Distributed modelling of flash floods in ungauged basins

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Abstract This paper concentrates on an analysis of major flash flood in Slovakia, which occurred in July 1998 and caused great damage to property and also loss of lives. The selected flash flood occurred on the 20th of July in 1998 in the Malá Svinka and Dubovický creek basins. To understand rainfall-runoff processes during this extreme flash flood, runoff responses during selected major event was examined using the KLEM (Kinematic Local Excess Model) spatially-distributed hydrological model. It is based on the availability of raster information of the landscape's topography, the soil and vegetation properties, and radar rainfall data. In the model, the SCS-Curve Number procedure is applied on a grid for the spatially-distributed representation of runoff-generating processes. A description of the drainage system response is used for representing the runoff's routing. The simulated values achieved by the KLEM model were comparable with the maximum peaks estimated on the basis of post-event surveying. The consistency of the estimated and simulated values by the KLEM model was evident both in time and space, and the methodology has shown its applicability for practical purposes. It was concluded that for the short duration of the storm events, temporal variability seems to be less important than spatial variability.

Keywords flash flood; the KLEM model; Slovakia

INTRODUCTION

Phenomena of flash floods started to be in great interest of hydrologists and forecasters within last decades when flash flooding was increasing over the world. Flash floods are processes occurring in basins of few hundred square kilometers or less, with response times of a few hours or less (Borga et al., 2007). The small scale of the distribution of flash floods in space and time means that conventional observation systems are not able to monitor the rainfall and river discharge. Consequently, the atmospheric and hydrological generating mechanisms of flash floods are poorly understood and lead to highly uncertain forecasts of these events.

In recent years many extreme flash floods have been reported in the literature (e.g., Anquetin et al., 2005; Delrieu et al., 2005; Borga et al., 2007; Gaume et al., 2008) and new methodologies for improving flash floods estimation and forecasting were suggested. Approaches based on estimating threshold characteristics, like threshold runoff or rainfall indicate maximal sustainable surface runoff for a given basin. In Norbiato et al. (2008) a threshold-based flash flood warning method, based on the flash flood guidance (FFG) approach was developed and tested for different climatic and physiographic conditions. The flash flood guidance methodology follows from estimation of the threshold depth of uniform rainfall with a given duration which can cause flooding at the outlet of a basin. If the observed or forecasted rainfall depth in the basin is greater than the flash flood guidance, a flood probably will occur. While the FFG in Norbiato et al. (2008) was based on results of rainfall-runoff modelling, in Georgakakos (2006) the analytical solution of operational flash flood guidance systems was developed, based on relationships between the rainfall volume of a given duration and the resulting volume of surface runoff.

The important problem of estimating occurrence and magnitude of flash floods is the lack of measured data, particularly in small ungauged catchment. Spatially distributed hydrological models with a high spatial resolution of physiographical and morphological basin's characteristics have been used to decrease uncertainties of flash flood estimation and forecasting here. In Blöschl et al. (2008) a spatially distributed model with the grid based structure for runoff generation and the lumped structure for flood routing in river reaches was developed for operational forecasting of flash floods in northern Austria. Younis et al. (2008) examined short-range numerical weather forecasts with a spatially distributed rainfall-runoff model for early flash flood warning in ungauged river basins. The methodology is based on flood thresholds simulated continually using the LISFLOOD hydrological model. Reed et al. (2007) suggested a methodology how to improve the accuracy of flash flood forecasts at ungauged sites based on distributed hydrologic modelling and a threshold frequencie (DHM-TF). During rainfall events, the model simulates grids of peak flow forecast frequencies with the high resolution and these grids are then compared to locally derived threshold frequency grids.

This paper concentrates on distributed modelling of the flash floods in Svinka na Dubovický Creek basin in Slovakia which occurred during recent years and caused great damage to property; in one case, the loss of lives was registered as well.

FLASH FLOODS IN SLOVAKIA

Slovakia is located in a part of Central Europe where flooding regularly occurs every year. There are approximately 2,300 small catchments within a range of 5-50 km2 with a great potential risk of flooding, especially with respect to flash floods. Historically, flash floods have rarely been documented; 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. From the 1950s through the mid-1990s, larger flash floods were not recorded by the Hydrometeorological Service; however, cloudbursts occurred from time to time.

