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Post-event analysis and flash flood hydrology in Slovakia

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Abstract: This work examines the main features of the flash flood regime in Central Europe as revealed by an analysis of flash floods that have occurred in Slovakia. The work is organized into the following two parts: The first part focuses on estimating the rainfall-runoff relationships for 3 major flash flood events, which were among the most severe events since 1998 and caused a loss of lives and a large amount of damage. The selected flash floods occurred on the 20th of July, 1998, in the Malá Svinka and Dubovický Creek basins; the 24th of July, 2001, at Štrbský Creek; and the 19th of June, 2004, at Turniansky Creek. The analysis aims to assess the flash flood peaks and rainfall-runoff properties by combining post-flood surveys and the application of hydrological and hydraulic post-event analyses. Next, a spatially-distributed hydrological model based on the availability of the raster information of the landscape's topography, soil and vegetation properties, and rainfall data was used to simulate the runoff. The results from the application of the distributed hydrological model were used to analyse the consistency of the surveyed peak discharges with respect to the estimated rainfall properties and drainage basins. In the second part these data were combined with observations from flash flood events which were observed during the last 100 years and are focused on an analysis of the relationship between the flood peaks and the catchment area. The envelope curve was shown to exhibit a more pronounced decrease with the catchment size with respect to other flash flood relationships found in the Mediterranean region. The differences between the two relationships mainly reflect changes in the coverage of the storm sizes and hydrological characteristics between the two regions.

Keywords: Flash flood; Slovakia; Post-event analysis; Hydrological modelling.

INTRODUCTION

The estimation of flash flood hazards is a challenging component of a flood protection system. Owing to the characteristics of their triggering convective rainfall, flash floods generally occur in small to medium-sized basins of some hundred square kilometres or less. Marchi et al. (2010), in an investigation of European flash floods, showed that the relevant response times are generally less than 8 hours. The space-time scales of the occurrence of these floods are small relative to the sampling characteristics of rain and discharge measurement networks; this makes it particularly difficult to detect and analyse flash floods (Borga et al., 2008). It is therefore not surprising that flash flood data are relatively rare in systematic flood data archives.

In the last decade, a remarkable body of research work has shown that reliable flash flood data can be obtained by means of spatially detailed post-event surveys of flash flood responses along a stream network (Gaume and Borga, 2009). These surveys aim to estimate peak discharges based on the identification of high-water marks left by water and sediments during floods (Marchi et al., 2009). Several indirect methods (slope-area, flow-over-dam, flow-through-culvert) can be used to estimate the peak flows based on high water marks and high-quality topographic surveys. Specific care is required for the selection of the river sections which are suitable for indirect estimations of peak discharges. These estimates may be compared with the corresponding peak flows simulated by using weather radar reanalysis and distributed hydrological modelling, thus permitting a close assessment of the quality of the data. The results from several case studies (Blaškovičová et al., 2011; Delrieu et al., 2005; Pekárová et al., 2012; Ruiz-Villanueva et al., 2012; Zanon et al., 2010 among others) have shown that post-event surveys may deliver a spatially consistent analysis of flash flood responses.

Together with data from conventional hydrometric monitoring, data collected from post-flood surveys can be used for flash flood frequency assessments on local and regional scales. This approach is exemplified by the work of Gaume et al. (2010), which provides a method for using data from major flash flood events to estimate regional flood quantiles. From a different perspective, Merz and Blöschl (2008) showed that identification of a flood's causal factors by means of a post-flood survey may enable the obtaining of more informed estimates of flood frequencies.

The aim of this work is to provide a characterisation of the flash flood post–event hydrology and flash flood regime in Slovakia, which is taken as a representative region for Central-Eastern Europe. Slovakia is located in a part of Central Europe where flash flooding in small catchments regularly occurs every year in the summer season. There are approximately 2,300 small catchments within a range of 5–50 km^2 with a great potential risk of flash flooding. Historically, only a few flash floods have been documented in the reports of the Slovak Hydrometeorological Institute; we only have evidence of a flash flood on the Vydrňanka Creek (the Váh River basin) on June 17, 1939, and a flash flood on August 15, 1949, which occurred in the small tributaries of the Torysa River basin in Eastern Slovakia.

An analysis of the flash floods which occurred in the last 100 years on the territory of Slovakia was done in a frame of the HYDRATE (2006) project. The characteristics of the flash flood regime in this region have been examined by Gaume et al. (2010), in the frame of a broader work dedicated to selected regions in Europe. These authors noted that in Central Europe, extreme flash floods occur generally in the summer season, while there is a shift towards the fall and winter seasons when moving to Southern Europe and to the Mediterranean region. They also reported that flash floods in this region tend to be shorter and involve a smaller depth of accumulated rainfall with respect to the flash floods in Southern Europe. It is therefore not surprising that the maximum peak discharges collated by these authors in Central Europe are less than half the maximum peak discharges reported for the Mediterranean region for a given watershed area. However, one should note that the flash flood peak discharge data considered by Gaume et al. (2009) for Slovakia were all obtained from streamgauge sections. It is therefore likely that the methodology used by these authors may have led to an undersampling of flash floods that have occurred in smaller ungauged basins.

In this work we examine three major flash floods, all of which occurred in ungauged basins located in Slovakia. The events in the study analysed belong among the largest ones in the past 20 years. They occurred on the 20th of July, 1998, in the Malá Svinka and Dubovický Creek basins; on the 24th of July, 2001, at Štrbský Creek; and on the 19th of June, 2004, in the Turniansky Creek basin. For these events, a classical post-event analysis by hydrological and hydraulic surveying was undertaken. Then, the peak discharges, runoff volumes and runoff ratios were simulated by a distributed hydrological model, and the results were compared with estimates achieved by the classical post-event approach. The analysed flash data were then combined with the whole archive of flash floods recorded for Slovakia to permit an examination of flash flood regimes characterised in terms of envelope curves.

The organization of the paper is as follows: In the first chapter the problems of flash flood hydrology are introduced. In the second chapter of the paper the methods used are described, with a focus on the characteristics of the KLEM distributed rainfall-runoff model. The third chapter contains a description of the basins along with the selected flash floods, and the results of the post-survey reconstruction of the flash flood events are described. The processing of the data required and the simulation of the selected flash floods by the KLEM model in different sections of the basins are provided in the fourth chapter. In the fifth chapter the extremity of the selected flash floods is evaluated by comparing the events with historical flash floods in Slovakia and flash floods analyses in Central Europe and the Mediterranean region within the Hydrate project. In the last part of the paper the results achieved are summarized and discussed.

METHODS

All the selected flash flood events occurred in small ungauged basins, and classical methods of hydrological and hydraulic analysis based on post-event surveying were applied for their reconstruction. The hydrological methods are based on analyses of the meteorological situations and rainfall reconstructions, estimations of the flood volumes by estimates of the runoff coefficients, and estimating the lag time and shape of the flood hydrographs. The hydraulic methods are based on post-event surveying directly after the flood, measurements of the channel slopes and channel cross sections, flood marks, and estimations of the roughness and flow velocities by simple hydraulic equations. All these post-event analyses were provided by the Slovak Hydrometeorological Institute (Danáčová and Velčická, 2004; Majerčáková et al., 2004; Šťastný, 1998; Šťastný and Majerčáková, 2003) and the Institute of Hydrology of the Slovak Academy of Sciences (Svoboda and Pekárová, 1998). These results are completed and summarised in this paper.

