

# Reconstruction and post-event analysis of a flash flood in a small ungauged basin: a case study in Slovak territory

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Received: 26 April 2017 / Accepted: 16 February 2018 / Published online: 2 March 2018  
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**Abstract** Flash floods are one of the major natural hazards occurring in small streams with a negative effect on the country as well as on human lives. Heavy rainfall occurred on July 20, 2014 and July 21, 2014 and caused severe surface water flooding and a flash flood in the Malá Fatra National Park (Slovakia). The most affected was Vrátna Valley with the Varínka stream. This study presents a reconstruction and post-event analysis of a flash flood on small ungauged basin located in this protected area of Slovakia. The reconstruction included hydraulic terrain measurements on estimating the flood's culmination and documenting the flood's development. The measurements were taken at three cross sections of the Varínka stream. This paper is focused mainly on post-event analysis of the Varínka stream in two profiles: Stráža (gauged profile) and Tiesňavy (ungauged cross section). Subsequently, the extremeness of the flash flood was preliminary evaluated. Results of the post-event analysis showed that the July 2014 flood was not the highest flood in this area despite its catastrophic consequences. By studying historical materials, we came to the conclusion that in the past (e.g. in 1848 or 1939) some devastating floods in this area had occurred, which had disastrous consequences for the population. The second part of the study is focused on comparing this flash flood with three major floods which have occurred in Slovak territory since 1998. The first flood occurred on the 20th of July, 1998 on the Malá Svinka stream, and the two others are floods which occurred on the 7th of June, 2011 in the Small Carpathian Mountains: on the Gidra stream in Píla village and on the Parná stream in Horné Orešany village. Such comparison of flash floods from different geographical regions and different rainfall events can provide comprehensive information about their regimes, threats and disastrous effects.

**Keywords** Flash flood · Post-event analysis · Flood wave reconstruction · Natural hazard · Small basins · Slovak territory

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## 1 Introduction

Extreme floods are one of the major types of natural disaster in Europe. Climate change and the increase in land use in some areas are reflected in an increase in extreme floods. There is expected to be an increase in the number of unexpected, locally bounded but heavy floods (flash floods), which may increase the risk of loss of life. Flash floods can be defined as strong flows occurring shortly after rainfall (Gruntfest and Huber 1991). Such floods are often caused by relatively high rain intensity and an intensive watershed response to rainfall. The factors that affect flash flood generation are very complex and mainly include characteristics of the rain (e.g. intensity, volume and time–space distribution), physical and hydrological characteristics of the watershed (area, slopes, shapes, type of soil and land use, vegetation, and others) (Rozalis et al. 2010). Flash floods are a relatively rare event on the local scale. The time–space scales of the occurrence of these floods are small compare to the rain sampling characteristics and discharge measurement networks; these facts make it particularly difficult to detect and analyse flash floods (Borga et al. 2008; Gaume and Borga 2008). It is therefore not surprising that flash flood data are relatively rare in systematic flood data archives. Improving the scientific basis of flash flood forecasting by extending the understanding of past flash flood events, advancing and harmonizing a European-wide innovative flash flood observation strategy and developing a coherent set of technologies and tools for effective early warning systems were the main objectives of the HYDRATE project. The obtained data were combined and used for analysis of the relationship between the flood peaks and the catchment area. Gaume et al. (2009) analysed the dates of occurrence and flood peak distribution of flash floods from an catalogue of events that occurred in selected regions of Europe over a 60-year period (from 1946 to 2007). Analysis of the flash flood regimes in the North-West and South-Eastern Mediterranean regions was investigated by Tarolli et al. (2012). The main results of their analysis show some peculiar seasonal effects on flood occurrence, differences between envelope curves, rainfall duration and depth, and minor differences between the runoff coefficients of extreme flash floods for selected regions. A map and catalogue of the major flood events of the last 56 years (1950–2005) in the European Union (EU), Bulgaria and Romania were presented in Barredo (2007). His analysis showed that there have been a rising number of flood disasters in Europe over the last few decades. An analysis of natural hazards and identification of deficits in natural disaster management were published in Prochazkova (2014), from the viewpoint of the safe community concept that has been promoted by the EU since 2004. The sensitivities of runoff generation on rainfall variability and initial wetness conditions were examined for a major flash flood event in the study by Nikolopoulos et al. (2011). Similar problems had been investigated by several authors (e.g. Hino et al. 1988; Yatheendradas et al. 2008; Castillo et al. 2003; or Moody and Martin 2001). For example, in recent years Smith et al. (2014) applied the data-based mechanistic (DBM) models to forecast flash floods in a small Alpine basin. The flash flood prediction by coupling KINEROS2 and HEC-RAS models for tropical regions of Northern Vietnam was carried out by Nguyen et al. (2015). The results revealed strong relationships between river geometry and flow velocity, water level and streamflow power. Although the results showed some minor errors in forecast results, the model-predicted discharge and water level corresponded well to the gauged data. Kjeldsen et al. (2013) tested the effect of urban land cover in basin flood response using a lumped rainfall–runoff model. They compared flood events from selected UK basins with mixed urban and rural land use. A multilateral approach to estimating flash flood peak discharge, hydrographs and volume in poorly gauged basins was presented by Aristeidis et al. (2010).

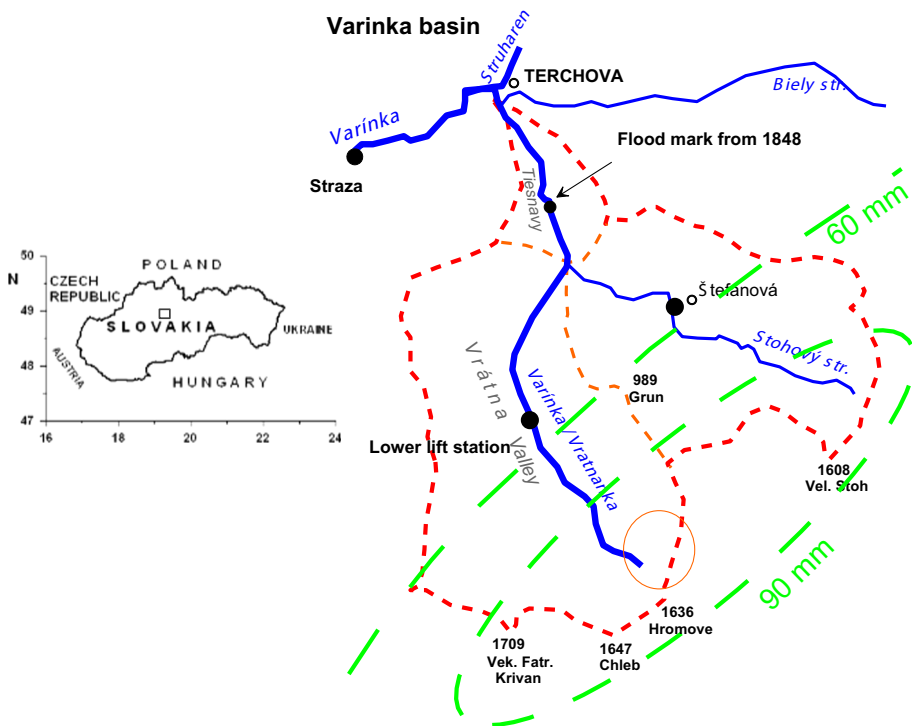
Intensive rainfall causes not only a hydrological response from the basin but also a hydro-geomorphological response. The incorrect use of land areas plays a significant role in the basin's negative response to heavy rainfall. The type, magnitude and intensity of the hydro-geomorphological response may affect hazard and risk in the downstream channel system and floodplains (Jakob et al. 2006; Marchi et al. 2009). The possible effects of climatic and land-use change on storm runoff generation are presented in Bronstert et al. (2002). The hydro-geomorphological response of headwater systems to extreme rainfall was published also in Borga et al. (2014). The occurrence of these extreme natural hazard events entails acute danger not only for properties, but mainly for human lives. Jonkman and Kelman (2005) focused on 13 flood events that happened in Europe and in the USA in order to improve understanding of the circumstances of flood deaths and contribute to prevention strategies. Other studies have also focused on defining and understanding the circumstances surrounding flood fatalities for different environments in Australia (Coates 1999) and Puerto Rico (Staes et al. 1994). Peak discharge data for more than 50% of the studied watersheds in Europe derive from post-flood measurements in ungauged streams. The large percentage of discharge data obtained from post-event analysis underlines the importance of indirect discharge estimates in setting up catalogues of flash floods. This is particularly the case for events which impact small catchment areas. Discharge data from gauging stations generally concern catchments which are significantly larger than those for which estimates are obtained from post-event analysis (Marchi et al. 2010). The results from several case studies (Delrieu et al. 2005; Parajka et al. 2010; Zanon et al. 2010; Blaškovičová et al. 2011; Pekárová et al. 2012; Ruiz-Villanueva et al., 2012; Danko 2014; Rodriguez-Morata et al. 2016; and others) have shown that post-event surveys may deliver a spatially consistent analysis of flash flood responses in Europe. Post-event analysis of flash floods in ungauged basins located in Slovakia and the application of a hydrological model that simulates runoff were carried out in Hlavčová et al. (2016). The authors concluded that the crucial problem in estimating the occurrence and magnitude of flash floods is the lack of measured data, particularly in small ungauged catchments, and in this case, all the data and information obtained from the post-event analyses are useful.

