The Influence of Temporal Rainfall Distribution in the Flood Runoff Modelling

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Abstract: The rainfall input is one of the main factors influencing the magnitude of the runoff response during a flood event. Its temporal and spatial distribution significantly contributes to the formation of hydrograph shape, peak discharge and flood volume. A novel approach to the evaluation of the role of the temporal rainfall pattern of hydrograph is presented in this contribution. The methodology shown is based on the coupling of the deterministic event based runoff model with the stochastic rainfall disaggregation model. The rainfall model simulates the hyetograph ensemble, which is the direct input to the calibrated event based runoff model. The event based runoff model calibration is based on the evaluation of real flood events. The rainfall ensemble is simulated according to the preservation of important statistical properties, which are estimated from the real rainfall data inputs. The proposed combination of two simulation techniques enables to generate the hydrograph ensemble upon a single flood event. The evaluation of the temporal rainfall distribution impact on the flood runoff response is performed through the determination of the selected rainfall runoff characteristics of the simulated hydrograph ensemble. The main result confirms the importance of the rainfall volume inputs and its temporal distribution on the flood runoff generation. The methodology shown enables to evaluate the potential of the real flood event to generate the flood event within the conditions of the small catchment scale.

Keywords: flood; hyetograph; ensemble simulation; peak discharge; flood volume

The rainfall forms the main water input to the watersheds in the conditions in the Czech Republic. It influences the catchment runoff response mainly through its space and time distribution, therefore the study of this impact on the runoff process is the objective of the majority of theoretical and research studies (Ogden & Julien 1993; Obled *et al.* 1994).

The detailed monitoring of the space-time rainfall distribution in a small natural basin (4.4 ha) was explored by Goodrich *et al.* 1995. They conclude that the record of one rain-gauge is sufficient for the representation of temporal rainfall distribution within the explored catchment scale.

Afterward, this detailed rainfall field evaluation was used in the analysis of its impact on the runoff process (Faures *et al.* 1995). The results obtained enable to test the influence of the space – time rainfall distribution on the runoff process in the catchment conditions, where the dominant runoff process is the hortonian one.

The rainfall kinematics (Niemczynowics 1987) is described by the speed and direction of the

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rainfall field movement, clusters of rain cells, or cells (Hobbs & Locatelli 1978).

It was shown that, in the case of the rainfall cell movement in a direction similar to the main stream, the flood peak is higher than in the case of moving in the opposite direction (Singh 1998).

The hydrological runoff model together with the synthetic rainfall storms was used in order to evaluate the impact of the moving storm in an urbanized watershed with a fast runoff response. The newly derived methodology enabled again to evaluate the influence of the rainfall movement on the peak discharges, which is parameterised by the direction and speed of the rainfall event (Ngirane-Katashaya & Wheather 1985).

New information on the possible impacts of the space-time rainfall distribution on the runoff process is reflected within hydrologic design practises. The rainfall runoff comparison analysis of different design rainfall hyetographs confirmed that the temporally varied storm profiles produce higher peak flows than so called block rainfalls (Ball 1994).

The evaluation of uncertainty during the outflow process, which is caused by rainfall inputs, depends on the spatial scale of the analysed basins. The tests were performed at the hillslope scale (Bronstert & Bardossy 2003; Hearman & Hinz 2007). Ogden and Julien 1993 and Obled *et al*. 1994 performed a similar study at the small catchment scale. The rainfall evaluation estimated for the large basin scale is given in (Diermanse 1999).

A commonly used approach for this type of study is the coupling of the deterministic runoff model with stochastic rainfall generator. This approach is applied for the design purposes in the Czech Republic (Blažková & Beven 1997). The methodology shown enables to extend the studied ensemble of the rainfall runoff events and provides probabilistic information about the rainfall runoff process.

The objective of this contribution is to present the methodological approach for the evaluation of the influence of the temporal rainfall distribution on the flood runoff. The approach used is based on the coupling of the deterministic hydrologic runoff model with stochastic rainfall disaggregation model and contributes to the extreme flood events evaluation.

MATERIALS AND METHODS

This chapter briefly describes the modelling techniques, experimental setup, analysed data set, and catchment. Two modelling techniques were combined: the deterministic event based runoff model and stochastic rainfall disaggregation model, in order to evaluate the influence of the temporal rainfall distribution on the flood modelling.