As opposed to a post-event estimation by hydrological and hydraulic surveying, the selected flash floods were examined using a simple spatially-distributed hydrologic model, i.e., the KLEM (Kinematic Local Excess Model) rainfall-runoff model (Borga et al., 2007). The distributed model is based on the availability of the raster information of a landscape's topography and soil and vegetation properties. In the model, the SCS-Curve Number (SCS-CN) procedure (U.S. Department of Agriculture, 1986) is applied on a grid for the spatially-distributed representation of the runoff generating processes. A simple method (Da Ros and Borga, 1997; Giannoni et al., 2003) is used to represent runoff propagation for the response of a drainage system. The SCS-CN runoff equation is expressed in the form:

$$\begin{aligned} q &= \frac{(P-I_a)^2}{(P-I_a+S)} \quad \text{for} \quad P \geq I_a \\ q &= 0 \qquad\qquad\quad \text{for} \quad P < I_a \end{aligned} \quad , \tag{1}$$

where q [mm] is the direct runoff depth, P [mm] is the rainfall event's depth, I_a [mm] is the initial abstraction or rainfall event required for the initiation of runoff, and S [mm] is a site storage index defined as the maximum possible difference between P and q as $P \to \infty$. $P – I_a$ is also called "effective rainfall" or P_e. The SCS-CN method can be applied by specifying a single parameter called the curve number (CN), which is a function of the hydrologic soil-cover complex and ranges from 1 to 100. The spatial distribution of the CN values for this analysis was obtained from previous investigations of the area studied (Cazorzi and Bincoletto, 2005). Following Ponce and Hawkins (1996), the value of S for a given soil is related to the curve number as:

$$S = C \cdot \left(\frac{100}{CN} - 1 \right), \tag{2}$$

where C is a calibration parameter [mm] known as "infiltration storativity". The use of the parameter C allows one to use the spatial distribution of the CN values, which represents the input data in this work and, at the same time, to simulate the observed flood water balance correctly. In the SCS-CN equation (in SI units) the value of C is 254 mm, and the initial abstraction is specified as a percentage of S. Given the initial exceptionally low soil moisture conditions, the proportionality factor between I_a and S (herewith called "X") was considered as a further parameter in this study.

The distributed routing of a runoff is based on the identification of drainage paths and requires the characterization of hillslope paths and channeled paths. The separation of hillslope elements from channel elements is based on a channelization support area (A_s) [km^2], which is considered to be constant on a subbasin scale. A discharge at any location along a river network is represented by:

$$Q(t) = \int_A q\left[t - \tau(x), x\right] dx \tag{3}$$

where A_s [km^2] indicates the area draining to the specified outlet location; $q(t, x)$ is the runoff at time t and location x; and $\tau(x)$ is the routing time from x to the outlet of the basin specified by the region A. The routing time $\tau(x)$ is defined as

$$\tau(x) = \frac{L_h(x)}{v_h} + \frac{L_c(x)}{v_c} \tag{4}$$

where $L_h(x)$ is the distance from the generic point x to the channel network following the steepest path of descent; $L_c(x)$ is the length of the subsequent drainage path through streams down to the watershed outlet; and v_h and v_c [m.s^{-1}] are two invariant hillslope and channel velocities, respectively.

The model also includes a conceptual linear reservoir for base flow modelling, the structure of which is kept invariant over all the basins. The reservoir input is provided by the infiltrated rate, which is computed based on the CN-SCS method; the method is applied on the subbasin scale.

There are six calibration parameters in the model: the channelization support area (A_s), two kinematic parameters (v_h and v_c); the parameter C, which is required for the calibration of the SCS-CN procedure; and the parameter of initial abstraction I_a. The model can even be implemented in very short time steps (10–15 min) and uses a user-defined grid size cell for the description of a landscape's morphology and soil properties.

POST-EVENT RECONSTRUCTIONS OF THE FLASH FLOODS

The flash flood events in the study analysed belong among the largest ones of the past 20 years. They occurred on the 20th of July, 1998, in the Malá Svinka and Dubovický Creek basins; the 24th of July, 2001, at Štrbský Creek; and the 19th of June, 2004, in the Turniansky Creek basin (Table 1).

Malá Svinka and Dubovický Creek basins

Description of the study sites

The Malá Svinka is a small tributary of the Hornád River, whereas the Dubovický Creek is a small tributary of the Torysa River (Fig. 2a). The altitude of the Malá Svinka basin ranges from 400 to 1061 m a.s.l.; the mean altitude is 646 m a.s.l.; and the mean slope is 17.9%. The altitude of the Dubovický Creek ranges from 377 to 1017 m a.s.l.; the mean altitude is 596 m a.s.l.; and the mean slope is 20.6%. The climate of both of the selected catchments is characterised as moderately warm and humid with monthly temperature means from about –5ºC (January) to +18ºC (July), a mean annual air temperature of 7.8ºC, and mean annual precipitation totals in a range of 600–650 mm. In its higher elevations the catchment belongs to a moderately cool and humid sub-region. The basins belong geologically to a flysh belt created by sand and clay layers in Northern Slovakia. The soil texture in the Malá Svinka Creek basin is represented by sandy-loamy and loamy soils (65:35) and in the Dubovický Creek basin by loamy and clay/loamy soils (58:42). The basins are mainly forested in the upper part, whereas agricultural areas predominate (60%) in the downstream parts.

Meteorological situation on July 28, 1998

On July 28th, 1998, a very unstable air mass appeared due to the high humidity of the air, and two isolated areas of torrential rain occurred. The first storm activity was in the Topľa basin with precipitation totals above 60 mm, which caused a local flood on the Malá Svinka basin. The second storm activity had two isolated parts in the Topľa watershed and the Hornád and Torysa watersheds with higher precipitation totals. The most catastrophic flash flood occurred on two tributaries of the Svinka River, i.e., on the Malá Svinka and Dubovický Creeks.

Unfortunately, no equipment such as rain gauge recorders or water gauging stations was available at these two basins (the Malá Svinka and Dubovický Creek), and the core of the torrential rainfall (cloudburst) was not detected by any rain-gauge station. The thunderstorm in this region had several cores with different trajectories and different commencement times. In many places the inhabitants observed a strong wind or gustiness, very loud thunder and hail.

The reconstruction of the rainfall showed that the duration of the rainfall at the rain-gauge station in the village of Lipovce in the Svinka Creek Basin was recorded from 16:10 to 17:45. The most intense precipitation occurred during a time interval of 10 to 30 minutes. Precipitation in the most vulnerable areas reached about 100–130 mm in 150 min (according to the analyses of the Slovak Hydrometeorological Institute); the 24-hour total precipitation with a probability of occurrence of 0.01 is about 80–90 mm in this area (Šťastný, 1998). The location of the climatic and gauging stations around the Malá Svinka and Dubovický Creek basins is shown in Fig. 2a.

Table 1. Selected flash floods.

Stream	Occurrence of the flash flood event	Basin area [km^2]
Dubovický Creek	20/07/1998	15.2
Malá Svinka Creek	20/07/1998	35.4
Štrbský Creek	24/07/2001	11.2
Turniansky Creek	19/06/2004	70.4

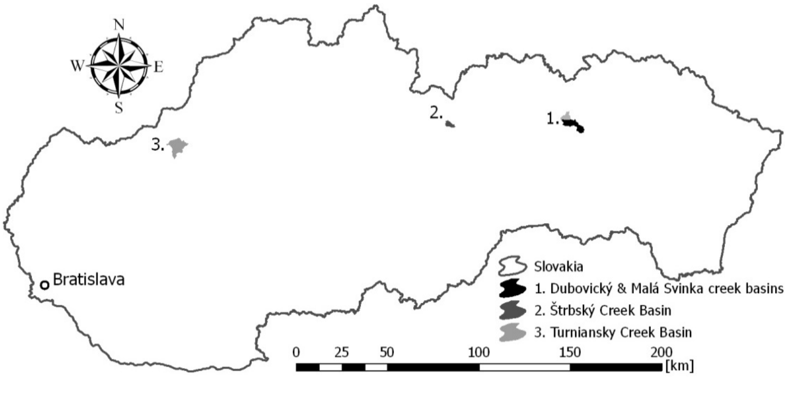


Fig. 1. Location of catchments with the three flash floods selected in Slovakia.

