Simulating scenarios of extreme floods for flood protection and control

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Abstract In the paper the flood risk from extreme spring and summer floods is estimated. The upper Myjava River basin with an area of 238 km^2, which is located in the western part of Slovakia was selected as a pilot region for the study. Two representative extreme flood events which occurred in the past were chosen from the database: an extreme spring flood in 2006 and a summer flood in June, 2009. The spring flood was caused by the joint effect of rapid snow melt and high precipitation, the summer flood by the joint effect of high precipitation and antecedent soil moisture. For modelling the runoff a conceptual rainfall-runoff mode was used with a daily time step. The parameters of the rainfall - runoff model were calibrated based on the data from the period 1981-2006, and the model's efficiency was checked by the Nash – Sutcliffe coefficient. Different scenarios of extreme floods were simulated (combining high precipitation totals and snow water equivalent with design values from 50 to 1000 years). The design values of the simulated flood peaks were estimated and discussed. Scenarios of extreme floods will be used for the proposed flood protection in the Myjava River basin.

Keywords runoff modelling, scenarios of extreme flood events, Myjava River basin

INTRODUCTION

In recent years, extreme weather events have significantly affected the occurrence of extreme flood situations in our country. The most severe has been flash floods, which threaten the small catchments in the central and eastern parts of Slovakia, but also the spring time, so-called snowmelt floods, have become more frequent.

One of the most important elements in flood protection is the estimation of N-year maximum design discharges and precipitation totals. To ensure effective flood protection, the knowledge about extreme discharges and precipitation that could occur during the lifetime of water works is necessary (Szolgay *et al*., 2008). During recent decades, the development of methods for design value estimation has gained a great deal of importance in engineering hydrology. In European countries, many new methods and methodologies have been introduced into practice during the last few decades. For example, within the British research programme, the UK Flood Estimation Handbook (FEH, 1999), includes recommendet procedures for estimating design floods and precipitation in the UK. The FEH also describes the methodology for analyzing the seasonality of flooding, as well as new regionalisation procedures based on the Hosking and Wallis (1997) methodology. In New Zealand the High Intensity Rainfall Design System (Thompson, 2002), HIRDS, was developed; it contains mapping of the index rainfall and derivation of regional growth curves. Statistical methods for estimating design discharges in Germany are described in the DVWK/101 (1999) methodology, which includes data processing, estimating parameters and probabilistic analysis. A sub-study of the FRAMEWORK project (De Michele & Rosso, 2002), which was published in Italy, evaluates current methods and provides an innovative method of estimating extreme flows, which was tested on the rivers of Northwest Italy.

The estimation of design discharges, especially in small catchments, often lacks of actual discharge observations. In such cases the methodologies are based on genetic concepts of runoff generation in basins. These methodologies involve various simplified empirical relationships, respectively for calculating the peak discharge or volume of a flood wave.

A number of uncertainties can occur when applying methods based on simplistic assumptions about the creation and formation of runoff in catchments in practice. They can lead to a relatively large dispersion in the estimated design values that have been discussed, for example, in the studies of Szolgay & Kohnová (2001a, b, 2003b); Szolgay *et al*. (2003). There are also unsatisfactorily resolved issues about the estimation of design flood waves for polders, which affects the evaluation of their effectiveness and safety (Bačík *et al*., 2005). In recent years a lot of studies have been published in Slovakia dealing with problems in selecting methods for the estimation of design maximum discharges in small catchments, see e.g.: Antal *et al*. (2004, 2005); Kohnová *et al*. (2000, 2005, 2006a,b); Majerčáková *et al.* (2006); Szolgay, Kohnová (2003a, 2001a,b); Szolgay *et al*. (1999, 2001, 2008).

In this paper we have tried to assess the flood risk from extreme spring and summer floods for the Myjava River basin. Various scenarios of extreme events causing spring and summer floods were modeled by rainfall-runoff modeling. Finally, design flood discharges were estimated.

THE RAINFALL-RUNOFF MODEL

The Hron rainfall-runoff model, which was developed at the Slovak University of Technology in Bratislava (Kubeš, 2002; Kubeš & Hlavčová, 2002; Kubeš & Zvolenský, 2003; Kubeš, 2007), was used in this study. The hydrological balance in this conceptual model is based on the principles used in the HBV model (Bergström & Forsman, 1973). The model contains three basic storage components with 15 calibrated parameters. The Surface and subsurface processes can be modeled separately for elevation zones, and model parameters can also be set up separately for the sub-basins. The scheme of the Hron rainfall-runoff model is presented in Fig.1.

