Morphometric analysis of low mountains for mapping flash flood susceptibility in headwaters

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Abstract

Morphometric indices from high-resolution DEMs can contribute to the estimation of flash flood susceptibility in mountainous areas. We have screened 25 morphometric indices commonly used in literature, and based on a correlation matrix, selected those which showed the strongest relationship with flash flood generation: area (A), drainage texture (Rt), drainage density (Dd), elongation ratio (Re), form factor (Ff), lemniscate method (k), Gravelius coefficient (GC), forested area (Fa) and relief ratio (Rr). Among them Dd, Rt and Rr had a direct impact on flash flood generation, while A, Re, Fa, Ff, k and GC are in inverse relationship with the intensity of flash floods. Our summary map shows the prioritization of the watersheds on a scale of 0 to 9. The flash flood susceptibility ranking was empirically verified using hydrological data (20-year water regime obtained from 14 official stream gauges). Our conclusions only partially agree with former observations which may be explained by the particular lithology and morphology of the Mecsek Mountains. Since the lower sections of the watersheds are urbanized, for optimal watershed management more detailed GIS analyses of anthropogenic controls on flash flood hazard are needed in the future.

Keywords Morphometric indices · Watershed prioritization · Flash flood susceptibility · Runoff · Compactness · Mecsek mountains

1 Introduction

The shapes of watersheds may influence (flash) flood hazard (Gregory and Walling 1968). Therefore, the control of watershed morphology on local hydrology has been studied extensively and is a widely discussed scientific topic (Mangan et al. 2019). The
earliest investigations aimed at determining the characteristics and regularities of the individual river basins using a large number of numerical indices (Strahler 1957). Mathematical formulae are often used to define the morphometry of catchments, stream networks and drainage patterns (Schumm 1956; Strahler 1957; Bogaert et al. 2000; Fryirs et al. 2007a, b). Recent research has complemented empirical modelling with the use of GIS software (Masoner and March 2006; Biswas 2016; models are reviewed by Saleh et al. 2020). Morphometric calculations based on high-resolution DEMs and other vector databases may provide a sound basis for runoff and flood susceptibility estimations (Al-Juaidi et al. 2018). However, it is also true that the reliability of GIS application depends on data quality, defined by the survey implementation and the available databases (Lahsaini et al. 2018).

Depending on the algorithm applied for watershed delineation, small headwater catchments and their watercourses account, by number, for about 60% of all drainage networks on Earth (Alexander et al. 2007). The analysis of their morphometric properties is crucial to understand the morphological evolution of river networks and the intensity of the hydrologic processes related to the water cycle operating on them, including both water retention and flooding (Bywater-Reyes et al. 2017).

Flash floods are a rather frequent phenomenon in the drainage basins of the hilly and low mountain regions of Hungary (Lóczy et al. 2012). Over the last decades, as a consequence of land use changes and global climate change, flash floods have been occurring with decreasing return periods and increasing severity (Pirkhoffer et al. 2009; Archer and Fowler 2021). One of the most flash flood-prone areas of Hungary is the Mecsek Mountains, with more than one hundred reported flash flood events over the past decades (Gyenizse and Vass 1998; Koris 2021). Although with reduced severity due to their low relative relief, the rolling hills of South Transdanubia (SW Hungary) are also frequently affected by flash floods (Czigány et al. 2008).

In addition to a wide range of factors, including climate, topography, land use types, soils and catchment morphometry, anthropogenic factors also control hydrological processes at catchment scale (Santangelo et al. 2011). The extent of the developed areas, percentage of sealed surfaces, infrastructural development, population density and economic activity do not only have a landscape-modifying effect but also fundamentally influence the ratio of infiltration to runoff. Changes in land cover during commercial forestry operations and changes in the percentage of forested areas significantly control the amount of deadwood and woody debris accumulated in streambeds, hence hindering water flow in the channel (Dixon and Sear 2014; Short et al. 2015; Galia et al. 2017, 2018).

Field research may provide an adequate basis for detailed river basin analyses (Kamykowska et al. 1999; Krzemien 1999; Płaczkowska and Krzemień 2018). Surveys on both morphological and land-use characteristics of catchments contribute to the understanding of the dynamics of watercourses and the general behaviour of the components of drainage systems (Fryirs et al. 2007a, 2007b).