Post-event hydrological analysis

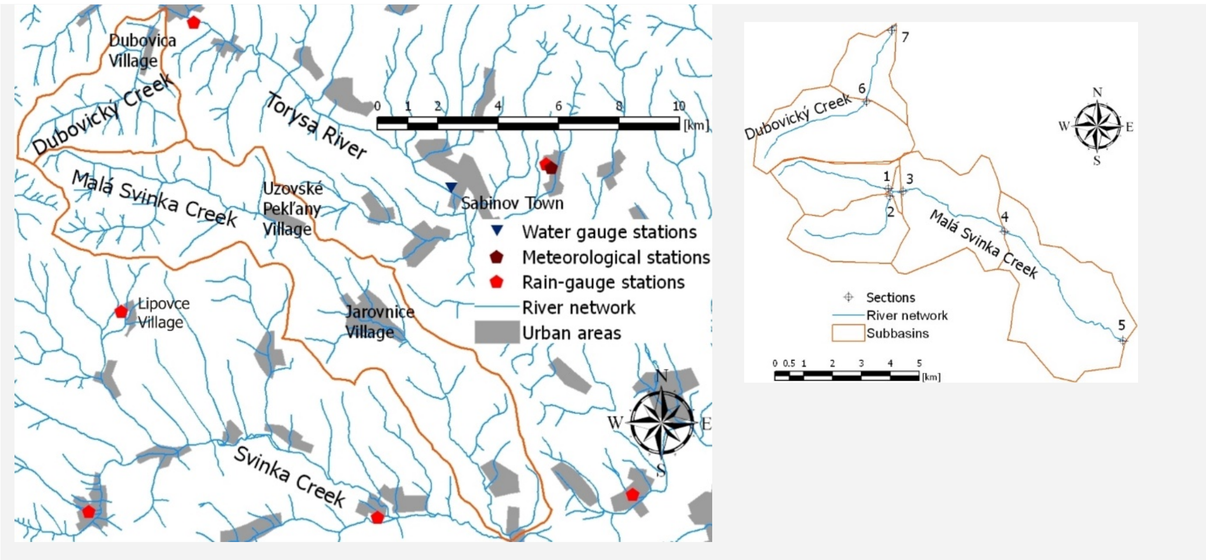
From the reconstruction of the flood wave on the Malá Svinka according to Majerčáková et al. (2004), the following conclusions can be made: The assessed velocity of the flood wave was 2–2.5 m.s^{-1} (7.2–9 km.h^{-1}); the lag time of the Malá Svinka watershed might be estimated as being from 80–90 minutes; therefore, the lag time was approximately equal to the thunderstorm's duration. It may be considered from this estimate that the entire rainfall and the entire watershed created the discharge in the village of Uzovské Pekľany. The flood wave here could have had the shape of a narrow triangle with a volume of 1,330,000 m^3 and a very high maximum discharge of 190 m^3.s^{-1}, which can be expressed as a specific runoff of 7.8 m^3.s^{-1}.km^{-2}. The runoff coefficient was estimated as having a value of 0.64. A similar situation is also assumed to have occurred in the village of Dubovica, but with a lower maximum discharge of around 160 m^3.s^{-1}. Based on the theoretical assumptions and reconstructed flood waves, it was determined that 1000-year discharges had occurred in the local streams in the villages of Renčišov, Uzovské Pekľany, Jarovnice and Dubovica. The characteristics of the flash flood were estimated in seven river sections in the basin (Fig. 2b). The estimated characteristics of the flash flood reconstructions in these river sections are listed in Table 2.

Post-event hydraulic analysis

The findings of the post-event hydrological analysis were compared with the hydraulic estimation of the flood peak magnitudes, which were provided on August 12th 1998 by the Institute of Hydrology of the SAS (Svoboda and Pekárová, 1998). The estimation was performed for two river sections: 1*. Malá Svinka above Renčišovský Creek and 2. Renčišovský Creek at the mouth to Malá Svinka. (The section 1* Malá Svinka above Renčišovský Creek was located more upstream in comparison with the section used in the hydrological analysis). Due to the fact that the river channel in the lower part of Malá Svinka was destroyed during the flood, only these two river sections were appropriate for the hydraulic evaluation. The areas of the channel's cross-profiles were measured for the maximal water level; the longitudinal slope of the water level was approximated to the bottom slope; and the roughness was estimated according to the river banks and channel bottoms. The flow velocities were calculated using the Chézy equation and Manning roughness coefficient.

The measured and estimated hydraulic parameters and flood wave characteristics of the two river sections selected are listed in Table 3.

From a comparison of the hydrological and hydraulic estimations, it can be seen that for section 2 at Renčišovský Creek, the calculated flood peaks are rather close (98 and 112 m^3 s^{-1}). For the profile 1* at Malá Svinka, the flood peak estimated by the hydraulic analysis is lower than the hydrological estimate. The difference could mainly be caused by the difference in the catchment area (the profile for the hydraulic estimation was situated more upstream; the basin area was only 4.825 km^2 in comparison to the basin area of 6.5 km^2 for section 1).



a) b)

Fig. 2. The Malá Svinka and Dubovický Creek basins **a)** the location of the climate and gauge stations **b)** sections for the post-event analysis.

Table 2. Hydrological evaluation of the flood in the Malá Svinka and Dubovický Creek basins (Majerčáková et al., 2004).

Stream	River section	Basin area [km^2]	Estimated flood wave volume [m^3]	Estimated maximum peak Q [m^3.s^{-1}]	T-year of maximum Q
Malá Svinka	1 above Renčišovský Creek	6.5	400,000	90	>1000
Renčišovský Creek	2 mouth to Malá Svinka	7.1	425,000	98	>1000
Malá Svinka	3 under village of Renčišov	13.5	825,000	140	>1000
Malá Svinka	4 in village of Uzovské Pekľany	24.3	1,330,000	190	>1000
Malá Svinka	5 in village of Jarovnice	35.4	1,900,000	230	>1000
Dubovický Creek	6 above village of Dubovica	10.9	650,000	120	>1000
Dubovický Creek	7 under village of Dubovica	15.2	850,000	160	>1000

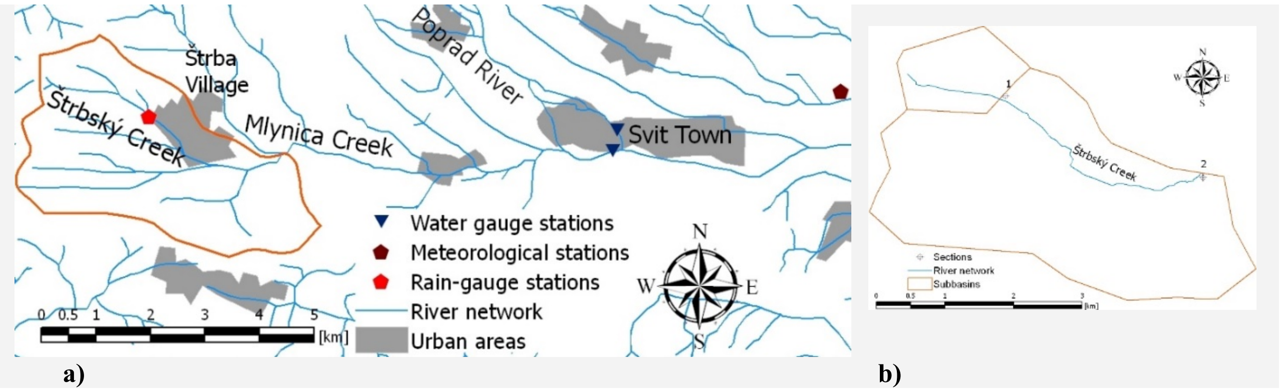


Fig. 3. The Štrbský Creek basin **a)** the location of the climate and gauge stations **b)** sections for post-event analysis.

Table 3. Measured and estimated a) hydraulic and b) flood wave characteristics (Svoboda and Pekárová, 1998).