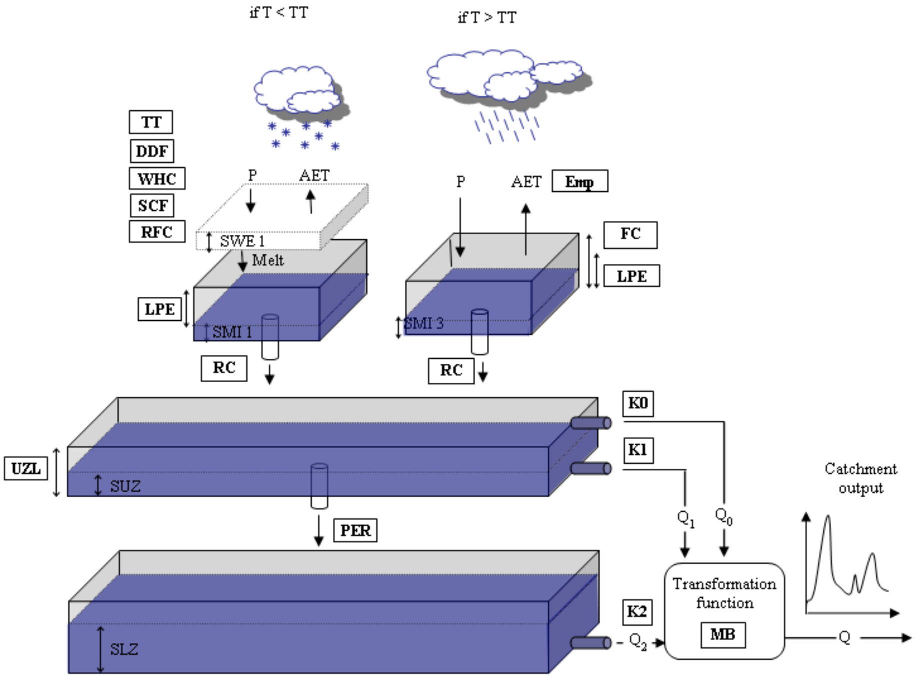

Fig. 1 Scheme of the Hron rainfall-runoff model. The framed symbols represent the model's parameters; the unframed symbols model input or output variables.

where: P - precipitation [mm], AET - actual evapotranspiration [mm], SWE - actual snow water equivalent [mm], SMI - soil moisture [mm], DDF - degree-day factor [mm/ºC/day^{-1}], TT - threshold air temperature [ºC], WHC - water holding capacity [-], RFC - refreezing coefficient [-], SCF - snow correction factor [-], FC - maximum field capacity [mm], LPE - limit of potential evapotranspiration [-], RC - recharge coefficient [-], Emp - empirical parameter for evapotranspiration [-], K0 - recession coefficient for surface runoff (Q_o) [-], K1 - recession coefficient for subsurface runoff (Q_1) [-], K2 - recession coefficient for base flow (Q_2) [-], UZL - limit for upper zone [mm], PER - percolation parameter [mm/day], MB - parameter of runoff retardation [day].

The snow sub-model contains 5 to 6 parameters and uses the degree-day method for snow accumulation and snowmelt calculations. The sub-model for soil moisture simulation contains three parameters and calculates the soil water storage, groundwater storage and actual evapotranspiration from the soil profile, depending on the relation between the water content in the soil profile and the field capacity value. The runoff sub-model with six parameters consists of one nonlinear and one linear reservoir and simulates both quick and slow runoff components (surface and subsurface runoffs and base flow). The recharge is added to the upper reservoir with the actual capacity *SUZ* (mm). If the *SUZ* is above the maximum threshold capacity for subsurface runoff generation, the surface runoff starts. The parameter *PER* (mm/day) defines the maximum percolation rate from the upper zone to the lower reservoir with the capacity *SLZ* (mm). The basin runoff is calculated as the sum of all the partial runoffs and is routed by a discrete cascade of linear reservoirs with a discharge-dependent time parameter (multilinear cascade model).

The input data needed for runoff simulation with a daily time step are: the catchment's average mean daily precipitation values, the catchment's average mean daily air temperature values, the mean monthly potential evapotranspiration , athe long-term mean monthly temperature values, and the daily potential evapotranspiration.

It is also possible to use daily potential evaporation values if they are available. In order to calibrate the model's parameters, the mean daily discharge values in the closing profile of the selected basin are needed. A more detailed description of the model is given in Kubeš (2002).

DATA ANALYSIS

The upper Myjava River basin to the Jablonica gauging station, which an area of 238 km^2 and is located in the western part of Slovakia, was selected as the pilot region for the study.