Hitherto, less attention has been paid to the study of the morphology of headwaters and their catchments both globally and in Hungary. However, the increasing trend of high water discharge in several gauging stations (Koris 2021) would justify detailed investigation. Therefore, to authors’ knowledge, a significant scientific gap exists in the field of headwater hydromorphometric studies. Hence, the present paper aims at morphometrically characterizing headwater catchments in the Mecsek Mountains in SW Hungary, which are representative for many low-mountain regions of Hungary and Central and Eastern Europe. Secondly, we intended to overview all available indices and to identify those which are most relevant for flash flood studies. A third objective was to contribute to the evaluation of
flash flood susceptibility for headwater catchments in the Mecsek Mountains based on key morphometric parameters.

2 Study area

The study area is located in the Mecsek mountains (330 km²) and the surrounding rolling terrain of South-Transdanubia, Hungary, where 53 drainage subbasins (654.5 km²) were delineated based on a 10-m resolution DEM. The elevation of the study area varies between 105 and 682 m (a.s.l.) including both low-mountainous and hilly terrains. Relative relief averages between 120 and 240 m/km² and reaches maxima of 280–320 m/km², while it decreases to 40–80 m/km² in the foothill zone (Figs. 1 and 2).

Geologically the Mecsek is divided into two major structural units (Konrád and Sebe 2010; Haas 2013). The western unit has an anticline structure composed of Permian and Triassic sandstones, conglomerates and siltstones, while in the Central and Eastern Mecsek Jurassic and Cretaceous limestones, marls, shales and to a lesser degree dolomites prevail. Magmatic intrusions and interlayered volcanic materials (Mecsekjános Basalt Formation) are also found in the study area due to the tectonic movements in the Lower Cretaceous. The lower foothills and forelands covered by much younger lacustrine, fluvial and aeolian sediments from the Late Neogene and Quaternary periods.

As far as climate is concerned, the mean annual air temperature ranges from 7 °C in the summit regions and increases to 12 °C in wind-sheltered and south-facing slopes.

Fig. 1 Elevation and stream network of the study area. 1: Border of Mecsek microlandscape unit, 2: stream network
Mean annual precipitation totals vary between 650 and 850 mm with some orographic surplus in the summit regions and decreasing annual totals to the south-eastern margin of the study area. Precipitation showed significant extremities in the last decades (e.g. extreme highs in 2010 and 2014 and an extreme low in 2011) compared to the long-term averages (Hungarian Meteorological Service 2021).

The watercourses of the Mecsek are drained by the Danube via four catchments. The River Karasica drains the Mecsek Mountains in its southern, south-eastern portion and conducts water directly to the Danube. The Pécsi-víz is the main recipient to the southwest, while the Baranya Canal, the River Kapos and the Sió system drain the waters to the north and northwest (Kocsis 2018). There are altogether 298 streams in the study area with a total length of 590.1 km. The mean length of the watercourses ranges between 1.05 and 10.4 km. The maximum Horton-Strahler order of the watersheds 4, but dominantly is either 2 or 3 (Figs. 3 and 4). Peak discharge values vary between about 1 and 35 m³/s depending on watershed characteristics, whereas maximum specific discharge values fluctuate 0.12 and 0.36 m³/s/km².

Intensively managed deciduous forests cover about 320 km² within the studied catchments. The dominant species include European beech (Fagus sylvatica), English oak (Quercus robur) and sessile oak (Quercus petraea) mixed variously with numerous other hardwood species. Only scattered stands of conifers are found in the area (Mecsek Forestry Co. Ltd.).

The soils of the studied area are highly diverse showing a rather heterogeneous distribution. Brown forest soils with significant clay accumulation in the B horizon (WRB:
Fig. 3  Stream orders in watersheds of Mecsek. A border of the calculated watersheds, 1–5 = Strahler orders

Fig. 4  Highest Strahler order (0–4) in every watershed. 1–53 = ID of watersheds
Luvisols, Soil Taxonomy: Alfisols-Hapludalfs) dominate the area, spotted with Leptic Umbrisols, Cambisols, Leptosols, Phaeozems, Rendzinas and Fluvisols (Soil Taxonomy: Entisols, Inceptisols and Histosols). Due to the intense anthropogenic interventions, their general conditions are often deteriorated (Kocsis 2018).

