STRUCTURAL CONTROL OF DRAINAGE IN THE UPPER PART OF THE LUDA YANA RIVER BASIN, BULGARIA

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Abstract. Drainage pattern is influenced by the underlying surface and tectonic features of the territory. Lithology and tectonics are major controls of stream network and drainage. This study is motivated by the need to investigate the influence of lithological and tectonic factors on the formation and development of drainage networks, with the goal of advancing structural-geomorphological research in Bulgaria and exploring its applicability in risk assessment. The Panagyurska and Strelchanska Luda Yana drainage basins are the objects of study, and the analysis focuses on the drainage network density. The water permeability and erodibility of various rock types and lithological formations were also studied. Fault density and drainage pattern were also determined for the study area. Results confirmed that unconsolidated sediments contribute to higher drainage density. Sedimentary rocks tend to result in relatively high drainage density values, while volcano-sedimentary rocks exhibit both high and low drainage density, depending on specific lithological and topographic factors. Intrusive igneous rocks are associated with a relatively high drainage density, greater than that of migmatized rocks. The density of 1st order streams in volcano-sedimentary rocks further supports the conclusion that, in the development of the drainage network, both lithological properties and topographic factors are significant. The Panagyurska Luda Yana basin exhibits a higher fault density, while the Strelchanska Luda Yana basin shows a lower fault density. In both basins, the rectangular drainage pattern prevails in the middle course, while the annular pattern is prevalent in the upper course, with parallel patterns occurring predominantly in areas of sedimentary and volcano-sedimentary rocks. The findings provide a basis for further research, particularly into the weathering resistance of rocks, and contribute to the development of hydrogeological and hydro-climatic analyses of the studied area. The results also have practical value for regional and local authorities in developing strategies to prevent risk events and implement effective measures to mitigate their impact.

1. INTRODUCTION

The drainage network of a given basin is shaped by a complex interplay of tectonic, lithological, topographic, geomorphological, hydrological, climatic, soil, vegetation and anthropogenic factors. Among these, the drainage pattern and the type of the drainage network are predominantly influenced by the underlying surface and the tectonic features of the territory. Geology is the dominant control of stream network structure and should therefore play a central part in the analysis (Blöschl & Sivapalan,

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1995). Tectonics and lithology are among the major controls of drainage network development (Sockness & Gran, 2022). Several factors contribute to the formation and development of the drainage network, which can be examined from four key perspectives: 1) water permeability – the degree to which different rock types and lithological formations allow water to pass through; 2) erosion resistance (erodibility) – the ability of various rock types to withstand erosion; 3) topographic conditions – factors such as altitude, slope angle, and exposure; and 4) tectonic processes – the influence of tectonic activity and the resulting tectonic structures, particularly the characteristics of faults.

Of particular importance for the water permeability of rocks are fractures. The fracture intersections and lineaments are reflected in the morphology of the land surface (Freeze & Cherry, 1979), which subsequently affects the formation and development of the drainage network and the distribution of surface runoff. Water permeability plays a critical role in determining water infiltration rates and the characteristics of surface runoff. Bedrock permeability influences surface and subsurface flow, so that less permeable rock types are commonly associated with higher drainage densities (Gregory & Gardiner, 1975; Walsh, 1985; Knighton, 2014).

Erodibility, on the other hand, is directly linked to the destruction of rocks and the conditions that influence the formation and development of the drainage network. At the same time, erodibility is indirectly dependent upon susceptibility to weathering as well as susceptibility to removal and transportation, and describes a rate of action which can be related to the development of specific landforms (Leopold *et al.*, 1995), including fluvial ones.

The analysis of the tectonic control on drainage network geometry is of particular importance (Belisario *et al.*, 1999). Tectonic forces are factors for in-time channel changes and affect river systems through differential changes in gradient (Leopold *et al.*, 1995). For instance, the patterns of drainage network growth depend on tectonics (Tucker & Whipple, 2002; Castelltort & Simpson, 2006).

The following study focuses on two mountainous drainage basins and their corresponding stream network, located in Central Bulgaria. The geomorphological, lithological and tectonic conditions in the drainage basins of the Panagyurska Luda Yana River and the Strelchanska Luda Yana River and their role in the formation and development of the drainage network are outlined and discussed. The primary aim of this research is to examine the relationship between key morphometric features of the relief (such as drainage density and drainage density of 1st order streams) and the lithological and tectonic characteristics of the studied basins.

