.g., Gaidzik et al. 2016; Reitman et al. 2019). Presented examples do not coincide with the variations in lithology, but in most of the cases, these also do not follow the recorded fault network. The offset channel in the central-eastern part of the study area, within the Glinne catchment, suggests the activity of the NW-trending sinistral strike-slip fault (Figure 13B). This area is built mainly of thick-bedded sandstones and conglomerates intercalated with shales and thin-bedded sandstones of the Magura Nappe. The other offset channel in the eastern part of the study area, within the Łękawka catchment, on the southern slopes of the Beskid Mały Mts., shows potential sub-latitudinal dextral strike-slip faults disturbing rivers flowing to the south (Figure 13C). Observed river deflections vary from < 50 m to > 300 m, which might implicate several stages of fault activity (e.g., Reitman et al. 2019). In the eastern part, the proposed structure follows the trace of a previously detected fault (Figure 13C). Shales, sandstones, and conglomerates of the Silesian Nappe occur in the N and build the mountain ridges (700 – 850 m a.s.l.), while sandstones and shales of the Dukla Nappe are present in the S and form the bottom of the Łękawka Valley (500 – 600 m a.s.l.). The trace of the proposed potentially active structure does not coincide with the contact of these two units. However, further studies, especially paleoseismological, are needed to confirm the Quaternary activity of these faults.

4.5 Factors controlling relief development in the Soła River catchment

The intensity of processes causing long-term...
changes in relief is controlled mainly by climatic, topographic, lithologic, and tectonic factors (e.g., Schumm et al. 2000). Observed variations in values of calculated geomorphometric indices can be the result of each of these factors or their combination.

Spatial variability of climate in the Sola River catchment is conditioned primarily by the topographic factor (i.e., elevation a.s.l.; Figure 3B). The climatic changeability of the study area fits within one climatic zone (Wypych et al. 2018). Climate could influence the relief development mainly during short-term extreme events (i.e., torrential rainfalls) (Łajczak et al. 2014) and long-term events (i.e., temperature fluctuations between glacial and interglacial periods) (Marks 2011; Starkel 2017). It is likely that the cluster of 15 knickpoints at elevation range 570-620 m a.s.l. is related to such event and the resulting drop of regional base-level, which led to the transient wave of incision propagating through the system (Figure 11B). Torrential rainfalls, on the other hand, could trigger mass movement processes leading to valley damming and consequently producing knickpoints. However, other presented anomalies do not seem to be related to climate variations.

Landscape analysis reveals that the relief of the Sola River catchment is partially also controlled by lithology, i.e., rock resistance (Wójcik et al. 2006; Jankowski and Margielewski 2014). A nearly complete absence of crystalline rocks in the Sola River catchment causes a lack of significant differences in erosive vulnerability of rocks. Nevertheless, differences in resistance among sedimentary rocks can exert influence on relief development (Jankowski and Margielewski 2014). The most susceptible to destructive processes in the Sola River catchment are shales, whereas conglomerates are the most resistant (Oszczypko 2004; Oszczypko et al. 2008). For example, a highly elevated area of the Beskid Śląski Mts. (Figure 1C) built predominantly from sandstones and conglomerates (Figure 4B) shows a lack of dense fault network (Figure 5) and generally low values of the minimum bulk erosion (Figure 12A). The Łękawka catchment (Table 1 and Figure 8), on the other hand, with a predominance of shales and sandstones (Figure 4B), is located in the intra-mountainous depression with dense fault network (Figures 5 and 7B). Lithological differences can
explain the formation of some of the recorded knickpoints (Figure 11A), but not the observed anomalies in other geomorphometric indices, especially the minimum bulk erosion.

Thus, the processes of relief development in the Sola catchment appear to be primarily controlled by inherited tectonic structures and processes. We found evidence for the significant influence of tectonic structures (i.e., nappes, thrusts and faults, folds) on the development of river network, spatial distribution, and directions of mountain ranges, location of intra-mountain basins, etc. Currently, tectonic activity does not play a dominant role in the shaping of the relief in the Sola River catchment; nevertheless, its presence should not be excluded. Recorded anomalies in values of calculated geomorphometric indices suggest variations in rock uplift rates. Observed channel offsets imply the possibility of the existence of active strike-slip faults. The Late Neogene and Quaternary fault activity in the low mountains of moderate relief of the Carpathians was corroborated by the presence of fractured clasts (Tokarski and Świerczewska 2005; Tokarski et al. 2007, 2016; Zuchiewicz et al. 2011). The recent tectonic activity was also suggested based on the analysis of river longitudinal profiles and drainage anomalies (Zuchiewicz 1998; Zuchiewicz et al. 2002, 2009; Placzkowska 2014), the analysis of river terraces (Olszak 2011), paleomagnetism (Tokarski et al. 2016) and the analysis of Neogene and Quaternary gravels (Tokarski et al. 2012). Even seismic activity, although generally of small magnitude and with long return periods, has been proven by instrumental and historical records (Guterch 2009; Plesiewicz and Wiszniewski 2015).