This study presents a reconstruction and post-event analysis of the flash flood which occurred on the Varínka Stream in the Vrátna Valley in the Malá Fatra National Park on July, 21, 2014. Terrain measurements for estimating the peak discharge were taken, and the flood's development was documented. Consequently, this flash flood was compared with three major floods which had occurred in Slovak territory since 1998. The first one occurred on the 20th of July, 1998 on the Malá Svinka Stream at Jarovnice (ungauged catchment) and the two others floods occurred on the 7th of June, 2011 in the Little Carpathians on the Gidra stream at Píla village below the water gauge station, and on the Parná stream at the Horné Orešany water reservoir below the water gauge (gauged catchments). Post-event analysis and investigation is one way to gain experience in estimating risk and natural hazards. Furthermore, such surveys and analyses play an important role as an information source in determining the culmination and the course of flash floods in ungauged basins together with information about geology, topography, vegetation and precipitation in the development of hydrological models, which are extremely important for flood risk management.

## 2 Study area

### 2.1 Description of the Varínka basin and historical flood reports

The Varínka stream basin is located in the Malá Fatra National Park (in Slovak: Národný park Malá Fatra), in the north-west part of the Malá Fatra mountains called Krivánska Malá Fatra. The acreage of the National Park territory (NP) is 226.3 km<sup>2</sup>; the protective zone covers an area of 232.62 km<sup>2</sup>. The mountain is covered mainly by mixed beech forests, and with fir and spruce at higher elevations. Dwarf pine and meadows occur at the highest altitudes. About 83% of the area is covered by forest. The Malá Fatra Park was declared in 1988. Between 1967 and 1988, it was a protected landscape area. The highest peak is Veľký Kriváň with an altitude of 1709 m. A significant hill is Veľký Rozsutec, which is also the logo of the National Park. The Varínka stream (stream ID 4-21-05-6465) is created from several brooks in the Vrátna Valley, near to Terchová village (Fig. 1). The Varínka stream is an area of European importance, especially for travertine springs and hydrophilic tall herb fringe communities. The basin has an area of 167.307 km<sup>2</sup>, and stream length is 24.46 km. The Varínka originates in Krivánska Fatra, the Malá Fatra subunit. The source of the Varínka is located on the northern slope of the mountain section of the ridge between the peaks Chleb (1647 m a.s.l.) and Hromove (1636 m a.s.l.). The Varínka stream flows along the bottom of Vrátna Valley and flows into the Váh River at Varin village. The Stohový stream (stream ID: 4-21-05-6748, area 10.671 km<sup>2</sup>, length



**Fig. 1** Location of the Varínka basin in the Malá Fatra National Park (Slovakia) and rainfall depth occurred on July 21, 2014

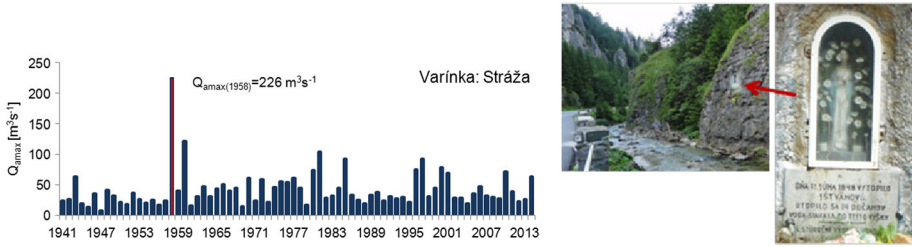
5.30 km) is one of the tributaries of the Varínka stream. The next tributaries of the Varínka are Biely stream (stream ID: 4-21-05-6715, area 17.162 km<sup>2</sup>), Struhareň stream and Beliansky stream. Table 1 presents the basic geographical and runoff characteristics of the Varínka stream at Stráža and in the Tiesňavy gorge. The most extreme discharge on the Varínka stream in Vrátna Valley occurred in 1958 (Pacl 1959; Pekarova et al. 2010). The whole upper basin of the Váh River was flooded that year. The most extreme peak discharge reached a value of 226 m<sup>3</sup> s<sup>-1</sup> ( $q_{\max} = 1.62 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ ) on the Varínka stream at Stráža. Figure 2a presents the extreme annual discharges which occurred on the Varínka stream at Stráža gauge station (basin area 139.5 km<sup>2</sup>) during the period of 1941–2013.

The records on historical floods occurring in Malá Fatra National Park can be found in some scientific literature and chronicles in many towns and villages. When we go more into the past, the information about floods become rarely and less precise. The publication of Dub (1941) describes a catastrophic flood in the year 1939. This catastrophic flood occurred on the 17th of June, 1939 on the Vydrňanka (tributary of the Biely stream), and the culmination of this flood was estimated at a value of 100 m<sup>3</sup> s<sup>-1</sup> with a specific yield of approximately 10 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup>. It showed that intensive rainfall can cause catastrophic runoff in a small flysch belt basin although the stream bed has been adjusted by stone steps. The most interesting and most valuable information about the catastrophic flash flood on the Varínka/Vrátnanka stream was sculpted into the rock in the Tiesňavy gorge in 1848. In the post-WWII period, around 1948, the original table was rebuilt in the place where it stands today (Fig. 2b). Historical records (as well as flood marks) of the floods allow the occurrence of past floods to be identified. The answer to the question whether the current flooding in this area actually occurs more frequently than in the past has been focused on for several years at our institute. By studying historical materials, we came to the conclusion that in the past there also occurred devastating floods in this territory, which had disastrous consequences for the population. When the next flood will occur in future, history does not tell us; however, it suggests that its occurrence in the country is real. Therefore, it would be desirable to build flood marks after each flood on buildings, bridges and water gauges. Old flood marks, up to 1000 years old, can be found in Italy and Austria. Kjeldsen et al. (2014) and Blöschl et al. (2015) dealt with historical flood analysis and an investigation into whether floods changed in the past and explored the driving processes of such changes in the atmosphere, the catchments and the river system based on historical examples from Europe. Benito et al. (2015) described the methodological evolution of quantitative historical hydrology under the influence of developments in hydraulics and statistics on some European rivers. In addition, the comparison of the historical records with present measurements lead to a better understanding of stream and landscape response to flash floods and to improve the effectiveness of forecasts and warning systems. Knowledge of previous extreme natural disasters and their analysis, improvement of the observation methods and use of rainfall–runoff models are necessary for the further development of watershed management.

