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THE INFLUENCE OF EFFECTIVE RAINFALL ON MODELED RUNOFF HYDROGRAPH

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Influence of the pattern of effective rainfall on modeled hydrograph was investigated in the study. The modelling was performed with the U.S. Army Corps of Engineers hydrograph package HEC-HMS 3.2 and calibrated and validated on measured hydrographs of Glinscica watershed. Six different models of rainfall loss were applied and their effect on modeled hydrograph was evaluated. Peak discharge, time of peak discharge and runoff volume were compared. The best results with the lowest RMSE in the study was obtained with the SCS curve number loss method. Also synthetic hyetographs of different probability and duration were used. Three positions of the maximum rainfall intensity at 25, 50 and 75 % of the rainfall duration were applied. The results showed essential differences in simulated time to peak and also differences in peak discharge. The differences in time to peak increases considerably with the increasing of the rainfall duration. Finally, the results of constant intensity distribution of rainfall of different durations were compared with those obtained with typical rainfall distribution with the position of the maximum intensity at 50 %. Results showed considerable differences in peak discharge and time to peak by longer durations of the rainfall.

KEY WORDS: Rainfall Loss Model, Rainfall Temporal Variability, Maximum Rainfall Position, Rainfall-Runoff Relationship, Synthetic Hyetograph, HEC-HMS.

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Práca obsahuje výsledky výskumu vplyvu efektívnych zrážok na modelovaný hydrograf. Odtok bol modelovaný pomocou nástroja U.S. Army Corps of Engineers hydrograph package HEC-HMS 3.2, potom kalibrovaný a verifikovaný na meraných hydrografoch povodia Glinscica.

Vplyv zrážok na modelovaný hydrograf bol vypočítaný pre šesť rôznych modelov priebehu zrážok. Porovnali sme maximálne prietoky, časy ich trvania a odtečené množstvá. Najlepšie výsledky s najnižším RMSE sme získali s SCS modelom odtoku. Použili sme tiež syntetické hyetografy rozdielnej pravdepodobnosti a trvania. Použili sa tri polohy maximálnych intenzít zrážok; pre 25, 50 a 75 % ich trvania. Výsledky ukázali zásadný rozdiel v simulovaných časoch maximálneho prietoku a tiež rozdiely v maximálnych prietokoch. Rozdiely v časoch dosiahnutia maximálnych odtokov sa výrazne zvyšovali s časom trvania zrážky. Nakoniec sme porovnali výsledky výpočtov s konštantnými intenzitami rozdelenia s rôznym trvaním zrážky s tými, ktoré boli vypočítané s použitím typických rozdelení, s polohou maximálnej intenzity zrážok pri 50 % ich trvania. Výsledky ukazujú významné rozdiely v maximálnych prietokoch a v časoch ich dosiahnutia v závislosti od trvania zrážky.

KĽÚČOVÉ SLOVÁ: model odtoku, časová závislosť rozdelenia intenzít zrážok, čas maximálnej intenzity zrážky, závislosť zrážka-odtok, syntetický hyetograf, HEC-HMS.

1. Introduction

The rainfall-runoff process is difficult to simulate precisely. Models usually use the concept of the effective rainfall where rainfall hyetograph is divided into losses and effective rainfall. The effective rainfall is then used as the model input to provide runoff hydrograph. Accurate representation of the effective rainfall is essential for rainfall-runoff models (*El-Jabi*, *Sarraf* 1991; *Ball*, 1994; *Faures* et al., 1995).

One of the problems of the ungauged basins is the estimation of loss rates. Loss rates depend on precipitation pattern and basin characteristics (*DeVries*, 1982). Also when we have some measurements, it is costly, time-consuming and difficult to measure all of the soil characteristics thoroughly enough and on the other hand, each rainfall event produces a different loss parameters. In fact, we usually have a limited range of measurements in practice.

The objective of this study was to evaluate the influence of effective rainfall on modeled runoff hydrograph. For this purpose the rainfall-runoff model of the Glinscica experimental watershed was made with the U.S. Army Corps of Engineers hydrograph package HEC-HMS 3.2. Six different models of rainfall loss (Infiltration index model, Horton model, Initial and uniform method, SCS method, Green Ampt method and Smith-Parlange method) were applied and their effect on modeled hydrograph was evaluated. Also the influence of rainfall intensity distribution and the maximum rainfall intensity position of synthetic hyetographs of different probability and duration were evaluated. To evaluate modeled results peak discharge, time-to-peak, runoff volume and root mean squared error (*RMSE*) of the modeled and measured hydrograph were compared.

