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MORPHOMETRIC INDICATORS OF HIGH TATRA MTS. LAKES AND THEIR CATCHMENTS TO ANALYSE DEBRIS FLOW DYNAMICS (SLOVAKIA)

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Abstract

Čajková S., Hrivnáková K., Hreško J.: Morphometric indicators of High Tatra Mts. lakes and their catchments to analyse debris flows dynamics (Slovakia). Ekológia (Bratislava), Vol. 43, No. 2, p. 140–149, 2024.

This paper provides a quantitative assessment of debris flows, the morphometric properties of high-mountain lakes, and their catchments in the Slovak part of the High Tatra Mts. Our database comprises 29 high-mountain lakes in 11 valleys. We utilised vector models to derive some maps, and for a detailed study, we employed a digital elevation model of the study area and applied map algebra within a geographic information system environment. Using ArcGIS software, we calculated 18 morphometric parameters (such as basin orientation, topographic slope factor, basin length, basin ruggedness, etc.). This study is valuable for conducting various analyses of hydrological and morphometric characteristics of catchments. It is based on a comprehensive approach that integrates Earth remote sensing with aerial image interpretation and detailed field research of the High Tatra Mts.' lakes. The study has shown a significant influence of morphometric parameters of catchments on the dynamics and frequency of morphodynamic processes.

Key words: morphometric parameters, debris flows, the High Tatra Mts., high-mountain lakes.

Introduction

Understanding the shape, size, and relief characteristics of catchments is essential for hydrology. Morphometric analysis provides a mathematical tool to evaluate these properties, leading to a deeper comprehension of individual drainage networks and hydrological processes within the catchment (Horton, 1945; Smith, 1950; Strahler, 1957; Schumm, 1956; Evans, Cox, 1974; Nikolova, 2022). Calculating the morphometric parameters forms the foundation for comprehensive catchment modelling and analysis, uncovering relationships between various parameters within a catchment. When combined with geomorphological and geological data, morphometric assessment becomes a valuable tool for developing fundamental hydrological diagnostics of a catchment (Esper, 2008). This diagnostic allows us to predict its approximate behaviour, which is crucial for effective water resource protection and management. Morphometric parameters, including stream length, catchment area, slope, and relief ratio, significantly influence the catchment's runoff rate, volume, soil erosion, and sediment transport. Despite its importance, there is no consensus on a standard set of parameters for assessing catchment susceptibility to geomorphological processes. The selection of parameters varies across studies, complicating the comparison of results and the generalisation of knowledge (Chen, You, 2011; Alam et al., 2021; Giano et al., 2021).

The advancement of geographic information system (GIS) technologies has facilitated the development of innovative approaches for quantifying landslides, erosion, and material transport characteristics. Recent topographic survey techniques, such as LiDAR, have empowered detailed topographic analysis by providing high-quality digital terrain models (DTMs) (Tarolli, Fontana, 2009). These methods involve spatially distributed, digitally organised data. Topographic attributes derived from digital elevation models (DEMs), including slope, catchment orientation, and drainage area, form the foundation for topographic analyses. Several researchers have investigated the impact of DEM resolution on landscape representation (Wilson, Gallant, 2000; Claessens et al., 2005). However, less emphasis has been placed on the systematic effects of different resolutions and accuracies of DEMs on geomorphological models and the most suitable scale for observing geomorphological processes.

The mapping of geomorphological processes offers a valuable method for capturing, analysing, and quantitatively expressing their dynamics. Geomorphological hazards, including debris flows, landslides, and rockfalls, play a significant role in shaping the landscape of the Tatra Mts. Despite their varying frequencies, these phenomena can have a lasting impact on the configuration of slopes and valley floors. The combined effects of slope-gravity and water-gravity processes contribute to the development of new relief forms (Rączkowska, 2006). Morphodynamic