**Table 1** Basic geographical and runoff characteristics of the Varínka stream at Stráža and Tiesňavy

	A (km <sup>2</sup> )	River (km)	Forestation (%)	Average slope (°)	$Q_{\max}$ (m <sup>3</sup> s <sup>-1</sup> )
Varínka: Tiesňavy	28.05	17.5	71.61	24.46	–
Varínka: Stráža	139.5	5.19	65.9	19.65	42

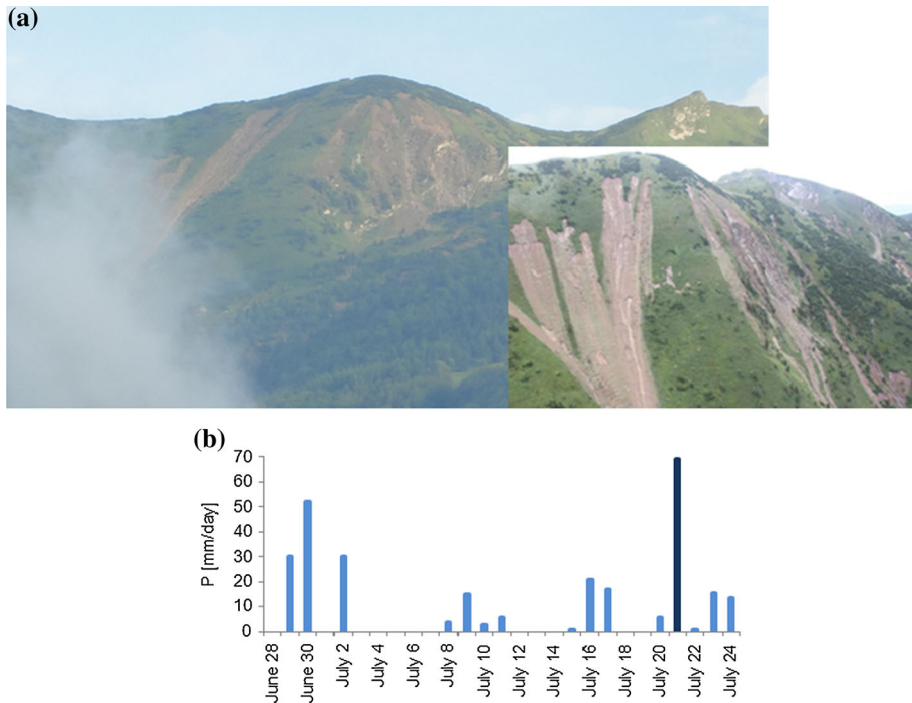
A Basin area and  $Q_{\max}$  average maximum annual discharge during the period of 1941–2014



**Fig. 2** Annual peak discharges on the Varínka stream at Stráža during the period of 1941–2014 and detail of the flood mark and water level in 1848, Varínka: Tiesňavy (Photographs by Pekárová, 2014)

### 3 Rainfall situation and post-event analysis of the flash flood on July, 21, 2014 on the Varínka stream

The July 21, 2014 flood had the character of a flash flood. The flash flood in Vrátna Valley was created as a result of the heavy rainfall on July 21, 2014 and the landslides in the area of Hromove and Steny in the headwater of the Varínka stream (Fig. 3a). The rainfall on July 21, 2014 was characterized by its extreme intensity and extreme rainfall total depth over a very short period. Two rainfall events occurred in this area: the first one occurred between 15:30 and 16:05 (CEST) with maximum short-time intensity between 50 and



**Fig. 3** **a** Landslides in the area of Hromove and Steny in the headwaters of the Varínka stream (Photograph by Pekárová, 2014) and **b** the daily precipitation depths in the Vrátna Valley (at Štefanova station) on July 2014

60 mm h<sup>-1</sup>, and the second was between 16:05 and 17:00 (CEST) with a maximum short-time intensity between 60 and 80 mm h<sup>-1</sup>. Assessment of the meteorological situation in this north-west area of Slovakia was described in Št'astný et al. (2014). The maximum precipitation depth per 24 h in the Vrátna Valley (at Štefanova station) was about 66 mm (Fig. 3b). According to the Slovak Hydrometeorological Institute's (SHMI) measurements, the maximum hourly total rainfall depth reached a value of 37 mm in the afternoon on July 21, 2014 in Vrátna Valley (near the mountain rescue cottage). The SHMI rain gauge station is located in the valley near Štefanova at an altitude of 632 m. In the area of maximum precipitation intensity, directly in Vrátna Valley, no rain gauge station is situated. In calculating the average rainfall for the Varínka to Terchová basin, we additionally took into account the high altitudes in the basin area and the fact that due to rising altitudes the rainfall totals generally grow (an average of 5–10% per 100 m of altitude). On the windward side of Hromove Mountain at an altitude of 1450 m, the rainfall might reach 100 mm. The SHMI estimated maximum rainfall depths based also on meteorological radars measurements. According to the maximum radar reflectivity, SHMI estimated an extreme rainfall intensity of 90 mm per 105 min (1 h and 40 min) (Št'astný et al. 2014). These rainfall depths would be above average even if they fell over a 24-h period.

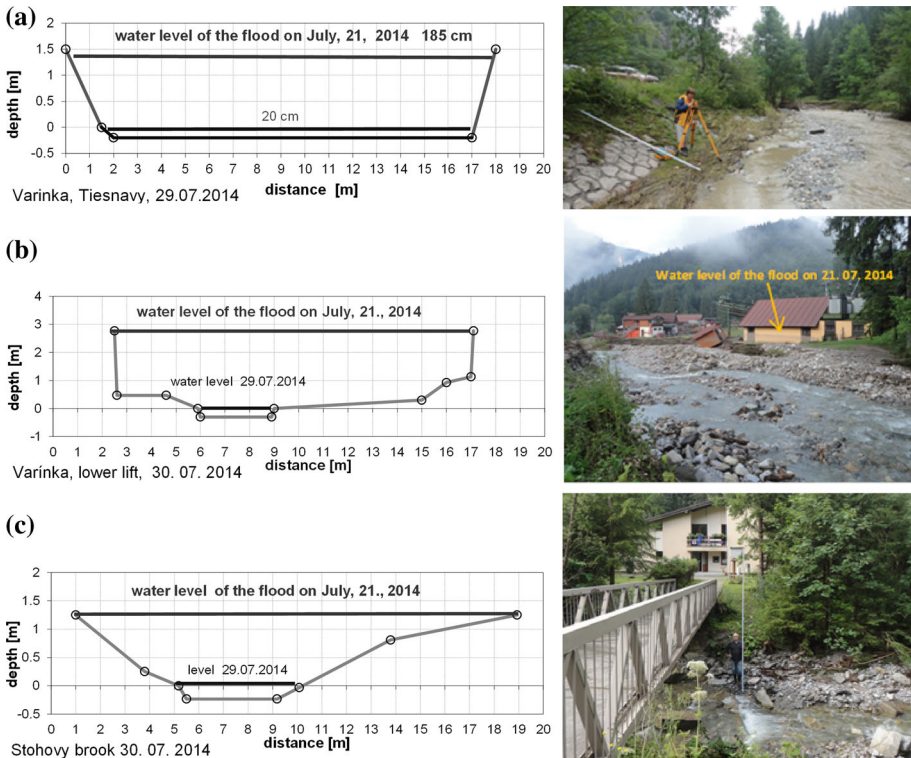
### 3.1 The post-event analysis of the flash flood on July, 21, 2014 on the Varínka stream