The study area has multiple communities and developed areas (as a legacy of uranium and coal mining), to which headwater hydrologic processes, including flash floods, may pose a significant threat. The largest city is Pécs with 140,237 residents as of 2021, while 61 other communities with a total population of 85,962 people are also found in the area. The main traffic route of national highway 6 and the main railway line connecting Pécs and the capital also passes through the area. The strategic protection of these transport routes from flooding and related mass movements is also of utmost importance.

3 Materials and methods

Similarly to numerous studies (e.g. Tucker et al. 2001; Masoner and March, 2006; Czigány et al. 2008; Pareta and Pareta 2011), the watersheds were delineated from a hydrologically correct DEM of 10-m resolution. ArcGIS 10.2 and the open-source ArcHydro Toolbox were used for morphometric analyses. The delineation of watersheds was adjusted to the boundaries on the map of the national microregion classification presented in the National Atlas of Hungary (Kocsis 2018). In total, 53 watersheds have been delineated.

3.1 Flash flood susceptibility (FFS) mapping

Susceptibility in general is defined as the probability that a risk occurs in a particular area and in a not determined date (Santangelo et al. 2011). Susceptibility mapping (a kind of potential natural hazard mapping) is usually based on the comparison of certain conditioning factors with the distribution of previous events, the latter used as model validation. The occurrence of disasters in time is much less predictable since it depends on hydrologic factors. The patterns of flash-flood generating rainfalls are not identical from year to year (irreducible uncertainty—Compton et al. 2013) but follow some regularities. Empirically, critical levels of storm can be identified from hydrologic data series (e.g. the amount of rain falling within a 6-h period).

The conditioning forces which are assumed to explain flash floods are expressed in the international literature by different sets of indices. For instance, Abedi et al. (2021) employed ten indices: slope inclination and aspect, land use/land cover (LULC), hydrological soil type, lithology, topographic wetness index (TWI), topographic position index (TPI), profile curvature, convergence index and stream power index (SPI), while Youssef and Hegab (2019) used seven flood factors: distance from streams, slope, curvature, lithological units, angle, elevation and topographic wetness index (TWI).

Based on the analysis of morphometric parameters, we employed an improved watershed prioritization according to the main findings of the previous studies (Kadam et al. 2016; Abdo 2020) to establish “site-specific FFS”. Among the morphometric factors discussed by former literature (Esper Angillieri 2008; Singh et al. 2013; Abdel-Fattah et al. 2017; Puno and Puno 2019; Alam et al. 2020; Obeidat et al. 2021) the following parameters have been selected for analysis: area (A), drainage texture (Rt), drainage density (Dd), elongation ratio (Re), form factor (Ff), lemniscate index (k), Gravelius coefficient (GC), forested area (Fa), relief ratio (Rr). Among them A, Dd and Rr were in direct relationship
with the probability of flash flood generation, while $R_t$, $R_e$, $F_a$, $F_f$, $k$ and $G_C$ are in inverse relationship with flash floods. All selected factors are related to runoff intensity and flash flood generation; hence, they are applicable for the evaluation of FFS at watershed levels.

Each factor was reclassified on a linear scale of 0 to 9 (0 = lowest, 9 = highest) using percentile ranking. The mean values of the nine conditioning factors were calculated for each watershed; then, average values were ranked in deciles of even width. Ultimately, in the FFS map, three susceptibility classes were generated from the deciles in the following way: low 0–4, moderate 5–6 and high 7–9.

### 3.2 Calculation of areal parameters

We wanted to investigate as many elementary hydromorphological parameters as they are described in the international geomorphometric literature. In total, 25 parameters were calculated for each watershed; hence, more than 1500 numeric data were generated (Table 1). After checking their interrelationships statistically, 12 areal parameters were found relevant and selected for analysis. Drainage pattern, topography and land use distribution were determined for each catchment. Beyond the fundamental geometric parameters (area and perimeter), ten commonly used morphometric indices were calculated, adapted for the physical characteristics of the study area (Schumm 1956, 1963; Strahler 1957; Morisawa 1962; Mesa 2006; Sassolas-Serrayet et al. 2018).