The major flash flood in Slovakia, which is documented in the HYDRATE database, occurred on the 20th of July 1998 in the Malá Svinka and Dubovický creek basins. The basic characteristics of this flash flood and basins are listed in Tables 1 and 2.

Tab. 1 Selected flash floods in Slovakia

Streams	Basin area	Estimated peak discharge (*)	Estimated basin sections
	[km^2]	[m^3.s^{-1}]	
Dubovický Creek	15.2	160	2
Malá Svinka Creek	35.4	230	5

Tab. 2 Available rainfall data and estimated return period of the flash floods selected

Streams	Hourly rain-gauges	Daily rain-gauges	Availability of radar data	Estimated return period (*)
	In-Out of basin	In-Out of basin		Years
Dubovický Creek	0-0	0-5	No	> 1000
Malá Svinka Creek	0-0	0-10	No	>1000

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DESCRIPTION OF THE SVINKA AND DUBOVICKÝ CREEK RIVER BASIN

The Malá Svinka is a tributary of the Svinka River, which is a tributary of the Hornád River. It flows in a south-easterly direction but then turns to the south. The Dubovický Creek flows in a northerly direction and is a small tributary of the Torysa River. These basins belong geologically to a flysh belt created by sand and clay layers. The soils have the character of a cambisol. The maximum gradient of the slopes in the Malá Svinka area reaches 30%; the slope of the creek itself is 2.7% on average; it is approximately 6% in the Dubovický Creek. The entire geological basement of the Malá Svinka Creek Basin is formed by permeable sandstones and nearly water-impermeable calcic claystones from the Late Cretaceous and Paleogene eras of the Inner Carpathians. The basin is mainly forested up to the Uzovské Pekľany Village (section 4, over 53%); agricultural areas begin to predominate in the downstream parts (the upstream ratio of the forests and agricultural areas is 62:14; the downstream ratio is 43:38). Agricultural areas predominate in the Dubovický Creek Basin (41%). 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 climate of both of the selected catchments is characterised as moderately warm and humid with monthly temperature means from –5ºC (January) to +18ºC (July), with a mean annual air temperature of 7.8ºC and mean annual precipitation totals in the range of 600 – 650 mm. In its higher elevations the catchment belongs to a moderately cool and humid sub-region. The basic land use and soil characteristics are listed in Tables 3 and 4.

Tab. 3 Percentage of land use types in selected basins and sections [%]

Streams	River sections	Artificial surfaces	Agricultural areas	Grasslands	Shrubs	Forests
Malá Svinka	1 Upstream of Renčišovský Creek	0	7	12	28	53
Renčišovský	2 Confluence with Malá Svinka Creek	0	13	13	19	55
Malá Svinka	3 Downstream of Renčišov Village	0	11	12	24	53
Malá Svinka	4 Uzovské Pekľany Village	1	14	9	15	62
Malá Svinka	5 Jarovnice Village	5	38	6	9	43
Dubovický	6 Upstream of Dubovica Village	0	28	12	19	41
Dubovický	7 Downstream of Dubovica Village	5	41	12	13	30

Tab. 4 Percentage of soil texture in selected basins and sections [%]

Streams	River sections	Sandy loam	Loam	Clay loam
Malá Svinka	1 Upstream of Renčišovský Creek	45	55	0
Renčišovský	2 Confluence with Malá Svinka Creek	90	10	0
Malá Svinka	3 Downstream of Renčišov Village	69	31	0
Malá Svinka	4 Uzovské Pekľany Village	58	42	0
Malá Svinka	5 Jarovnice Village	35	65	0
Dubovický	6 Upstream of Dubovica Village	0	73	27
Dubovický	7 Downstream of Dubovica Village	0	58	42

Meteorological Situation on 28th of July in 1998

On 28th of July in 1998 a very unstable air mass appeared due to the high humidity of the air and two isolated areas of torrential rain were occurred. The first storm activity was in the Topľa River 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 basins 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 Creek.