In general, the most accurate way of determining the culmination is to measure the discharge during the flood by direct measurement. In the case of this flash flood, it was not possible in the upper part of the Varínka stream basin. This was mainly due to the extremely rapid onset of culmination and the subsequent rapid drop, as well as the difficult accessibility to the river profile when the water overflows. The post-event reconstruction was based on the hydraulic method. This method is based on post-event surveying directly after a flood, measurements of the channel slopes and channel cross sections, flood marks, and estimations of the roughness and flow velocities by simple hydraulic equations. In determining the peak discharges through the calculation, the input data are the sources of uncertainty, in particular the determination of flow velocity during the culmination and in an area where the water overflows the river banks. Due to this, the similar profiles with SHMI were selected in order to make a comparison of the calculated culmination and the flood's development. During the days of July 29, 2014, and July 30, 2014, we measured the characteristics of the stream necessary to calculate the culmination (peak discharges) at three profiles:

- (a) Varínka stream in Tiesňavy gorge (Fig. 4a);
- (b) Varínka stream at lower lift station r. km. 22 (Fig. 4b);
- (c) Stohový stream near the mountain rescue cottage and rain gauge station in Štefanova (Fig. 4c).

During the first steps of the reconstruction of the flood on the Varínka stream, experimental hydrometric measurements and photograph documentation were made. The areas of the stream profiles were measured for the maximal water level; the longitudinal slope of the water level was approximated to the bottom slope; the roughness was estimated according to the river banks and channel bottoms. The flow velocities were calculated using the Chezy formula with Manning roughness coefficient, and continuity formula that was then used to calculate the peak flow (Eqs. 1–3):





**Fig. 4 a–c** Fixation of the cross sections for the Varínka stream according to flood tracks of the flood occurred on July 21, 2014

$$v = C\sqrt{Ri} \tag{1}$$

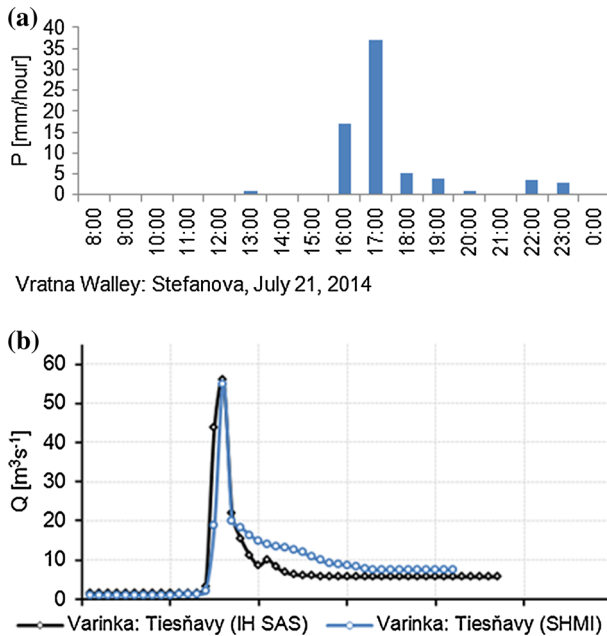
$$C = \frac{1}{n} \cdot R^{1/6} \tag{2}$$

$$Q = F \cdot v \tag{3}$$

where  $v$  is average velocity ( $\text{m s}^{-1}$ ),  $C$  is Chezy’s coefficient ( $\text{m}^{1/2} \text{s}^{-1}$ ),  $R$  is the hydraulic radius (m),  $i$  is the bottom slope (%),  $n$  is Manning’s roughness coefficient and  $F$  is the water-filled area of cross section.

According to hydrometric measurements after the flash flood on Varínka, the peak discharge reached at least a value  $56 \text{ m}^3 \text{ s}^{-1}$  with a specific yield  $2 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  in Tiesňavy, with basin area  $28.05 \text{ km}^2$  (Fig. 1a). Peak discharge reached a value of  $57 \text{ m}^3 \text{ s}^{-1}$  with a specific yield of  $4.4 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  on the Varínka stream near the lower lift station, with basin area  $3.82 \text{ km}^2$  (Fig. 1a). Peak discharge reached a value of  $63.40 \text{ m}^3 \text{ s}^{-1}$  ( $H = 141 \text{ cm}$ , 18:30 CEST and basin area  $139 \text{ km}^2$ ) at Stráža gauge station. The specific yield was calculated according to the defined regional relations of the Sectorial Technical Standard of the Ministry of Environment, Slovakia OTN ŽP 3112-1:03. The time course of the hourly rainfall amounts in Vrátna Valley at Štefanova is presented in Fig. 5a. On the basis of the calculated value of the peak discharge at Tiesňavy, the schematic flood waves were created and compared with the estimated flow wave by SHMI





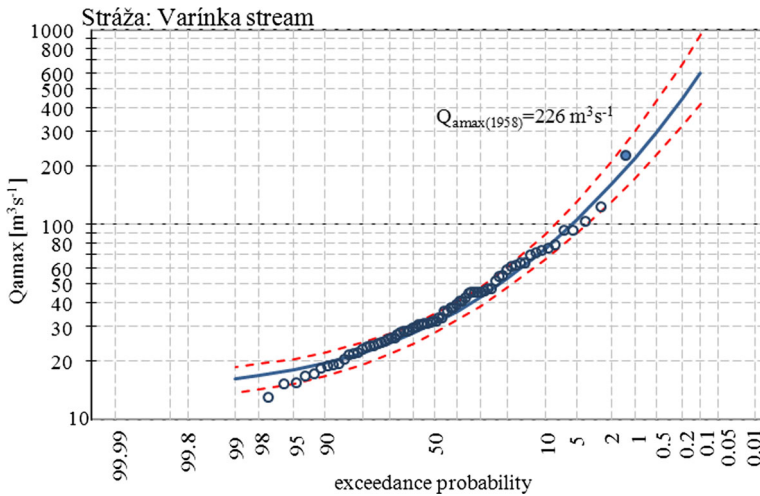
**Fig. 5** **a** Time course of the hourly rainfall amounts in Vrátna Valley: Štefanova and **b** computed hydrographs of the flood wave occurred on July 21, 2014 on the Varínka at Tiesňavy (shadow circle line—SHMI estimation)

(SHMI report 2015). The estimation shows a faster decrease in the falling limb of the flood wave compared to the SHMI wave. The course of the estimated flood wave on the Varínka at Tiesňavy according to SHMI and according to our calculations is shown in Fig. 5b. The different results (but comparable) result from slightly different profiles of culmination wave estimation.