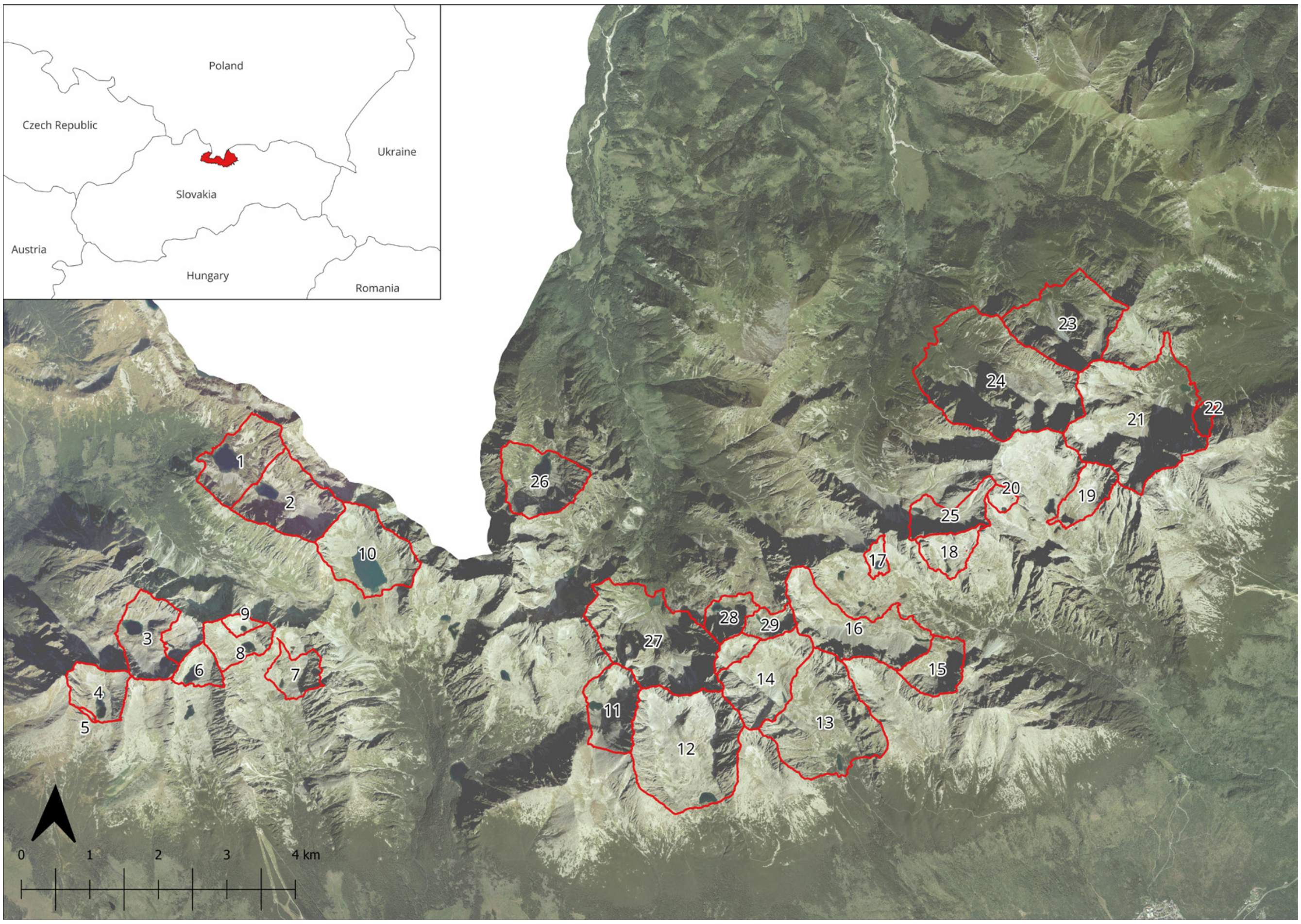

Fig. 1. Study area.

processes have notably influenced glacial lakes in recent years. This trend is strongly influenced by climate change, particularly the increased frequency and intensity of extreme rainfall and the occurrence of numerous freeze–thaw cycles. In the High Tatra Mts. environment, these rain events affect the formation of debris flows, which exhibit substantial geomorphological activity, especially in rocky gullies and on talus cones. The heightened frequency of extreme rainfall has led to an increase in the number of debris flows and their geomorphological impact (Kapusta et al., 2010).

High-mountain lakes are a significant geomorphological and hydrological feature in the Tatra Mountains (Hreško et al., 2012). Currently, these lakes are gradually being filled and covered by various types of materials, ranging from fine-grained fractions to coarse-grained sediments, often including boulders (Tomko-Králo et al., 2017). Consequently, the lake basin diminishes over time as material accumulates, eventually leading to the disappearance of the lake. The formation of lake sediments is a typical morphodynamic process in the high mountain environment of the Tatra Mountains (Hreško et al., 2012). Sediments settle more rapidly, particularly in the shallow peripheral parts of the lake, gradually reaching the water level and forming typical alluvial cones. These geomorphological formations are widespread around many lakes in the Tatra Mts., and their extent can indicate the intensity of sedimentation processes, providing indirect evidence of the lakes' original larger size. Some shallow alpine lakes experience significant sedimentation of clastic and fine fractions of material, and in some cases, the water surfaces become overgrown with vegetation (Kapusta et al., 2018).

Material and methods

The work is based on the latest knowledge about the high mountain environment of the High Tatra Mts. and the geomorphological processes occurring there. The field research was carried out from June to September 2022.

Study area

The database encompasses 29 lake catchments in 11 valleys of the High Tatra Mts. (refer to Fig. 1, Table 1). The total area of the studied region spans 2752 ha. The High Tatra Mts., the northernmost and highest alpine mountain range in the entire Carpathian arc, constitute a geomorphological subunit of the Eastern Tatras Mts. and are also part of the Tatra Mts. Although glaciers no longer exist, characteristic traces of Pleistocene glaciation are still observable (Zasadni, Klapyta, 2009). The high-mountain lakes represent the most recent glacial formations (Kotarba, 2007; Hreško et al., 2012; Kapusta et al., 2021). In the Slovak part