The climatic and hydrological data was provided by the Slovak Hydrometeorological Institute in Bratislava for the period 1.1.1981-1.12.2008. The data comprises the daily precipitation totals from 16 precipitation stations and the average daily air temperature from 5 climatic stations. The flow data consists of the daily average discharges at the Jablonica - Myjava gauging station, Fig.2.

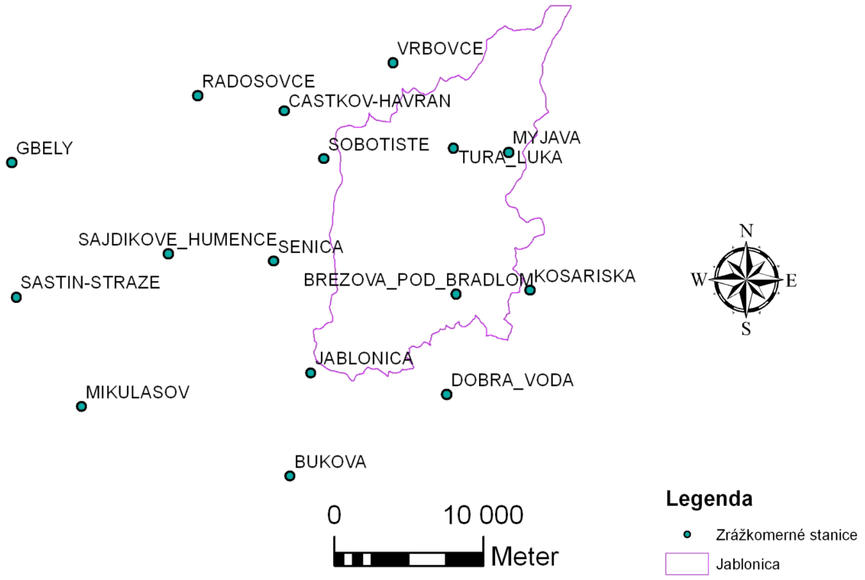

Fig. 2 Location of the precipitation and climatic stations in the Myjava River basin.

Given that a model version with lumped parameters was used for the rainfall-runoff modeling, the average daily air temperature values were determined using the temperature gradient method, where for each day the regression relationships between the average daily air temperature and the altitudes of the stations were calculated. The average basin altitude (361.194 m a. s. l.) was estimated from a digital terrain model using the GIS Idrisi. The mean daily precipitation totals for the model's input were processed by interpolating the daily precipitation totals measured at the stations using the inverse distance weighting method. The average daily values of the potential evapotranspiration were calculated by the Blaney-Cridle method, which uses the average daily air temperature and the sunshine duration index.

METHODOLOGY

Calibration and validation of the rainfall-runoff model

The calibration of the model was performed for various periods with an emphasis on extreme flood events in the spring and summer. Finally, two extreme events were selected and the model was calibrated based on the extreme snowmelt runoff situation from March 2006 and the extreme flash flood in June 1999.

Table 1 Values of the Nash-Sutcliffe coefficient estimated for various calibration periods

Period	Calibration
1.1.1981 - 3.3.1981	0.94529
22.11.1992 - 1.4.1993	0.93966
30.11.1986 - 23.7.1987	0.79065
14.11.1986 - 14.4.1987	0.73702
4.11.1987 - 17.1.1992	0.77160
18.3.1989 - 8.9.1994	0.75052
19.2.2000 - 31.10.2007	0.64049
1.1.1981 - 31.5.1994	0.66702
1.6.1994 - 31.10.2007	0.57081
1.1.1981 - 31.10.2007	0.58710

Figs. 2 and 3 shows the simulation of the two extreme spring and summer flood events selected.