Based on the series of annual extreme peak discharges (1941–2014), a theoretical exceedance probability curve (Log-Pearson, type III) was constructed for the Varínka stream at Stráža (Fig. 6). We included into the calculation the peak of the June 2014 flood on the Varínka stream at Stráža, too. From the theoretical exceedance probability curve according to Log-Pearson type III, the *T*-year values of the discharge were derived for the Varínka stream at Stráža and Tiesňavy (Table 2). The results showed that the peak discharges during the flash flood on July, 21, 2014, on the Varínka stream correspond to the value with a return period of 12 years at Stráža and a value of between 20 and 50 years at Tiesňavy.

### 3.2 The extremeness of the flash flood on July, 21, 2014, on the Varínka stream

To demonstrate the extremeness of the flash flood which occurred in July 2014 on the Varínka stream, the specific runoff of the flood in selected profiles was ranked among the specific runoff of flash floods with a return period over 50 years from the period of 1994–2014 which occurred in Slovakia (Fig. 7). The positions of the specific runoff of the flash flood occurred on the Varínka stream in July 2014 show that this flood was not extreme



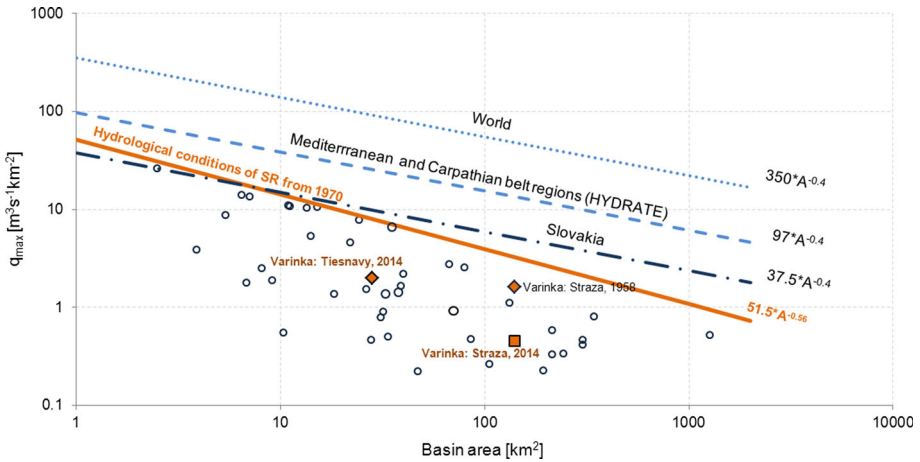
**Fig. 6** Theoretical exceedance probability curve of annual extreme peak discharges (Log-Pearson, type III) of the Varínka stream (period: 1941–2014,  $Q(5)$  and  $Q(95)$ —confidence limits)

**Table 2**  $T$ -year discharges (1941–2014), Varínka stream at Stráža (Log-Pearson III distribution)

$T$ (year)	20	50	100	200	500	1000
$P$ (–)	0.05	0.02	0.01	0.005	0.002	0.001
$Q_{T\text{Stráža}}$	106	162	222	302	452	610
$Q_{(5)}$	130	211	303	432	686	970
$Q_{(95)}$	89	131	174	229	327	427
$Q_{\text{Tiesňavy}}^*$	<b>47</b>	<b>66</b>	84	–	–	–

$Q_{(5)}$  and  $Q_{(95)}$  are 5‰ and 95‰ confidence limits, and  $QT^*$  is estimated  $T$ -year peak discharges in the Tiesňavy gorge: Varínka stream

from a hydrological point of view in Slovak territory. Figure 7 also presents the envelope curves from various sources: the HYDRATE project derived for Slovakia, the Mediterranean and the Carpathian Region, Hydrological conditions of Slovakia from 1970, and lastly for the world (Borga et al. 2011; Gaume et al. 2009; Hydrological conditions of Czechoslovakia III 1970; Marchi et al. 2010; Herschy 2002; Hlavčová et al. 2016). The envelope curve according to the Hydrological conditions of CSSR from 1970 still quite accurately represents the positions of the specific runoff in Slovakia. This envelope curve was derived from flash floods which occurred and were recorded in Slovak territory before 1964. The envelope curve derived from flash floods in Mediterranean regions has a higher position than envelope curves for Slovakia. This behaviour highlights the different space and time scales of the generating storm events under the Continental climate. The space and time scales of flash floods increase systematically when moving from Inland Continental to Mediterranean regions, while seasonality shifts accordingly from summer to autumn months (Norbiato et al. 2008). In the case of Central Europe, Lapin and Pišútová (1998) investigated the impact of atmospheric circulation patterns and changes in cyclonicity and air pressure on the changes in precipitation totals in the context of climate

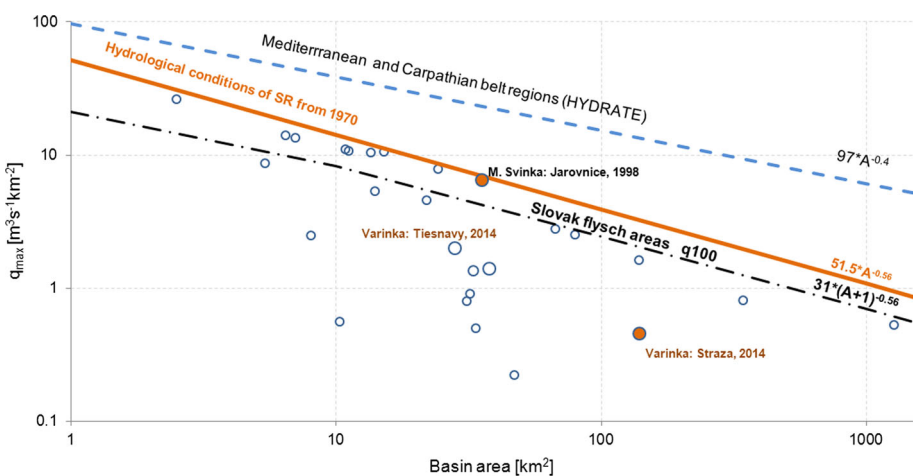


**Fig. 7** Some maximum specific runoff positions of the flash floods observed in Slovakia (1958; 1994–2014) and the envelope curves derived for Slovakia (Slovakia—HYDRATE project, Hydrological conditions till 1964 (HMI Prague 1970), Mediterranean and Carpathian Region (HYDRATE project) and for the world

change. Highlands and mountains, interwoven with streams and rivers, cover about 89% of the land in Slovakia. Generally, the most precipitation falls in the spring–summer period, and the most humid month is July. The envelope curve of the 100-year maximum specific runoff of summer floods derived for the flysch areas of Slovakia and the position of the specific runoff of the compared floods are presented in Fig. 8. The equation envelope curve is expressed as (Dub 1941):

$$q_{\max} = B \cdot (A + 1)^{-n} \tag{4}$$

where  $A$  is the basin area ( $\text{km}^2$ ),  $B$  and  $n$  are regional constants.