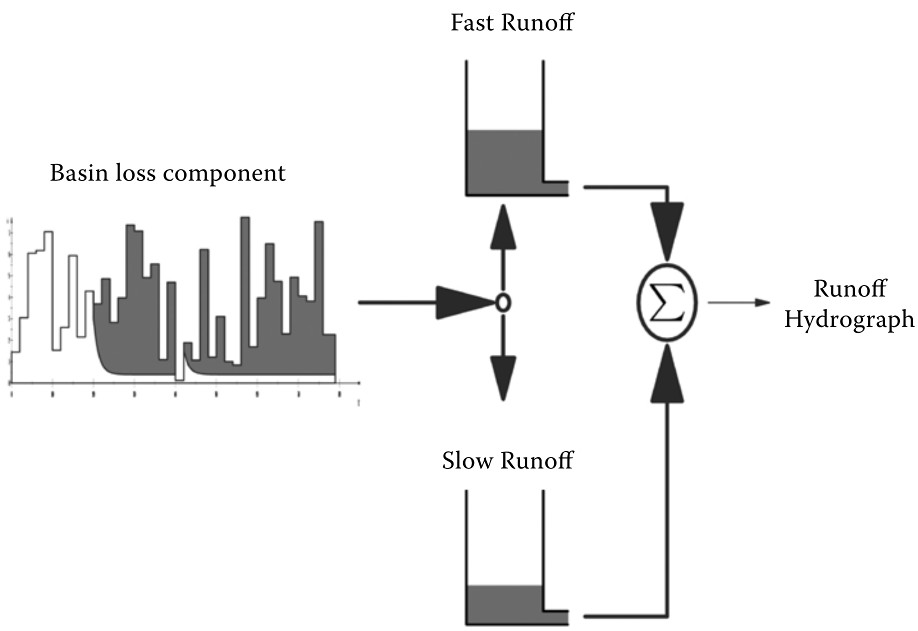

Figure 1. SEBRM model scheme

The even based runoff model – SEBRM

The SEBRM model used (Short Event Based Runoff Model) follows the standard structure of event based runoff models (Singh 1988, 1996; Beven 2001). The SEBRM is a deterministic event based rainfall runoff model. Its lumped version was used in the analysis presented.

The model consists of three main components: the effective rainfall component, and the slow and fast runoff response components. Its scheme is presented in Figure 1.

The main model assumptions are that the main part of the flood runoff can be modelled by the transformation of the effective rainfall. This transformation is performed by means of the fast runoff component. Another important assumption is the recovery of the loss capacity during the flood event (Akan & Houghtalen 2003).

Therefore, the main model parameters are the parameterisation of the fast runoff component and estimation of the effective rainfall.

The slow runoff component. The component of the slow response expresses that part of the outflow which is not connected with the actual basin runoff reaction on the current rainfall input. This component represents the pre-event catchment outflow response. According to the flood event studied, the simple linear separation of the baseflow is used (Singh 1988). The baseflow equals to the initial flow before the beginning of the rainfall event and was constant in the study presented.

The effective rainfall component. The second SEBRM component is the estimation of the effective rainfall input. The technique applied is almost similar to the approach found in (Faures *et al.* 1995). The estimation of the flood volume and the temporal distribution of the effective rainfall are the outputs from this component. The regeneration of the loss reservoir is enabled during the flood runoff modelling (Akan & Houghtalen 2003).

At first, the initial loss volume is subtracted from the input rainfall before the basin starts to react on it, and then the temporally varied loss starts to form the net rainfall (McCuen 1989).

The effective or net rainfall in a given hour is the difference between the input rainfall and total loss in the given hour. The net rainfall H_e is estimated with the following assumptions:

$$H_e(t) = \begin{cases} 0 & \textit{for} \quad H_r(t) < F(t) \\ H_r(t) - F(t) & \textit{for} \quad H_r(t) > F(t) \end{cases} \qquad (1)$$

where:

$F(t)$ – integral from loss intensity described as

$$f(t) = \frac{1}{2} \cdot S_p t^{1/2} + K_p \qquad (2)$$

The parameter S_p reflects the fast part of losses during the given temporal section and parameter K_p reflects the long term part of losses for the given temporal section. These are estimated during the calibration process.