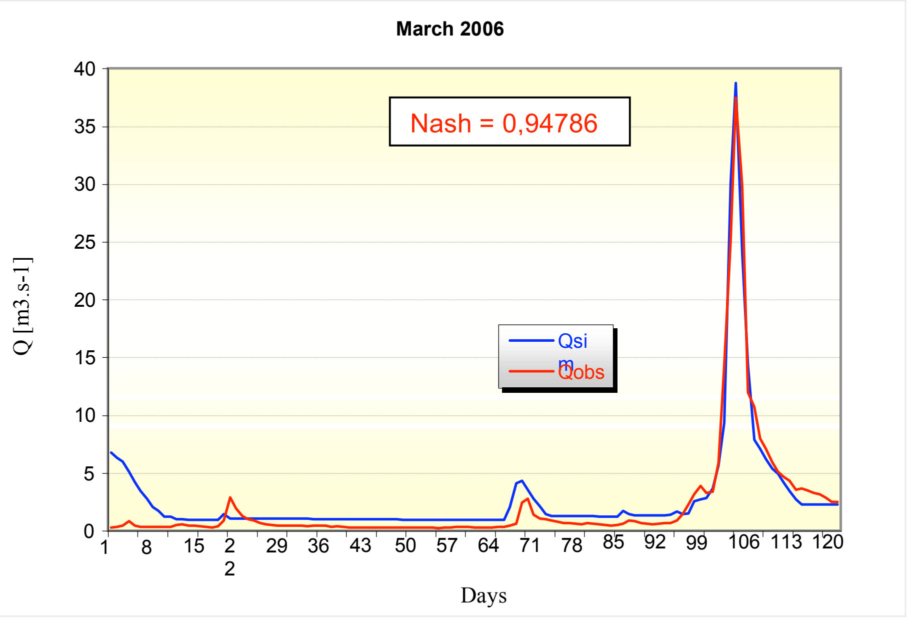

Fig. 2 Comparison of the simulated and observed discharges for the extreme snowmelt runoff situation in March 2006

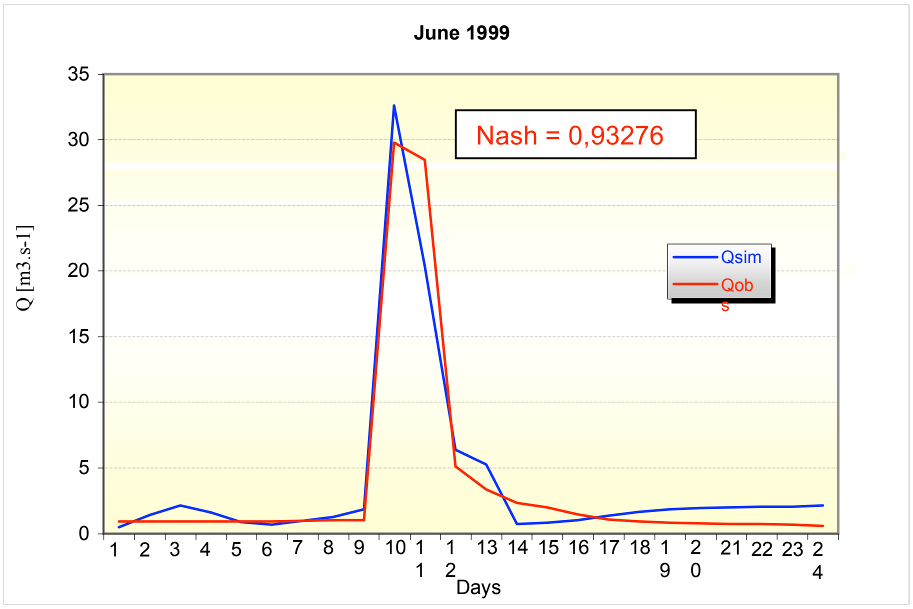

Fig. 3 Comparison of the simulated and observed discharges for the extreme flash flood in June 1999

Estimation of the N-year maximum design discharges

In this study the DVWK/101 (1999) methodology was used to estimate the design discharges. In this methodology, the plotting positions of the maximum precipitation totals are calculated according to Cunnane, WMO (1989) as:

$$P = \frac{m - 0.4}{n + 0.2} \tag{1}$$

where:

- n is the sample size, and
- m is the rank of the observations in a descending order.

To estimate the parameters of the theoretical distribution functions, three alternative methods can be used:

- the method of moments (MOM),
- the maximum likelihood method (ML),
- the method of probability-weighted moments (PWM).

The following theoretical distribution functions were tested for their applicability:

- E1 – (Gumbel) with a parameter estimation (MOM, ML, PWM),
- GEV – (Generalised extreme value) with a parameter estimation (MOM, ML, PWM),
- ME – (Rossi) with a ML parameter estimation,
- LN3 – (3-parameter Lognormal) with a parameter estimation (MOM, ML, PWM),
- P3 – (Pearson III) with a parameter estimation (MOM, ML, PWM),
- LP3 – (logPearson III)- with a parameter estimation (MOM, ML, PWM),
- WB3 – (3-parameter Weibull) with a parameter estimation (MOM, ML, PWM).

In order to select the most appropriate fitted distributions, a statistical test is recommended. The testing criterion is computed from the relationship:

$$D + n\varpi^2 + \left(1 - r_p\right) \tag{2}$$

where:

- D is the value of the Kolmogorov test,
- ϖ 2 is the value of the omega-squared test,
- rp is the correlation coefficient between the values of the descending sorted values and their distribution quantiles.

The best fit gives the lowest values of ϖ 2 , D and the highest values of rp, by minimizing the value of equation (2). The selected distributions are presented in Figs. 4 and 5.

The N-year maximum design discharges were estimated using data from the period 1981-2007, which is presented in Table 2.