The individual parameters selected were conceived according to the following definitions. Drainage density ($D_d$) is the ratio between the total length of the stream and the area of watershed and is commonly classified into 5 categories by former literature (Sukristiyanti et al. 2018 and Daipan 2020). The drainage texture ratio ($R_t$) is the total number of stream segments of all order divided by the perimeter of the watershed (Horton 1945). Its division into classes is similar to that of drainage density. Maximum basin length ($L$) is the diameter of the circle drawn around the margins of the catchment. Hack (1957) found a correlation between catchment area and maximum basin length ($L = 1.4A^{0.6}$). Elongation ratio ($R_e$) is the diameter of a circle of the same area as the basin over the maximum basin length (Sukristiyanti et al. 2018). The form factor ($F_f$) shows the ratio of basin area to the square of the maximum basin length (Mesa 2006; Sukristiyanti et al. 2018; Daipan 2020, referring to Horton 1945). Form factors above 0.78 indicate more circular watersheds, while lower values (<0.78) refer to more elongated catchments. Circularity ratio ($R_c$) is the ratio of the watershed area to the area of a circle having the same circumference as the perimeter of the watershed (Daipan 2020). Moores (1966) defined the so-called lemniscate index ($k$) as a measure of deviation of the actual shape of the watersheds from the ideal shape. Chorley (1957) used a loop to measure the shape of drainage basins. If $k = 1$, the basin is circular and becomes more elongated with increasing $k$ values (Moores 1966). The value of the Gravelius coefficient ($G_C$) refers to the compactness of a watershed. $G_C$ is the ratio of the perimeter of the watershed to the circumference of a circle where area is equal to that of the given drainage basin (hence $G_C = 1$ is a circle). The fitness ratio ($R_f$) (Pareta and Pareta 2011) or channel length to perimeter ratio (Melton 1957) is a dimensionless measure for the topographic pattern of watersheds.
3.3 Calculation of linear parameters

The vector-based GIS database of the channel network of Hungary, provided by the South Transdanubian Water Directorate (DDVIZIG, Pécs), was used for the calculation of linear parameters. Seven linear parameters were calculated for each watershed (Table 1) using the approaches by Apaydin et al. (2006) and Biswas (2016).

3.4 Calculation of topographic and land use parameters

The topographic parameters considered were relative relief and relief ratio. The latter is calculated as the difference of the highest and lowest point of the catchment divided by maximum basin length \( L \). According to Schumm (1956) and Daipan (2020), relief ratio \( (Rr) \) is a ratio between the total relief of the watershed (difference the highest and lowest elevation in m) and the maximum catchment length. The Corine Land Cover 2012 database was used to spatially analyse the distribution of land use types of the area (Kamykowska et al. 1999) (Fig. 5). Statistical calculations were performed in Microsoft Excel software environment.

3.5 Hydrological verification

A robust time series of stream gauge data (water stage) from 14 sites (a-n) obtained from the Directorate DDVIZIG were applied for verification (see Figs. 1, 6). Although these time series vary in length (4–21 years), we believe that the number of flash flood events is relevant for our topic. Flash floods were defined as marked stage changes between two measurement times (typically 15 min to 60 min). All stage changes were sorted into ten bins of equal width considering the minimum and maximum stage changes at each stream gauge (Fig. 7). Consequently, flash flood events of the three highest deciles were then used for the verification of the FFS map.

4 Results and discussion

Our formulae were grouped based on areal/geometric properties, linearity, relief and land use presented in former literature (Srinivasa Vittala et al. 2004; Farhan et al. 2016; Fenta et al. 2017; Daipan 2020). Although we aimed at adjusting our analyses to the formerly published systems, some minimal subjectivity was unavoidable during the classifications. Table 2 shows the investigated morphometric parameters employed in the current study.

4.1 Areal and geometric parameters

At this level of detail areas of the studied watersheds ranged from 1.45 to 37.3 km\(^2\). According to the classification scheme proposed by Daipan (2020) they belong to the micro \( (A \leq 10 \text{ km}^2, \ n = 20) \) and small \( (A = 10 \text{ to } 100 \text{ km}^2, \ n = 33) \) watershed categories. In accordance with the findings of Zavoianu (1985), performed on watersheds of hilly and mountainous terrains, we found a close linear correlation between catchment perimeters and catchment area with an \( R^2 = 0.78 \) (Fig. 8). The general inverse relationship between
watershed size and flash flood susceptibility, therefore, suggests high levels of flash flood hazard for the study area (Daipan 2020).

This is explained by the rapid hydrologic response due to the steepness of slopes of small headwater catchments and the surplus precipitation of orographic origin. In terms of runoff intensity, the short times of concentration have already been documented for the small headwater catchments of the Mecsek Mountains (Czigány et al. 2008).