2. STUDY AREA

The chosen drainage basins of the Panagyurska Luda Yana and the Strelchanska Luda Yana belong to the larger Luda Yana River basin (Fig. 1). The two sub-basins are characterized by various lithological conditions and tectonic processes, providing valuable insights for analysing the mountainous drainage network. The third sub-basin of the Luda Yana drainage basin – that of the Banska Luda Yana River – is not included in this study due to significant anthropogenic impacts.

The areas of the Panagyurska Luda Yana River and the Strelchanska Luda Yana River are nearly identical – 172.8 km² for the Panagyurska Luda Yana and 173.04 km² for the Strelchanska Luda Yana. These basins are situated in the mountainous part of the Luda Yana River basin, within the Sashtinska Sredna Gora Mountain, which is part of the Srednogorie morphostructure zone (Kanev, 1990). Bozhkov (2022) conducted a study on the drainage basins on the northeastern slopes of Sashtinska Sredna Gora Mountain. The highest point in the Panagyurska Luda Yana basin is at 1511 m, while its lowest point is at 382 m. In the Strelchanska Luda Yana basin, the highest point reaches 1604 m, where the peak of Sashtinska Sredna Gora – Bogdan – is located, and the lowest point is at 331 m.

Fig. 1 – Map of the studied area.

The studied territory of Sashtinska Sredna Gora Mountain is occupied by the Srednogorski (in the northern part) and Panagyurski (in the southern part) anticlinoria. Subparallel fault structures are presented – the South Srednogorski fault, as well as submeridional ones – the Medetski fault (Kanev, 1990).

The majority of the drainage basin areas are occupied by intrusive igneous rock group (Fig. 3). The southern parts of the basins are occupied by volcano-sedimentary and sedimentary rocks, and the northern - partly by migmatized rocks (Iliev, Katskov, 1990).

The Panagyurska and Strelchanska valleys have formed along the rivers of Panagyurska Luda Yana and Strelchanska Luda Yana, respectively (Kanev, 1990).

The area of interest has a transitional continental climate (Velev, 2010), and the soils are Luvisols, Planosols, Cambisols and Umbrosols (Shishkov & Kolev, 2014).

3. DATA AND METHODOLOGY

The following data were used in this study:

• Shuttle Radar Topography Mission (SRTM 1 Arc-Second Global) Digital Elevation Model (DEM) (30 m), n42_e024_1arc_v3 (United States Geological Survey, Earth Resources Observation and Science Center, 2018);

• Geological map of Bulgaria (M 1:100 000), Map sheet Panagyurishte (Iliev, Katskov, 1990).

DEM was used to generate a hypsometric map of the two studied drainage basins, as well as the drainage network within them (Fig. 2). Based on the geological map, a lithological map of the studied drainage basins was generated (Fig. 3).