Table 2 Values of the peak discharges observed during the period 1981-2007

Year	Date	$Q_{K,max}$	Year	Date	$Q_{K,max}$
1981	12.3.1981	8.258	1995	3.7.1995	17.86
1982	7.1.1982	6.797	1996	6.4.1996	17.8
1983	18.1.1983	5.844	1997	9.7.1997	31.36
1984	27.2.1984	3.7	1998	7.10.1998	15.59
1985	6.3.1985	17.7	1999	22.6.1999	63.57
1986	6.6.1986	19.87	2000	31.3.2000	10.73
1987	22.5.1987	14.8	2001	26.3.2001	6.974
1988	21.12.1988	15.07	2002	28.1.2002	9.02
1989	25.12.1989	5.212	2003	28.1.2003	8.22
1990	24.4.1990	2.396	2004	25.3.2004	8.35
1991	18.5.1991	3.455	2005	19.3.2005	36.08
1992	13.6.1992	3.752	2006	30.3.2006	41.47
1993	15.5.1993	13.38	2007	20.3.2007	11.15
1994	25.5.1994	14.1			

The simulated mean daily discharges were transformed to the simulated peak discharges using the ratio between the observed peak discharge Q_K (Tab.2) and the measured mean daily discharge $Q_{P,max.}$ The ratio coefficient k for the extreme summer flood reached a value of 2.1375 and 1.10734 for the snowmelt flood. The N-year values of the simulated peak discharges were subsequently estimated using the selected distribution functions, see Figs. 4 and 5.

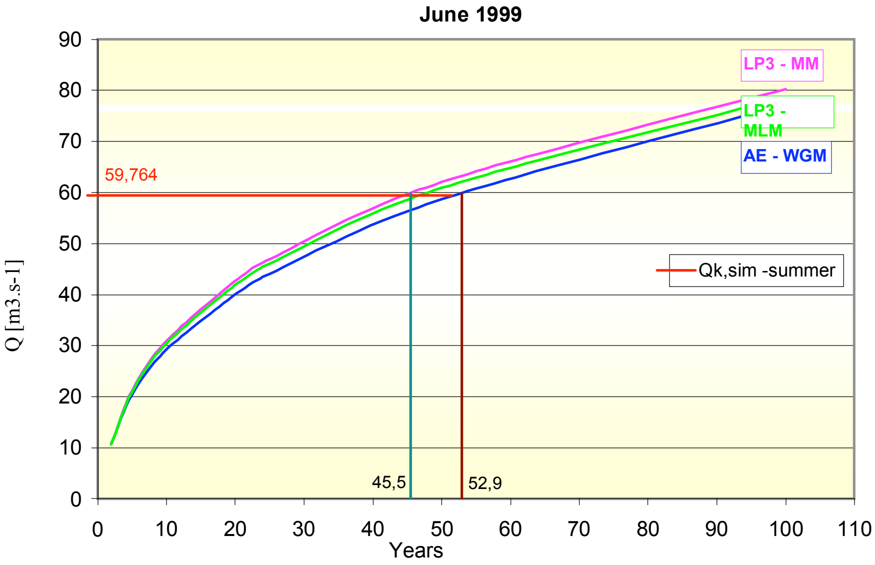

Fig. 4 Estimation of the N-year value of simulated discharge Q $_{K,sim\text{-}summer}$ – summer flood

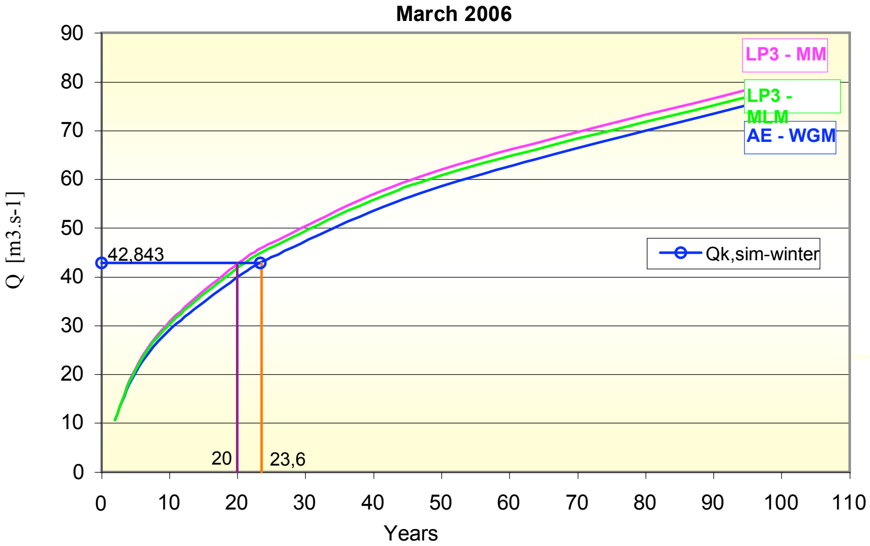

Fig. 5 Estimation of the N-year value of simulated discharge Q $_{K,sim\text{-}winter}$ snowmelt flood

Finally, we assigned a 50-year return period for the 1999 summer flood wave and the 2006 snowmelt flood wave with a return period of 20 years.