Stream	River section	River slope	Roughness coefficient	Hydraulic radius [m]	Mean velocity [m s^{-1}]
Malá Svinka	1* above Renčišovský Creek	0.035	0.067	0.823	2.458
Renčišovský Creek	2 mouth to Malá Svinka	0.037	0.08	1.231	2.746

Stream	River section	Basin area [km^2]	Estimated flood wave volume [m^3]	Estimated maximum peak Q [m^3.s^{-1}]
Malá Svinka	1* above Renčišovský Creek	4.825	204,000	37.918
Renčišovský Creek	2 mouth to Malá Svinka	6.700	607,000	112.57

Štrbský Creek basin

Description of the study sites

The Štrbský Creek is a tributary of the Mlynica Creek; it originates at an altitude of 910 m a.s.l. and flows in an easterly direction through the village of Štrba. The Mlynica Creek flows under the village; it is a tributary of the Poprad River in its upper part. The altitude of the Štrbský Creek basin (Fig. 3a) ranges from 800 to 941 m a.s.l.; the mean altitude is 862 m a.s.l.; and the mean slope is 6.5%. The maximum gradient of the slopes in the Štrbský Creek basin reaches 30%; the slope of the creek itself is 2.1% on average. The catchment of the Štrbský Creek belongs to a moderately cool and humid sub-region; the mean monthly air temperature ranges from about –5.6ºC (January) to +15.8ºC (July); the mean annual air temperature is around 5.8ºC; and the mean annual precipitation is about 750 mm. From a hydro-geological point of view, the whole catchment is formed by the quarter sediments at the foot of the High Tatras. The Štrbský Creek basin is formed by the alternating of sandstones and claystones from the Late Cretaceous and Paleogene eras of the Inner Carpathians; a slight occurrence of karstic limestones (18%) from the Mesozoic and Paleogene eras of the Klippen Belt appears in the lower part. Loamy soils (79%) prevail in the area. Agricultural areas extend over the whole area (83%); artificial surfaces in the village of Štrba cover more of the area than do forests (ratio 9:5). The vegetation cover is composed of meadows, pastures and forests.

Meteorological situation on July 24, 2001

On July 24, 2001, an upper cyclone with a centre above the East-Slovak Lowlands caused the north-eastern movement of a wet, unstable air mass across a ridge of the High Tatras. The unstable air created a cumulo-nimbus type of cloud from 11:00 to 13:30 p. m., which severely affected the surroundings of the village of Štrba.

The following resources were used to provide a time and spatial analysis of the precipitation field, especially the core of the torrential rain: the observation and measurement of the meteorological, precipitation and hydrological stations, satellite and radar measurements, terrain investigation activities in the Štrbský Creek catchment and neighbouring catchments, and interviews with residents (Grešková, 2003; Majerčáková et al., 2004; Šťastný and Majerčáková, 2003).

The highest measured precipitation in the village of Štrba occurred from 15:20 to 16:10 (the total precipitation was 73.6 mm), while in the higher located station of Štrbské Pleso, the daily precipitation total was only 52.2 mm.

The radar and satellite observations suggested an isolated cumulo-nimbus cloud on the leeward side of a High Tatras massif. The movement of this cumulo-nimbus was from a NE – NNE direction in the area of the village of Štrba. The radar records from Kojšovská hoľa (75 km away) did not show either the extreme phenomena, the reflectivity, or the height of the upper boundary of the cloud. At 13:15, a small cloud with an upper boundary height of about 9–10 km was detected in the Štrba region; at 14:15 an extension of its upper boundary was growing, and the cloud moved over a Low Tatras massif.

The radar reflexivity from this object at 13:15 was 18–24 dB, 30–36 dB at 13:45, and 18–24 dB at 14:15. The satellite pictures showed the occurrence of an isolated cumulo-nimbus in the Štrba region at 13:30 and its movement southward. A resident who was interviewed stated that the position of the rain core near the village boundary was in a north-westerly or westerly direction.

The total rainfall measured was 73.6 mm near the location of the first cross section on Štrbský Creek. The rain continued for about 55 minutes; however, 95% of the precipitation fell in 30 minutes (Majerčáková, et al., 2004; Šťastný and Majerčáková, 2003). Figure 3a shows the location of the climate and gauge stations at the Štrbský Creek basin; Figure 3b shows the sections of the Štrbský Creek for the post-event analysis.

Post-event hydrological analysis

The reconstruction of the hydrological situation in the locality of the village of Štrba performed by the experts from the Slovak Hydrometeorological Institute (Majerčáková, et al., 2004; Šťastný and Majerčáková, 2003) was based on identifying an area with intense torrential rainfall, analysing the measurements from the rain-gauge station in the village of Štrba, interviewing residents about the duration of the rainfall as well as its distribution over time and in space, and an investigating the terrain. A video recording the course of the flood, which was made by a citizen approximately 5–10 minutes after the culmination, was very useful.

The reconstruction of the flood situation was performed by the genetic method of calculating the maximum discharges and comparing the volumes of the flood wave and effective rainfall (Šťastný and Majerčáková, 2003). Two cross sections of the stream were evaluated: 1. a section on the Štrbský Creek above the first bridge in the village of Štrba, and 2. a section on the Štrbský Creek above the main road before the confluence of the Štrbský Creek and Mlynica Creek (Fig. 3b). The estimated value of the peak discharge was 120 $m^3.s^{-1}$; the culmination discharge was estimated to have a return period higher than 1,000 years.

Turniansky Creek Basin

The altitude of the Turniansky Creek basin (Fig. 4a) ranges from 200 to 1013 m a.s.l.; the mean altitude is 348 m a.s.l.; and the mean slope is 12.7%. The geological basement of the whole Turniansky Creek Basin is quite variable. The individual subbasins have various compositions. While the Turniansky Creek Basin up to its confluence with Rígeľský Creek (section 1) is composed of limestone (49%), sandstone and claystone (32%) from the Mesozoic era of the Inner Carpathians, the Rígeľský Creek Basin (section 2) is mainly composed of gneiss, mica schist and their products from metamorphism from the Early Paleozoic or Proterozoic eras (64%). The Hukov Creek basin is composed of alternating sandstone and claystone (60%) from different complexes of the Inner Carpathians, i.e., the Late Cretaceous, Paleogene and Mesozoic eras, but the whole basin (section 6) was surprisingly mainly generated in the Neogene era (29%) by clays and silts. The main soil textures are loamy (55%) and sandy/loamy (32%). There is a karstic aquifer, especially in the higher parts of the Turniansky Creek basin. Forests predominate in the mountains (sections 1–3, 64–83%) and agricultural areas in the lowlands and the whole area (47%). Artificial surfaces occur in 9% of the area.

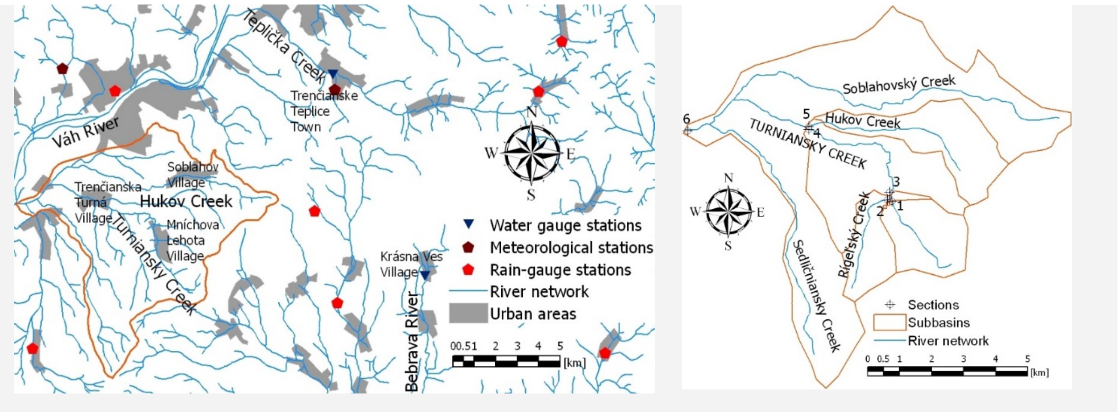
Meteorological situation on June 19, 2004

Two storm cores with an assumed total rainfall of about 55–60 mm occurred on June, 19, 2004, in the Turniansky Creek basin region. The exceeded value of Q_{100} at the Rígeľský Creek was caused by the first storm core, the centre of which was located above the village of Mníchova Lehota. The second storm core occurred above the Hukov Creek basin, where the rainfall's intensity caused a flood with a return period of 50 years. The location of the Turniansky Creek basin and the rain-gauge, meteorological and water gauge station is illustrated in Fig. 4a, Fig. 4b shows the sections of the Turniansky Creek for the post-event analysis.