For drainage texture (Rt) all studied watersheds belong to the very coarse class (low drainage density) as its value was found to be less than 2 km km\(^{-1}\) in all cases. The low surface density of drainage is likely explained by the jointing of limestone and the relatively dense vegetation cover in the majority of the area (mean forest cover: 46.5%). These properties reduce flash flood susceptibility.

| Parameters                        | Formula          | References          |
|-----------------------------------|------------------|---------------------|
| Areal/geometry parameters         |                  |                     |
| Perimeter (P) [km]                | –                | –                   |
| Area (A) [km\(^2\)]              | –                | –                   |
| Drainage texture (Rt)             | \(Rt = Nu/P\)    | (Horton 1945)       |
| Max. basin length (L) [km]        | –                | –                   |
| Integration index (C) [km\(^2\)/km] | \(C = A/L\)     | (Kamykowska et al. 1999) |
| Drainage density (Dd) [km/km\(^2\)] | \(Dd = \sum L/A\) | (Strahler 1957)     |
| Elongation ratio (Re)             | \(Re = D/L\)    | (Schumm 1956)       |
| Form factor (Ff)                  | \(Ff = A/L^2\)  | (Mesa 2006)         |
| Circularity ratio (Rc)            | \(Rc = 4\pi A/P^2\) | (Mesa 2006)       |
| Lemniscate index (k)              | \(k = L^2 \pi/4A\) | (Moores 1966)     |
| Gravelius coefficient (GC)        | \(GC = P/2\sqrt{\pi A}\) | (Sassolas-Serrayet et al. 2018) |
| Fitness ratio (Rf)                | \(Rf = Cl/P\)   | (Pareta and Pareta 2011) |
| Linear parameters                 |                  |                     |
| Number of streams (Nu)            | –                | –                   |
| Stream length (SL) [km]           | –                | –                   |
| Total stream length (\(2L\)) [km] | –                | –                   |
| Max stream order (\(u_{max}\))   | –                | (Morisawa 1962)     |
| Total length of stream orders (\(\Sigma u\)) [km] | – | – |
| Mean stream length (Lu) [km]      | \(Lu = SL/Nu\)  | (Biswas 2016)       |
| Length of main channel (Cl) [km]  | –                | –                   |
| Relief parameters                 |                  |                     |
| Maximum height (H); minimum height (h) [m] | – | – |
| Basin relief (r) [m]              | \(r = H - h\)   | –                   |
| Relief ratio (Rr)                 | \(Rr = H - h/L\) | (Schumm 1956)       |
| Land use parameters               |                  |                     |
| Forested area (Fa) [%]            | –                | (Kamykowska et al. 1999) |
| Grassland area (Ga) [%]           | –                | (Kamykowska et al. 1999) |
| Arable land area (Aa) [%]         | –                | (Kamykowska et al. 1999) |

\(D\) diameter of the circle of the same area as the basin
Maximum catchment lengths ($L$) varied broadly, spanning between 2.60 and 17.11 km. Maximum basin length, in accordance with our presumptions, showed a close relationship with watershed areas and perimeters ($R^2 = 0.62$ and 0.85, respectively) (Fig. 8). The $L$ value is assumed to be inversely proportional with flash flood susceptibility.

Drainage density (Dd) is supposed to be closely correlated with lithology and the tectonic evolution of the catchment (Tucker et al. 2001). Others found correlation between relative relief and Dd value (Nag 1998). Our results revealed no correlation with basin relief ($R^2 = 0.003$) (Fig. 8). Calculated Dd varied between 0.16 and 1.57 with a standard deviation of 0.33. Based on the available classification of the aforementioned two literary sources, the studied watersheds belong to the group of very low drainage density catchments ($Dd < 2 \text{ km km}^{-1}$). Adopting the results of Melton (1957) to our study site, we found different Dd values for watersheds of different area and identical lengths. Low Dd values indicate basins of relatively low surface stream density and a prolonged hydrologic response and refer to permeable near-surface rocks, dense vegetation and low relief (Sukristiyanti et al. 2018).