Extreme runoff scenarios based on changes in N-year design maximum precipitation totals

The aim of this part of the study was to construct extreme runoff scenarios caused by extreme summer and winter precipitation with different return periods. In the first step, the duration and total amount of the causal precipitation of the selected extreme summer and winter events were analysed. The summer flood was caused by a total amount of 3 days of causal precipitation (94.04 mm) with a return period of 20 years (Table 3). The winter flow wave was caused by 5 days of causal precipitation with a return period of less than 2 years (Table 4). In the next step the original causal precipitation with a duration of 3 days for the summer flood and 5 days for the winter flood was replaced by precipitation of the same duration and a higher return period (50, 100, 200, 500 and 1000 years). New input precipitation data with a daily percentage distribution equal to the original precipitation was used for simulating of the extreme summer and winter flood scenarios.

Table 3 Design values of N-year maximum k-day (1D to 5D) precipitation totals for the warm season (Gaál, 2006)

N [year]	1D [mm]	2D [mm]	3D [mm]	4D [mm]	5D [mm]
2	33.7	44.9	51.5	55.9	59.8
5	44.8	59.6	68.9	74.7	80.5
10	52.5	70.0	81.0	87.4	95.0
20	60.1	80.5	93.1	99.7	109.5
50	70.5	94.8	109.5	115.8	129.1
100	78.5	106.2	122.4	128.0	144.6
200	86.9	118.1	135.7	140.4	160.6
500	98.3	134.6	154.1	156.9	182.8
1000	107.3	147.8	168.6	169.5	200.3

Table 4 Design values of N-year maximum k-day (1D to 5D) precipitation totals for the cold season (Gaál, 2006)

N [year]	1D [mm]	2D [mm]	3D [mm]	4D [mm]	5D [mm]
2	24.3	32.4	37.7	42.1	46.6
5	32.3	43.1	49.6	55.2	60.5
10	37.9	50.5	57.7	63.7	69.3
20	43.6	58.0	65.4	71.8	77.3
50	51.4	68.1	75.6	82.1	87.2
100	57.5	76.0	83.3	89.7	94.2
200	64.0	84.2	91.0	97.2	101.0
500	72.9	95.6	101.3	106.9	109.5
1000	80.1	104.6	109.2	114.2	115.6

The simulated extreme summer floods caused by different inputs of N-year maximum precipitation totals in the warm season are shown in Fig. 6; simulated extreme snowmelt flood events caused by different N-year maximum precipitation totals in the cold season are shown in Fig. 7.

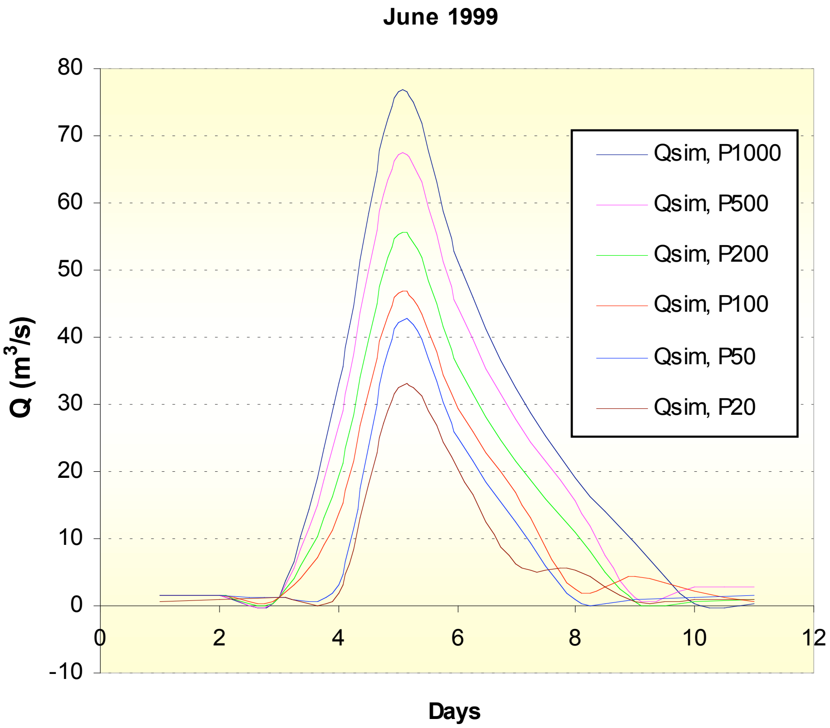

Fig. 6 Simulated extreme summer floods caused by different N-year maximum 3-day precipitation totals in the warm season