Post-event hydrological analysis

The closest discharge gauge station of the Slovak Hydrometeorological Institute (SHMI) is on Teplička Creek in the town of Trenčianske Teplice. The flood wave culminated on the 19th of June, 2004, at 21:00 with a discharge of 4.94 $m^3.s^{-1}$, which is less than the value of the 1-year return period (6 $m^3.s^{-1}$). The Bebrava River in the village of Krásna Ves culminated at the same time with a discharge of 0.53 $m^3.s^{-1}$, which is substantially less than the 1-year return period. These values clarified the fact that the surrounding basins were not caught up in the huge storm.

The following assessments were obtained as a result of the post-event investigations and interviews with local people done by (Danáčová and Velčická, 2004): a huge storm did not occur in the upper part of the Turniansky Creek basin, but it was a different situation in the tributary basins (Rígeľský Creek and



a) b)

Fig. 4. The Turniansky Creek basin **a)** the location of the climate and gauge stations **b)** sections for post-event analysis.

Table 4. Estimates of the peak discharges obtained by field surveying for the 24/07/2001 flash flood (Šťastný and Majerčáková, 2003).

Stream	Cross-section	Estimated maximum peak [$m^3.s^{-1}$]	Area [km^2]
Štrbský Creek	1. above the village of Štrba	65	2.5
Štrbský Creek	2. under the village of Štrba	120	11.2

Hukov Creek). A regulated channel part of the Rígeľský Creek brought about a higher flow velocity, and this runoff ran faster than the runoff in the Turniansky Creek basin. The Hukov Creek channel was grassy and covered with garbage; therefore, the water slowed down there. This explains why there were no culminations in the creek confluences at the same time. There could have been more damage, but a huge flood wave was nevertheless generated due to unsatisfactory compliance with stream regulations such as right-angled stream bends, low access bridges to houses through creeks, etc. The parameters of the regulated Turniansky Creek in the village of Trenčianska Turná permitted the higher runoff to flow out, but the incorrect enforcement of the stream regulations in the stream mouths created break waves in many places (Danáčová and Velčická, 2004).

The beginning of the flood wave was at about 20:00; the culmination was reached at 21:00. Other assessments estimated the duration of the flood to have lasted between 3 to 9 hours, with 9 hours generally agreed as the best assessment. If the duration of the flood wave was 9 hours, the wave volume could have been about 1.21×10^6 m^3, representing 17 mm of runoff. The results of the hydrological evaluation of the flood are listed in Table 5 (Danáčová and Velčická, 2004).

FLASH FLOOD RECONSTRUCTION BY HYDROLOGICAL MODELLING

Data processing

A digital elevation model as well as the soil, geology, land use and rainfall data are required as input data for a model. The first idea about constructing the rainfall maps was to combine the rain-gauge and radar observations together for a short time (15 minutes) with a space resolution (100 x 100 m). Unfortunately, the available radar data could not be used in all the cases. No radar measurement was available for the events at the Malá Svinka and Dubovický Creeks in 1998; therefore, for these events, only the daily data from the closest rain-gauge stations together with the expert assessments were used for constructing the spatial distribution of the rainfall (no rain-gauge or meteorological station was located inside the basins except for one rain-gauge station in the village of Štrba in the Štrbský Creek basin). Isohyets of the total rainfall were drawn for all the events and were then calculated for the required time step of 15 minutes (Figs. 5a b, 6a b, 7a b). This means that the rainfall event was scaled to each time step to get the spatial input for the hydrological model and that the rainfall spatial pattern for each time step was expected to be the same as the rainfall event's spatial pattern.

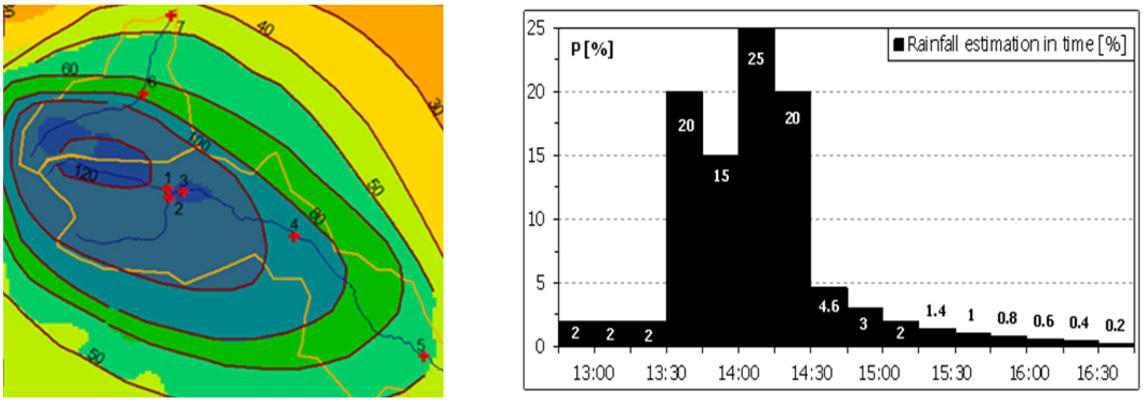
Simulation of flash floods by the KLEM model

The magnitudes of the flash floods were simulated in the same river sections which were selected for the classical post-event analysis in each basin. The river sections analysed are illustrated in Chapter 3 in Figs. 2b, 3b and 4b. At first, the routing parameters have to be set. Their lower threshold is an interface between a channel and no channel cells. The channel cells reach the channel flow velocity; no channel cells are controlled by the slope velocity. The KLEM parameters consist of parameter X, which regulates the infiltration storativity; the recession parameter influences the quantity of the base flow; and the initial abstractions have an impact on the initial rainfall losses. All parameters of the KLEM model are non-calibrated parameters. The simulated discharge is composed of the base flow direct runoff and total simulated discharge.

The simulated characteristics of the flash flood events in all the river sections are listed in Tables 6, 7 and 8. In the Tables the simulated maximum peaks are also compared with estimated maximum peak discharges from the post-event analyses. A comparison of the simulated and estimated peak discharges for all the flood events and all the sections is illustrated in Fig. 8.

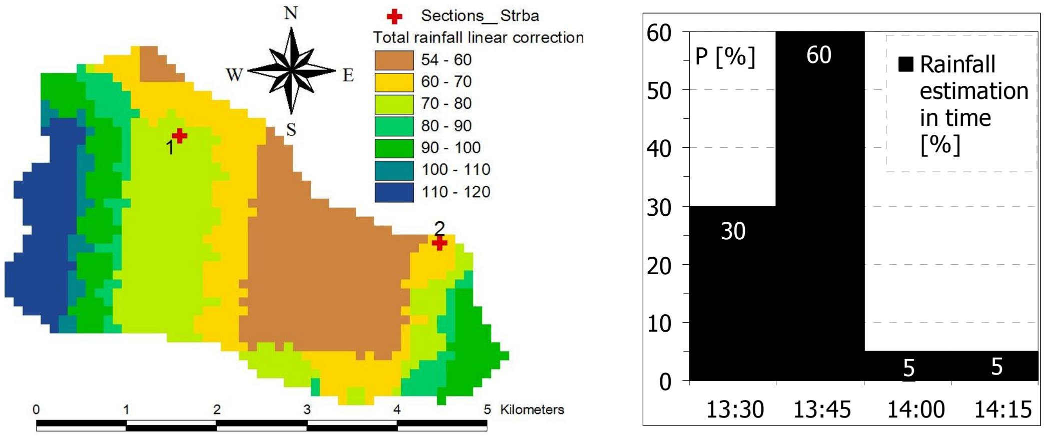
Table 5. Estimates of the peak discharges obtained by field surveying (Danáčová and Velčická, 2004).