Computed low elongation ratios ($\bar{x} = 0.56$) demonstrate that the majority of the analysed watersheds are elongated (0.5–0.7, $n = 33$) or highly elongated ($< 0.5$, $n = 13$). Only a minority of them are less elongated (0.7–0.8, $n = 6$) and oval (0.8–0.9, $n = 1$). The large number of elongated and highly elongated basins suggests younger and
neotectonic evolution, whereas oval and circular basins show higher runoff intensity. This finding corroborates the results of Daipan (2020); Elsadek et al. (2019) and Sukristiyanti et al. (2018). Furthermore, the low Re values indicate low flood hazard in basins 5, 48, 51 and 53 (Re = 0.44, 0.32, 0.37 and 0.47, respectively). In contrast, the high Re values of basins 12, 19, 21 and 35 (0.71, 0.76, 0.75 and 0.82, respectively).
likely demonstrate intense erosion and high flash flood hazard. Elongated watersheds are usually characterized by longer distances between the adjacent confluences (hydrographic nodes), low peak flows and broader hydrographs. All studied watersheds have low form factors and, therefore, are considered to be elongated rather than circular (0.08–0.53). This parameter did not provide any additional information on flood hazard.

Circularity ratio (Rc), essentially the same as elongation ratio and form factor, of less than 0.5 was found for all studied watersheds of the current study, again indicating low runoff. The calculated lemniscate ($k$) values (1.47 to 9.59) in our study are dominantly high and, hence, similarly to the circularity ratio, indicate elongated catchments. This finding also confirms the fact that reduced $k$ values are coupled with increasing stream orders. Gravelius coefficients (GC) of 1.53 to 2.97 were found for the watersheds from which GC values of 1.7 to 2.1 covered 68% of the total area. According to the classification of Sassolas-Serrayet et al. (2018), 25 catchments (47.1%) with a total area of 295.7 km$^2$ (45.4% of the mountainous area) belong to the group of elongated (GC ≥ 2) catchments (Fig. 9).

In correspondence with previous literature, maximum basin length showed a markedly higher correlation with catchment area ($R^2 = 0.67$) than with main channel stream
Fig. 8 Charts of correlations between some measured watershed parameters

Fig. 9 Various types of the watershed according to Gravelius coefficient and its histogram. According to (Sassolas-Serrayet et al. 2018)
length. It was due to the inaccuracy of the drainage network database, where streams with order = 1 were not included (Fig. 10).

### 4.2 Linear parameters

For the stream order we used the traditional hierarchical ranking by Strahler (1957). The lowest and the highest orders and the number of stream segments in the studied basins are shown in Table 2. The maximum Strahler orders \( u_{\text{max}} \) in the studied catchments were found to be dominantly between 1 and 3. Watercourses of Strahler order of 3 \( (n=4) \) were only found in the periphery of the studied area (Figs. 3 and 4). Total stream lengths \( (\Sigma L) \) varied between 1.05 and 36.27 km. We found a correlation of \( R^2 = 0.75 \) between the two parameters which points out that number of streams is associated with greater total length (Fig. 8).

### 4.3 Topographic parameters

Properties associated with relief were characterized by the parameters of maximum height \( (H) \), minimum height \( (h) \), basin relief \( (r) \) and relief ratio \( (R_r) \). The highest \( (H) \) and the lowest \( (h) \) points of the studied catchments are located at elevations of 201 to 680 m and 105 to 224 m, respectively. Basin relief changes in close correlation with \( H \) \( (R^2 = 0.93) \) (Fig. 8). In accordance with former findings (Daipan 2020), relief ratio was also found higher for watersheds of smaller area.
4.4 Land use parameters

In accordance with the findings of Kamykowska et al. (1999), we revealed that response times of flash floods in the studied area are significantly controlled by land use, i.e. the extent of forests (Fa), grasslands (Ga) and arable land (Aa). Percentage forest cover in the headwaters was found especially influential on delaying and mitigating runoff and changing the proportions of evaporation, infiltration and surface runoff. Percentage of forests, strongly correlated with high relief and higher elevation, exceeds 70% in the studied watersheds. (The average ratio of forests is 23.4% for the Mecsek Mountains.) However, the higher percentage of forested areas contributes to an intense production of woody debris contributing to flash flooding in the area through hindering runoff. In the foothill areas of lower elevation arable lands dominate the watersheds, while the total area of natural pastures is negligible (Fig. 5).

4.5 Flash flood susceptibility (FFS)

We revealed that the parameters most significantly contributed to flash flood generation were watershed size (small or medium) and compactness. Runoff was further intensified by high relief and low forest cover. The highest flood susceptibility (7 to 9) was revealed in, e.g. watersheds 2, 10, 12, 16, 19, 29, 35, 49, whereas low susceptibility (0 to 4) was found for watersheds of large area, elongated shape, low relief and extensive forest cover (e.g. 5, 13, 15, 17, 18, 31, 32, 38). Moderate susceptibility (5 and 6) characterized watersheds of high forest cover and headwater position (e.g. 4, 7, 8, 11, 23, 24, 27, 43, 44) (Fig. 6).