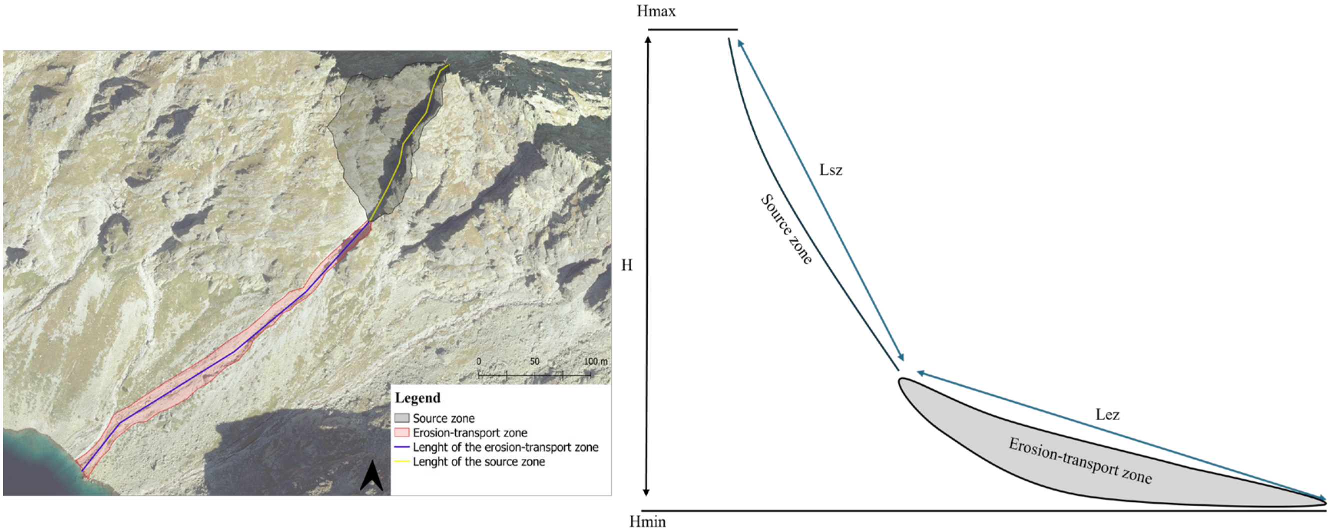

Fig. 2. Morphometric parameters of the debris flow (DF) divided into two zones: the erosion-transport zone and the source zone. H, elevation difference of DF; H_{max}, the highest elevation of the source zone; H_{min}, the elevation of the debris material accumulation of DF; Lsz, length of the source zone; and Lez, length of the erosion-transport zone.

of the High Tatra Mts., there are an estimated 170–223 mountain lakes, primarily concentrated in the high mountain area. Most lakes are situated at altitudes ranging from 1800 to 2200 m above sea level. The majority of the lakes are small, with an area of up to 1 ha and a depth of up to 2 m. Fewer lakes have an area of up to 10 ha and a depth of up to 10 m, and the fewest lakes have an area exceeding 10 ha (Pacl, 1973, 1994; Gregor, Pacl, 2005; Kapusta et al., 2018).

Analysis of debris flows

The analysis of debris flow in the designated study areas involved the vectorisation of remote sensing (RS) data and field surveys. We utilised orthophotos from 2022 and a high-resolution DEM to map the spatial distribution of debris flows. These resources, obtained from the Geodetic and Cartographic Institute in Bratislava (GKÚ), provided detailed information at an approximate scale of 1:5000. The initial phase of the evaluation focused on processing digital layers representing the spatial distribution of debris flows, followed by quantifying specific parameters of the erosion-transport zone and identifying their source zones using ArcHydro tools. All the processing and outputs were generated within the ArcMap 10.8.1 environment. Please make a note of the following information.

For talus cones, only areas of the debris flow erosion-transport zone exhibiting signs of recent surface destruction were identified as active within the specified time frame. Inactive flows, which are stabilised by vegetation, were not specifically outlined. The parameters we obtained (refer to Fig. 2) include the area of the erosion-transport zone (AreaET), area of the source zone (AreaSZ), length of the erosion-transport zone (Lez), length of the source zone (Lsz), total length of the debris flow (L), orientation of the erosion-transport zone (Aez), orientation of the source zone (Asz), slope of the erosion-transport zone (Sez), and slope of the source zone (Ssz).

Table 1. Location of 29 high-mountain lakes (pl.).

Locations		Geographical coordinates	
1	Nižné Temnosmrečinské pl.	49,1925619N	20,0296439E
2	Vyšné Temnosmrečinské pl.	49,1886617N	20,0380892E
3	Nižné Terianske pl.	49,1697808N	20,0131078E
4	Zelené Krivánske pl.	49,1594181N	20,0075425E
5	Malé Krivánske pl.	49,1574342N	20,0062028E
6	Vyšné Wahlenbergovo pl.	49,1640153N	20,0259653E
7	Nižné Kozie pl.	49,1635242N	20,0434531E
8	Capie pl.	49,1680000N	20,0363078E
9	Okrúhle pl.	49,170385N	20,0352992E
10	Veľké Hincovo pl.	49,1791103N	20,0594392E
11	Ľadové pl. Mengusovské	49,1632364N	20,1063886E
12	Batizovské pl.	49,1521006N	20,1299197E
13	Velické pl.	49,1576808N	20,1558811E
14	Dlhé pl. Gerlachovské	49,1657483N	20,1440539E
15	Vareškové pl.	49,1743061N	20,1771806E
16	Dlhé pl. Zbojnícke	49,1744481N	20,1708289E
17	Ľadové pl. Zbojnícke	49,1840039N	20,161425E
18	(Vyšné/Prostredné) Sivé pl.	49,1844508N	20,1749886E
19	Prostredné Spišské pl.	49,1914325N	20,1984800E
20	Modré pl.	49,1922319N	20,1856161E
21	Zelené pl. Kežmarské	49,2095092N	20,2202886E
22	Čierne pl. Kežmarské	49,2076167N	20,2245908E
23	Kolové pl.	49,2203650N	20,1913656E
24	Čierne Javorové pl.	49,2138753N	20,1710258E
25	(Veľké)Žabie Javorové pl.	49,1914333N	20,1684592E
26	Vyšné Žabie Bielovodské pl.	49,1936211N	20,0928228E
27	Zelené Kačacie pl.	49,1773603N	20,1168117E
28	Litvorové pl.	49,1771256N	20,1294878E
29	Zamrznuté pl.	49,1758911N	20,1382211E

Table 2. Physical-geographic and morphometric parameters.