Stream	Cross-section	Basin area [km^2]	Estimated maximum peak [m^3.s^{-1}]	T-year maximum Q
Turniansky Creek	1. upstream of Rígeľský Creek	5.2	4	5
Rígeľský Creek	2.	3.9	15	>100
Turniansky Creek	3. downstream of Rígeľský Creek	9.1	17	>50
Turniansky Creek	4. upstream of Hukov Creek	18.4	25	<100
Hukov Creek	5.	8.1	20	<100
Turniansky Creek	6. outlet	26.5	40	>100



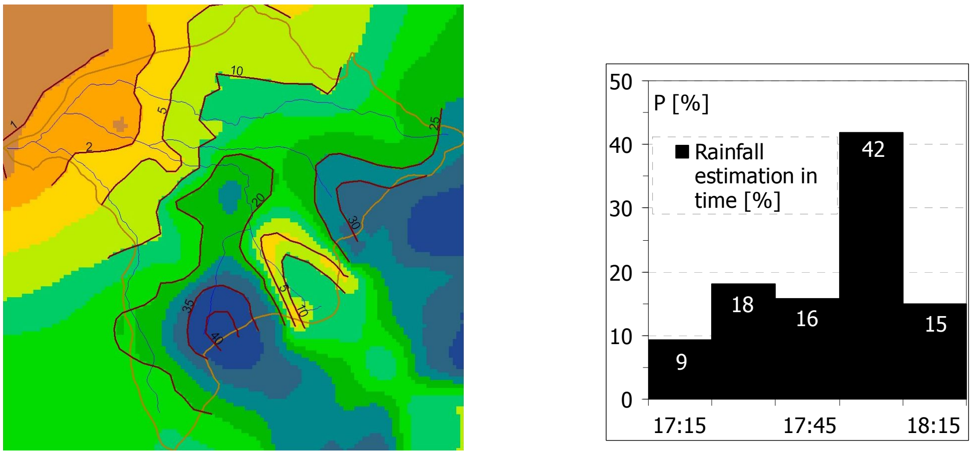
a) b)

Fig. 5. a) Estimated isohyet map [mm] and **b)** time resolution of the rainfall distribution [%] in the Malá Svinka and Dubovický creek basins.



a) b)

Fig. 6. a) Interpolated total rainfall in space [mm] and **b)** time resolution of rainfall distribution [%] in the Štrbský Creek Basin.



a) b)

Fig. 7. a) Estimated isohyet map [mm] and **b)** time resolution of the rainfall distribution [%] in the Turniansky Creek Basin.

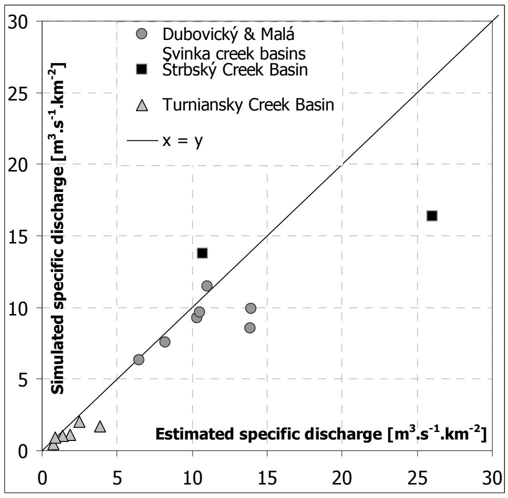


Fig. 8. Comparison of the estimated and simulated peak discharges and specific peak discharges for all the flood events and river sections.

From the outcomes illustrated in Fig. 8, it can be seen that the KLEM distributed rainfall-runoff model was able to reproduce the selected storm event responses sufficiently. The consistency of the estimated and simulated values by the KLEM model was evident both over time and in space.

EVALUATION OF THE FLASH FLOOD REGIMES

To demonstrate the extremity of the events, the specific discharges of the selected flash floods were ranked among the largest specific discharges of flash floods which occurred in Slovakia during the last 100 years till 2015 (Fig. 9). We can see that the specific discharges of the three events on the Malá Svinka and Štrbský Creek basins are very close to the derived envelope curves of the maximum specific dischages for Slovakia and belong still among the largest flash floods in Slovakia. The Turniansky Creek flash flood was the smallest among the analysed floods.

Figs. 10, 11 and 12 present the positions of the flash floods analysed in this study together with selected maximum summer floods recorded in the gauging stations of the separate regions to the envelope curves of the selected 100-year maximum specific discharges of summer floods derived for the geomorphological regions in Slovakia and to the envelope curves of the maximum specific discharges of flash floods for Slovakia and for the Mediterranean and Carpathian regions derived in the frame of the HYDRATE Project (Hydrate, 2006). We can conclude that all the flash floods analysed lie above the envelope curves of the 100-year maximum specific discharges of summer floods in the relevant regions, which proves that their return periods were far above the 100-year return period.

The specific discharges also excceded all the selected annual summer floods observed in the regions.

Table 6. Rainfall-runoff properties for the 20/07/1998 flash flood.

Section	Total runoff mm	Total rainfall mm	Estimated discharge $m^3.s^{-1}$	Simulated discharge $m^3.s^{-1}$	Runoff coefficient –
1 Malá Svinka above Renčišovský C.	45	116	90	64	0.39
2 Renčišovský C. mouth to Malá Svinka	38	106	98	60	0.36
3 Malá Svinka under village of Renčišov	47	112	140	125	0.42
4 Malá Svinka, village of Uzovské Pekľany	52	109	200	183	0.47
5 Malá Svinka, village of Jarovnice	**62**	**95**	**230**	**224**	**0.65**
6 Dubovický C. above village of Dubovica	56	102	120	125	0.55
7 Dubovický C. under village of Dubovica	**49**	**87**	**160**	**147**	**0.56**

Table 7. Rainfall-runoff properties for the 24/07/2001 flash flood.

	Total runoff mm	Total rainfall mm	Estimated discharge $m^3.s^{-1}$	Simulated discharge $m^3.s^{-1}$	Runoff coefficient –
1 Štrbský C. above village of Štrba	22	84	65	41	0.26
2 Štrbský C. under village of Štrba	**31**	**78**	**120**	**154**	**0.40**

Table 8. Rainfall-runoff properties for the 19/06/2004 flash flood.

Section	Total runoff mm	Total rainfall mm	Estimated discharge $m^3.s^{-1}$	Simulated discharge $m^3.s^{-1}$	Runoff coefficient –
1 Turniansky C. above Rígeľský C.	2	25	4	2	0.06
2 Rígeľský C., mouth to Turniansky C.	6	56	15	7	0.11
3 Turniansky C. under Rígeľský C.	4	38	17	10	0.11
4 Turniansky C. above Hukov C.	5	34	25	19	0.16
5 Hukov C., mouth to Turniansky C.	7	42	20	16	0.17
6 Turniansky Creek, mouth	**5**	**33**	**62**	**66**	**0.14**