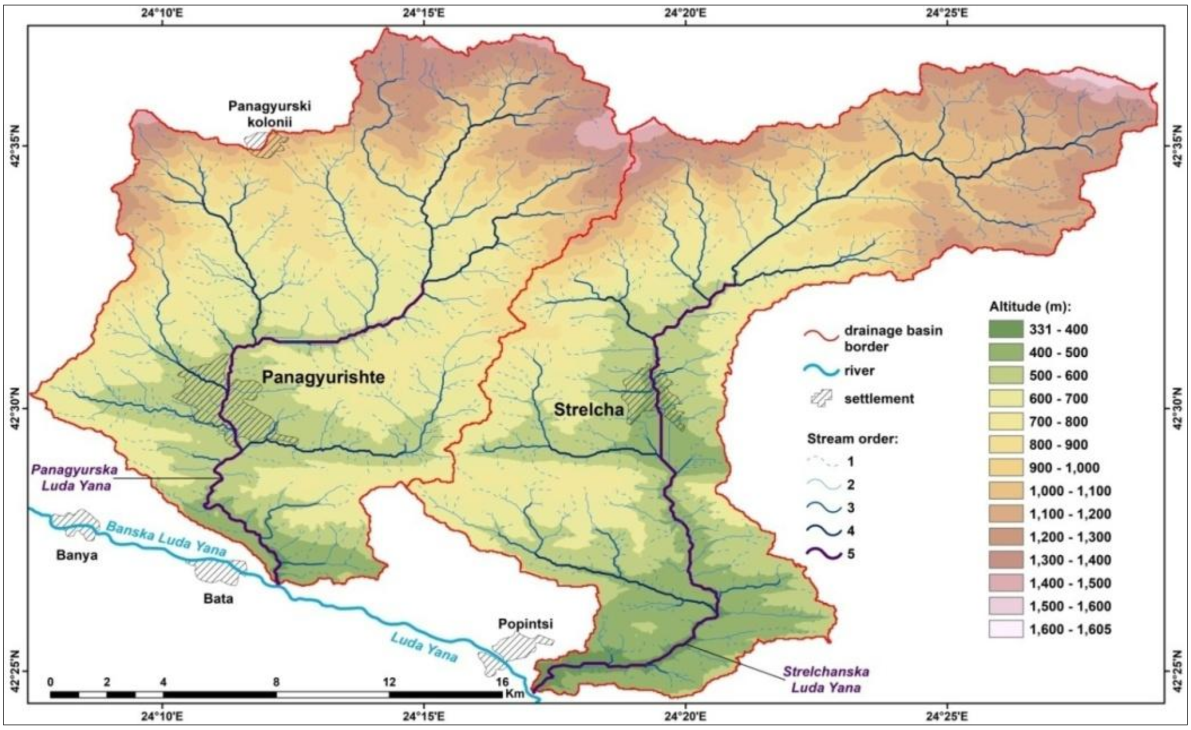

Fig. 2 – Hypsometric and stream ordering map of the studied drainage basins.

The drainage network for the two studied basins was generated in the GIS environment, using the approach developed by Tarboton *et al.* (1991). A morphometric analysis of the drainage basins and their networks was performed by calculating key parameters, including: Area (A), Drainage network length, and Drainage density (D_d). This analysis aimed to clarify the role of lithology in determining the drainage network density within the two studied basins.

For this purpose, the Drainage density (D_d) was calculated for each generalized rock group in the studied basins. Drainage density, as defined by Horton (1945), is the degree of drainage development within a basin and is calculated using the formula:

$$D_d = L_d / A \text{ (Horton, 1945)},$$

where L_d is the total drainage network length, and A is the area of the drainage basin.

Fault density was also calculated using the formula:

$$F_d = L_f / A,$$

where L_f is the length of fault lines within the drainage basin, and A is the area of the drainage basin.

