Flood Hazard in a Mountainous Region of Slovakia

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Contents

Abstract Slovakia is a mountainous country, and the occurrence of floods in headwater areas is thus an important phenomenon. The chapter concerns the identification of regional types of flood hazards in a mountainous region resulting from the physical geographic characteristics of the upper basins. The regional type is the unit of regional taxonomy, which is not contiguous in geographical space and is referred to as the flood hazard potential or disposition of the basins to floods. A brief overview of flood events in Slovakia is provided. Then, the rest of the chapter presents the assessment of the flood hazard itself. The evaluation process consists of four steps. The first step of the regional taxonomic process is creation of a basic set of upper basins and a database of their physico-geographic attributes. The second step is identification of the physical geographic attributes that significantly influence the basic features of the drainage process

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and the spatial variability of the flood hazard. The delineation of flood hazard classes based on a combination of physical basin attributes and classification of upper basins into flood hazard classes is the third one. Testing the significance of differences between the assigned flood hazard classes in terms of the frequency of flood situations is the last fourth step.

Keywords Flood hazard, Flood situation, Regional type, Slovakia, Upper basins

1   Introduction

The period from the second half of the 1970s to the 1980s was exceptionally peaceful in terms of the occurrence of floods in the Slovak Republic (MoE SR). However, since the second half of the 1990s, we have seen more frequent occurrence of floods in Slovakia, as in other European countries, causing loss of life and considerable damage to the property of citizens and municipalities as well as to organizations in the private and public sectors [1, 2]. Preventing flood damage or minimizing its extent is, therefore, becoming a very urgent requirement. The issue of floods has become a major societal issue for government, local authorities, academic and research institutions, and water management and hydro-meteorological organizations as well as non-governmental organizations.

With regard to flood issues, the paradigm of their solution is changing from a traditional engineering approach to integrated assessment and management of flood risk (c.f. [3–9]). The integrated approach is based on idea that "in evaluating disaster risk, the social production of vulnerability needs to be considered with at least the same importance that is devoted to understanding and addressing natural hazards" [10]. In the case of flood hazard, it also underlines the principle "that all types of flooding should be managed coherently, thereby including sewer flooding, pluvial flooding and groundwater flooding alongside the traditional coastal and riverine flooding" [11]. The emphasis placed only on river flooding can be considered legitimate and understandable, particularly in the middle and lower parts of rivers in lowland and basin territories. In these river sections, this type of flood hazard dominates, and flood protection structural measures are practically the only measures that can be used to reduce the extent of flooding. The situation is different, however, in the upper basins in the mountain, foothill, and hill areas. The diversity of physical attributes of upper basins not only causes various hydrological responses to precipitation but also, together with the impact of local anthropogenic factors, creates conditions for the emergence of other forms of flood hazards (e.g. sheetwash flooding) besides natural river flooding. Therefore it is necessary to assess flood hazard in headwater areas in a comprehensive way. The upper basins are of key importance in the framework of flood risk management. Increasing their retention capacity and reducing the influence of local factors that accelerate floods is the first step that is needed to reduce flood hazard in downstream areas.

Slovakia is a country where the mountains occupy 71% of the total area, and 37% of the total of 2,928 municipalities (i.e. 1,093) are located in upper basins in mountainous, foothill, or hill areas [12]. Analysis of the occurrence of flood situations in Slovakia in 1996–2006 showed that 67% of flood events occurred in

municipalities located in upper basins [1]. The occurrence of floods in upper basins in the mountain, foothill, and upland areas is thus an important phenomenon in Slovakia. For this reason, it is necessary to give appropriate attention to an integrated assessment and management of flood hazard in the upper basins.

2 A Brief Overview of Flood Events in Slovakia

2.1 *Historical Floods Up to the Second Half of the 1970s*

The references to historical floods in Slovakia are mainly related to floods that have occurred in large streams. Basic information about the history of floods in Slovakia is provided by the website of the Ministry of Environment SR [13] or the Slovak Water Management Company [14]. Through the study of available historical documents, the occurrence of floods was documented in detail on the river Váh by [15], on the Danube by [16, 17], and on the Slana River by [18].

Probably the biggest flood on the Danube in Bratislava was the flood in 1516, marking the height of the peak level at the pillar of Vydrická Gate, and is also the oldest preserved flood mark in the territory of Slovakia [17]. The most famous flood in the eighteenth century took place at the beginning of November 1787 and was also referred to as the "Hallowmas flood". The whole of the nineteenth century was marked by ice floods, in which accumulated blocks of ice caused clogging and raised the water level. Disastrous for Bratislava was that of 5 February 1850. One of the preserved flood markings at the corner of Laurinska and Uršulinska in the historic core of the city is 182 cm above the pavement level. The flood caused tremendous damage, and six people died. From the point of view of the extent of the flooded area and the damages caused, the flood on the Danube in 1965 was extremely destructive. The prolonged high water conditions in the Danube and frequent rain from early March to the second half of July had adverse effects on the stability of the protective dykes and their subsoil, which resulted in considerable seepage. Despite the enormous efforts made, it was not possible to prevent the three breakdowns that occurred in June on the dykes along the Danube (two breaks) and the Váh River (one break). After the breakdown of the Danube dykes, 46 municipalities and three settlements were threatened, which resulted in the evacuation of 53,693 residents as well as 35,759 cattle, 394 horses, 58,041 pigs, 8,700 sheep, 654 goats, more than 83,000 poultry, and some other livestock. Flooding destroyed 3,910 houses and seriously damaged 6,180, and the water flooded 71,702 ha of agricultural land, while another 114,000 ha were waterlogged. Water damaged 250 km of roads and about 70 km of railway lines. The state insurance company registered damage amounting to 100 million euros, but the actual flood damage was probably much higher.

Historically, the biggest flood on our longest river, the Váh river (with a length of 406 km), which is preserved by archival documents, was the flood of 1813 [15]. It ravaged the entire valley of the Váh, from Žilina to Sereď. As a consequence, 243 people

died, and most of the houses in 50 villages were destroyed. In the first half of the twentieth century, there were several major floods in the Váh catchment area. For example, the July 1903 flood in Orava is mentioned. Further floods on the Vah River occurred in August 1925 and 1938, in July 1943, in February 1946, and in January and June 1948. In the Váh catchment area, the largest flood since 1813 occurred in June 1958. A flood in the Liptov and Kysuca region caused extensive damage. In Liptov, 21 communes and parts of the towns of Liptovský Mikuláš and Ružomberok were flooded. The flood situation also required the evacuation of 60 families from Terchova. In the Kysuce catchment, the settlement of Skorka; the communes of Svrčinovec, Stará Bystrica, and Krásno nad Kysucou; and part of the Kysucké Nové Mesto town were flooded. The water flooded several stretches of roads, including the state roads in the Liptovský Mikuláš–Ružomberok and Turany–Sučany sections, as well as the railway line between Vrútky and the Strečno.

Past floods of the Hron catchment lack more compact records. However, some reports of floods in 1784, 1813 (the largest known flood, whose highest water status is recorded on the flood marker in Banská Bystrica), 1847, 1853, 1899 (larger than the flood in 1974), 1928, 1931, and 1960 have been preserved. The largest flood in the Hron basin in the twentieth century occurred in October 1974. A devastating flood flooded 4,650 family houses, 82 km of roads, and 30 km of railway lines, and an area of 64,000 ha was underwater. In the upper and middle parts of the Slana catchment, the course of the floods was reinforced in October 1974 by joining with flood waves in the Murán and Turiec tributaries. At the Lenártovce Slaná station, the flood culminated in a maximum discharge of $350 \, \text{m}^3 \, \text{s}^{-1}$, which is repeated, on average, once every 500 years.