**Fig. 8** Specific runoff position of the flood on the Varínka stream occurred on July 21, 2014, the specific runoff positions occurred in flysch areas in Slovakia (1958; 1994–2014) and the envelope curve of the 100-year specific runoff derived for flysch areas in Slovakia

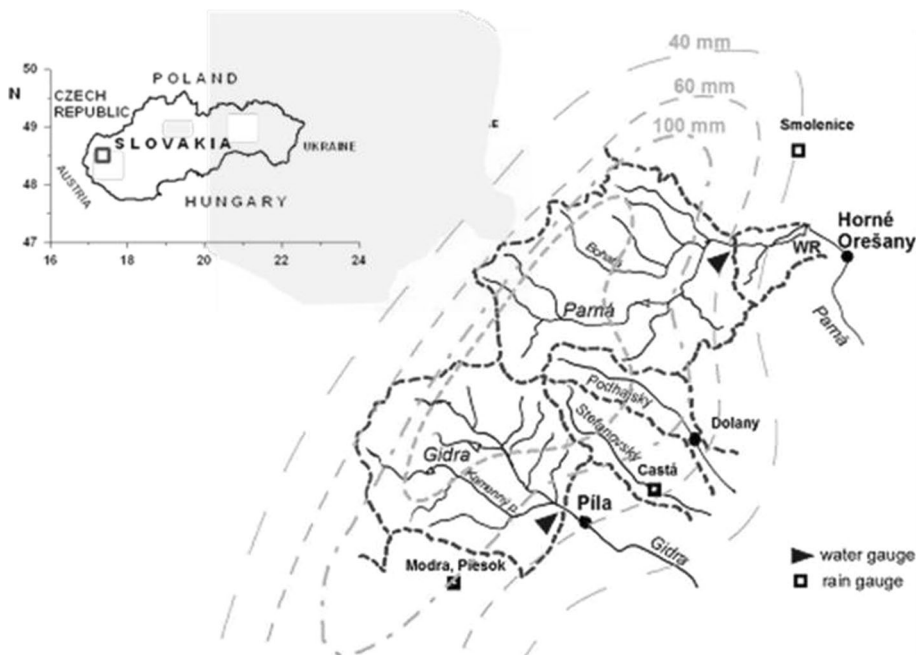
## 4 Comparison of the some extreme summer flash floods occurred in Slovakia

### 4.1 Gidra and Parná, Small Carpathians Mountain

The Gidra and Parná streams are located in the southern part of the Small Carpathians (western Slovakia) (Fig. 9). In their upper parts, the streams flow through a more or less original beech forest environment. The only human interventions are a small dam on the Parná and fishponds on the Gidra, upstream of the water-level observation stations. The highest point in the catchment area reaches 694 m a.s.l. (Jelenec and Geldek hills on the Gidra and Parná watershed divide). After leaving the Small Carpathian mountain range, the rivers flow through agriculturally used land and also through some of the local villages. The SHMI built hydrometric stations on the Gidra and Parná streams, after 1961, for average daily flow evaluation. The geographical and hydrological characteristics of the Gidra at Píla and Parná at Horné Orešany are presented in Table 3.

On the 7th of July, 2011, in the afternoon, flash flooding on the Gidra and Píla streams occurred. The houses and roads near the Gidra stream in Píla village were destroyed by the flood wave. Upstream on the Parná stream the water reservoir was constructed in 1994. This water reservoir stored some 0.817 mil m<sup>3</sup> of water. As to this source, the flood wave with a peak of 140–150 m<sup>3</sup> s<sup>-1</sup> on the reservoir's inflow was transformed to 11.5 m<sup>3</sup> s<sup>-1</sup> on its outflow.

The flash floods in the Small Carpathian region were created as a result of the daily precipitation amount of 104 mm at Modra–Piesok station (Fig. 10a). Such a daily amount

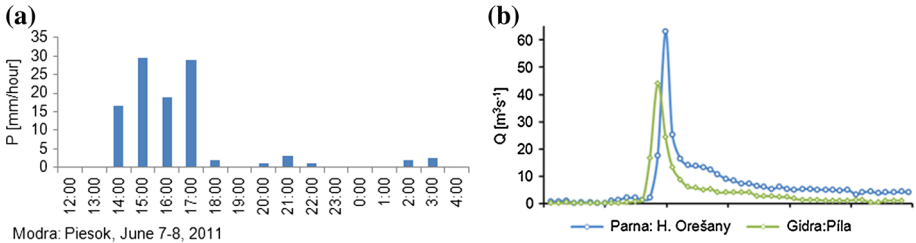


**Fig. 9** Location of the Gidra and Parná basins in the Little Carpathian (Slovakia) and rainfall depth occurred on June 7, 2011

**Table 3** Basic geographical and runoff characteristics of the Gidra stream at Píla and Parná stream at Horné Orešany

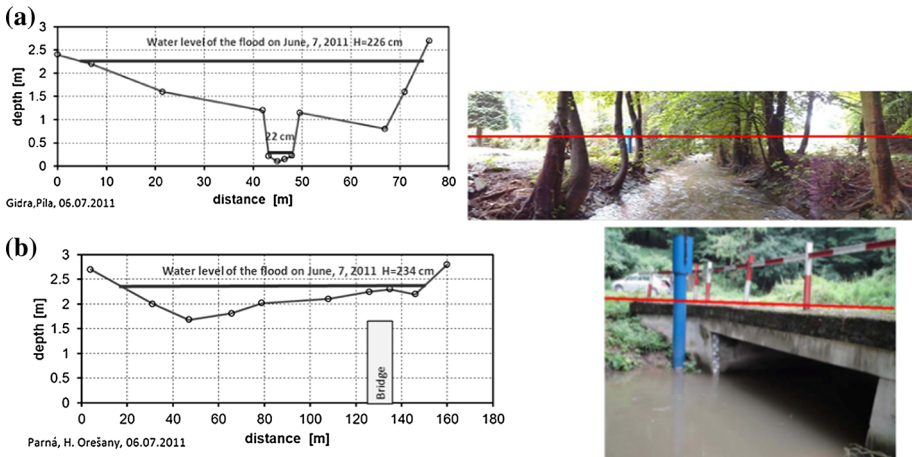
	A (km <sup>2</sup> )	River (km)	Forestation (%)	Average slope (°)	Q <sub>amax</sub> (m <sup>3</sup> s <sup>-1</sup> )
Gidra: Píla	32.95	33.3	91.15	10.8	4.39
Parná: H. Orešany	37.86	26.8	88.83	11.38	4.9

A Basin area and Q<sub>amax</sub> average maximum annual discharge during the period of 1961–2014



**Fig. 10** a Time course of the hourly rainfall on July 7–8, 2011, at Modra–Piesok and b computed hydrographs of the flood waves occurred on July 7, 2011 on the Gidra at Píla and Parná at Horné Orešany

is not unusual in the Small Carpathian region. For example, at Limbach station, a daily precipitation of 147 mm was observed in 1957; at Myjava station 142 mm in 1954; or, at Trnava station (school), even 162.8 mm a daily precipitation amount was observed in 1951. Pekárová et al. (2012) estimated the peak discharge to be above 44 m<sup>3</sup> s<sup>-1</sup> (1.36 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup>) on the Gidra stream and above the value of 60 m<sup>3</sup> s<sup>-1</sup> (1.61 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup>) on the Parná stream. The estimated hydrograph of the flood waves which occurred in July 2011, on the Gidra and Parná is presented in Fig. 10b. With respect to the terrain near the gauging stations, experimental measurements were complicated and estimation of the peak discharges was subject to some errors (Fig. 11a, b). SHMI estimated