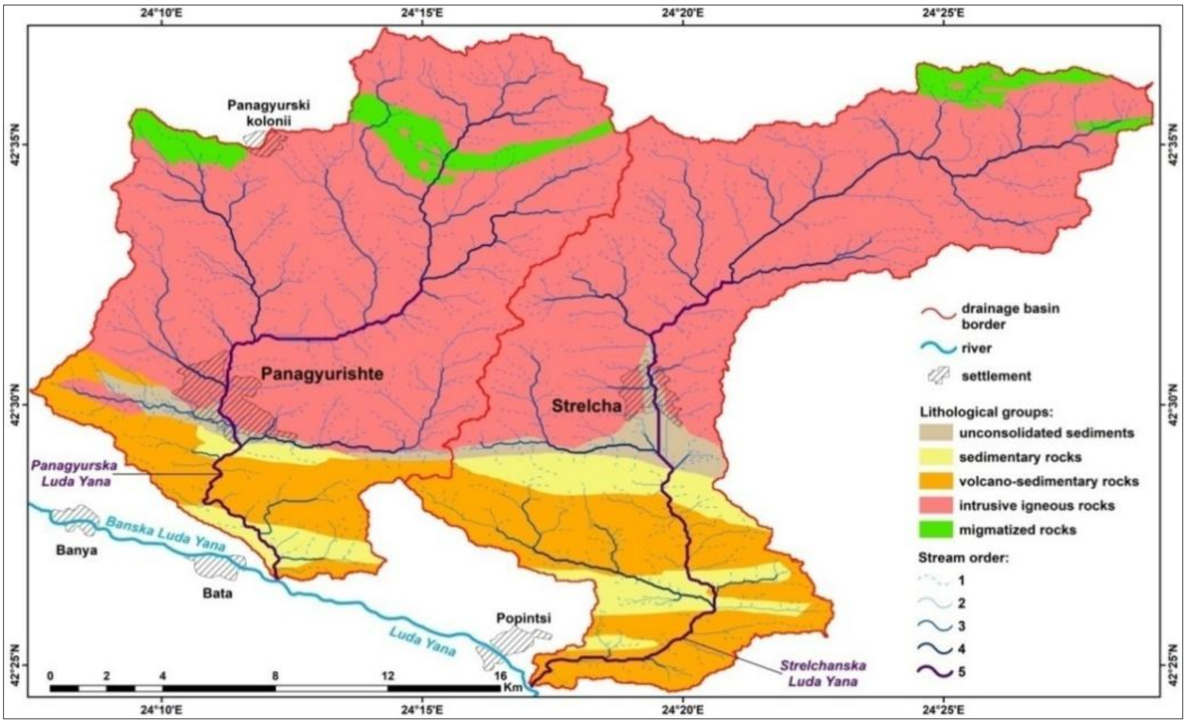

Fig. 3 – Lithological map of the studied drainage basins.

Additionally, drainage density was calculated for the 1st order streams. According to Zavoianu (1985), the first order is assigned to the smallest elongated depressions which have the capacity to organize runoff, have an elementary channel and receive no other tributary. Thus, the drainage density of 1st order streams serves as an indicator of the erodibility of the individual rock groups and plays a role in the formation and development of the drainage network.

The water permeability and erodibility of the individual rock types and lithological formations were analysed. For this analysis, data from scientific literature were used, along with average values of the erodibility index for various rock types and lithological formations, as presented in the study by Moosdorf *et al.* (2018).

The density of tectonic faults, including the length of all lineament features (such as normal faults, reverse faults and thrust faults), was calculated for the Panagyurska Luda Yana River and the Strelchanska Luda Yana River drainage basins. This calculation, known as Fault density, was then compared to the total fault density of the entire Luda Yana River drainage basin. The study primarily focuses on the role of tectonics in the formation and development of the drainage network within the two studied basins.

The rock types and formations were categorized based on their genesis and physical-mechanical properties. Five main rock groups were identified, as shown in Table 1.

Table 1

Rock types and formations and generalized rock groups

Rock types and formations	generalized rock group
Alluvial deposits	unconsolidated sediments
Conglomerate Formation	sedimentary rocks
Chugovo Formation (alternation of marl, clayey limestone and calcareous sandstone)	
Mirkovo Formation (clayey limestone)	

Table 1 (continued)

Rock types and formations	generalized rock group
Chelopech Formation (andesitic and agglomerate tuffs and tuffites with marl, argillite and clayey limestone layers)	volcano-sedimentary rocks
Chelopech Formation (propylites)	
coarse-grained leucocratic bi-mica granite (Strelcha pluton)	intrusive igneous rocks
gabbro-diorite to peridotite	
granodiorite, quartz-diorite, plagiogranite	
porphyritic granite and granodiorite	
uniform-grained leucocratic biotite granite (Karavelovo pluton)	
migmatized banded and augen gneiss, amphibolite, gneiss and gneiss-schist	migmatized rocks

4. RESULTS AND DISCUSSION

The unconsolidated sediments group includes deposits containing a mix of small boulders, gravel, sandy material and unsorted clayey material. According to Freeze & Cherry (1979), clay layers are considered low-permeable, while sand formations are high-permeable. The damage zone of highly porous sands adjacent to faults and shear bands is an area of enhanced permeability (Antonellini & Aydin, 1994; Zoback, 2007). In both studied drainage basins, particularly along the southern periphery, a fault zone passes through the unconsolidated sediments. This fault zone contributes to tectonic deformations within the deposits and is expected to increase their water permeability. However, the drainage density results indicate that the unconsolidated sediments group has the highest drainage density values in both basins. This can be attributed to two main reasons: the high clay content in these deposits and their high degree of erodibility. The high erodibility is evidenced by the erodibility index values for unconsolidated sediments (Moosdorf *et al.*, 2018), as well as by the highest drainage density values for the 1st order streams in both basins.