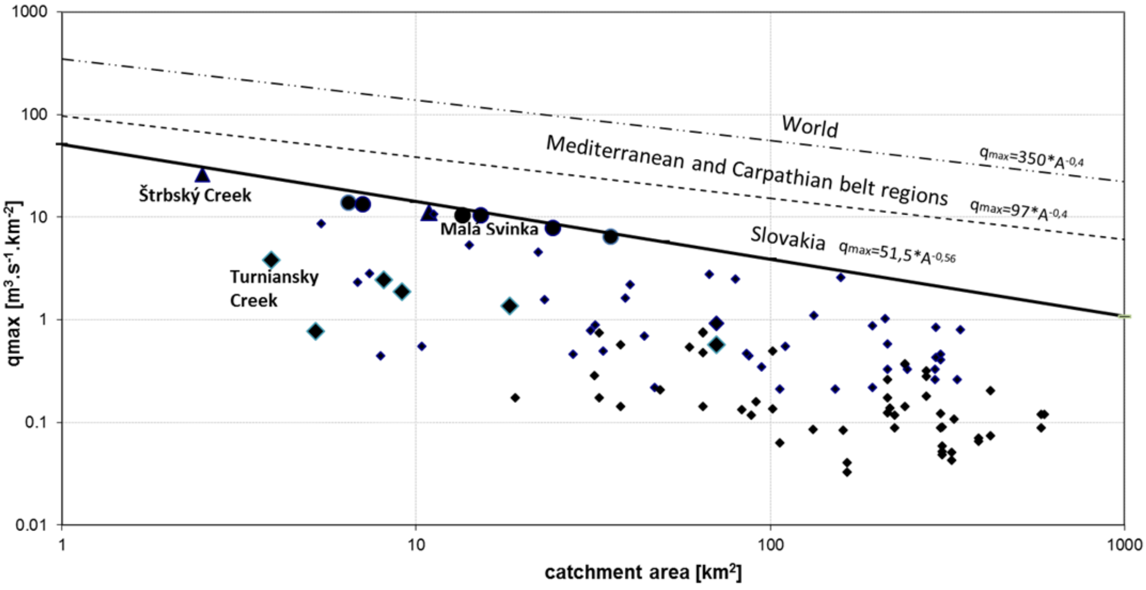


Fig. 9. The position of the flash floods analysed in this study and flash floods observed during the last 100 years in Slovakia to the envelope curves of the maximum specific dischages for Slovakia, and for the Mediterranean and Carpathian regions in the frame of the HYDRATE Project (Hydrate, 2006) and for the world. Legend: flash floods analysed in this study: ▲ Štrbský Creek, ◆ Turniansky Creek and ● Malá Svinka; ◆ flash floods observed on the territory of Slovakia from 1930 till 2015.

Although the three flash floods analysed in the study were the most extreme ones in Slovakia, their comparison with maximum specific discharges observed in the Mediterranean climate region as analysed in Gaume et al. (2009) shows that they lie far from the maximum values observed in the Mediterranean area. The Mediterranean flash floods are more than twice as high as the maximum peak discharges reported in Central Europe for a given watershed area.

Finally, the extremity of the selected flash floods in the Malá Svinka, Dubovický, and Štrbský Creek basins can also be confirmed by the simulated runoff coefficients for these events: 0.39–0.56 for the Malá Svinka and Dubovický Creeks; and 0.26–0.40 for the Štrbský Creek. The simulated runoff coefficient for the flash flood in the Turniansky Creek only achieved the value of 0.17.

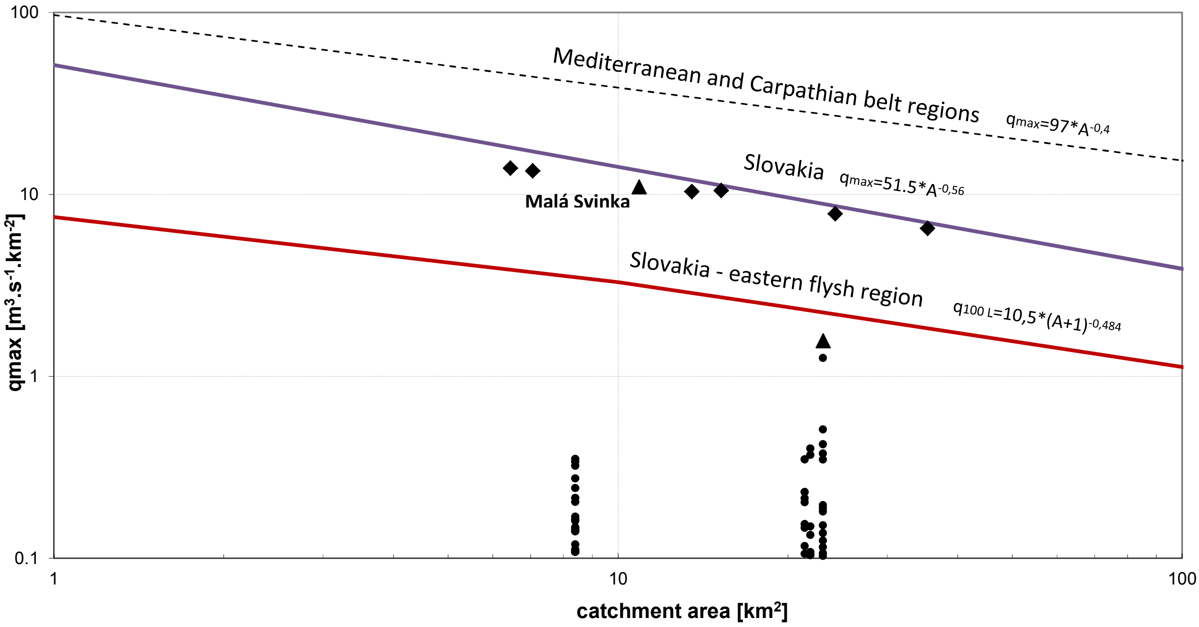


Fig. 10. The position of the Malá Svinka Creek flash floods analysed in this study (◆), flash floods observed during the last 100 years in the Eastern flysh region of Slovakia (▲) and the selected maximum summer floods recorded in the gauging stations of this region (●), to the envelope curves of the 100-year maximum specific discharges of the summer floods derived for the Eastern flysh region (Kohnová, 2013) and to the envelope curves of the maximum specific discharges of flash floods for Slovakia (SR) and for the Mediterranean and Carpathian regions derived in the frame of the HYDRATE Project (Hydrate, 2006).

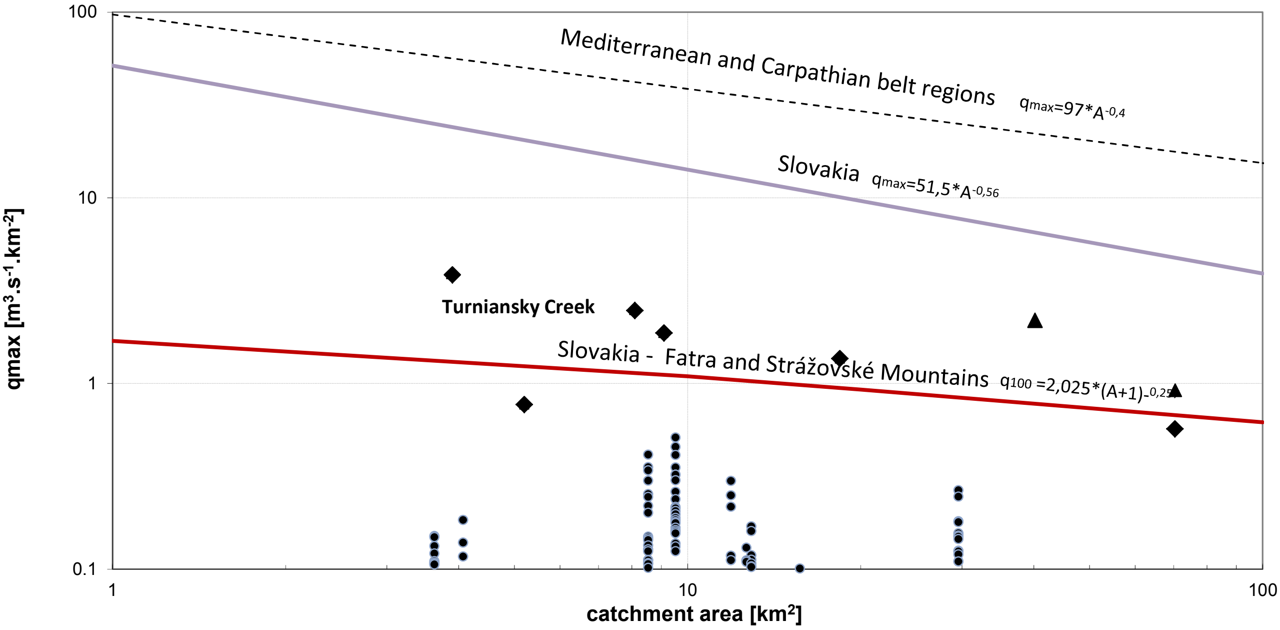


Fig. 11. The position of the Turniansky Creek flash floods analysed in this study (◆), flash floods observed during the last 100 years in the Fatra and Strážovské Mountain regions (▲) and the selected maximum summer floods recorded in the gauging stations of this region (●), to the envelope curves of the 100-year maximum specific discharges of the summer floods derived for the Fatra and Strážovské Mountain regions (Kohnová, 2013) and to the envelope curves of the maximum specific discharges of the flash floods for Slovakia and for the Mediterranean and Carpathian regions derived in the frame of the HYDRATE Project (Hydrate, 2006).