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. At 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 Lipovce Village 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).

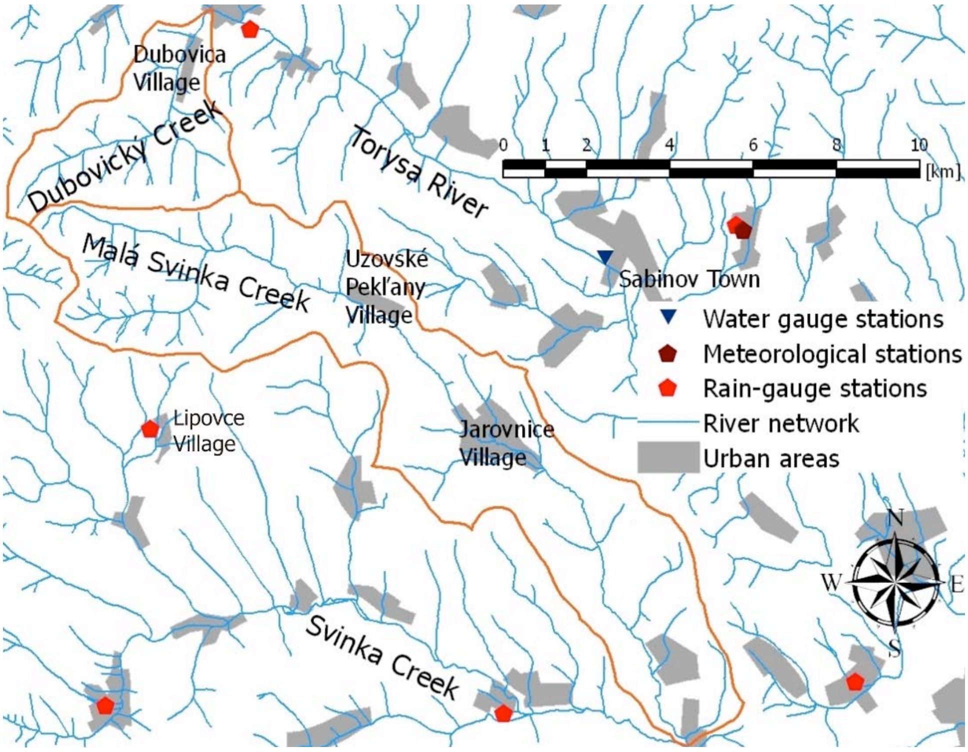


Fig. 2 The Malá Svinka and Dubovický Creek basins and the location of climate and gauge stations

Hydrological analysis

The basic data used for the reconstruction of the flash flood on the Malá Svinka and Dubovický Creek was the water level record from the gauging station on the Torysa River in Sabinov Town. This station is located just below the river's confluence with the Dubovický Creek. Additional terrain investigations provided by the Slovak Hydrometeorological Institute were aimed at flood marks after water overflowed from creek banks and marks after the heavy rain on meadows and fields (Majerčáková and Škoda, 1998; Majerčáková et al., 1998, Majerčáková et al., 2004).