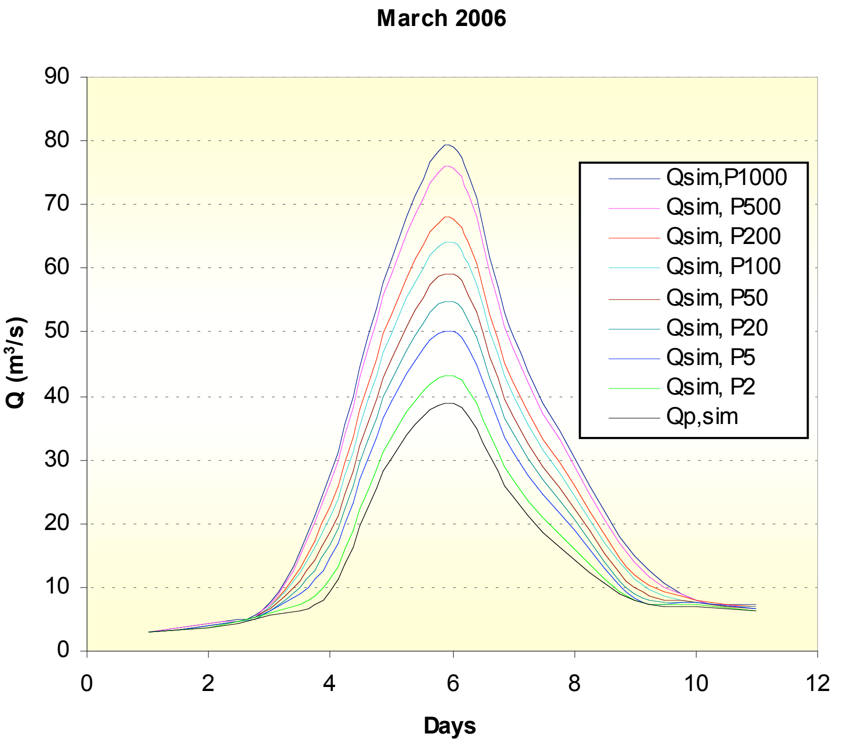

Fig. 7 Simulated extreme snowmelt floods caused by different N-year maximum 5-day precipitation totals in the cold season

Next, the maximum mean daily discharges for each simulated flood wave were recalculated for the peak discharges, and their return periods of them were estimated. The results are shown in Tables 5 and 6. From a comparison of the return periods of the peak discharges a higher nonlinear basin response can be indicated for the summer floods. While, for instance, for the summer flood, precipitation with a return period of 100 years caused a peak discharge with a return period of 200 years, for the winter flood a causal precipitation with a return period of 100 years caused a peak discharge with a return period of only 94 years.

Table 5 Return periods of simulated peak discharges $Q_{k,sim}$ for various scenarios of extreme precipitation totals in the warm season

Return period of causal precipitation	Mean daily discharge $Q_{p,sim}$	Peak discharge $Q_{k,sim}$	Return period of $Q_{k,sim}$
(years)	(m3/s)	(m3/s)	(years)
20	32.60	69.68	80
50	42.04	89.86	150
100	46.50	99.39	200
200	55.19	117.97	335
500	67.21	143.66	620
1000	76.68	163.90	960

Table 6 Return periods of simulated peak discharges $Q_{k,sim}$ for various scenarios of extreme precipitation totals in the cold season

Return period of causal precipitation	Mean daily discharge $Q_{p,sim}$	Peak discharge $Q_{k,sim}$	Return period of $Q_{k,sim}$
(years)	(m3/s)	(m3/s)	(years)
2	43.09	47.72	30
5	50.25	55.64	44
10	54.81	60.69	55
20	58.97	65.30	65
50	64.13	71.01	81
100	67.80	75.08	94
200	71.37	79.03	107
500	75.85	84.00	129
1000	79.07	87.56	145

Extreme runoff scenarios based on changes in N-year snow water equivalent and precipitation totals

The objective for creating the scenarios of extreme runoff from snowmelt was to simulate situations that might arise from an assumption of much higher snow cover and higher causal precipitation than during the selected extreme runoff event in March 2006.