There is no doubt that in the past, Eastern Slovakia was a frequent area of flood disasters. On the basis of preserved records, floods with an average return period of 100 years can be considered, as occurred in the Bodrog and Tisza basins in 1888. The occurrence of large floods was also frequent in this area in the twentieth century. The largest floods in the Bodrog and Tisza catchments which should be mentioned were those of 1924 and 1932. Large floods also occurred in 1967, 1974, 1979, and 1980. A major flood hit the entire catchment area of the Hornád River in 1958, and the Torysa catchment experienced flooding in 1952.

2.2   Incidence of Floods from the Second Half of the 1990s

Basic knowledge of the occurrence of floods, with an emphasis on the analysis of the meteorological conditions that caused the floods, is processed annually in the reports issued by the Slovak Hydrometeorological Institute (SHMÚ) and in materials prepared by the Ministry of Agriculture of the Slovak Republic (MP SR) and the Ministry of the Environment of the SR (MoE SR) for the negotiations of the Government of the SR. The incidence of flood situations in the municipalities of Slovakia in the period 1996–2014 is shown in Fig. 1.
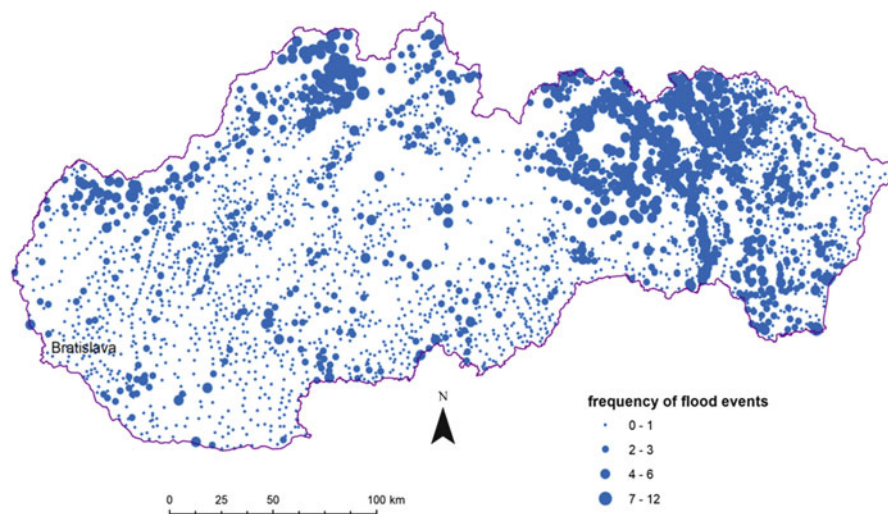
Fig. 1 The occurrence of floods in the municipalities of Slovakia in the period of 1996–2014

The analysis of the floods that occurred in 1997–1999 in small river basins in relation to their physical geographic conditions was addressed by [19, 20]. Reference [21] employed a geographical information system (GIS) to analyse the occurrence of floods on Slovak rivers in the period of 1985–2000. A detailed analysis of the occurrence of the flood events in the territory of Slovakia in the period 1996–2006 was presented by [1]. A flood event refers to a state of a river that requires the declaration of the third level of flood activity because the river has begun to overflow its channel or there is a threat that a dyke will overflow or break down. The analysis showed that during the period in question, flood events occurred in 1367 out of a total of 2,928 municipalities in Slovakia. Of these, 920 municipalities, that is, 67% of those that experienced flooding, were located in the small upper basins, 6% were located along medium-sized rivers (basin areas of 300–1,000 km^2), 20% along large rivers (basin areas over 1,000 km^2), and the remaining 7% of those affected by floods were outside the upper basins and buffer along medium and large streams (Fig. 2).

In terms of the types of flood events, they were mainly flash floods in municipalities located in upper basins (Table 1). Of the more than 800 flash floods that occurred between 1996 and 2006, the most tragic consequences were caused by the flood on the Little Svinka Creek in July 1998. During the storm, more than 100 mm of precipitation occurred in the upper part of Svinka basin in about an hour, and the subsequent flood wave with high of up to 4 m caused the loss of 50 lives and considerable material damage.

In terms of scope, extreme floods occurred in 2010, when the floods affected virtually the entire territory of Slovakia. The main cause of the floods in 2010 was the extraordinary to extreme and especially long-lasting precipitation that hit the larger areas of Slovakia repeatedly, in many cases in the same regions. The floods in 2010 affected 33,080 inhabitants, two people died, 12 were injured, and 25,224 were

Fig. 2 The flood situations
in the period of 1996–2006
in municipalities located
along rivers of different
sizes (reproduced from [1])

small rivers (67,37%)

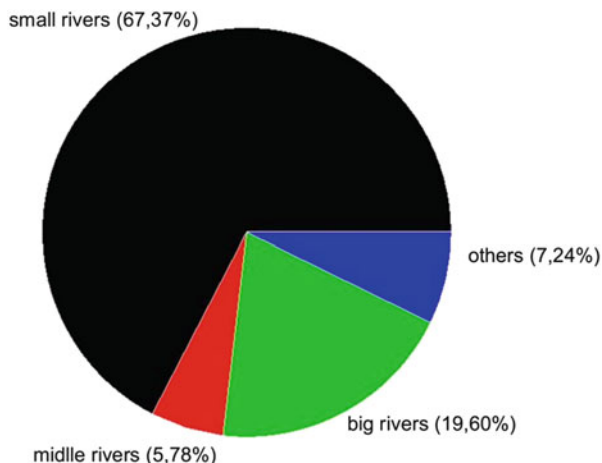others (7,24%)

big rivers (19,60%)

midlle rivers (5,78%)

Table 1 Frequency of
occurrence of flood events in
1996–2010 according to the
type and size of the
watercourses (reproduced
from [1])

Size of river	Type of flood event					Total
	R	F	L	V	H	
Small rivers	656	813	34	18	6	1,527
Middle rivers	89	78	5	2		174
Large rivers	275	152	24	26	21	498
Outside of river buffers	31	18		66	9	124

R, river or regional floods; *F*, flash floods; *L*, ice jam flood; *V*,
internal flood; *H*, flood due to breakage of a water structure

evacuated, and the water flooded 27,521 residential buildings, of which 26,364 were
family houses. An area of 97,290 ha was underwater, of which 6,680 ha was in
residential areas; floods damaged 2.7 km of class I roads and 47.5 km of class II and
III roads. The verified flood damage amounted to 336.9 million euros. This amount
excludes flood damage in the primary agricultural, forestry, and fish farming sectors.

3   Impact of Physical Geographic Attributes of River Basin on the Spatial Variability of Flood Hazard in Headwater Areas

The primary cause of floods is precipitation or specific climatic situations. The trans-
formation of rainfall into a runoff is, however, a complex process [22–26]. The physical
geographic attributes of the basin affect three important hydrological variables (water
retention areas, infiltration, and the movement of water [27]) and cause disparities in the
flood hazard between upper basins. The diversity of physical geographic attributes of the
upper basins (relief and soil substrate properties as well as the character of landscape

cover and land use), however, means that snow melt or the same long- or short-term precipitation falling onto basins with different attributes may not always result in floods. This is also documented by the spatial variability of the occurrence of flood situations in Fig. 1. There is a higher frequency of flood events in some parts of Slovakia than in others.