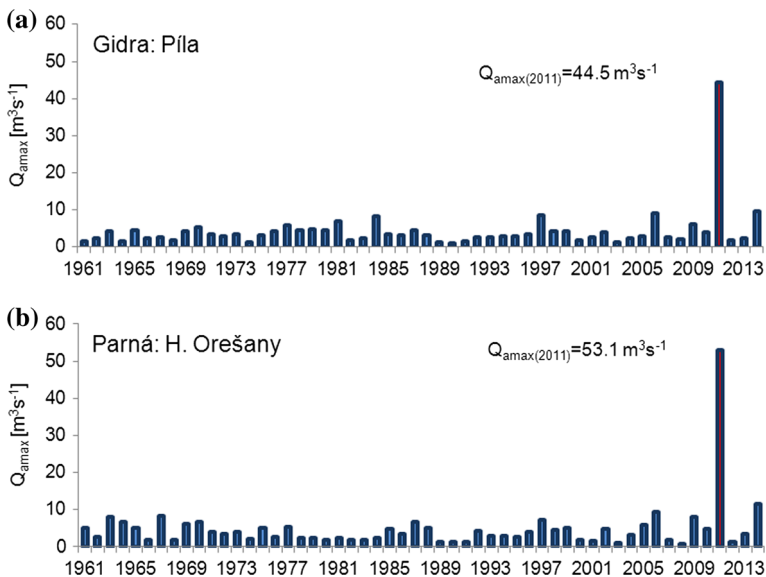


**Fig. 11** a, b Fixation of the cross sections for a the Gidra at Píla and b the Parná at Horné Orešany according to the flood tracks of the flood occurred on July 7, 2011

the peak discharge at a value of  $44.5 \text{ m}^3 \text{ s}^{-1}$  and  $q_{\max} = 1.35 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  on the Gidra stream and  $53.1 \text{ m}^3 \text{ s}^{-1}$  which corresponds to a specific runoff of  $1.40 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  on the Parná stream (Blaškovičová et al. 2013). The peak discharges which occurred during the floods in 2011 were the most extreme discharges recorded during the period of 1961–2014 on the Gidra and Parná streams (Fig. 12a, b).

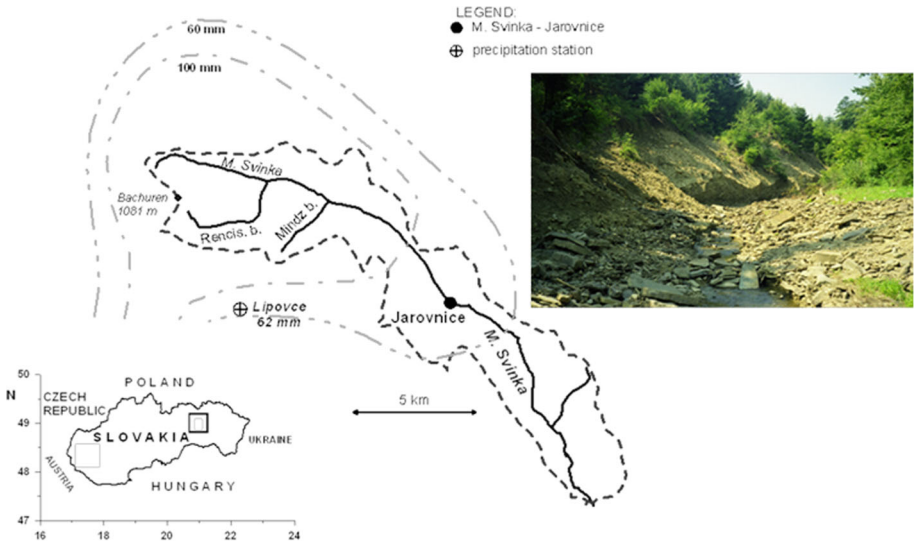
## 4.2 Malá Svinka, Bachuren Mountains

The most extreme (catastrophic) flash flood during the last 20 years was the flood which occurred on the Malá Svinka stream in the Bachúreň Mountains (east Slovakia) in 1998 (Fig. 13). Basic geographical and runoff characteristics of the Malá Svinka at Jarovnice are presented in Table 4. A flood event on July 20, 1998, on the Malá Svinka stream was caused by 1.5-h rainfall (80 mm) and the specific flow reached value of  $6.19 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  and maximum discharge reached a value of  $178 \text{ m}^3 \text{ s}^{-1}$  according to Svoboda and Pekárová (1998). SHMI estimated the peak discharge at a value of  $230 \text{ m}^3 \text{ s}^{-1}$  and  $q_{\max} = 6.83 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  (Majerčáková and Škoda 1998). A reconstruction of the isohyets of the extreme rainfall depth which could cause the flash flood in 1998 in the Malá Svinka basin is presented in Fig. 14a. A computed hydrograph of the flood wave which occurred on July 20, 1998, on the Malá Svinka at Jarovnice (Svoboda and Pekárová 1998) is presented in Fig. 14b.



**Fig. 12** a, b Annual extreme discharges a on the Gidra at Píla and b on the Parná at Horné Orešany occurred during the period of 1961–2014 (SHMI data)

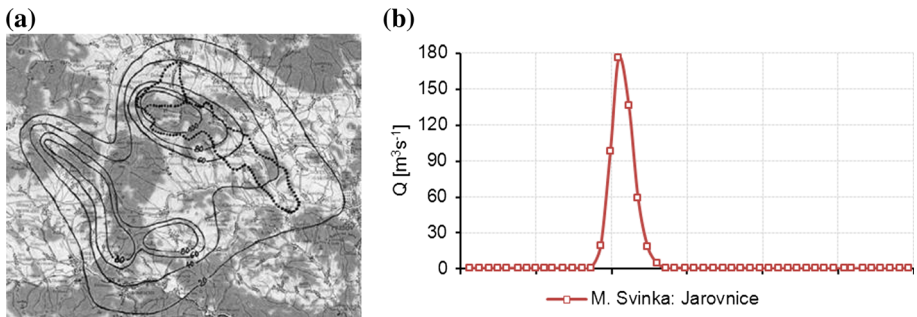




**Fig. 13** Location of the Malá Svinka basin in the Bachuren Mountains (east Slovakia) and rainfall depth occurred between 4 and 5 p.m. on July 20, 1998

**Table 4** Basic geographical and runoff characteristics of the Malá Svinka at Jarovnice

	A (km <sup>2</sup> )	River (km)	Forestation (%)	Average slope (°)	Q <sub>amax</sub> (m <sup>3</sup> s <sup>-1</sup> )
Malá Svinka: Jarovnice	34.39	14.68	71.4	14.12	–



**Fig. 14** **a** Reconstruction of the isohyets of the extreme rainfall which caused the flash flood in 1998 on Malá Svinka basin and **b** computed hydrograph of the flood wave occurred on July 20, 1998, on the Malá Svinka at Jarovnice (Svoboda and Pekárová 1998)

### 5 Results of the comparison

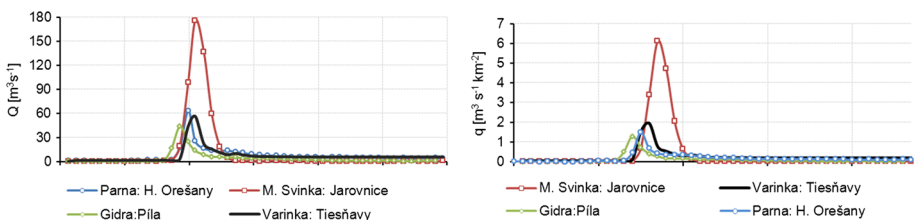
The flash flood on the Varínka stream (July 2014) was compared with summer floods which occurred on the Parná at Horné Orešany (July 2011), on the Gidra stream at Píla (July 2011) and on the Malá Svinka stream at Jarovnice (July 1998). All four floods

occurred in small basins (30–40 km<sup>2</sup>) and showed the effect of intensive rainfall small saturated basins. The runoff during these flash floods was so extensive and so fast that the retention capacity of the shallow soil profile together with the vegetation cover was not able to retain or effectively mitigate it. The average rainfall depth of 80–100 mm per 2 h caused runoff from every km<sup>2</sup> of the basin area of about 7 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup> on the Malá Svinka at Jarovnice but “only” of about 1.5 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup> on the Gidra at Píla and Parná at Horné Orešany, and of about 2 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup> on the Varínka at Tiesňavy. The comparison of the extreme flash floods is illustrated in Fig. 15.