The input rainfall is divided into several temporal sections. Each section is connected to different loss capacity in the basin, which is described by varying the values of the S_p and K_p parameters in Eq. (2).

During one temporal section, one part of the rainfall contributes to losses and the second part forms the effective rainfall, which is the input to the fast runoff component of SEBRM model. The capacity of losses recovers between two following temporal sections.

The final temporal distribution of the losses forms the basin conditions of water saturation during flood event. The losses estimated on the basis of real event were used constant in the presented ensemble hydrograph simulation.

The fast runoff component. The last SEBRM component transforms the effective rainfall input to the hydrograph of the fast runoff component. The fast runoff component represents the flood reaction of the basin. The SEBRM structure assumes that the main part of the flood outflow is described by the fast runoff transfer function, whose description is based on the use of St. Venant for the overland flow (Goodrich *et al.* 1995; Faures *et al.* 1995; Singh 1996).

The system of equations is formed from the mass balance equation

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = e(t) \qquad (3)$$

where:

q – specific discharge

h – flow height

$e(t)$ – lateral inflow

The next equation is the momentum one (here presented in diffusion approximation):

$$i = i_{sv} - \frac{\partial h}{\partial x} \qquad (4)$$

where:

i – friction slope

i_{sv} – slope

$\frac{\partial h}{\partial x}$ – shows the change of the flow height in the dependence on the distance x

Finally, the specific discharge is computed using Basin's friction equation

$$q = \frac{87}{\gamma} \cdot \sqrt{i} \cdot h^m \tag{5}$$

where:

γ, m – calibrated parameters

The numerical solution of the proposed St. Venant equations is expressed by the diffusion wave approximation for the overland flow (Singh 1996). The set of the equations shown is solved by the finite difference method with the implicit numerical scheme. The detailed description of the numerical scheme applied can be found in (Máca 2005).

The main parameters for this fast runoff component are γ and m which reflect the friction of the basin and are constant during the flood event.

The rainfall disaggregation model

The second model used in this study is the stochastic rainfall disaggregation model which enables to simulate the ensemble of the rainfall input hyetographs with a different temporal rainfall distribution. The model was tested and developed under the cooperation with the WUR Wageningen and follows the theory of wavelet coefficients published in (Torfs 1997, 1998).

The model used simulates the rainfall ensemble, which preserves the important statistical properties – the first two statistical moments. Preserving the rainfall expectation (mean value) helps to conserve the mass balance of the input rainfall volume. The rainfall volume is identical in all simulated hyetographs of the ensemble. The second preserved statistical property is the hyetograph variance across all the possible time resolutions for the rainfall events studied. The variance is preserved in average within the whole simulated ensemble.

The basic disaggregation steps are shown in Figure 2.

The disaggregation starts on the largest time scale, where the rainfall input has a constant intensity. During the downscaling, the just right amount of variance is added and the time scale is halved. The variances over the different time scales are estimated via the variance reduction function (Vanmarcke 1983), which is estimated directly from the real rainfall event and which shows the distribution of variance over the different rainfall aggregation scales.

More or less similar approach was used in (Hearman & Hinz 2007).

Experimental setup

In order to evaluate the impact of the temporal rainfall distribution on the flood runoff, two real data sets of extreme flood events were selected. The evaluated floods caused large flooding in the Moravka basin – outlet Uspolka (northern part of Moravia) and represent the flood response in the headwater catchment.

At the first, the parameters of the stochastic rainfall disaggregation model (Variance reduction function and mean rainfall intensity) are identified and new hyetograph ensembles are simulated. All