Our results partly corroborated the findings of previous modelling which had been based on the spatial distribution of precipitation totals and intensities (e.g. Lóczy et al. 2012b). The spatial distribution of flash flood susceptibility showed a good spatial correspondence with the documented locations of flash flood events in the Mecsek Mountains (watersheds 2, 7, 12, 16, 41, 46, 47, 49) (Pirkhoffer et al. 2009) (Fig. 6).

In contrast, ranking purely based on morphometric parameters performed somewhat poorly in the south-central part of the studied area (downtown Pécs, watersheds 36, 39, 40, 45, 48). Here, urban development, improper maintenance of hydrologic structures used for flood mitigation and smooth conveyance of stormwater and large extent of impervious surfaces may significantly increase runoff and may alter flow directions. Such factors increase the actual flood potential of these watersheds (Czigány et al. 2010) (Fig. 6).

From the comparison of watershed ranking for flash flood susceptibility with stage data of official stream gauges, the following conclusions have been drawn. The number of events undoubtedly qualified as flash floods and the susceptibility rank established from shape, morphological, relief and land use variables do not correlate ($R^2 = 0.28$) (Fig. 11). Verification of the FFS map may be distorted by a plethora of factors. Out of the 53 studied watersheds stage data were only available in ten cases. Additionally stream gauges were rather unevenly distributed with four watersheds monitored with two gauges each. Furthermore, the outlets of the delineated watersheds did not coincide with the locations of the stream gauges and the available stage datasets did not chronologically overlap.

Verification could be improved by the reported flash flood-related economic losses available from the General Directorate of Water Management. Czigány et al. (2011) published an FFS map for Hungary and verified results based on losses of settlements.
However, these losses were recorded at settlement level instead of watershed level. Hence, marked spatial disparity must exist between the two geographical entities. Therefore, the dataset of settlement-level losses could be applied for the verification of the current results with limitations.

## 5 Conclusions

In the present study twenty-five morphometric parameters were used to characterize 53 watersheds of the Mecsek Mountains. Based on the computed parameters, the watersheds were evaluated and prioritized according to their flash flood susceptibility. The highest FFS was found in watersheds of foothill positions, dissected topography and areas of low infiltration rates (sandstone and marl). These findings aptly reflect the morphometry and the ruggedness of the Mecsek Mountains, as well as its variable lithology and intense tectonics all of which indirectly contribute to flash flood generation.

However, validation based on stage data and the reported flash flood-related losses is rather challenging. The low correlation ($R^2 = 0.28$) between stage data and FFS map was not unexpected due to the low number ($n = 10$) of gauged watersheds in the study area. This necessitates the installation of stream gauges and hydrometeorological monitoring networks in ungauged watersheds, as measured data are vital for the adequate verification of FFS maps and models.

Nonetheless, the high flash flood susceptibility should not be exclusively attributed to specific morphometric traits. Flash flood events are rather triggered by extreme runoffs due to intense meteorological events, further augmented by inappropriate landscape management and altered land use patterns due to human interventions. Additionally, channel parameters like sinuosity, spatial density of confluences and the frequency of coarse woody debris jams may also contribute to the inundation of the valley bottoms. These parameters should also be weighted site-specifically for increasing the accuracy of models of this sort.

For the more profound investigation of urban catchments, an analysis of microwatersheds DEMs of submeter resolution and GIS databases of urban drainage utility networks
would be indispensable (Burns et al. 2015; Towsif Khan et al. 2020). Also, the integration of land use data, infrastructure for managing excess stormwater runoff and linear flowpaths are vital for the refinement of the present FFS map. Such improvements are expected to increase the efficiency of flash flood prediction in urban areas and may decrease flood-related loss of lives and economic damage. Based on these maps, decision makers could develop and appropriately locate flood mitigation facilities, such as flood retention pools and permeable surfaces to enhance infiltration over excess runoff. Similarly, for optimal watershed management more detailed GIS analyses of anthropogenic controls on flash flood hazard are also needed in the future.

Our findings are applicable for the headwater sections of low mountains in the humid and semi-humid temperate zone, where the mosaic pattern of partially urbanized areas and forested lands dominates the landscape.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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