General information on the basic features of the drainage process in the river basin and the resulting flood hazard is provided by a hydrogram of average daily discharges. Figure 3 shows hydrograms of three upper basins with different physical geographic attributes. The hydrogram in Fig. 3a includes a basin that is built up by a Palaeogene flysch with a predominance of clay, on which soils with very low permeability of the soil texture are created, and the forestry covers 63% of the basin. The hydrograph is characterized by sudden and steep flood waves and suggests that the dominant drainage process in the river basin is surface or direct runoff. The maximum values of normalized average daily discharges are more than ten times higher than the average annual discharge. The hydrograms in Fig. 3b, c are for river basins, the first of which is characterized by a permeable soil texture on the crystalline slate, with forestry covering 84% of the basin. In the second river, aeolian sand with a very permeable soil texture predominates, and the forest covers 47% of the river basin. The hydrograms indicate that the predominant drainage in the basins is basic runoff. In this form of runoff, there are typically shallow and longer-lasting flood waves with values of normalized average daily discharge that are only four and two times higher, respectively, than the average annual discharge.

In addition to the visual interpretation of the hydrograms, the basic features of the drainage process in the basin can be expressed in a quantitative way in the form of a base flow index (*BFI*). The value of the BFI indicates the ratio of basic runoff to total runoff. A high *BFI* suggests that the basic runoff dominates in the runoff process and that the potential for flood hazard is low. On the contrary, a low value *of BFI* indicates that the prevailing form of runoff in the catchment is a direct runoff, and the potential for flood hazard is higher. For example, the *BFI*s for the river basin shown in Fig. 3a–c are 0.26, 0.68, and 0.93, respectively. Due to the different
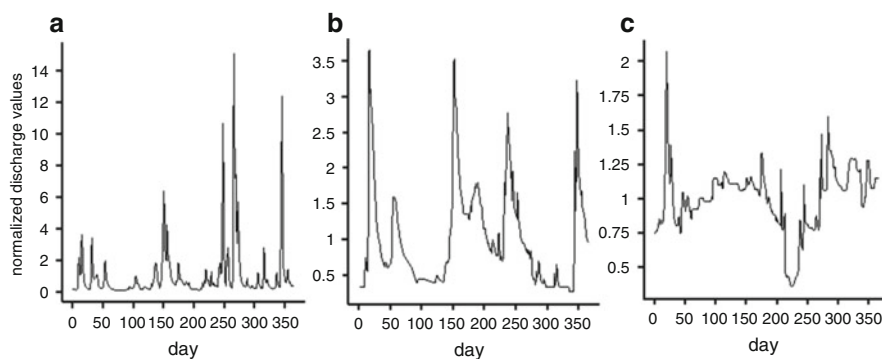

Fig. 3 Examples of different hydrological responses: (**a**) river Ladomírka, (**b**) river Rimava, (**c**) river Láb

transformations of precipitation into runoff caused by the physical geographic attributes of the river basin, we can assert that there is a greater flood hazard in the river basin in Ladomírka (Fig. 3a) than in the basins of the rivers Rimava and Láb (Fig. 3b, c).

The threat of flood occurrence resulting from the physical geographic characteristics of the basin is referred to as the flood hazard potential [28], geoecological flood hazard potential [29], or disposition of the catchment to flood [30]. The assessment of the spatial variability of the flood hazard potential in the upper basins requires:

(a) The creation of a basic set of upper basins and database of their physico-geographic attributes
(b) Identification of the physical geographic attributes that significantly influence the basic features of the drainage process and the spatial variability of the flood hazard
(c) Delineation of the flood hazard classes based on a combination of physical basin attributes and classification of the upper basins into flood hazard classes
(d) Testing of the significance of differences between the assigned flood hazard classes in terms of frequency of occurrence of flood situations

3.1 Basic Set of Upper Basins of Slovakia and a Database of Their Physical Geographic Characteristics

A digital layer of small basins had been digitalized by the Slovak Environmental Agency (SAŽP) in the years 1997–1998 from the map of water management in scale of 1:50,000. However, water divides of basins had to be adjusted by [31] to take the function of the basic spatial units for the needs of regional taxonomy. The digital layer contains almost 4,587 autochthonous small upper river basins with areas ranging from 0.04 to 150 km^2. In view of the fact that the response from the river basin, whose area occupies more than 5 km^2, is hydrologically significant [32], the original set of upper river basins was reduced to 1,678 basins with an area in the range of 5–150 km^2. The upper limit of the size of the area of the basin reflects the diversity of the relief of the territory of Slovakia.

A database of physico-geographical characteristics of upper basins containing a large set of attributes representing precipitation, relief, geology, soil, and land cover was created by [33]. The input digital layers for the determination of river basin attributes were a digital relief model [34], soil map [35], a map of the CORINE Land Cover [36], hydrogeological map [37], and a map of average annual precipitation [38]. Graphical visualization of the basic physical geographic attributes of the upper basins is presented in Figs. 4, 5, 6, and 7.

Differentiation of soils from the point of view of permeability is the result of two basic physical soil properties, texture and structure, which determine the size, shape, and geometric arrangement of soil pores. Permeability is the ability of the soil to allow the
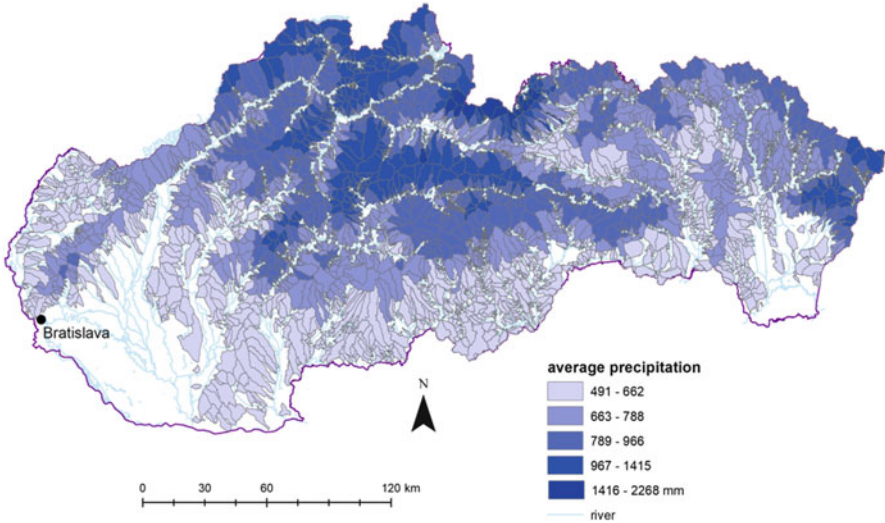
Fig. 4 Average annual precipitation (1976–1995) of the upper basins (reproduced from [33])
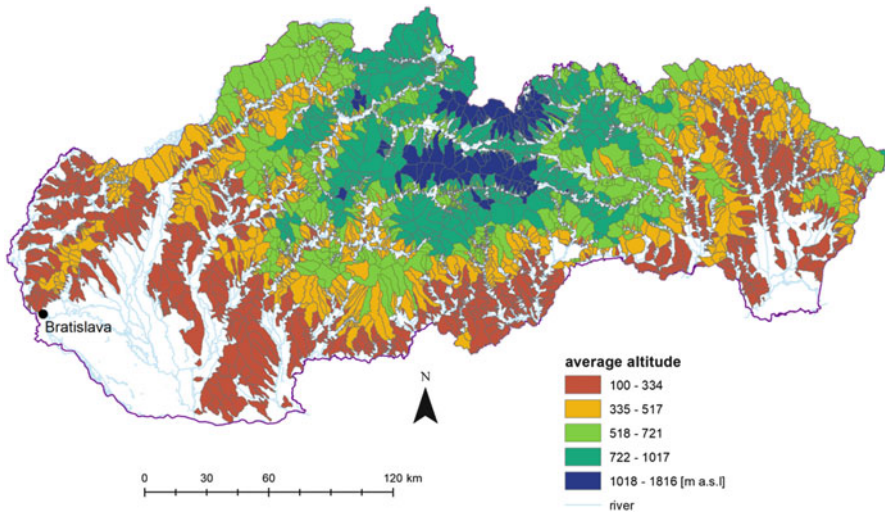
Fig. 5 Average altitude of upper basins (reproduced from [33])