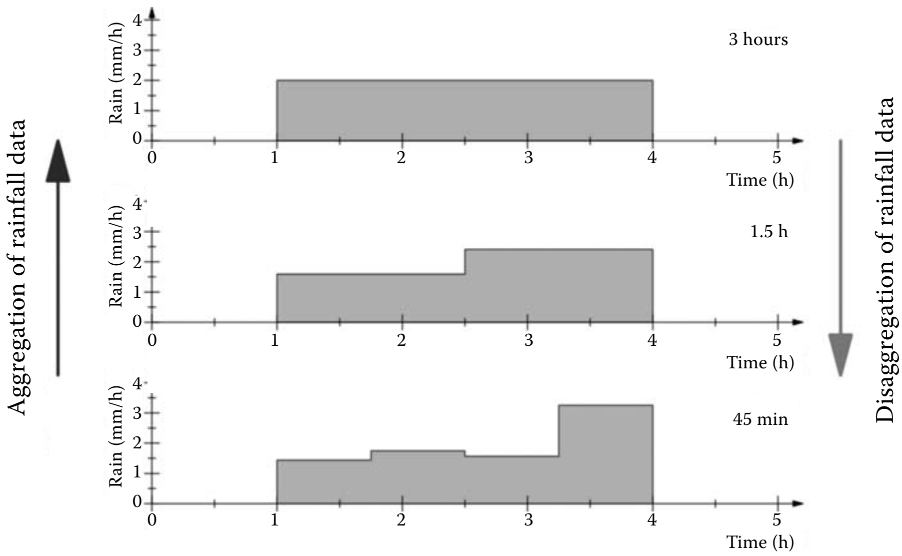

Figure 2. The rainfall disaggregation

simulated hyetographs are connected with the real extreme rainfall hyetographs by preserving the rainfall volume and variance.

The newly simulated rainfall ensembles are the direct inputs to the SEBRM model, which had been successfully calibrated before. The results of SEBRM calibration are: the estimation of the loss component and parameterisation of the fast runoff component. It was assumed that, by keeping similar losses as were those during the recorded events, almost identical wetness conditions are preserved within the estimated ensemble hydrograph, similarly the same parameterization of the fast runoff response preserves the conditions during the recorded flood events. The uncertainties of these two assumptions were not tested within the simulation exercise presented.

The slow runoff response represented by constant values of the baseflow was estimated on the basis of the flood event data and was kept constant for all simulated flood hydrographs in ensembles.

The hydrograph ensembles were finally obtained via hydrologic simulation and the ensemble was simply evaluated by the scatter plots of the selected hydrograph characteristics.

Catchment and flood event description

The studied mountainous basin is located in the northern part of Moravia, the basin area is 22.29 km^2, the average slope according to Herbst is 0.3, the elevation is 766 m a.s.l. The catchment land use represents 1.6% pastures, 15.4% arable land, and 82.3% forest stand.

The two extreme flood events were tested. They were selected according to the hyetograph and hydrograph properties. Their characteristics are shown in Table 1, where *Hs* is total rainfall rate, *Ho* total outflow rate, *Q* peak discharge, *Tr* rainfall duration, *T* hydrograph duration, runoff coefficient and *Hzt* total initial loss rate.

The selected flood events are similar as concerns the return period of the peak discharge, which was estimated for the flood event from 1996 to be longer than 20 years and for the flood event from 1997 as equal to 20 years. The data were evaluated within the framework of the research project (Elleder & Drbal 2002). The input rainfall hyetographs were spatially averaged on the basis of the surrounding rain gauge stations from Horní Lomná, Úspolka, and Lysá Hora, the estimates were provided by CHMI.

The selected rainfall stations are the closest stations in the region of the Moravka basin. The estimation of the spatially averaged rainfall was done by combining the expert knowledge and application of the spatial averaging method of CHMI. The accuracy of the input rainfall was confirmed by the work (Elleder & Drbal 2002).

RESULTS AND DISCUSSION

SEBRM model calibration

The SEBRM calibration was performed with the emphases on the two main SEBRM parts: the regeneration of the catchment losses capacity and the fast runoff component. The resulting fitted hydrographs are presented in Figure 3.

The γ and m parameters of the fast component were estimated with the help of the results coming from the study of (Kuřík 2002) providing physically meaningful ranges of these parameters; therefore, the selected values have a plausible interpretation. The sensitivity analyses were performed and confirmed the selection of suitable values for the fast response parameters.

The resulting loss component consists of finding the number of sections and the values of both parameters of Eq. (1). The high value of Nash Sutcliffe values confirmed the goodness of the calibration results (see Figure 3). The evaluation of uncertainty of the resulting combination of the loss component parameters was not included in the present study, thus the final vector of parameters was used in the following simulations.