## 6 Conclusions and discussion

In the present study, the post-event reconstruction was made of the flash flood which occurred on July 21, 2014, on the Varínka stream in the Vrátna Valley (the Malá Fatra National Park). The July 2014 flash flood on the Varínka stream again reminded us of the power of water flow. Because the upstream part of the Varínka stream (above Terchová village) is ungauged, the post-event analysis of the stream was made at three cross sections. This paper was focused mainly on post-event analysis of the Varínka stream at the Stráža profile (139.5 km<sup>2</sup>, gauged profile by SHMI) and at Tiesňavy cross section (28.05 km<sup>2</sup>, ungauged cross section). The results show that:

1. Small mountain basins where the extreme floods occur often cannot be provided with a measuring device. Therefore, hydrological explorations are performed in the basins and river profiles are measured after each major flash flood to estimate the culmination of the wave. Every flash flood (as well as every natural extreme event) is a source of unavailable information; therefore, the description, analysis and reconstruction of such events are extremely important.
2. A comparison of the historical records of the floods which occurred in the Malá Fatra National Park and the reconstruction of the July 2014 flood on the Varínka stream at Stráža showed that the July 2014 flood was not the highest flood in this area despite its catastrophic consequences.
3. The maximum discharge on the Varínka stream at Stráža reached peak discharge with a return period of  $T = 12$  years. The calculated maximum discharge reached return period between 20 and 50 years at Tiesňavy.
4. The position of the maximum specific runoff at selected profiles showed that this flood was not extreme from a hydrological point of view in Slovak territory as well as in the Mediterranean and Carpathian Regions. But, also the peak discharge with a return



**Fig. 15** Hourly flows during the extreme flash floods on the Svinka stream at Jarovnice (July 1998), the Gidra at Píla (July 2011), Parná at Horné Orešany (July 2011) and on the Varínka stream at Stráža and at Tiesňavy (July 2014): **a** flow and **b** specific runoff

period of “only” between 20 and 50 years showed the devastating effect of the flash flood in a flysch area where alternation between claystone and sandstone creates a specific rock environment and where the surface runoff prevails over water infiltration. Despite the relatively good permeability of the sandstone, there is a very low permeability of the claystone.

The flash floods in the flysch regions of Slovakia are not unique phenomena. With more or less intensity, they are found in various river basins, depending on the intensity and duration of the rainfall. Gaál et al. (2012) used comparative hydrology to analyse the timescale of the flash floods for various catchment areas in Austria. The authors compared catchments with contrasting characteristics (synoptic and convective storms, rain-on-snow, snowmelt, geology, soils, soil moisture, and land form). The results showed that flysch tends to produce very a flashy response as the flow paths are at the surface or very near the surface with little infiltration and flysch catchments have relatively shallow soils and therefore a much faster flood response, which in turn tends to enhance erosion.

In the second part of the paper, four major summer floods that occurred in Slovak territory since 1998 were compared. The first one occurred in July 2014 on the Varínka stream in Vrátna Valley, the second in July 1998 on the Malá Svinka Stream at Jarovnice and the two other floods occurred in June 2011, on the Gidra stream at Píla, and on the Parná stream at Horné Orešany in the Small Carpathians. The results show that:

1. All floods showed the main negative factors involved in the formation of the flash floods: the high degree of the saturation of the catchment caused by previous rainfall just before extremely heavy precipitation dropped on the basin.
2. The flash flood on the Mala Svinka is still one of the largest events in Slovakia for basins with an area of 10–100 km<sup>2</sup>.
3. The peak discharge reached a value with a return period of 100 years on the Malá Svinka and above 200 years on the Gidra at Píla and the Parná at Horné Orešany.
4. The peak discharge with a return period of “only” between 20 and 50 years on the Varínka stream at Tiesňavy showed the devastating effect of a flash flood (Table 5).
5. The upstream reservoir located on the Parná stream shows the positive effect of flood wave flattening. Despite the stream having overflowed and only a few houses, roads and gardens in the villages having been destroyed, the reservoir played an important

**Table 5** Maximum discharges, specific runoff and *T*-year discharges on the Varínka stream (July 2014), the Gidra stream (July 2011), the Parná stream (July 2011) and the Malá Svinka stream (July 1998)

Stream	Station	<i>A</i> (km <sup>2</sup> )	$Q_{\max}$ (m <sup>3</sup> s <sup>-1</sup> )	$q_{\max}$ (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	$V_{\max}$ (mil. m <sup>3</sup> day <sup>-1</sup> )	<i>T</i> -year (Log-Pearson III)
Varínka	Tiesňavy	28.05	56	1.99	0.839	20–50
Gidra	Píla	32.95	44.5	1.35	0.548 <sup>a</sup>	500
Parná	H. Orešany	37.86	60.5	1.60	0.703 <sup>a</sup>	500
Malá Svinka	Jarovnice	34.39	178	5.18	1.900 <sup>b</sup>	1000 (SHMI)

<sup>a</sup>Blašková et al. (2013)

<sup>b</sup>Svoboda and Pekárová (1998)

role in flood protection. Without the effect of the water reservoir, property damage could have been many times higher.

6. The results also indicate that the primary cause of such events is the relevant precipitation together with the initial soil moisture conditions in the catchment area. An intensive rainfall over a small catchment area sufficiently wetted by prior, even moderate, precipitation, can cause a disastrous flood which cannot be effectively reduced either by retention capacity of the shallow soil or by interception by a dense and healthy forest.

Merz and Blöschl (2003) studied the seasonality of maximum annual flood peaks as one of the flood process indicators describing the timing of floods. They found that the seasonal pattern of flood occurrence is related to both snow processes and the occurrence of flooding in the summer months. Kriegerová and Kohnová (2005) analysed the seasonality of rainfall- and snowmelt-induced floods in 142 small- and mid-sized catchment areas in Slovakia and found that convective storms are the main causal factor of the annual peak discharges. They concluded that the seasonality indices represent an important indicator of flood processes that can be used as a pooling characteristic in regional flood frequency analysis.

It is supposed that the presented results would supply additional data on rare events needed for the development and use of regional formulae for peak flow estimates in structural design. They also indicate that the primary cause of such events is the relevant precipitation together with the initial soil moisture conditions in the catchment, in contrary to some recently popular statements attributed them to the anthropogenic interventions into the vegetation cover and to the river channel regulation. An intensive rainfall over a small catchment sufficiently wetted by the antecedent even moderate precipitation can cause a disastrous flood which cannot be effectively reduced neither by retention capacity of the shallow soil, nor by interception of a dense and healthy forest. The results also indicate a need for revision of our views upon the use of regional formulae in general, and upon the meaning of the “design peak flow” in particular.

**Acknowledgements** This work was supported by the Project Vega 2/0009/15 and results from the project implementation of the “Centre of excellence for integrated flood protection of land” (ITMS 26,240,120,004) supported by the Research and Development Operational Programme funded by the ERDF.

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