passage of precipitation water from the surface of the soil into deeper soil horizons. With regard to the soil texture of non-capillary pores, there is a decline from coarse-grained categories to fine-grained categories [39]. As a result, the permeability decreases from coarse-grained categories to fine-grained categories (Table 2).

Based on the relationship between the rock and soil texture determined by [40, 41], as shown in Table 3 and on the hydrogeological map of Slovakia at a scale of 1:500,000, a
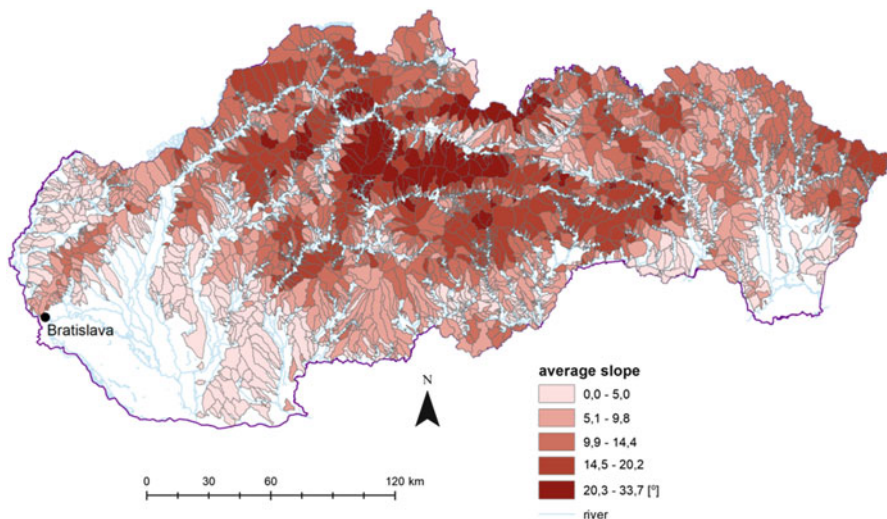
Fig. 6 Average slope of upper basins (reproduced from [33])

Fig. 7 Percentage of forest in upper basins (reproduced from [33])

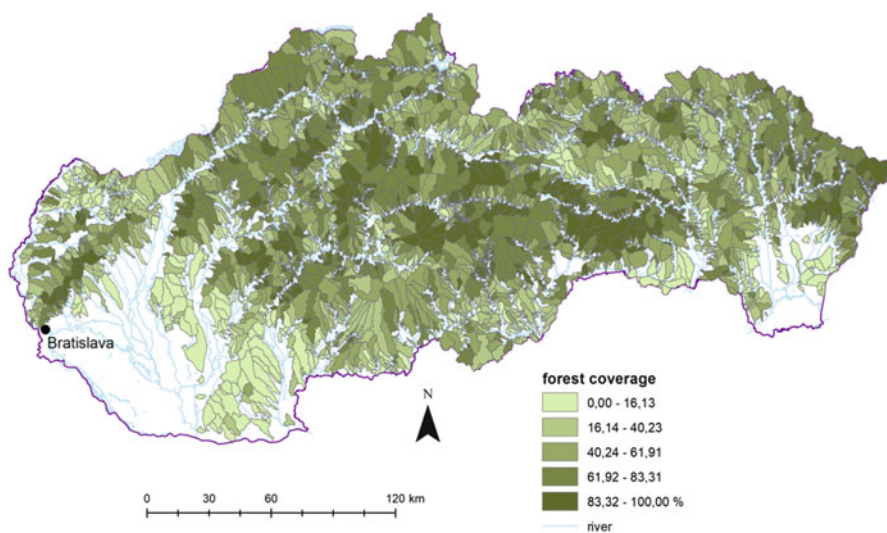map of the spatial distribution of the soil texture categories was compiled. By overlaying this thematic layer with that of the small basins of the SR, the percentages of the individual soil texture categories in each basin were assessed. The index of soil texture permeability of the basin (*ISTP*) was set afterwards by:

Table 2 Permeability of soil texture categories

Soil texture category	Share of particles smaller than 0.01 mm	Category of permeability	Ordinal value of permeability
Sandy	0–10%	Absolutely permeable	7
Loam-sandy	10–20	Very well permeable	6
Sand-loamy	20–30	Well permeable	5
Loamy	30–45	Permeable	4
Clay-loamy	45–60	Poorly permeable	3
Very clayey	60–75	Very poorly permeable	2
Clay	>75	Not permeable	1

Table 3 Relationship between soil texture and rock

Soil texture	Rock
Sandy	Sand deposits
Loam-sandy	Quartzite, granite, granodiorite
Sand-loamy	Melaphyre, granodiorite, gneiss, porphyroid, flysch-sandstone
Loamy	Andesite rocks, porphyroid, gneiss, amphibolite, loess, dolomite
Clay-loamy	Andesite rocks, phyllites, loess, limestone, flysch-clayey shale
Clayey	Marlite, marly shale, marly limestone
Clay	Neogenic formations of clay and marl

$$ISTP = \frac{\sum P_{pj} \cdot I_{pj}}{100} \tag{1}$$

where $ISTP$ is the permeability index of the basin, P_{pj} is the percentage of soil texture category of the total basin area, and I_{pj} is the corresponding permeability value. The values of $ISTP$ were then grouped into interval classes of soil texture permeability (Table 4). The classification of the upper basins in terms of $ISTP$ is visualized in Fig. 8.

In the case of the soil structure of the soil horizons, it is assumed that the permeability decreases from unstructured aggregates and structural aggregates that are evenly developed in three directions towards structural aggregates that are vertically and horizontally elongated (Table 5). Each soil unit is characterized by a certain grouping of soil horizons, and in the assessment of the soil unit permeability as a whole, the "bottleneck" principle was applied [42]. This means that the permeability corresponding to the least permeable soil horizon was attributed to the soil unit (Table 6, numbers in bold in the last column).