Table 1. Flood event properties

Flood event	*Hs* (mm)	*Ho* (mm)	*Q* (m^3/s)	*Tr* (h)	*Tpv* (h)	φ (–)	*Hzt* (mm)
4. 9. 1996	210	155	53.8	45	80	0.74	31.1
4. 7. 1997	535	356	50.1	90	160	0.67	90.4

Hs – total rainfall rate, *Ho* – total outflow rate, *Q* – peak discharge, *Tr* – rainfall duration, *Tpv* – time of hydrograph rise, φ – runoff coefficent, *Hzt* – total initial loss rate

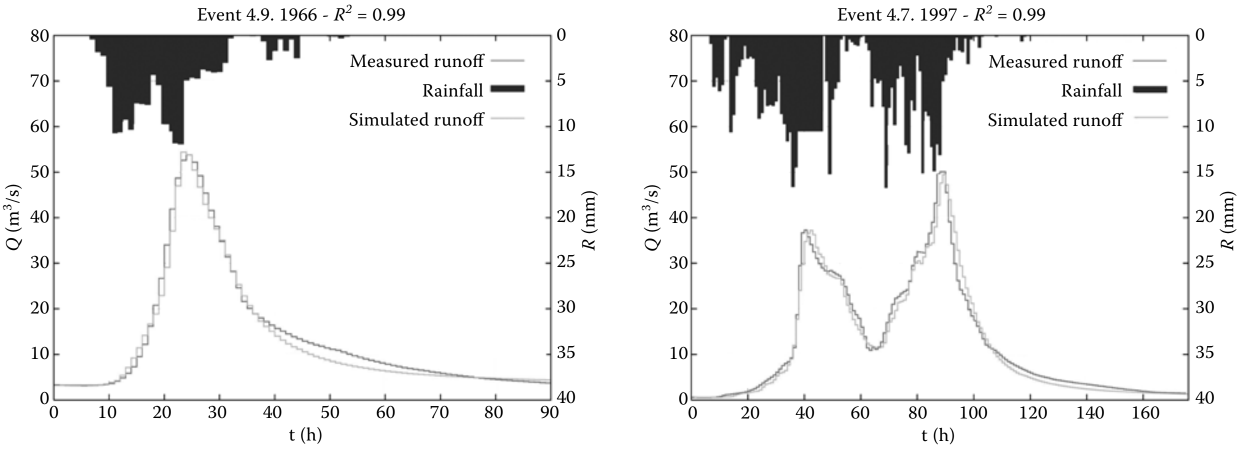

Figure 3. SEBRM calibration of selected flood events

The final values of SEBRM model parameters are presented in Table 2.

Table 2. SEBRM parameters – calibration results

Flood event	No. of sections	Range of K_p	Range of S_p	γ	m
4.9. 1996	7	0–0.8	0–10	16	2.5
4.7. 1997	23	5–1.75	1–17	16	2.5

K_p – parameter for long term losses, S_p – parameter for fast losses, γ – friction parameter, m – friction parameter

Rainfall disaggregation model identification

The disaggregation model was used for the simulation of the rainfall ensemble consisting of the set of the generated hyetographs with different temporal rainfall distributions. The estimate of the first two statistical moments is part of the rainfall data simulation. The rainfall data cover only the time interval in which the flood runoff is generated. Because the input rainfall data have no long intermittent intervals, the type of disaggregation model was used, which does not simulate the rainfall intermittency (Torfs 1997, 1998). Both simulated ensembles comprised 10 000 generated hyetographs. The simulations showed that 1000 of them were sufficient for preserving the original variance of the rainfall events on average. However, the total number of 10 000 members in the