	Physical-geographic parameters		Definition	References
1	Geographical position		Location of the lake	Topographic maps
2	Geological structure		Geological structure of the bedrock	Landscape Atlas of the Slovak Republic (2002)
3	Geomorphology of the lake		Lake formation	Topographic maps
	Morphometric parameters of catchment	**C**		
5	Area	AreaC	Topographically defined area of the catchment (m^2/ha)	GIS
6	Maximum elevation	H_{max}	m	GIS
7	Minimum elevation	H_{min}	m	GIS
8	Catchment relief	H	$H = H_{max} - H_{min}$, where H_{max} is the maximum elevation and H_{min} is the minimum elevation within the catchment	GIS
9	Slope	Sc	Slope gradient (°)	GIS
10	Aspect	Ac	Orientation of slope (°)	GIS
11	Length	Lc	The horizontal distance along the longest dimension of the basin parallel to the main streamline	GIS
12	Longest flow path	Ls	Length of the major stream (m)	GIS
13	Relief ratio	Rh	Rh = H/Lc, where H represents the catchment relief and L is the catchment length.	Schumm (1956)
14	Form factor	F	F = AreaC/Lc^2, where AreaC is the catchment area and Lc^2 is the squared basin length	Horton (1945)
15	Stream power index	SPI	SPI = AreaC× tanβ	Moore et al., (1991)
16	Topographic wetness index	TWI	TWI = ln (AreaC/tanβ)	Moore et al., (1991)
17	Topographic position index	TPI	TPI = $z_0 - z$, where z_0 is the elevation of the model point undervaluation; z is the elevation of grid	Weiss (2001)
	Morphometric parameters of lake	**PL**		
18	Area	AreaP	Topographically defined area of the lake (m^2)	GIS
19	Volume	Op	m^3	Gregor, Pacl (2005)
21	Perimeter	Pp	Length of the lake boundary (m)	GIS
22	Length	Lp	The total length of lake (m)	GIS
23	Width	Wp	The maximum length at a right angle to Lp (m)	GIS
24	Ratio	Rp	$Rp = Lp/Wp$, m	GIS
25	Maximum depth	Dmax	m	Gregor, Pacl (2005)
26	Minimum depth	D	m	Gregor, Pacl (2005)

Morphometric analysis of high-mountain lakes and their catchments

The study utilised morphometric methods to analyse the lakes and their catchments. Characteristics for each catchment were determined as either average values (e.g., slope and aspect) or exact values (e.g., catchment length). The hydrological properties of the catchments were analysed using hydrological tools in ArcMap 10.8.1. Some parameters (e.g., form factor and relief ratio) were derived from primary parameters using map algebra. All identified characteristics were included in the final database for 29 catchments. The database contains three categories: (1) physical–geographical parameters, (2) morphometric parameters of the catchment, and (3) morphometric parameters of the lake. The names and descriptions of individual parameters are provided in Table 2.

We utilised various topographic indices to characterise the geomorphological features of the catchment, focusing on those relevant to debris flows. Our primary input data for the topographic analysis was a DTM with a 1 × 1 cm resolution. The catchment parameters we derived include topographic wetness index(TWI), stream power index(SPI), STI, topographic position index (TPI), slope (Sc), orientation (Ac), form factor (F), average elevation (ELV), length (Lc), area (AreaC), relief ratio (R), and catchment relief (H).

Results

The data in the table above illustrates various types of data collection. Through the use of map algebra and local statistics, we were able to derive characteristics for 29 catchments. Additionally, spatial analysis of vector data enabled us to calculate the