By overlaying the map soil units with the layer of small basins in Slovakia, the percentage of each type of soil unit in the basin was expressed. Subsequently, an

Table 4 The classes of soil texture permeability index

Permeability index *ISTP*	Class of soil texture permeability
1.00–1.50	1 – Not permeable
1.51–2.50	2 – Very poorly permeable
2.51–3.50	3 – Poorly permeable
3.51–4.50	4 – Permeable
4.51–5.50	5 – Well permeable
5.51–6.50	6 – Very well permeable
6.51–7.00	7 – Absolutely permeable
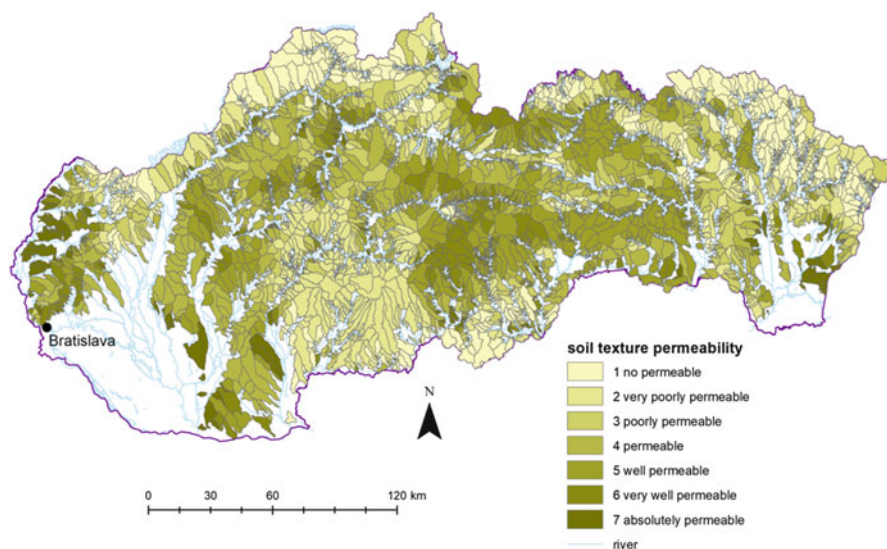
Fig. 8 Classes of soil texture permeability of upper basins

index soil structure permeability (*ISSP*) was assessed for each basin by using Eq. (1), where classes of soil structure permeability were used instead of soil texture permeability classes. The distribution of upper basins into classes in terms of soil structure permeability is presented in Fig. 9.

3.2 Analysis of the Influence of Basin Attributes on Spatial Variability of the Flood Hazard

The analysis of the impact of the physical geographic attributes on flood hazard includes the investigation of the dependence between classes of physical geographic attributes of the basins on the one hand and *BFI* values and frequency of flood events on the other hand [28]. In the case of *BFI*, the analysis was carried out

Table 5 Permeability of soil horizons

Soil horizon	Soil structure	Class of soil structure permeability
Layer of loose sandy material	Structureless – loose	7 – Absolutely permeable
Weathered substrate	Structureless – stone	6 – Very well permeable
Humus	Granular	5 – Well permeable
Metamorphic	Polyhedron	4 – Permeable
Illuvial	Prismatic, columnar	3 – Poorly permeable
Eluvial	Platy	2 – Very poorly permeable
Gley	Structureless – dense	1 – Not permeable

Table 6 Classification of permeability of soil units

Soil unit	Soil horizons	Soil structure	Class of soil structure permeability
Leptosols	Shallow humus	Granular: fine to medium	6
	Weathered rock		
Arenosols	Loose sand	Structureless loose	7
Rendzic leptosol and calcaric cambisols	Humus	Granular: fine to medium	5
	Metamorphic	Granular: fine to medium	4
	Weathered rock		
Chernozems	Humus	Fine granular	5
	Loose loess		
Haplic luvisols	Humus	Granular: fine to medium	5
	Illuvial	Polyhedron to prismatic	3
	Loose substratum		
Albic luvisols	Humus	Granular: fine to medium	5
	Eluvial	Platy	2
	Illuvial	Prismatic	3
	Loose substratum		
Cambisols and andosols	Humus	Granular: fine to medium	5
	Metamorphic	Polyhedron	3
	Weathered rock		
Podzols	Humus	Medium granular	5
	Eluvial	Structureless loose	6
	Illuvial	Polyhedron	3
	Weathered rock		
Planosols and stagnosols	Humus	Granular: fine to medium	5
	Gley	Structureless dense	1
	Loess loams deposit		
Fluvisols	Alluvial deposits	Structureless	5
Mollic fluvisols and mollic gleysols	Humus	Fine granular	4
	Gley	Prismatic to platy	2
	Loose deposit		

in the basins by hydrometeorological observation. A sample of 126 small gauged catchments was selected, and the *BFI* values were set by applying the IHACRES precipitation/runoff model [43]. The relationship between the *BFI* and the basin attributes was analysed by the box plot method. In the case of frequency of flood events, their relationship to the basin's attributes was studied within the whole set of
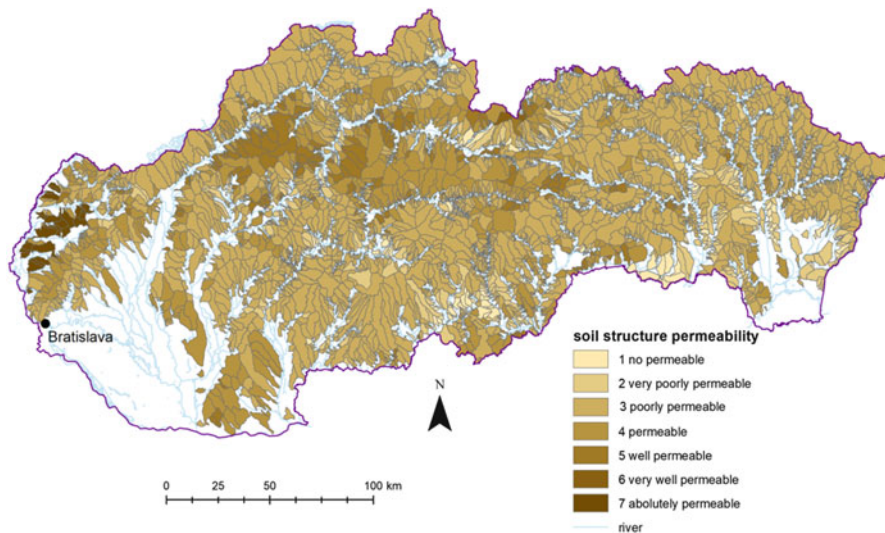
Fig. 9 Classes of soil structure permeability of upper basins

1,678 upper basins, and the significance of their differences was tested by the
ANOVA method.

With regard to the altitude, slope, and forestry, the upper basins are divided into
the following four physical geographic classes:

- Classes of average altitude of the basin: A, 101–385 m a.s.l.; B, 385–652 m a.s.
  l.; C, 652–976 m a.s.l.; D, 976–1,816 m a.s.l.
- Classes of average slope of the basin: A, 0–6°; B, 6–12°; C, 12–18°; D, 18–33°
- Classes of basin forestry: A, 0–24%; B, 24–5%; C, 51–76%; D, 76–100%

The intervals of each class are defined by the breakpoints corresponding to the
division into four classes when processing the classification of upper basins in
the GIS.

In terms of the soil texture permeability, the upper basins have been grouped into
seven classes (see Table 4; class 1, not permeable soil texture; class 7, absolutely
permeable soil texture). In relation to soil structure, instead of the seven original
classes, three classes of permeability of the soil structure were used. The first one
(class 1) is poorly permeable and consists of basins with a prevalence of soil types
for which prismatic and columnar structure with vertically elongated soil aggre-
gates is typical. The second (class 2) is permeable and contains the upper basins
with a prevalence of soil types typified by the cubiform and polyhedral structures
with distinctly developed edges in three directions. The third (class 3) is very well
permeable and consists of an upper basin with a prevalence of soil types, for which
a granular structure with spherical soil aggregates is typical.