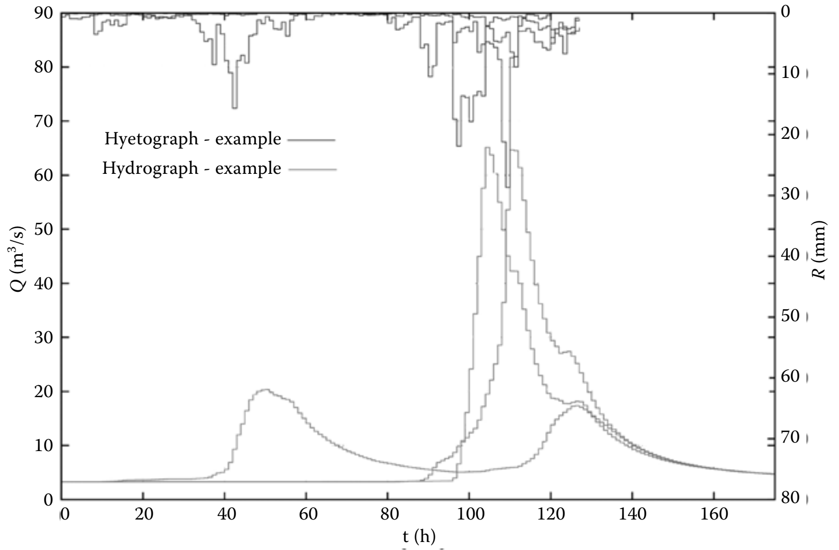

Figure 4. Example of 4 randomly selected hydrographs and hyetographs from an ensemble from event of 1996

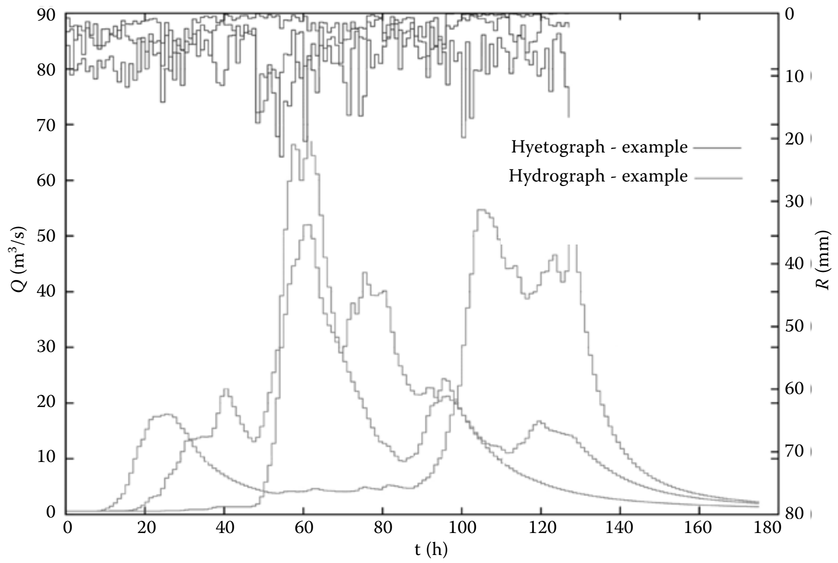

Figure 5. Example of 4 randomly selected hydrographs and hyetographs from an ensemble from event of 1997

ensemble was shown in this study to demonstrate the effect of outliers.

Simulation of hydrograph ensemble

The simulated temporally varied rainfall profiles were direct inputs to the SEBRM, which had been already calibrated. The initial loss *Hzt* (Table 1) together with the estimated parameters of the loss component was kept similar for all artificial rainfalls. By this assumption, similar wetness of the basin was preserved. Because the temporal distribution of the loss component is the same as in the rainfall event recorded and the temporal distribution of the input rainfall varied, the simulated hydrographs show different volumes and timing. The examples of 4 randomly selected simulated hydrographs with hyetographs are given in Figures 4 and 5.

The selected results of the ensemble simulation are presented in Figures 6 and 7. The hydrograph simulations are evaluated via two-dimensional scatter plots of the selected characteristics of the rainfall runoff events. The results presented show the dependency between the peak discharges and maximum hyetograph intensities (Figure 6), and the relationship between the peak discharges and flood volumes (Figure 7).