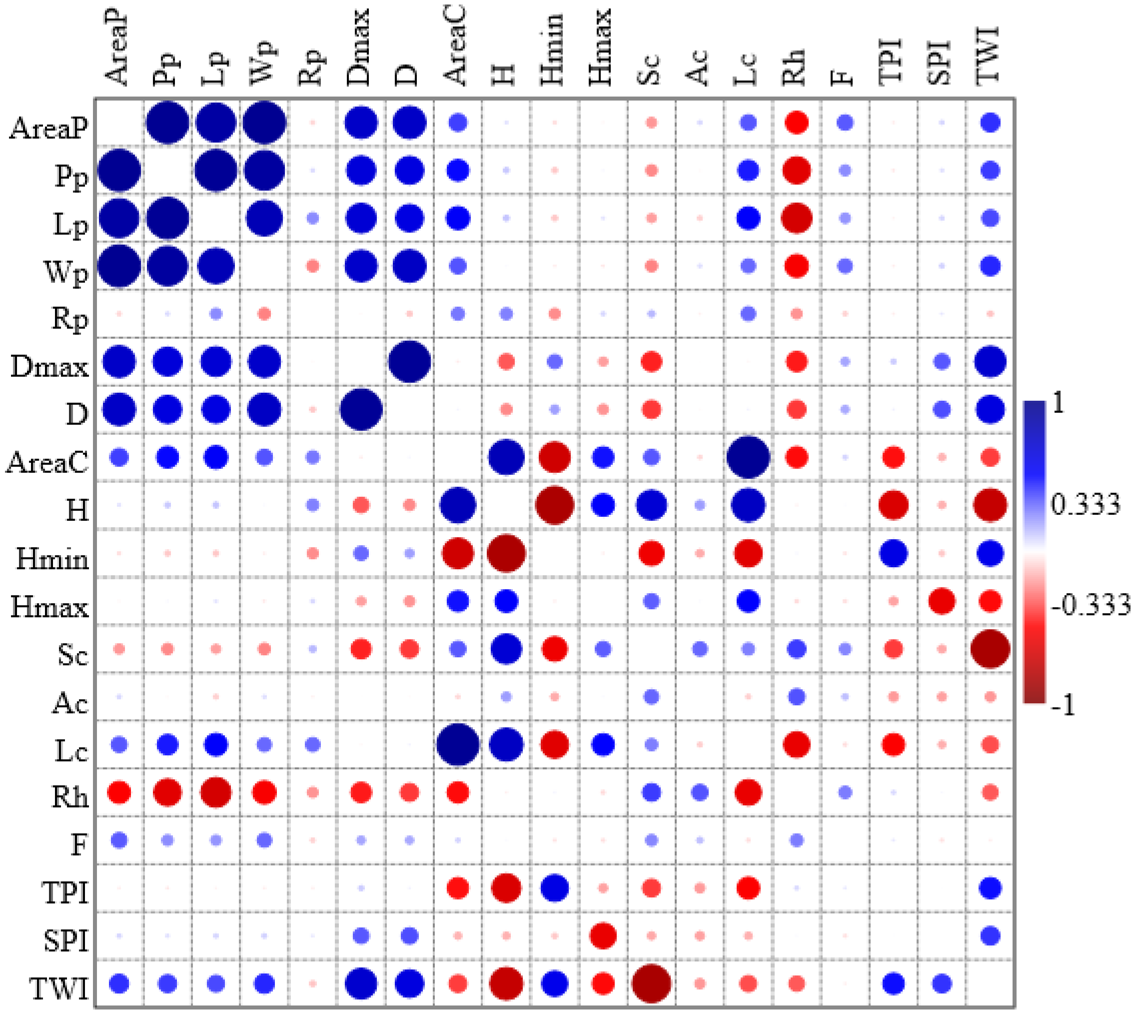

Fig. 3. Correlation matrix between selected morphometric parameters of the lake and the catchment, where AreaP, lake area, Pp, perimeter, Lp, lake length, Wp, lake width, Rp, lake ratio, D_{max}, maximum lake depth, D, average lake depth, AreaC, catchment area, H, basin ratio, H_{min}, the minimum elevation of the catchment, H_{max}, the maximum elevation, Sc, slope of the catchment, Ac, aspect of the catchment, Lc, length of the catchment, Rh, relief ratio, F, shape factor of the catchment, TPI, topographic position index, SPI, stream power index, TWI, terrain wetness index.

characteristics of 273 debris flows within the examined catchments. The upcoming section will centre on presenting our primary findings.

The area of the studied catchments ranged from 1.87 to 304.6 ha, with the maximum catchment lengths (*Lc*) varying significantly, ranging from 0.3 to 2.3 km. The catchment of the Čierne Javorové pleso lake boasted the longest maximum catchment length, while the catchment of the Malé Krivánske pleso lake exhibited the shortest length. Our database primarily comprises catchments with southern orientations. In accordance with assumptions and previous studies (Daipan, 2020; Víg et al., 2022), we discovered strong relationships (see Fig. 3) between the maximum catchment length (Lc) and the catchment area (AreaC, rs = 0.97, $p < 0.001$), as well as the catchment relief (H, rs = 0.76, $p < 0.001$). These findings suggest that the source areas of the smaller lakes are characterised by small areas, high ruggedness, and steep slopes.

Based on the form factor (*F*) values, it is evident that catchments with slightly elongated shapes ($F = 0.68$) are predominant. A small subset of analysed catchments exhibits low *F* values ($n = 5$), indicating a high degree of elongation. Specifically, five lakes have catchments with typically oval shapes. A lower shape factor value signifies a more elongated catchment. Catchments with high shape factor values experience high peak flows with shorter durations, while those with low shape factor values, such as 0.42, have low peak flows with longer durations. Consequently, elongated catchments are more susceptible to flood flows than oval-shaped catchments. Notably, the catchment of Dlhé pleso lake in Veľká Studená dolina valley exemplifies a typically long catchment.

Additionally, we examined the relief ratio (Rh) for the catchments. This index represents the ratio between the total catchment relief and the length of the catchment parallel to the main drainage line and denotes the erosive activity intensity on the

Table 3. Basic morphometric characteristics of the erosion-transport zone of recorded debris flows.