The results of the relationship between *BFI* values and the classes of physical geographic attributes of the upper basins are presented in Fig. 10. The graphs show that only the permeability of the soil texture has a significant effect on the differentiation of *BFI* values of the basins (Fig. 10a); that is, with increases in the soil texture permeability of the basin, the proportion of the base runoff in the total runoff increases. In the case of other physical geographic attributes, box plots point only to insignificant dependencies. In relation to the soil structure, the average *BFI* value in the class of basins with the lowest permeability of the soil structure (class 1) is somewhat lower than the *BFI* value in the remaining two classes of basins with higher permeability (Fig.10b). Similarly, in the case of the average slope of the basin, the *BFI* is in the class of basins with a slope of up to 6%, which is slightly higher than that in the other classes with higher slope (Fig. 10d). In relation to the forestation and altitude of the basins, the differences between *BFI* values are very insignificant and do not indicate any trend (Figs. 10c, e).

With regard to the second indicator of the flood hazard, that is, the frequency of flood events, the results are given in Tables 7, 8, 9, and 10.

The comparison of the arithmetic average of the frequency of flood events vs the soil texture permeability classes of basins shows that in basin classes with low permeability (classes 1 and 3), the frequency of flood events is higher than that in basin classes with permeable soil texture (classes 4–7). Surprisingly, however, the lowest value of the average frequency of flood events is obtained in the case of class 2, with a low-permeability soil texture.

In terms of forestry, in classes B, C, and D, but not class A, the value of the arithmetic average of the occurrence of the flood events decreases as the basin forestation increases. Differences between arithmetic averages are quite clear. The impact of forestry is even more pronounced if it is judged within individual classes of soil texture permeability (Fig. 11). Within each of the soil texture permeability classes, the arithmetic mean of the frequency of flood events is higher in the upper basin group in which forestry fails to predominate than in the basin group with predominant forestry. The graph also shows that the impact of forestry on the occurrence of flood situations becomes weaker as the permeability of the river basin texture decreases.

Regarding the relief attributes of the river basins, the data do not indicate the assumption that the increase of the average slope of the river basin or altitude will increase the frequency of the flood events; rather, the data point to the opposite trend.

The above analysis suggests that the basin attributes that have a significant influence on the frequency of the flood events are mainly the permeability of the soil texture and the forest cover of the basins.
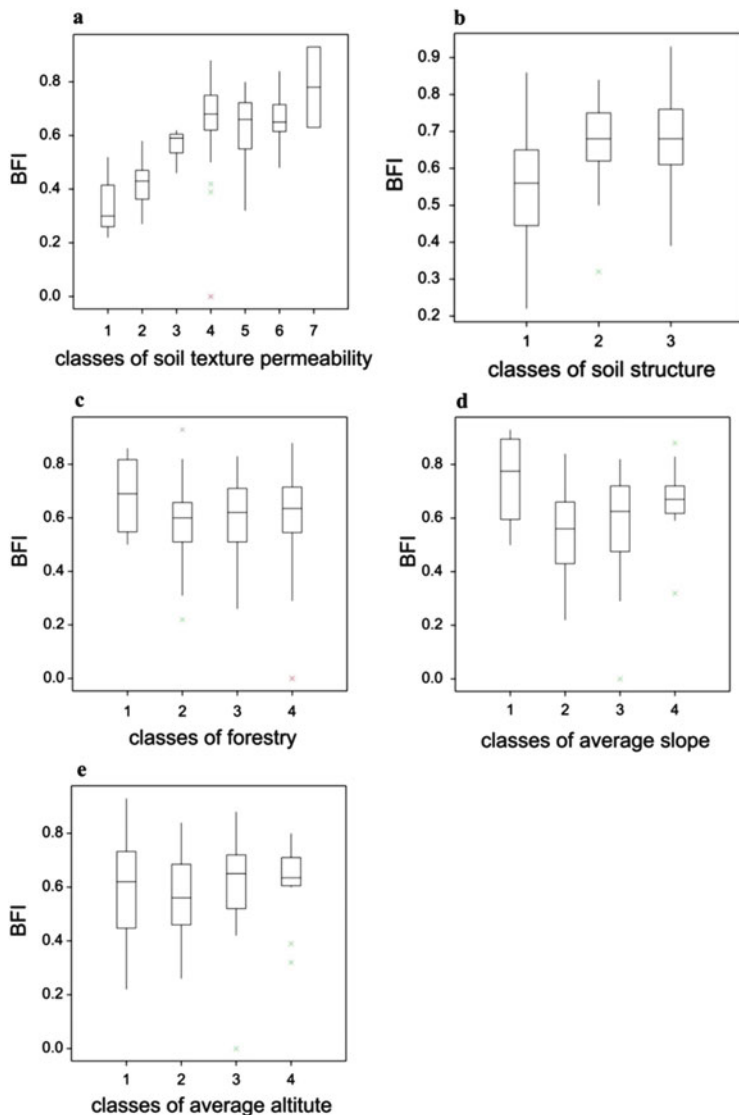
Fig. 10 *BFI* vs physical geographic basin attributes. (**a**) Classes of soil texture permeability: 1, not permeable; 2, very poorly permeable; 3, poorly permeable; 4, permeable; 5, well permeable; 6, very well permeable; 7, absolutely permeable. (**b**) Classes of soil structure permeability: 1, poorly permeable; 2, permeable; 3, well permeable. (**c**) Classes of percentage coverage by forest: A, 0–24%; B, 24–51%; C, 51–76%; D, 76–100%. (**d**) Classes of average slope: A, 0–6°; B, 6–12°; C, 12–18°; D, 18–33°. (**e**) Classes of altitude: A, 101–385 m a.s.l.; B, 385–652 m a.s.l.; C, 652–976 m a.s.l.; D, 976–1,816 m a.s.l.

Table 7 Permeability of soil texture of basins vs frequency of flood situations

Class of soil texture permeability	Number of basins	Arithmetic mean of flood frequency events
1	269	0.88
2	317	0.45
3	313	0.70
4	341	0.49
5	339	0.40
6	137	0.32
7	62	0.40

Table 8 Forestry of basins vs frequency of flood situations

Forestry class (%)	Number of basins	Arithmetic mean of flood frequency events
A: 0–24	314	0.44
B: 24–51	420	0.86
C: 51–76	517	0.62
D: 76–100	427	0.18

Table 9 Average slope of basins vs frequency of flood situations

Slope class [°]	Number of basins	Arithmetic mean of flood frequency events
A: 0–6	417	0.42
B: 6–12	589	0.68
C: 12–18	487	0.57
D: 18–33	185	0.26

Table 10 Average altitude of basins vs frequency of flood situations

Altitude class [m a.s.l.]	Number of basins	Arithmetic mean of flood frequency events
A: 101–385	633	0.43
B: 385–652	558	0.67
C: 652–976	380	0.62
D: 976–1,816	107	0.16

4 Identification of Regional Types of Flood Hazards in Headwater Areas

4.1 Assignment of Physical Geographic Classes

The aim of the regional typification process is to group the upper basins on the basis of physical geographic attributes that significantly influence the flood hazard into classes that will have the character of regional types. The regional type is a unit that