CONCLUSIONS AND DISCUSSION

In the modelling of flash flood events using the KLEM hydrological model, most of the difficulties have mainly occurred from uncertainties in the input rainfall data. Only some catchments have usable radar precipitation data, and in the Štrbský Creek basin only, one rain-gauge station with daily rainfall measurements was available. The surrounding precipitation stations did not measure the local rainfall event maximums sufficiently; the measured values were underestimated and difficult to use. Moreover, not a single catchment had a discharge gauge station available; all the discharges during the flash floods were not actually measured, but only estimated on the basis of the results of the post-event analyses.

Therefore, in some cases the total precipitation was only estimated and was spatially distributed by isohyets. In all three

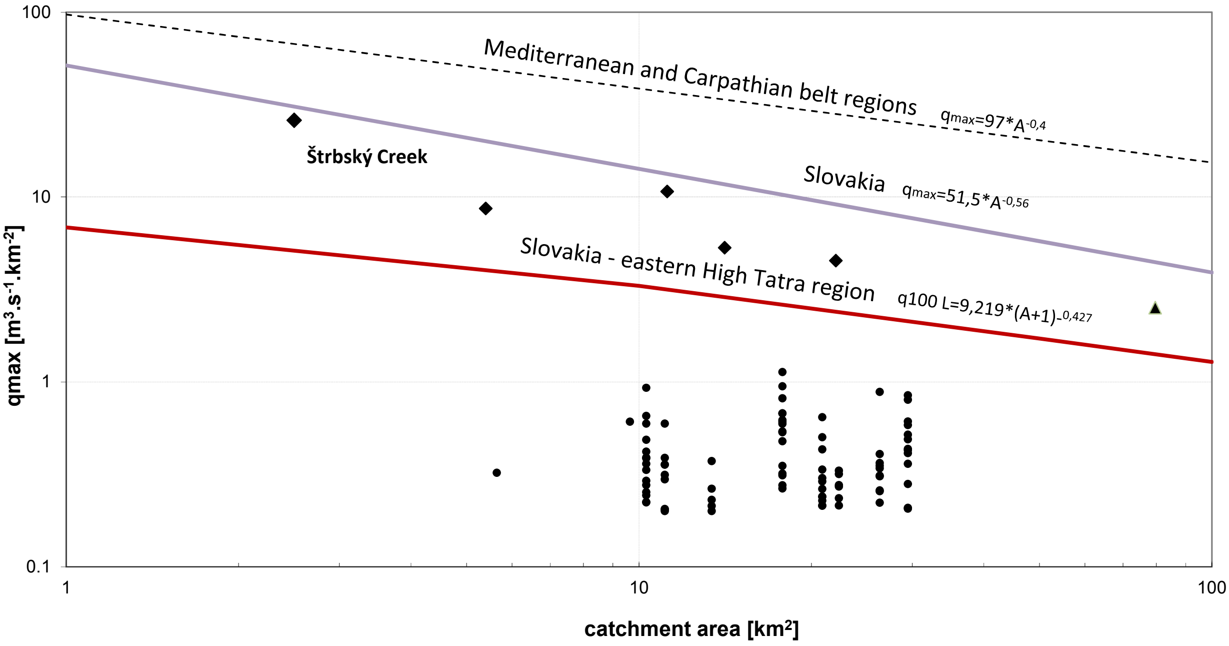


Fig. 12. The position of the Štrbský Creek flash floods analysed in this study (◆), flash floods observed during the last 100 years in the High Tatras region (▲) and selected maximum summer floods recorded in the gauging stations of this region (●), to the envelope curves of the 100-year maximum specific discharges of the summer floods derived for the High Tatras region (Kohnová, 2013) and to the envelope curves of the maximum specific discharges of the flash floods for Slovakia and for the Mediterranean and Carpathian regions derived in the frame of the HYDRATE Project (Hydrate, 2006).

catchments the time distribution of the rainfall was done retrospectively, according to the results of the post-event analyses of the travel time of the floods. The total rainfalls of events were scaled to each time step to get the spatial input for the hydrological model, and the rainfall event's spatial pattern for each time step was expected to be the same as the event rainfall spatial pattern. In modelling the discharges of all the selected events, it was not possible to achieve a concordance of the simulated discharges with the estimated discharges in all the river sections. Therefore, the simulations focused on achieving the best concordance with the maximum value of the discharges in the basin outlets and with the timing of the floods. With this methodology all the simulated discharges in the upper profiles (sections) were underestimated in comparison with the estimated discharges from the post-event hydrological analyses. On the other hand, a relatively good correspondence between the simulated and estimated discharges was achieved in the basin outlets: e.g., in the Malá Svinka outlet the simulated maximum discharge achieved 224 $m^3.s^{-1}$ in comparison with the estimated discharge of 230 $m^3.s^{-1}$.

Generally, from the outcomes illustrated in Fig. 8, it can be seen that the KLEM distributed rainfall-runoff model was able to reproduce the selected storm event responses sufficiently. The consistency of the estimated and simulated values by the KLEM model was evident both over time and in space.

The main focus of the hydrological simulation of flash flood responses is the best achievement of a maximum peak and behaviour of a flood wave. The crucial problem of estimating the occurrence and magnitude of flash floods is the lack of measured data, particularly in small ungauged catchments. In many cases, even if radar measurements of the precipitation are not available, there is a problem in estimating not only the sum of a rainfall event, but also, in particular, the rainfall distribution over time and in space. In this case all the data and information obtained from the post-event analyses are useful. In this study daily data from the closest rain-gauge stations together with the expert assessments were used for constructing the spatial distribution of the rainfall. The time distribution of the rainfall was done retrospectively, according to the results of the post-event analyses of the travel time of the floods. The event rainfall was then scaled to each time step to get the spatial input for the hydrological model and the rainfall spatial pattern for each time step was expected to be the same as the event's rainfall spatial pattern. As was tested in Zoccatelli et al. (2011), this approach may provide acceptable results for flash flood events.

If other data showing the topography, soil and land use characteristics are available, the spatially distributed rainfall-runoff hydrological models with a high spatial resolution of a basin's physiographical and morphological characteristics can represent a good tool for sufficiently reproducing an analysis of a storm event's response and can decrease the uncertainties of flash flood estimations.

Differences in the flood response of basins of varying catchment sizes are related to the effect of the spatial organization of the banded convection, the contrasting fractional coverage of the rainfall following from the basin's size and structure, and the differential response due to the highly nonlinear relationship between rainfall and runoff (Borga et al., 2007). An important source of nonlinearity is related to the strong dependency of the basin's response time to the storm's accumulation.

The degree of nonlinearity arising from the available data could not be reproduced by a flood response model with an invariant parameterization (Borga et al., 2007). Post-flood surveys and interviews play an important role as an information source. Together with the estimations of the maximum peak and total rainfall in space and over time as well as the readily available GIS data, the hydrologic modelling allowed us to generate a much more complete picture of the storm and flood environments than would otherwise be available at ungauged basins.

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