	Area(m^2)	Length(m)	Height of relief(m)	Slope(°)	Aspect(°)	Average altitude(m)
Min	15.65	5.70	0.63	5.97	35.82	1542.04
Max	69394.51	1150.78	776.00	43.76	328.44	2301.84
Mean	2757.54	188.53	132.20	31.79	170.19	2024.72
Std. error	303.20	9.48	6.66	0.26	4.55	10.13
Variance	26935280	26353	13015	20.04	6078.52	30049.76
Stand. dev	5189.92	162.34	114.08	4.48	77.96	173.35
Median	1223.78	140.93	98.98	32.31	179.20	2071.13

Fig. 4. The extensive debris flow in the catchments of Kolové pleso lake (Kolová dolina valley), Photo: Čajková, 2022.

catchment slopes. A high Rh value indicates steeper slopes in the catchment, leading to faster water flow and potential water-gravitational processes. In our study area, relief ratio values range from 0.21 to 1.2, with the highest values observed in the catchments of Čierne Javorové pleso in Javorová dolina valley, Modré pleso in Malá Studená dolina valley, Čierne pleso in Dolina Zeleného plesa valley, and Litvorové pleso in Litvorová dolina valley. Conversely, low relief ratio values suggest gentler slopes, with the lowest Rh value recorded for Dlhé pleso lake in Veľká Studená dolina valley. Our findings also indicated a significant, strong negative correlation between Rh and catchment length ($p < 0.001$), revealing that longer catchments have lower relief ratios, resulting in slower water flow and reduced slope erosion.

Through the analysis of topographic indices, TPI and TWI, we have observed a noteworthy negative correlation (rs = −0.45 to −0.78, $p < 0.001$) between the values of these indices and the size and length of the catchment. This correlation suggests that larger and longer catchments with greater changes in elevation tend to display lower TPI and TWI values. This correlation highlights the distinctive distribution of terrain based on catchment size and length. Larger catchments tend to exhibit a higher prevalence of depressions, gullies, and low-lying areas, while smaller catchments are characterised by steep slopes, rock formations, and ridges, thus increasing their overall slope.

When examining the size of lakes in relation to their catchment areas, it was observed that the majority of lakes with an area of up to 1 ha typically have smaller catchments. This occurrence can be attributed to their location at higher altitudes, nestled in cirques. The upper drainage area experiences a steeper slope compared to the middle and lower drainage areas, resulting in rapid sedimentation in the lower parts of the catchment. Consequently, the bottoms of these lakes serve as areas for the accumulation and deposition of various materials from the surrounding walls and slopes. An exception to this pattern is the Čierne Javorové pleso lake, which stands out due to its larger catchment formed in depressions behind moraine ridges in the lower part of the Čierna Javorová dolina valley. The analysis revealed a significant positive correlation between TWI and fundamental lake parameters, with correlation coefficients ranging from 0.42 to 0.64. The most notable relationship was observed between TWI and lake depth, as deeper lakes have a higher water retention capacity and are characteristic of areas with greater accumulation.

Analysis of debris flows and their relationship to morphometric parameters of lakes and catchments

We conducted an analysis of 273 active debris flows, with a focus on their erosion-transport (see Table 3) and source zones. The predominant location for debris flow occurrences was on talus cone slopes, a finding supported by other researchers (Midriak, 1984; Kotarba, 1992, 1997, 2005). The presence of coarse granite debris on these slopes enables rapid water infiltration during heavy rainfall, resulting in increased pore pressure and the initiation of material movement. The slope angles at the initiation points of the debris flows ranged from 6° to 44°, with an average of around 32°. These findings align with those of other studies, which indicate that most debris flows occur on slopes with gradients between 30° and 40° (Lorente et al., 2003; Rączkowska, Cebulski, 2022).

In our study area, an analysis of identified debris flows revealed that 82% of them occur in the alpine zone above 1900 m above sea level. The erosion-transport zone has an average length of 188 m, with the maximum measured length reaching 1150.78 m. Approximately 43% of the identified debris flows, including debris chutes, have lengths ranging from 500 to 1000 m, while 42% have lengths between 250 and 500 m. More than 1000 m

Table 4. Correlation matrix between morphometric parameters of debris flows (DF).

L		Length DF			Erosion-transport zone						Source zone				
		Let	Lzs	A	H_{max}	H_{min}	ELV	H	S	A	H_{max}	H_{min}	ELV	H	
Length DF	L														
	Let	0.83*													
	Lsz	0.80*	0.42*												
Erosion-transport zone	A	0.69*	0.84*	0.31											
	H_{max}	−0.3*	−0.11	−0.62	−0.05										
	H_{min}	−0.67*	−0.55*	−0.62*	−0.49*	0.82*									
	ELV	−0.59*	−0.41*	−0.65*	−0.35*	0.91*	0.97*								
	H	0.69*	0.94*	0.24	0.86*	0.00	−0.49*	−0.33							
	S	−0.27	−0.13	−0.36*	−0.04	0.14	0.09	0.12	0.13						
Source zone	A	0.84*	0.58*	0.90*	0.52*	−0.56	−0.68*	−0.67*	0.45*	−0.27					
	H_{max}	0.58*	0.49*	0.47*	0.42*	0.19	0.00	0.07	0.34*	−0.35*	0.50*				
	H_{min}	−0.38*	−0.12	−0.63*	−0.05	1.00*	0.82	0.91*	−0.02	0.13	−0.58*	0.18			
	ELV	0.03	0.13	−0.19	0.13	0.77*	0.57*	0.64*	0.12	−0.05	−0.13	0.65*	0.77*		
	H	0.75*	0.44*	0.88*	0.31	−0.69*	−0.74*	−0.75*	0.26	−0.34*	0.88*	0.45*	−0.70*	−0.21	
	S	0.10	0.21	−0.07	0.30	−0.03	−0.25	−0.16	0.26	0.13	0.13	0.23	−0.03	0.10	0.26

Note: Relationships between total length of debris flow (L), length of erosion-transport zone (Let), length of source zone (Lsz), area (A), minimum elevation (H_{min}), maximum elevation (H_{max}), average elevation (ELV), relief elevation difference (H), and slope gradient (S). Spearman correlation coefficient (rs). *$p < 0.01$.