Fig. 11 Frequency of flood events within the soil texture permeability classes with different classes of basin forestry
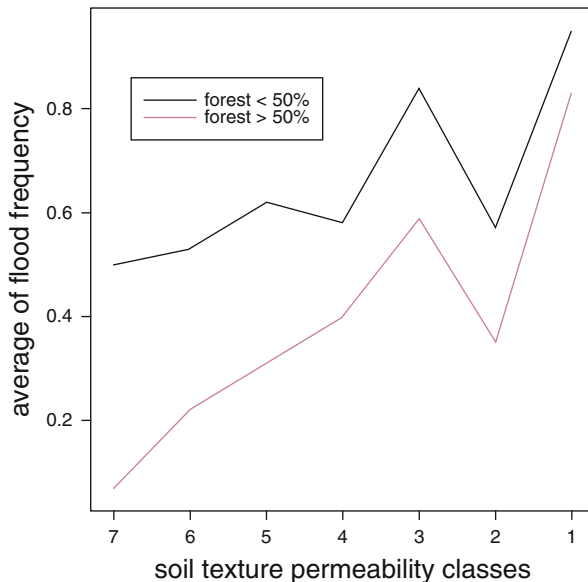
is not spatially contiguous in the geographical space and is the basic output of spatial analysis based on the regional taxonomic concept [44, 45]. The classes identified according to this concept acquire the character of regional classes only if they meet either the internal homogeneity or the external heterogeneity criterion in relation to the set of attributes.

An application of a regional taxonomic concept in hydrogeography or hydrology has some specificity, however. Classes are allocated based on the physical geographic attributes of the basins, but the regional status is assessed in relation to the hydrological attributes instead of physical geographical ones [46]. Physical geographic classes of flood hazards thus acquire regional status if, in terms of frequency of flood events, they meet the requirement of significant heterogeneity between classes while preserving some similarity of frequency within the physical geographic class. The regional types of flood hazards identified on the basis of the combination of physical geographic attributes of the basins then obtain an explanatory function in relation to the frequency of flood events.

Several methods can be used to group basins into classes, such as cluster analysis [47], discrimination analysis [48], artificial neural networks or fuzzy logic [49, 50], and methods based on the application of logical principles [51, 52]. Given the small number of physical geographic attributes that are relevant for explanations of the spatial variability of the flood events in the upper basins, it is effective to identify the classes of flood hazards by the logical division method. The general classification scheme of logical partitioning is displayed by Table 11. According to [51], consistency of logical division is achieved when the following rules are complied with:

Table 11 Hierarchical classification scheme of logical division

I				I				Classes of hierarchical level I
II		II		II		II		Classes of hierarchical level II
III	III	III	III	III	III	III	III	Classes of hierarchical level III
↓								↓
n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	Classes of hierarchical level n

– The division is exhaustive; that is, all individuals (spatial units) are included in classes.
– Classes within the hierarchical level are mutually exclusive.
– At each hierarchical level, only division according to one attribute is applied.
– An attribute at a higher hierarchical level is more significant than one at a lower hierarchical level in terms of the classification goal.

As shown by the results of the analysis of the relationship between frequency of flood events and basin characteristics, it is sufficient for the physical geographic classification scheme to contain only two hierarchical levels. At the first hierarchical level, the division of the basins into groups is done on the basis of the permeability of the soil texture, and the basins were allocated into seven classes. At the second hierarchical level, the classification attribute is forestry, and the basins were grouped into four classes. However, the data in Tables 7 and 8 suggest that in both cases, a certain reduction in the original number of classes is necessary to meet the requirement of heterogeneity among classes in terms of frequency of flood events.

It seems to be optimal for the classification scheme at the hierarchical level I to contain only two classes of soil texture permeability (*CSTP*) instead of the original seven classes. The first class (*CSTP A*) is formed by merging the original poorly permeable classes 1–3 into one class. The well permeable classes 4–7 are merged into the second (*CSTP B*). In the case of forestation, two classes of forestry were used instead of the four original classes at hierarchical level II. The first class includes river basins in which less than 50% ($L < 50\%$) of the total catchment area is forested, while the second class contains catchments with more than 50% forestation ($L \geq 50\%$). By combining two classes of soil texture permeability and two forestry classes, four physical geographic classes of flood hazard (*CFH*) were created (Table 12).

CFH A represents basins with low soil texture permeability (*CSTP A*) and less than 50% forest ($L < 50\%$).

CFH B represents basins with low soil texture permeability (*CSTP A*) and above 50% forest cover ($L \geq 50\%$).

CFH C represents basins with good soil texture permeability (*CSTP B*) and below 50% forest cover ($L < 50\%$).

CFH D represents basins with good soil texture permeability (*CSTP B*) and above 50% forest cover ($L \geq 50\%$).

The frequency of flood events in the flood hazard classes A, B, C, and D is shown in Table 13. Cell values reflect the joint effect of classes of permeability of soil

Table 12 Classification scheme of flood hazard classes

CSTP A		CSTP B	
L < 50%	L ≥ 50%	L < 50%	L ≥ 50%
CFH A	CFH B	CFH C	CFH D

Table 13 Joint and separate effect of reduced classes of permeability of soil texture and forestry on the frequency of flood events

	CSTP A	CSTP B	Row averages
L ≥ 50%	0.58/CFH B	0.31/CFH D	0.44
L < 50%	0.77/CFH A	0.58/CFH C	0.68
Column averages	0.66	0.42	0.54

texture and forestry on the arithmetic mean of the frequency of flood events. The values indicate that the highest mean frequency of the flood events is found in *CFH A* and the lowest in *CFH D*. *CFH B* and *CFH C* have the same values of arithmetic averages and correspond to the middle level of frequency of the flood events. They show mutual balancing of the impacts of both attributes. Increased forestry mitigates the increasing frequency of flood events due to the low permeability of the soil texture, and conversely, increased deforestation of the basin increases the level of flood frequency of the river basin with good soil texture permeability.

The values in the last row and column labelled "row averages" and "column averages" represent the impacts of forestry and soil texture permeability on the frequency of flood events separately. The column averages indicate a higher frequency of flood events in the less permeable basins (*CSTP A*) than in the more permeable ones (*CSTP B*). Also, row averages in relation to forestry indicate a higher frequency of flood events in the basins with *L < 50%* than in the basins with *L ≥ 50%*.

It follows from the above that there is no difference in frequency of flood events between *CFH B* and *CFH C*. Therefore, it is sufficient to classify the upper basins into three flood hazard classes: *CFH I* is identical to CFH A, *CFH II* is *CFH B* and *CFH C*, and *CFH III* is the same as *CFH D* (Table 14).

4.2 Testing the Significance of Flood Frequency Differences Between Flood Hazard Classes

The data in Table 14 indicate some differences among *CFH I, II,* and *III* in the arithmetic means of the frequency of flood events, but it is necessary to verify whether these differences are statistically significant. Only if this is the case will the classes become regional types of flood hazards. The testing of the significance of differences between arithmetic means was carried out by the analysis of variance (ANOVA) method [53].

First, the zero hypothesis (H_0) that the expected mean values of frequency of flood events (μ_r) of the flood hazard classes are equal was tested.