The sedimentary rock group includes consolidated sediments, such as conglomerates, marls, clayey limestones and calcareous sandstones. This group is characterized by relatively high drainage density values in both studied basins, although these values are notably lower compared to those of the unconsolidated sediments. This is due to the low erodibility of carbonate-rich sedimentary rocks (mainly limestone and dolomite) and mixed carbonate and siliciclastic sedimentary rocks (e.g., marl) (Moosdorf *et al.*, 2018). Siliciclastic sedimentary rocks, such as coarse-grained sandstones or conglomerates, exhibit higher erodibility (Moosdorf *et al.*, 2018), which increases the overall erodibility of the sedimentary rock group. In carbonate rocks, water permeability is influenced by several factors: 1) fractures or openings along bedding planes; 2) secondary openings in carbonate rock caused by changes in the stress conditions which may be enlarged as a result of calcite or dolomite dissolution due to circulating groundwater; 3) and in some carbonate rock lineations of concentrated vertical fractures providing zones of high permeability (Freeze & Cherry, 1979). For the conglomerates located in two strips south of the town of Strelcha, it is characteristic that the cement binding the rocks be sandy to clayey-sandy (Katskov, Iliev, 1993). When comparing the permeability of limestone and sandstone with values for other rock types proposed by Freeze & Cherry (1979), it can be concluded that limestone exhibits a moderate to low degree of permeability. In the studied drainage basins, a significant part of the limestone is clayey, further reducing its permeability. Consequently, the entire sedimentary rock group is characterized by a moderate to low degree of permeability. The drainage density values for the 1st order streams in both basins suggest that the erodibility of the sedimentary rock group is also moderate to low, compared to the other rock groups (Table 2).

The volcano-sedimentary rocks in the study area include andesitic and agglomeratic tuffs and tuffites, interbedded with marl, argillite and clayey limestone layers. These rocks exhibit higher drainage density values in the Strelchanska Luda Yana River drainage basin and lower values in the Panagyurska

Luda Yana River basin. These differences are mainly due to variations in the rock composition. For example, andesites have a slightly lower erodibility index than sandstones and conglomerates, but they are more erodible than limestones and marls (Moosdorf *et al.*, 2018). Therefore, the erodibility of this group of rocks in the two drainage basins – and, consequently, the drainage density – depends on the relative proportions of andesitic tuffs and tuffites compared to marls and limestones. Volcanic rocks generally differ from most other crystalline rocks in that they have primary features that cause permeability within the otherwise-solid rock mass (Freeze & Cherry, 1979). The permeability of volcanic rocks can change over time. For example, when magma extrudes to the ground surface and flows out as lava, the rocks that form on cooling are generally very permeable, but alteration by deep burial or by the influx of cementing fluids during geologic time causes the permeability to decrease (Freeze & Cherry, 1979). The presence of clayey limestone layers further reduces the permeability of the volcano-sedimentary rock group. Additionally, these rocks show the lowest drainage density for 1st order streams, suggesting that other factors - such as slope angle and slope length - affect the lengths of the 1st order streams, i.e., the lithological factor has predetermined the formation of 1st order streams, but smaller slope angles or the shorter length of the slopes predetermine the weaker potential for development and, respectively, the shorter length of the 1st order streams.

Table 2

Morphometric parameters of the drainage network and the generalized rock groups

Generalized rock group	Panagyurska Luda Yana River drainage basin				Strelchanska Luda Yana River drainage basin			
	area (km^2)	% of the basin area	drainage network length (km)	drainage density (D_d) (km/km^2)	area (km^2)	% of the basin area	drainage network length (km)	drainage density (D_d) (km/km^2)
unconsolidated sediments	4.1	2.37	total: 22.77 1st order: 11.23 2nd order: 4.64 3rd order: 3.81 4th order: 2.3 5th order: 0.79	total: 5.55 1st order: 2.74	7.38	4.26	total: 30.44 1st order: 13.04 2nd order: 5.73 3rd order: 3.79 4th order: 3.35 5th order: 4.53	total: 4.12 1st order: 1.77
sedimentary rocks	6.98	4.04	total: 17.89 1st order: 7.95 2nd order: 2.7 3rd order: 2.47 4th order: 0.14 5th order: 3.33	total: 2.56 1st order: 1.14	16.61	9.6	total: 35.66 1st order: 20.57 2nd order: 7.92 3rd order: 1.49 4th order: 2.81 5th order: 2.87	total: 2.15 1st order: 1.24
volcano-sedimentary rocks	21.81	12.62	total: 37.74 1st order: 21.51 2nd order: 10.04 3rd order: 2.48 4th order: - 5th order: 3.71	total: 1.73 1st order: 0.99	36.18	20.91	total: 83.43 1st order: 42.08 2nd order: 21.09 3rd order: 7.61 4th order: 2.81 5th order: 9.84	total: 2.31 1st order: 1.16
intrusive igneous rocks	130.53	75.54	total: 338.94 1st order: 184.64 2nd order: 79.64 3rd order: 44.16 4th order: 21.01 5th order: 9.49	total: 2.6 1st order: 1.41	108.38	62.63	total: 254.02 1st order: 141.8 2nd order: 57.1 3rd order: 32.15 4th order: 18.98 5th order: 3.99	total: 2.34 1st order: 1.31
migmatized rocks	9.38	5.43	total: 15.64 1st order: 10.11 2nd order: 3.22 3rd order: 1.26 4th order: 1.05 5th order: -	total: 1.67 1st order: 1.08	4.49	2.6	total: 8.27 1st order: 5.43 2nd order: 1.98 3rd order: 0.86 4th order: - 5th order: -	total: 1.84 1st order: 1.21