Table 5. Correlation relationships between the number of debris flows (DF) within the entire catchment and selected morphometric attributes of the lake and catchment.

DF	AreaP	AreaC	H	Sc	Lc	Ls	TWI
n = 273	0.54	0.727*	0.527*	0.385	0.671*	0.707*	−0.46*

Note: DF debris flows), AreaP (lake area), AreaC (catchment area), H (relief elevation difference), Sc (catchment slope), Lc (catchment length), Ls (longest stream length), and TWI (topographic wetness index). *$p < 0.01$.

in length are recorded for 11% of identified debris flows. Similar morphometric properties of debris flows were found in Midriak's (1984) Western and High Tatra Mts. study. North-facing slopes exhibit a lower occurrence of debris flows, with the source zones being more extensive. Conversely, south-facing slopes have a higher occurrence of debris flows, but the source areas of these flows are smaller, a difference related to temperature variations. The harsher local climate results in less regulation and fewer changes in terrain on north-facing slopes, leading to reduced weathered material formation and less slope fragmentation through avalanches and debris flow activity. A significant debris flow by area was identified near Kolové pleso lake in Kolová dolina valley (Fig. 4). Its source zone consists of three debris chutes, occupying nearly 5% of the catchment area.

The correlation analysis presented in Table 4 illustrates the relationship between various debris flow parameters. It was observed that longer and steeper erosion-transport zones correspond to larger debris flow areas and more pronounced differences between the start of transport and the end of material accumulation. These findings underscore the intricate interplay among different debris flow parameters. Table 5 reveals significant positive relationships between the number of debris flows and specific catchment parameters such as area, length (Lc), maximum stream length (Ls), elevation difference (H), catchment slope (Sc), and TWI (negative). In summary, it was observed that larger and longer catchments with higher slopes tend to experience a higher frequency of debris flows. Additionally, a weak positive correlation (rs = 0.38) was found between the per-

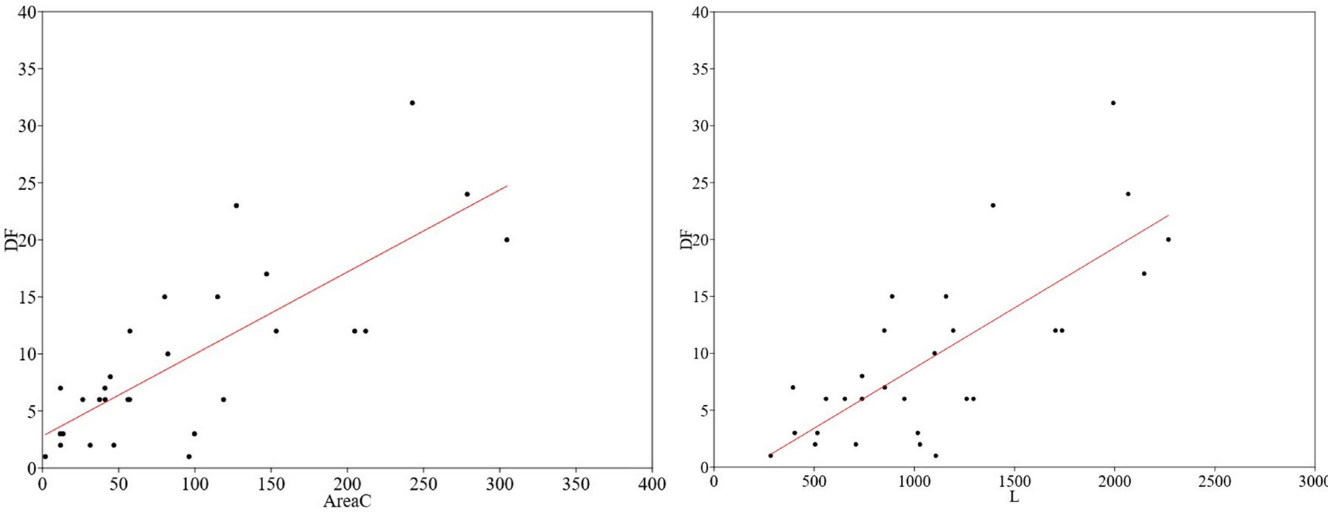

Fig. 5. Relationship between the total number of debris flows (DF) in a catchment and: AreaC, catchment area (ha); r2 = 0.61; L, catchment length (m), r2 = 0.57.

centage of debris flows in the catchment and the relief ratio Rh. Further analysis uncovered a tenuous positive relationship between lake size and the number of debris flows in its catchment. Moreover, a linear dependency was established between specific catchment attributes and the number of debris flows (DF), as depicted in Figure 5.