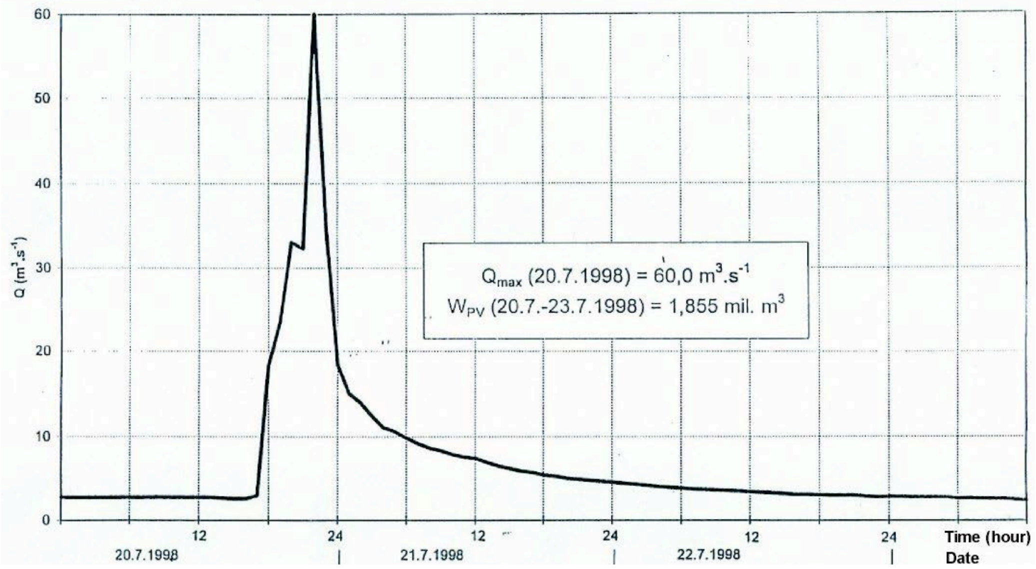


Fig. 3 Observed flood hydrogram at the water gauging station in Sabinov Town (Torysa River) on July 1998 (with the value of estimated peak discharge Q_{max} and volume W_{PV})

From the reconstruction of the flood wave on the Malá Svinka Creek 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 - 9 km.h^{-1}); the lag time of the Malá Svinka Creek Basin 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 Uzovské Pekľany Village. Theoretically, 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 equal to 7.8 m^3.s^{-1}.km^{-2}. The runoff coefficient was estimated by a value of 0.64. A similar situation is also assumed to have occurred in the Dubovica Village, but with a lower maximum discharge of around 160 m^3.s^{-1}.

Several negative factors occurred at the same time during this event: the rainfall might have been higher than 100 mm in some places, with the intensity during the short time period higher than 3 - 5 mm.min^{-1}; and the catchment with high slopes and low retention capacity was highly saturated by previous precipitation. 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.

Characteristics of the flash flood were estimated in 7 river sections in the basin (Fig. 4). Estimated characteristics of the flash flood reconstruction in these river sections are listed in Table 5.

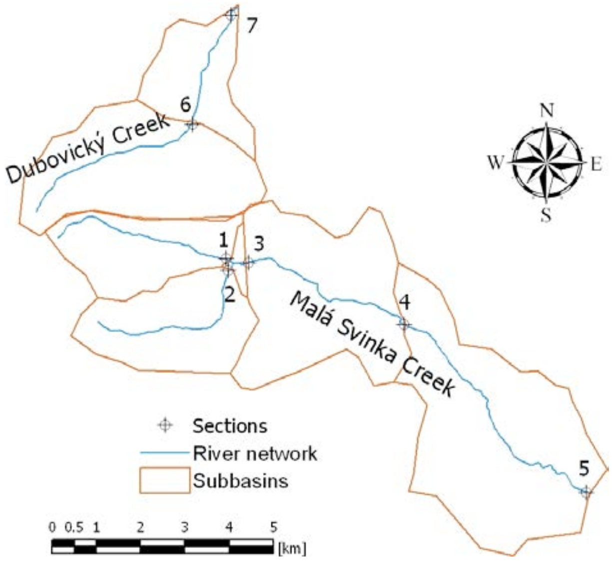


Fig. 4 Estimated river sections in the Malá Svinka Creek Basin

Tab. 5 Hydrologic evaluation of the flood in the Malá Svinka and Dubovický creek basins

River sections	Basin area [km^2]	Estimated flood wave volume [m^3]	Estimated maximum peak Q [m3.s-1]	T-year of maximum Q
1 Upstream of Renčišovský Creek	6.5	400,000	90	>1000

2 Confluence with Malá Svinka Creek	7.1	425,000	98	>1000
3 Downstream of Renčišov Village	13.5	825,000	140	>1000
4 Uzovské Pekľany Village	24.3	1,330,000	190	>1000
5 Jarovnice Village	35.4	1,900,000	230	>1000
6 Upstream of Dubovica Village	10.9	650,000	120	>1000
7 Downstream of Dubovica Village	15.2	850,000	160	>1000