The intrusive igneous rocks (represented in the studied drainage basins by coarse-grained leucocratic bi-mica granites, gabbro-diorites to peridotites, granodiorites, quartz-diorites, plagiogranites, porphyritic granites, uniform-grained leucocratic biotite granites) and the migmatized rocks (represented in the studied drainage basins by migmatized banded and augen gneisses, amphibolites, gneisses and gneiss-schists) share similar permeability characteristics. The primary permeabilities of unfractured metamorphic rocks and plutonic igneous rocks are extremely small and these rocks are impermeable, but in some cases appreciable fracture permeability generally occurs caused by changes in the stress conditions that have taken place during various episodes in the geologic history of the rocks (Freeze & Cherry, 1979). The erodibility index values for granites and gneisses are similar, though gneisses have a slightly higher erodibility potential (Moosdorf *et al.*, 2018). Notably, in both the Panagyurska Luda Yana and Strelchanska Luda Yana River basins, the drainage density for intrusive igneous rocks is higher than for migmatized rocks. Additionally, the drainage density of 1st order streams is higher in the intrusive igneous rocks compared to that of the migmatized rocks. This may be due to the formation of secondary fractures in the migmatized rocks. The formation of surface runoff and subsequent development of the drainage network in this case could be influenced by the slope angle, as well as by the specifics of the soil and vegetation cover. The greater slope gradient is likely the reason for the greater drainage density of the 1st order stream for the intrusive igneous rocks, where the values of the indicator are even greater compared to the values for the sedimentary rocks in both studied drainage basins. Future studies could further refine and expand this analysis.

Different types of fault lines with various strike and dip directions cross the entire drainage basin. The Panagyurishte volcanogenic strip is formed mainly of Upper Cretaceous sedimentary, volcanogenic-sedimentary and magmatic rocks bounded by faults with a strike of 110–130° (Table 3). The current tectonic configuration of the Panagyuriste strip is influenced by two fault systems: a longitudinal system oriented at 120° and a transverse system at 30–40° (Katskov, Iliev, 1993). In the middle course of the Luda Yana River the direction of the main channel (river bed) is influenced by these longitudinal faults (Fig. 4) as it is almost parallel to them.

Table 3

Length of fault lines within the studied drainage basins

Basin	Area (km^2)	Fault lines (km)	Density (km/km^2)
Panagyurska Luda Yana	172.8	128.81	0.75
Strelchanska Luda Yana	173.04	40.65	0.23
Luda Yana (whole basin)	789.41	285.04	0.36

All fault lines within the Luda Yana Basis have a total length of 285.04 km. Therefore, fault line density within the Luda Yana Basin is about 0.36 km/km^2. This value suggests an intermediate level of faulting when considering the basin as a whole system. Fault line density is expected to vary widely across the basin area and especially in the upper course of the Luda Yana River. The basin of Panagyurska Luda Yana has a fault density of 0.75 km/km^2. This high density indicates a relatively active tectonic environment or a history of significant faulting within this basin. Strelchanska Luda Yana shows a much lower fault density of 0.23 km/km^2, demonstrating fewer or less extensive fault lines relative to its area compared to Panagyurska Luda Yana. This lower density could reflect either less tectonic activity or fewer differences in fault distribution.