The methodology was based on combining different scenarios of the input values of the snow water equivalent (SWE) and 5-day causal precipitation totals (P) with different return periods. The values of the N-year snow water equivalents were developed at the Slovak Hydrological Institute in Bratislava. The scenarios of the 100-year events were constructed as a combination of 20-year SWE and 5-year P, 50-year SWE and 2-year P, 10-year SWE and 10-year P. The scenarios for 1000-year events were created as combinations of 20-year SWE and 50-year P, 50-year SWE and 20-year P. The courses of the simulated mean daily discharges are shown in Fig. 8.

Table 7 Combinations of N-year values of snow water equivalents and 5 days of precipitation

Return period (years)						
Event	SWE	P	SWE (mm)	P (mm)	$Q_{p,max}$ (m^3s^{-1})	V (m^3)
100	20	5				
100	50	2	116.96	46.6	43.09	18007056
100	10	10	80.94	69.3	42.67	16483392
1000	50	20	116.96	77.3	63.27	23038560
1000	20	50	96.35	87.2	58.97	21643632
10000	100	100	133.09	94.2	68.54	28347120

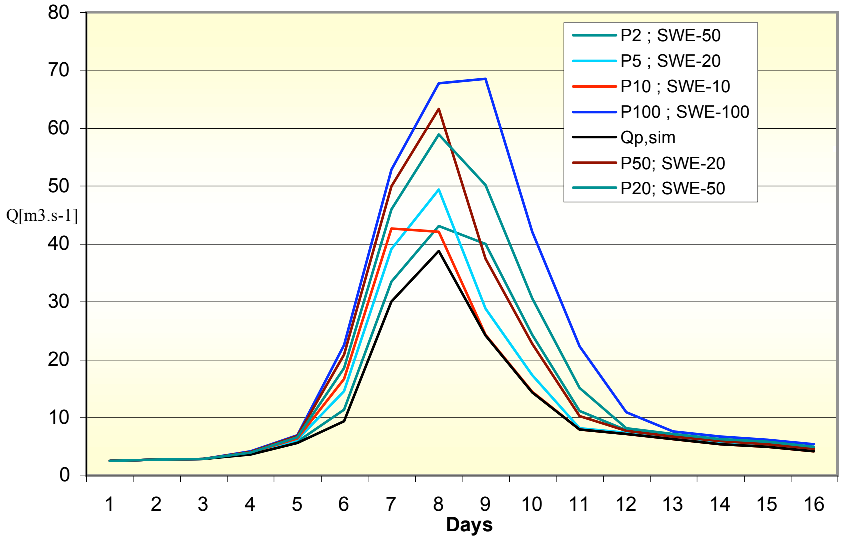

Fig.8 Simulated mean daily discharges for various scenarios of precipitation totals (P) and snow water equivalents (SWE)

As in the previous part, the maximum mean daily discharges for each simulated flood wave were recalculated based on the peak discharges, and their return periods were estimated. The results are shown in Table 7.

Table 7 Return periods of the simulated peak discharges

Return period of precipitation totals (P) and snow water equivalent (SWE)		Mean daily discharge $Q_{p,sim}$ (m^3/s)	Peak discharge $Q_{k,sim}$ (m^3/s)	Return period of $Q_{k,sim}$ (years)
P	SWE			
5	20	49,4	54,70	42
2	50	43,09	47,72	30
10	10	42,67	47,25	30
20	50	58,97	65,30	65
50	20	63,27	70,06	78
100	100	68,54	75,90	96

The following conclusion can be derived from different runoff scenarios. The highest discharge and flood wave volume were reached by the scenario which combines the snow water equivalent with a return period of 100 years and the 5-day precipitation totals with a return period of 100 years. The flood wave with the largest flood volume was reached by a combination of the snow water equivalent with a return period of 100 years and the 5-day precipitation totals with a return period of 100 years. The fact that the flood volume was mostly influenced by the input values of the snow water equivalent can be concluded from the scenarios.

CONCLUSIONS

Thee extreme runoff scenarios of for summer floods and floods from spring snow melt were created on the basis of an assumption of a change in causal precipitation and a snow water equivalent with higher return periods than the original causal events. For each scenario the return period of the simulated peak discharge was estimated. The results estimated showed that causal precipitation with a certain return period did not cause a peak discharge with the same return period. For the summer floods the extremity of the peaks was controlled by the antecedent soil moisture of the basin; for the winter floods the main controlling factor was the snow water equivalent. It was also shown that for winter floods from snow melting, the dominant response is based on increasing the flood volume, while for the summer floods; the dominant response is based on an increase in peak discharges. These facts can have an important effect on proposals and design of flood protection measures in the Myjava basin.

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