2. The study area

The Glinscica watershed is one of three experimental watersheds in Slovenia (*Rusjan* et al., 2008; *Šraj* et al., 2008a; b). It is located in the central part of Slovenia and reaches into the eastern part of the urban area of the capital city of Ljubljana (Fig. 1). Because of the removal of rainfall water with a sewage system in urban area the orographic water divide does not coincide with precipitation drainage area (*Brilly* et al., 2006). The precipitation drainage area comprises 16,85 km^2. The Glinscica stream has its source under the slopes of the hills of Polhograjsko hribovje at the altitude of 590 m and passes into the plain area of Ljubljana Plain. It flows into the Gradascica stream at the altitude of 209 m at the southernmost point of the watershed. The upper part of the watershed is a hilly region whereas the southern part is a plain area. A major tributary of the Glinscica is the Przanec creek. The wateshed is divided into three subwatersheds (*Šraj*, 2001).

The Glinscica watershed study site is equipped with rainfall station (Onset RG2-M), water station with the ultrasonic Doppler instrument (Starflow Unidata 6526 model) and a water quality multiprobe (Fig. 1).

The land use data were taken from the CORINE database (*Heymann*, 1993). Most of the watershed is forested (48.6 %), followed by agricultural land (22.9 %) (*Brilly* et al., 2006). The urbanised areas represents 19.6 % of the Glinscica watershed. The soil types C and D (SCS classification) (*Feldman*, 2000) with low infiltration rate prevailed.

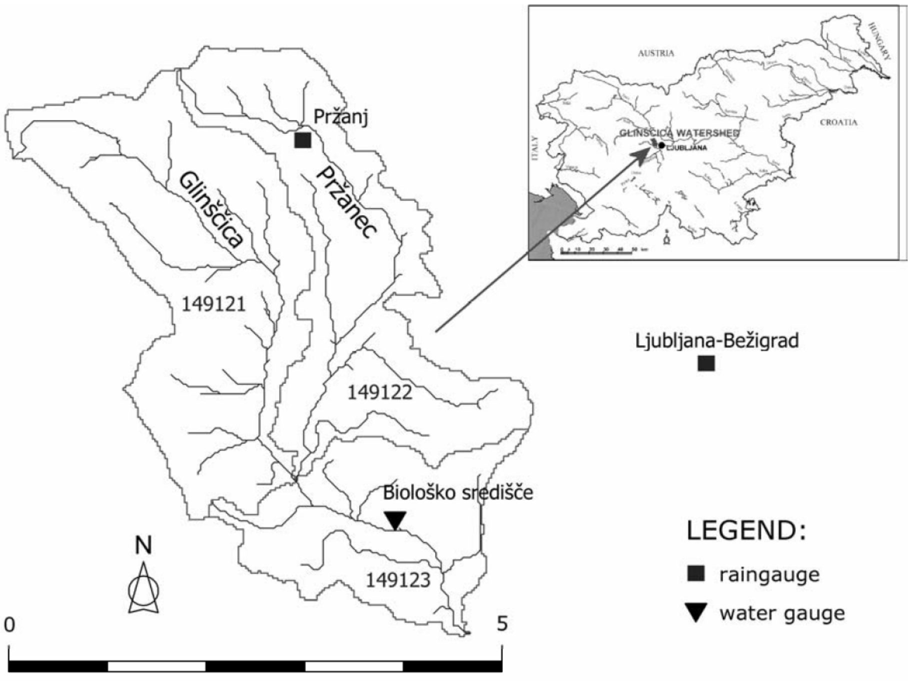


Fig. 1. Location of the Glinscica watershed and measurement stations.
Obr. 1. Poloha povodia a meracích staníc v povodí Glinscica.