The longitudinal profiles of the Panagyurska and Strelchanska Luda Yana rivers exhibit distinct changes in the slope of the riverbed. In the Panagyurska Luda Yana, a notable change in slope occurs just above 500 meters above sea level, coinciding with the location of a fault. Similarly, in the Strelchanska Luda Yana, a more pronounced slope change is observed between 400 and 500 meters, specifically around 430 meters, which is also linked to the presence of a fault at this elevation. In both rivers, the slope of the riverbed increases both within the fault zones and downstream, which likely contributes to an acceleration in the river's flow speed (Fig. 5).

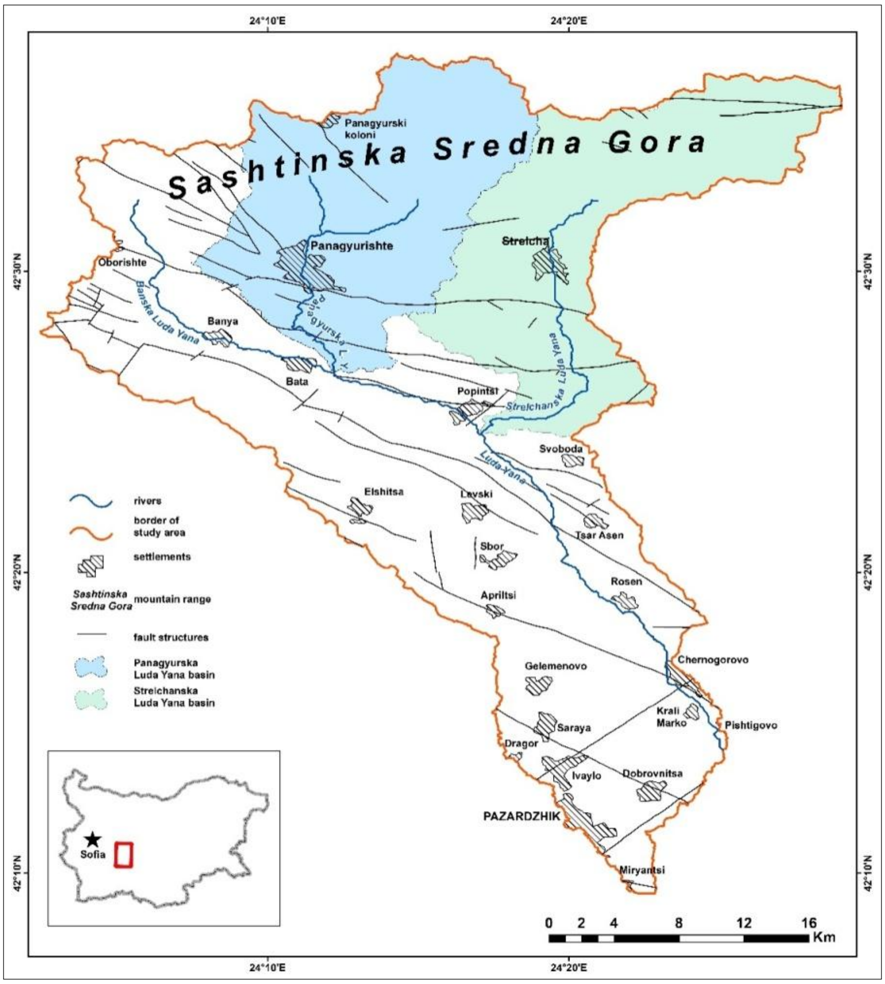

Fig. 4 – Tectonic map of the studied drainage basins.