Discussion

Debris flows are a widely observed geomorphological phenomenon in steep mountain catchments (Rączkowska, 2006; Kotarba, 2007; Hendrickx et al., 2020). According to Kenner (2019), debris flows transport material from upper slopes to lower areas, and their intensity is greatly influenced by intense rainfall, as noted by Kotarba (1997), Wieczorek and Glade (2005), Cannon et al. (2008), and Brunetti et al. (2015). Various geomorphological studies have examined the spatial and temporal distribution of debris flows, including the assessment of flow size (Marchi, D'Agostino, 2004; Jakob, Hungr, 2005; Hungr et al., 2008; Brardinoni et al., 2012; Cavalli et al., 2013), the volume of transported sediments (Brayshaw, Hassan, 2009), and the determination of their contributing area (source zone) (Cannon et al., 2003; Kotarba et al., 2013). Recording and measuring these rapid processes directly can be quite challenging and require sophisticated methods and techniques. It is essential to approach their interdisciplinary study using various methods in order to gain a deeper understanding of their dynamics and make accurate predictions. Recent studies have utilised methods based on the application of geographic information system tools and RS (Telling et al., 2017; Rączkowska and Cebulski, 2022; Hrivnáková et al., 2023). These studies, in conjunction with meteorological data analysis, compare the frequency and intensity of debris flows (Kotarba, 1997; Kapusta et al., 2010; Kotarba et al., 2013).

The initial step in understanding catchment dynamics involves conducting a morphometric analysis. A variety of topographic indices have been proposed to characterise catchments, offering insight into the impact of topography on erosion and sediment transport potential. The contributing area index, also known as the SPI, is one such index that describes potential erosion and landscape processes (Moore et al., 1991; Chen, Yu, 2011). Additionally, the TWI is commonly used to quantify the topographic influence on hydrological processes (Wilson, Gallant, 2000; Sorensen et al., 2006).

Nefeslioglu et al. (2008) established a correlation between TWI and landslides. A high TWI value signifies a flatter slope or a sizable catchment area in the valley bottom region. Additionally, the TPI, as utilised in studies by Amin et al. (2020) and Zhao et al. (2021), enables the differentiation of local elevation variances within the relief, depending on the surrounding scale (Walk et al., 2019). Although morphometric indicators derived from GIS exhibit lower predictive capability than more intricate physical models, they prove to be more valuable in research scenarios where comprehensive assessment of landscape features is hindered by area size and varying conditions. The indices employed in this study seek to evaluate their association with the spatial distribution of morphodynamic processes in the area and to establish connections between research findings based on the interpretation of orthophotos and field surveys.

Our research indicates that larger source zones result in more extensive debris flow accumulation. The correlations we found demonstrate strong positive relationships between the total elevation difference of the debris flow and its length, as well as the length of the erosion-transport zone. These results confirm that a greater elevation difference can effectively account for the distance travelled by the debris flow due to the energy of the process (Lorente et al., 2003). Similar relationships were observed for the elevation difference of the erosion-transport zone with its area and length. Alongside the identified correlations between various parameters of debris flows, we also noted a consistent linear relationship between the erosion-transport zone's elevation ratio and the source zone's area. This relationship implies that debris flows at higher elevations are characterised by smaller source zone areas compared to flows at lower elevations. The observed relationships are crucial for comprehending the dynamics of debris flows and predicting their activity.

Multiple authors have assessed catchment parameters to identify the primary processes in high mountain environments (Marchi et al., 1993; Grelle et al., 2019; Giano et al., 2021; and others). The morphometric characteristics of the catchment, including size, length, slope, and relief ratio, play a significant role in the occurrence and distribution of debris flows. Larger and more extensive catchments with steeper slopes and rugged terrain are more prone to debris flow activity. However, it is important to note that while the number of debris flows is higher in larger catchments, their relative representation in the total catchment area may decrease. In smaller catchments, even a small number of debris flows can profoundly impact the morphology and dynamics of the catchment.

Conclusion

The high mountain environment of the Tatra Mts. is shaped by extreme climatic and relief conditions, which play a crucial role in forming the Tatra Mts. landscape and showcasing the dynamic nature of its components. In recent decades, the development of the Tatra Mts. environment has been significantly impacted by processes closely linked to the accelerating global climate changes. Research conducted on both the Slovak and Polish sides of the Tatra Mts. indicates a concerning trend of increased frequency, abruptness, and severe unpredictability of these processes. Given the context of climate change, it is essential to assess the potential occurrence and impacts of these processes on the Tatra Mts. ecosystems, making it a critical task in the realm of research on changes in the high mountain environment of the Tatra Mts.

This research study focuses on the utilisation of GIS technology for determining the morphometric characteristics of subcatchments. A custom database containing 18 calculated parameters was developed for this purpose. The analysis conducted in the GIS system incorporated the latest knowledge in this field. The proposed approach for modelling morphometric characteristics has proven to be applicable to mountain catchments that exhibit a great diversity of natural components. The intricate mountainous terrain of the High Tatra Mts. exerts a significant influence on a wide range of factors that shape the hydrological and geomorphological characteristics of the catchments. Consequently, noticeable disparities in geomorphological and hydrological indicators, such as slope or terrain moisture, can be observed even within a small catchment area. The results presented indicate that none of the traditional cartographic methods employed previously offer as effective visualisation and detailed information as modelling in raster form. The application of focal statistics and map algebra facilitates a comprehensive characterisation of the geomorphological and hydrological features of the catchment. The research has demonstrated the significant impact of catchment morphometric parameters on the dynamics and frequency of debris flows. The advantage of this detailed modelling and mapping lies in its usefulness for identifying ongoing relief-forming processes, such as debris flows, landslides, massive rockfalls, or potential flood areas.

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