Hydraulic analysis

Findings of the post-event hydrological analysis were compared with hydraulic estimation of the flood peak magnitudes which has been provided on 12th of August in 1998 by Institute of Hydrology of Slovak Academy of Sciences (Svoboda and Pekárová, 1998). The estimation has been done for two river sections: 1* Malá Svinka Creek above Renčišovský Creek and 2 Renčišovský Creek at mouth to Malá Svinka Creek. (The section 1* Malá Svinka above Renčišovský Creek was located more upstream in comparison with the section used in hydrological analysis). Due to the fact that the river channel in the lower part of Malá Svinka Creek was destroyed during the flood, only these two river sections were appropriate for the hydraulic evaluation.

The areas of channel’s cross-profiles were measured for maximal water level, longitudinal slope of water level was approximated to the bottom slope and roughness was estimated according to the river banks and channel bottoms. Flow velocities were calculated using Chézy equation and Manning roughness coefficient. Measured and estimated hydraulic parameters and flood wave characteristics of two river sections selected are listed in Table 6.

Tab. 6 Measured and estimated hydraulic and flood wave characteristics

Hydraulic and flood wave characteristics	Malá Svinka Creek (1.* Above the Renčišovský Creek)	Renčišovský Creek (2. Mouth to Malá Svinka Creek)
River slope	0.035	0.037
Roughness coefficient	0.067	0.080
Hydraulic radius (m)	0.823	1.231
Catchment area (km^2)	4.825	6.700
Mean velocity (m.s^{-1})	2.458	2.746
Peak discharge (m^3.s^{-1})	37.918	112.570
Hydrograph volume (m^3)	204,000	607,000

From the comparison of hydrological and hydraulic estimation it is seen that for the section 2 at Renčišovský Creek calculated flood peaks are rather close (95 and 112 m^3.s^{-1}). For the profile 1* at Malá Svinka the flood peak estimated by hydraulic analysis is lower than the hydrological estimate. The difference can mainly be caused by the difference in the chatchment area (profile for the hydraulic estimation was situated more upstream, basin area was only 4.825 km^2 in comparison to the basin area of 6.5 for the section 1).

METHODOLOGY

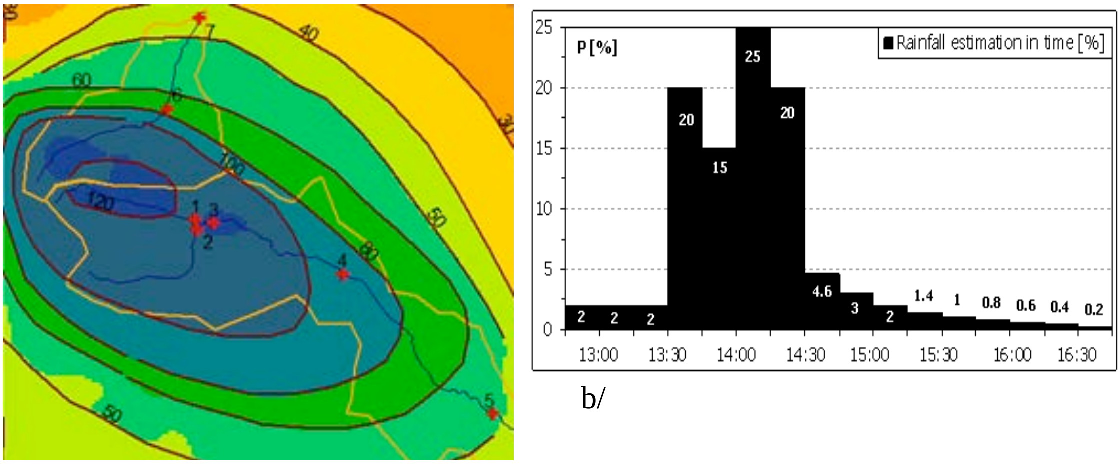
Description of the KLEM Model

As opposed to a post-event estimation, major flash flood was examined using a simple spatially-distributed hydrologic model, i.e., the KLEM (Kinematic Local Excess Model) rainfall-runoff model (Cazorzi & Dalla Fontana, 1992). The distributed model is based on the availability of 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 runoff generating processes. A simple method (Da Ros & Borga, 1997; Giannoni et al., 2003) is used to represent runoff propagation for the response of a drainage system. 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 at the sub-basin 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 I_a, which is required for the specification of the initial abstraction. 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 the landscape's morphology and soil properties.