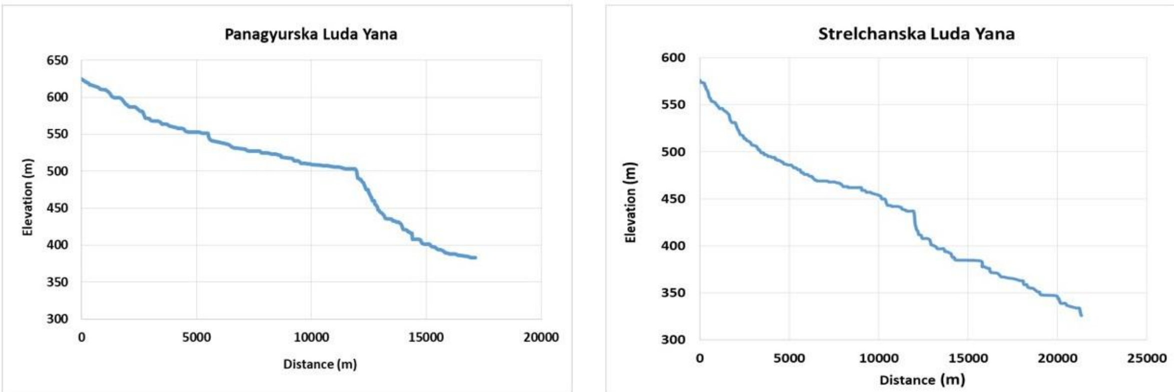

Fig. 5 – Longitudinal profiles of the Panagyurska and Strelchanska Luda Yana rivers.

Regarding the drainage pattern, annular, dendritic, rectangular and parallel patterns are observed within the studied basins. The annular pattern evolves in a breached or dissected dome or basin in which erosion exposes concentrically arranged hard and soft bands of rock. The dendritic pattern indicates that the drainage network follows a branching, tree-like structure. In contrast, the parallel pattern is mainly characteristic of areas where the drainage network is formed on sedimentary and volcano-sedimentary rocks, suggesting that the alignment of the streams tends to follow the slope and structure of the underlying rock formations. The rectangular type is associated with the presence of tectonic faults mainly in the middle part of the two studied drainage basins.

5. CONCLUSION

Volcano-sedimentary rocks can exhibit both higher and lower drainage density values compared to sedimentary rocks, depending on the proportion of andesitic tuffs and tuffites, on the one hand, and marls and limestones, on the other, on the presence of clayey limestone layers, and on the slope angle and slope length. The higher erodibility of the andesite containing rock formations than the limestones and marls and the lower permeability of the clayey limestones determine higher drainage density. Smaller slope angles or the shorter length of the slopes predetermine the lower drainage density of the 1st order streams within the studied basins. The intrusive igneous rock group determines a relatively high drainage density (mainly due to the low water permeability of granites), higher than the drainage density of the migmatized rocks probably due to the formation of secondary fractures in the rocks of the migmatized group, the influence of the slope angle, as well as the specifics of the soil and vegetation cover.

The values of the drainage density of the 1st order streams for the volcano-sedimentary rocks group confirm that not only does the lithological factor play an important role in the process of formation and development of the drainage network, but so do slope angle and slope length. Despite suitable lithological conditions, smaller slope angles or the shorter slope length predetermine a weaker potential for development and, respectively, a shorter length of 1st order streams.

The analysis of the longitudinal profiles of the studied rivers reveals that not all faults influence the slope of the riverbed. It is crucial to identify the activity of individual faults and their specific role in shaping the structural control of drainage. To gain a clearer understanding, further field studies are needed.

The high fault density of the Panagyurska Luda Yana River drainage basin indicates a relatively active tectonic environment or a history of significant faulting within this basin. The Strelchanska Luda Yana River drainage basin shows a much lower fault density, demonstrating fewer or less extensive fault lines relative to its area compared to the Panagyurska Luda Yana River drainage basin. The lower density could reflect either less tectonic activity or fewer differences in fault distribution. The variations in fault density may affect each basin’s susceptibility to tectonic events, influencing river morphology and sediment transport differently across these regions.

Regarding the drainage pattern, the rectangular drainage pattern prevails in both basins for the middle course, while the annular pattern is prevalent for the upper course. However, the parallel drainage pattern is found mainly in areas with sedimentary and volcano-sedimentary rocks. The observations show that the rectangular type of drainage pattern is associated with the presence of tectonic faults in both studied basins.

This study can serve as an initial remote analysis of the risk associated with the formation and development of torrential processes – such as floods, debris flows, mudflows, etc. Such an analysis has, in turn, practical value for regional and local authorities in developing strategies to prevent these events and implement effective measures to mitigate their impact. The findings also provide a basis for further research, particularly into the weathering resistance of rocks, and contribute to the development of hydrogeological and hydro-climatic analyses of the studied area. Additionally, the research could be extended to explore the relationship between tectonic activity and the stream network. This could involve applying morphometric methods to measure rock fractures in riverbeds, and analysing the correlation between tectonic structure orientations and the flow directions of streams at various orders.

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