Spatial variations in relative rock uplift rates within the Sola catchment constrained by our landscape analysis result from the current stress field within the nappes of the Outer Carpathians and the autochthonous basement produced by the tectonic push of the Alcapa (Alpine-Carpathian-Pannonian) microplate exerted on the topof the underthrust European plate (Jarosiński 1998). This tectonic push causes compressive reactivation of the Carpathians leading to the NNE-oriented maximum horizontal stress ($S_{\text{Hmax}}$) in the nappes of the Western Outer Carpathians (Jarosiński 1998, 2005, 2006; Fig. 4A), while the basement undergoes extension (Jarosiński 1998, 2006). The relative movement between these two plates in the western part is accommodated along the NE-striking active Mur-Žilina Fault Zone with an average sinistral displacement rate of 0.3 mm/yr, as constrained by geodetic measurements and by earthquake focal mechanism data (Aric 1981; Tomek 1988; Figure 4A). The kinematics of proposed possible active strike-slip faults (Fig. 13) does not seem to correspond with the NNE-SSW direction of the maximum horizontal stress ($S_{\text{Hmax}}$) constrained by breakthrough measurements (Figure 4A). However, the activity of these structures, together with the interpreted WNW- to NW-striking normal faults constrained by triangular facets (Figures 2B, 6E, and 7C) could be related to NE-SW directed extension proposed for the autochthonous basement and the western block of the Mur-Žilina Fault Zone (Jarosiński 1998, 2005, 2006; Figure 4A). Similarly oriented local-scale normal faults, commonly interpreted as the Tertiary structures reactivated in the Quaternary, have been reported in other areas of the Outer Carpathians (e.g., Tokarski 1978; Oszczypko 1979; Zuchiewicz et al. 2011). Thus, suspected faults constrained in this study by the landscape analysis could be produced in the nappe pile or be reactivated basement structures, copied in the thin-skinned nappe cover. Either produced or reactivated, these strike-slip faults, are probably the result of the accommodation of the Mur-Žilina Fault Zone.

Potential tectonic activity in this area suggested by our landscape analysis and corroborated by other studies for different areas in the Outer Carpathians (e.g., Zuchiewicz 1998; Zuchiewicz et al. 2002, 2009, 2011; Tokarski and Świerczewska 2005; Tokarski et al. 2007, 2012, 2016; Guterch 2009; Olszak 2011; Placzkowska 2014; Plesiewicz and Wiszniewski 2015) might have important implications for the geohazard estimations. Polish Outer Carpathians are prone to landslides due to lithological setting (Oszczypko 2004). Mass movements here are controlled by structural settings (Margielewski 2006) and can be triggered by heavy rainfall or tectonic activity (Wistuba et al. 2018). As demonstrated, even low magnitude earthquakes can lead to the formation of a landslide (Keefer 1984; Wolter et al. 2016). Hence, the determination of areas with potentially increased tectonic activity can improve efficiency in...
estimations of geohazard related to mass movement processes.

5 Conclusions

1) Landscape analysis using digital elevation models and GIS techniques facilitates the assessment of the influence of tectonic structures on relief development and provides the estimation of relative tectonic activity in a given area.

2) Inherited tectonic structures play a significant role in the relief development of the Sola River catchment, i.e., directions of principal ridges and valleys follow the orientation of main folds and faults recorded in this area.

3) The areas with potentially higher relative tectonic uplift include the Sola Gorge and the Beskid Żywiecki Mts., as corroborated by anomalously high values of the minimum bulk erosion, river gradient, and stream-length gradient index, relief ratio, circulatory ratio, elongation ratio, and hypsometric integral.

4) The role of recent tectonic activity in relief development of the Sola River catchment appears to be subsidiary at the most.

5) Observed bends in the river valleys direction that do not correspond with changes in lithology could be related to active strike-slip faults.

6) Suspected faults constrained by the landscape analysis are probably the reactivated basement structures, copied in the thin-skinned nappe cover, as a result of the accommodation of the Mur-Žilina Fault Zone.

7) Spatial variations in relative rock uplift rates within the Sola catchment result from the current stress field within the nappes of the Outer Carpathians and the autochthonous basement produced by the tectonic push of the Alcapa (Alpine-Carpathian-Pannonian) microplate against the European plate.

8) Further studies using geophysical and paleoseismological methods, together with geochronological dating are needed to confirm the actual impact of the Quaternary tectonic activity (especially active faults) on relief development in the study area.

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