Data Processing

A digital elevation model as well as soil, geology, land use, rainfall and temperature data are required as input data for the 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 radar data could not be used in all the cases for various reasons. No radar measurement was available for the event at the Malá Svinka and Dubovický creek basins in 1998. Therefore, 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. Isohyets of the total rainfall were drawn for all the events and they were then calculated for the required time step of 15 minutes (Fig. 5a, b). No rain-gauge, meteorological or discharge gauge station was located inside the basins.



b/

a/

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

Simulation of Flash Floods

Magnitude of flash flood was assessed in selected river sections. Analysed river sections are illustrated in Fig. 4. The velocity in the channels and slopes, the maximum peak, the volume of the flood wave, and the duration of the rising, culmination and decline of the flood wave during the flood were determined from the results of detailed post-event analyses and field survey 2 or 3 weeks after the events and from personal interviews (Svinka – SHMI team authors, 1998).

These estimated values were compared with the results from the KLEM model. At first, the routing parameters have been set. Their lower threshold is an interface between 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. The simulated discharge is composed of the base flow and direct runoff (Fig. 10: *Qbas* – base flow, *Qdir* – direct runoff, *Qsim* – simulated discharge, *Qobs* – estimated maximum peak, *Ptot* – total rainfall on the secondary axis in a reverse order).

The simulated characteristics of the flash flood events in all river sections are listed in Table 7. In the table also estimated maximum peak discharges from the post-event analyses are compared with simulated maximum peaks.

Tab. 7 Rainfall-runoff characteristics in each section simulated by the KLEM model

River sections	Basin area	Total runoff	Total rainfall	Runoff coefficient	Time of maximum peak	Estimated discharge	Simulated discharge	Lag time	Error in time of peak
	km^2	mm	mm	-	hh:mm	m^3.s^{-1}	m^3.s^{-1}	min	min
1 Malá Svinka	6.5	45	116	0.39	14:30	90	64	15	0
2 Renčišovský	7.1	38	106	0.36	14:30	98	60	15	0
3 Malá Svinka	13.5	47	112	0.42	14:30	140	125	20	15
4 Malá Svinka	24.3	52	109	0.47	15:15	200	183	60	-15
5 Malá Svinka	35.4	62	95	0.65	15:45	230	224	90	0
6 Dubovický	10.9	56	102	0.55	15:00	120	125	15	0
7 Dubovický	15.2	49	87	0.56	15:15	160	147	30	0