3. Methods

3.1 HEC-HMS modeling

The HEC-HMS (Hydrologic Modeling System) software was developed at the Hydrologic Engineering Center of the US Army Corps of Engineers (HEC-HMS, 2009). It is used to simulate the rainfall-runoff processes and it was applied in many studies in different environments all over the world (*Danil* et al., 2005; *Garcia* et al., 2008; *Unucka*, *Adamec*, 2008). In the U.S.A. it is commonly used for computing design discharges (*Marcus* et al., 2007). HEC-HMS includes several models to account for the precipitation losses. Precipitation loss is calculated with selected model and the remaining precipitation represents effective hyetograph. The transformation of effective precipitation into runoff can be done with unit hydrograph models or conceptual kinematic-wave model of overland flow (*Feldman*, 2000).

The simulated hydrograph was calculated by applying on the unit hydrograph derived from the measured one. The model was calibrated on the selected measured runoff hydrograph. Measurements from November 2003 were used. The selected precipitation event lasted for forty hours and had the maximum intensity of 6 mm h^{-1}. The total amount of the rain was 50.4 mm. That rainfall event caused recorded peak discharge of 9.4 m^3 s^{-1}. The model was successfully validated on the measured hydrograph of January 2004. Six different models of rainfall loss were then applied with calibrated model. Loss models that are not included in the HEC-HMS package (Horton's model and Φ-index model) were calculated manually.

3.2 Infiltration models

F-index model

The Φ-index model is the simplest infiltration model used in hydrology. The method assumes that the infiltration rate is almost constant during the storm, so the total volume of the rainfall loss during the storm is estimated and distributed uniformly during the storm pattern (*Viesmann* et al., 1977).

The Φ-index in our study was determined as the difference between the total gauged precipitation volume and the observed runoff volume from the measured hydrograph. The estimated Φ-index value was 0.778 mm h^{-1}. The results are showed in Fig. 2.

Horton's infiltration model

Horton's model is empirical and one of the most widely used infiltration models (Eq. (1)). Horton studied the infiltration process in the early 1930s (*Horton*, 1939). His equation indicates that infiltration tends to decrese in an exponential manner from the initial infiltration capacity f_0 to the final constant capacity f_c:

$$f(t) = f_c + (f_0 - f_c) \cdot e^{-kt}, \tag{1}$$

where f is the infiltration rate at time t and k – a constant representing the rate of decrease in infiltration capacity. Parameters used in our model are presented in Tab. 1 and results in Fig. 2.

Table 1. Parameters of the Horton's infiltration model.
Tabuľka 1. Parametre Hortonovej infiltračnej rovnice.

Subbasin	149121	149122	149123
Area [km^2]	7.20	5.99	3.66
f_0 [mm h^{-1}]	7.60	7.60	7.60
f_c [mm h^{-1}]	0.65	1.3	0.65
k [1/h]	2.00	2.00	2.00