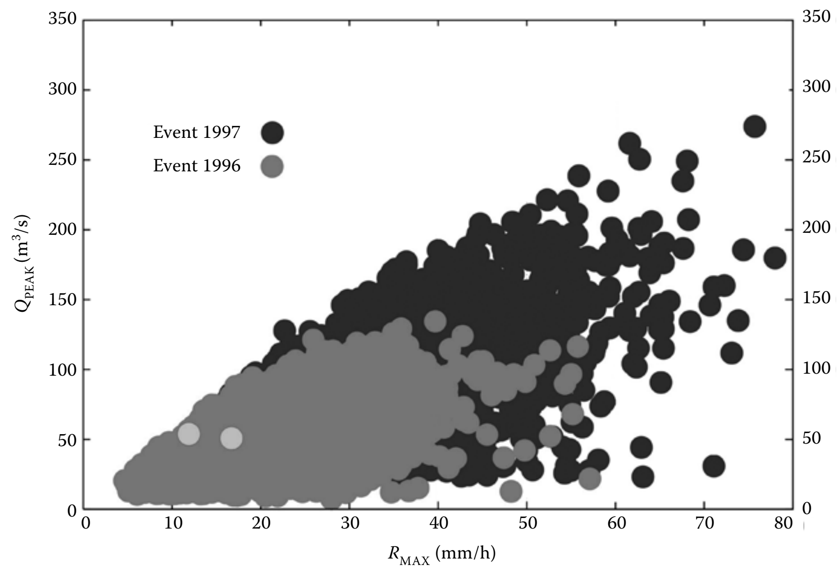

Figure 6. Relation between peak discharges and maximum hyetograph intensities – green dots show real event data

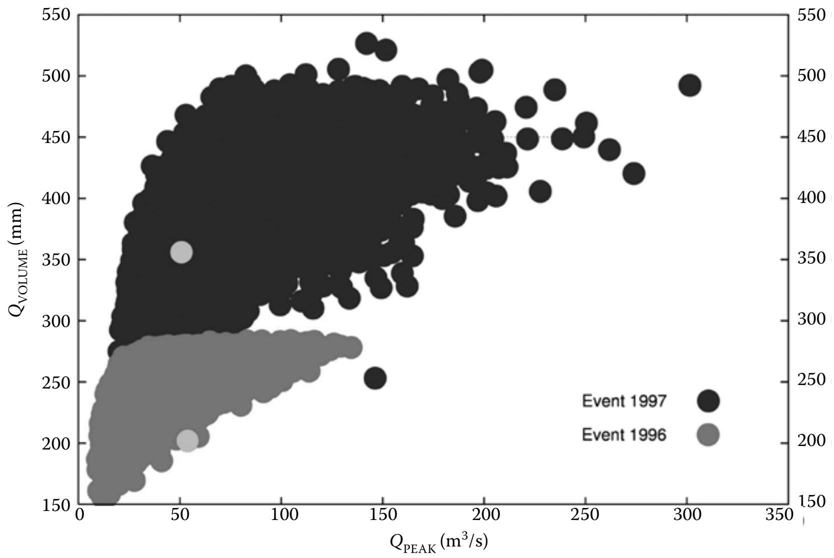

Figure 7. Relation between peak discharges and flood volumes – green dots show real event data

The results demonstrate that the input rainfall volume caused the dominant effect on the hydrograph ensemble simulation. The 1996 flood event rainfall ensemble did not consist of hyetographs with the maximum hourly rainfall intensity above 60 mm/h, which is considered as being close to the estimate of the probable maximum precipitation for this region in the Czech Republic. There were several artificial hyetographs within the ensemble of 1997 event with the maximum intensity above 60 mm/h. This fact was caused mainly by the rainfall input rate which was 535 mm. This rainfall volume was extremely high and therefore the rainfall disaggregation model was able to dissagregate different temporal rainfall profiles.

As the main result following from the ensemble hydrograph evaluation is the fact, that there occurred hydrographs simulated with a higher magnitude than the measured peak discharges and flood volumes of the flood events studied. Also, the patterns of the simulated values in the scatter plots showed the potential of the temporal distribution of the input rainfall to generate more extreme flood hydrographs than the real flood event.

CONCLUSIONS

Ensemble hydrograph simulation was used in order to compare the flood events extremity. The ensemble hydrograph simulation and evaluation were performed during the evaluation of two large flood events in the small Moravka basin (22.29 km^2).

The results show that the rainfall volume plays a significant role in the flood event extremity and confirm the suitability of the application of both simulation techniques tested.

The presented approach to the flood event evaluation based on combing the deterministic runoff event based model with the stochastic rainfall disaggregation model enables to extend the information on the extreme runoff response in the catchment scale.

A large potential exists for the application of the approach shown within the hydrological design activities. The models assumption provides a runoff model with a reasonable parameterization and a disaggregation model which simulates the hyetograph ensemble while preserving the main rainfall characteristics.

The proposed methodology is open for adding other hydrological components, which it improves towards more physically based process description of the main runoff response components. One of the challenging parts is also further exploration of the uncertainty of SEBRM parameterisations.

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