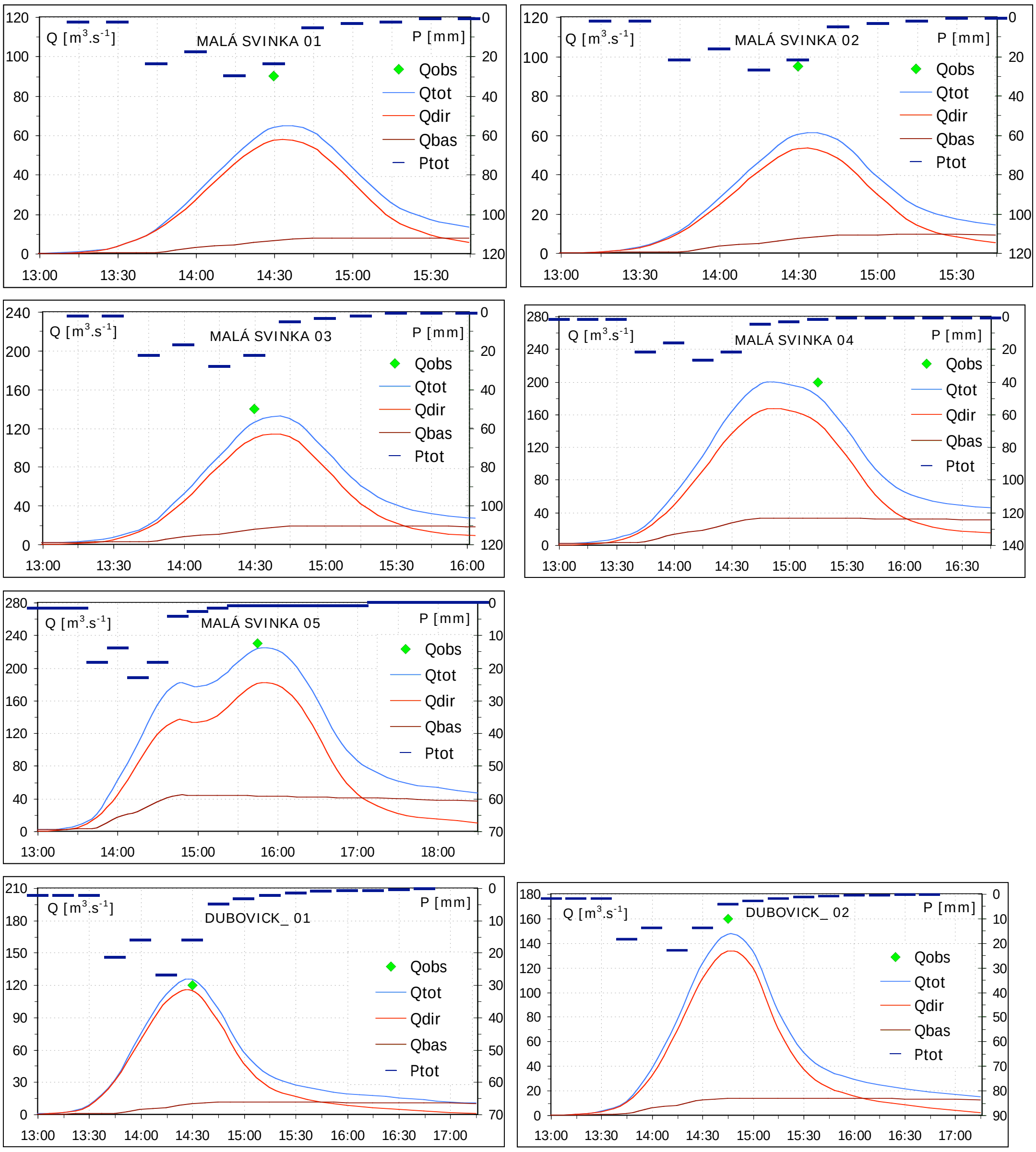


Fig. 6 Simulations of flood waves in each river section by the KLEM model

CONCLUSIONS

In the modelling of flash flood events using the KLEM hydrological model the most difficulties have mainly followed from uncertainties in input rainfall data. Not a single one catchment has the usable radar data of precipitation. Surrounding precipitation stations did not catch the local rainfall events sufficiently; the measured values were underestimated and poorly usable. Therefore, in that case the total precipitation was only estimated and it was spatially distributed by isohyets. The time distribution of rainfall was done retrospectively according to the results of post-event analysis of the travel time of floods. Also not a single one catchment has a discharge gauge station available; all discharges during the flash floods were not really measured but only estimated on the base of results of the post–event analyses.

In the modelling of discharges in all the selected events it was not possible to reach the concordance of simulated discharges with the estimated discharges in all river sections. Therefore the simulations were focused on reaching the best concordance with the maximum value of discharges in the basin outlets and with timing of the floods. By this methodology all simulated discharges in upper profiles (sections) were underestimated in the comparison with the estimated discharges from the post-event hydrological analysis. On the other hand, a relatively good correspondence between simulated and estimated discharges was achieved in basin outlets: 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. 6 it can be resulted 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 in time and space. Rainfall-runoff characteristics of the floods in the Malá Svinka and Dubovický creek basins were very similar; the floods had a similar progress and the runoff coefficient varied from 0.39 to 0.56 (Tab. 7).

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