Table 14 Arithmetic averages of frequency of flood situations in modified flood hazard classes

	CFH I	CFH II	CFH III
Arithmetic mean of frequency of flood events	0.77	0.57	0.31
Number of basins	346	812	520

$$H_0 : \mu_1 = \mu_2 = \cdots \mu_r \tag{2}$$

The test criterion is the value of the F^* ratio. The zero hypothesis of the equality of mean values μ_r is rejected if it is true that

$$F^* > F(1 - \alpha; r - 1; n_T - r) \tag{3}$$

where $(r - 1, n_T - r)$ are the degrees of freedom of the nominator and denominator in the F ratio (n_T, number of basins; r, number of factor) and $F(1 - \alpha; r - 1; n_T - r)$ is the $(1 - \alpha)$ 100th percentile of the F distribution. The significance level α has a probability value of 0.01. The rejection of the zero hypothesis means that there is some dependence between the identified flood hazard classes and the frequency of flood events.

If the zero hypothesis that the expected mean values are equal is rejected, the analysis proceeds to the second step, pairwise comparison by testing the zero hypothesis:

$$H_0 : \mu_1 - \mu_2 = 0, \cdots, \mu_i - \mu_j = 0 \tag{4}$$

That is that the difference between the expected mean values of the flood events of the two physical geographic classes of flood hazards is zero. Testing was performed using the LSD method (Fisher's protected least significant difference) [54]. The criterion for testing whether the difference is statistically significant is:

$$\frac{\bar{x}_i - \bar{x}_j}{s(\widehat{D}) \sqrt{2/n}} > t_{\alpha/\nu} \tag{5}$$

where $\bar{x}_i - \bar{x}_j$ is the difference in the arithmetic average of the flood situations of the two comparative flood hazard classes, $s(\widehat{D})$ is the standard deviation of the differences, $t_{\alpha/\nu}$ is the quantile of the t distribution for ν degrees of freedom, and n is the number of basins.

The zero hypothesis is rejected if the expression on the left side of the inequality (5) is greater than the quantile of the t distribution. The rejection of the zero hypothesis means that there are statistically significant differences between the physical geographic classes of the flood hazard in terms of the average values of frequency of the flood events. The flood hazard classes acquire regional status if all differences are statistically significant. The results of the variance analysis and the pairwise comparison are presented in Tables 15 and 16.

An F value with a probability of less than 0.001 means that the hypothesis that the expected mean values of the frequency of the flood events are equal can be rejected. Also, the pairwise comparison showed that all the differences between the arithmetic averages of the flood events of flood hazard classes are statistically

Table 15 Results of ANOVA

Source of variation	Degrees of freedom	Sum of squares	Mean square	F value	F probability
Between flood hazard classes	2	46.9316	23.4658	23.48	< 0.001
Error	1,675	1674.2776	0.9996		
Total	1,677	1721.2092			

Table 16 Results of pairwise comparison

Mean vs mean	T	Significant
CFH III vs *CFH II*	−4.808	Yes
CFH III vs *CFH I*	−6.614	Yes
CFH II vs *CFH II*	−2.951	Yes

significant. The three identified classes of flood hazard, therefore, have the character of regional types and, in terms of the number of classes, are the optimal distribution. The classification of small river basins of Slovakia into three regional types of flood hazards is shown in Fig. 12.

5   Summary and Conclusions

The primary cause of the floods is heavy rainfall or rapid melting of snow, but their appearance is also significantly influenced by the physical geographic attributes of the upper basins. As a result, the incidence of flood situations in Slovakia is clearly spatially differentiated. The disposition of the basin attributes to the most frequent flood events (river flooding and sheetwash flooding) is referred to as the flood hazard potential. Its evaluation results in identifying the regional variability of the flood hazard. The regional taxonomic process is based on identifying the physical geographic attributes of the upper basins that have a significant impact on the flood hazard, on creating physical geographic classes based on their combination, and testing the significance of differences in the frequency of flood events between them.

In assessing the flood hazard potential of the upper basins in the mountainous region of Slovakia, it has been shown that, in particular, the soil texture permeability and the forest cover are the basin attributes that have the greatest influence on the spatial variability of flood hazard. Based on their combination, several physical geographic classes were created. Physical geographic classes acquire the character of regional types of flood hazards if they meet the heterogeneity condition in terms of frequency of flood situations, that is, if that the differences in the frequency of flood events between physical geographic classes are statistically significant. This requirement is met if three classes of flood hazards are created on the basis of the combination of classes of soil texture permeability and forestry of the basin.
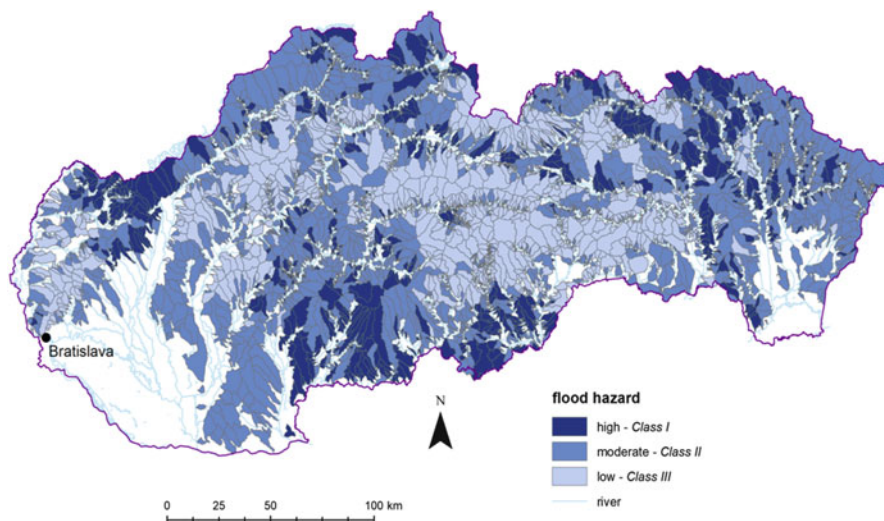
Fig. 12 Classification of small river basins into regional types of flood hazards

Identifying the regional variability of the flood hazard is one of the elements of flood risk assessment and provides exhaustive information on the spatial differentiation of the flood hazard in the upper basins. This enables the state administration and self-government authorities responsible for flood protection to spatially differentiate the application of mainly nonstructural measures to reduce the level of flood hazard.

6 Recommendations

In the present study, the assessment of the flood hazard in the upper basins is based on the physical geographic attributions of the catchment area, i.e. the systematic factors that form the basic features of the hydrological response of the basin. However, the impact on the occurrence of the flood events also has a number of local or incidental factors, e.g. pollution of river channel by solid waste, storing different materials on the bank of the river, deposition of sediment on the beds of watercourses, and overgrown and unkempt river channel. These factors slow down the flow of water, clogging the channel under the bridges by solid waste, increase level of water, and cause flooding. Important local factors also include the inappropriate use of land in the river basin and land devastation after logging forest, which accelerates the formation of overland flow and sheetwash flooding. An attention to local factors has not been given in this work. That is the challenge for further detailed research into flood hazard assessment in the near future.

The fact that local factors have a significant impact on the flood hazard in the upper basins increases the importance of activities aimed at raising public awareness of the flood hazard and increasing individual responsibility for reduction of the flood hazard. Effective management of this role is primarily a challenge for regional and local government and self-government authorities, as well as for non-governmental organizations. However, it is also required to increase the watercourse managers' awareness of the need to maintain the flow capacity and cleanliness of watercourses and zones near watercourses.

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