Initial and constant-rate loss model

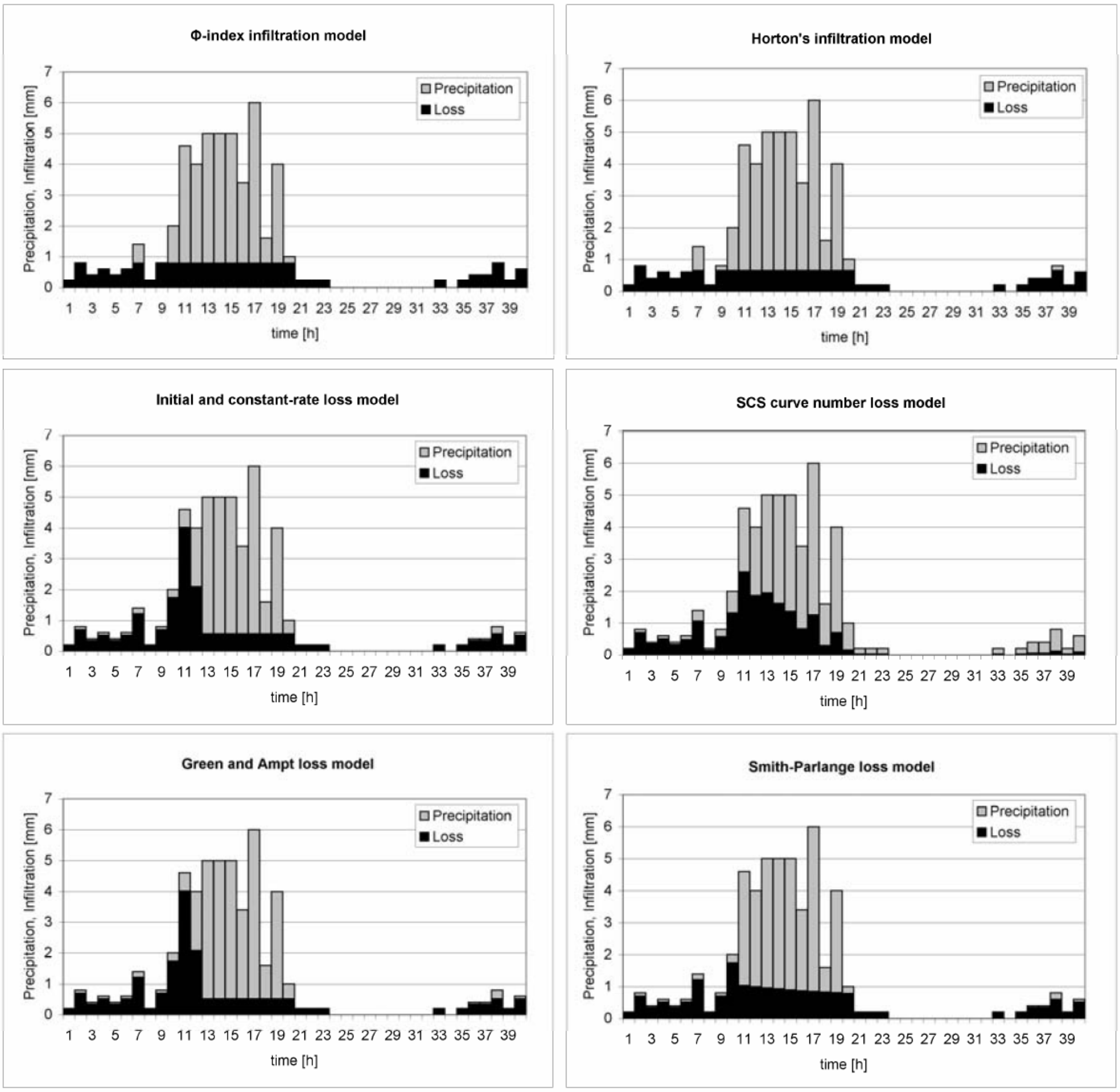
The concept of the initial and constant-rate model is that the maximum potential infiltration rate is constant. The initial loss is added to the model to represent interception and depresion storage (*Feldman*, 2000). The Soil Conservation Service SCS (1986) classified soils on the basis of infiltration rates. The classification is useful in the absence of measurements. Tab. 2 and Fig. 2 show initial and constant-rate losses of our model.

Table 2. Losses of the initial and constant-rate loss model.
Tabuľka 2. Odtoky vypočítane pomocou "počiatočného" modelu (initial loss) a modelu so stálym odtokom (constant rate).

Subbasin	149121	149122	149123
Initial loss [mm]	14.10	10.17	5.62
Constant rate [mm h^{-1}]	0.65	1.3	0.65

SCS curve number loss model

The SCS model is an empirical model. Model has its origins in the unit hydrograph approach to rainfall-runoff modeling. It is particularly useful for ungauged watersheds because the parameters of the



Φ-index infiltration model

Horton's infiltration model

Initial and constant-rate loss model

SCS curve number loss model

Green and Ampt loss model

Smith-Parlange loss model

Fig. 2. Results of different loss models.
Obr. 2. Výsledky výpočtu rozdielnymi modelmi.

model have been related to the watershed characteristics. The SCS curve number model estimates cumulative rainfall excess P_e as:

$$P_e = \frac{\left(P - I_a\right)^2}{P - I_a + S}, \tag{2}$$

where P is accumulated rainfall depth at time t, I_a – the initial abstraction and S is potential maximum retention. S and watershed characteristics are connected through curve number CN as:

$$S = \frac{25400 - 254 \cdot CN}{CN}. \tag{3}$$

CN values range from 30 to 98 and are tabulated by SCS (1971, 1986). *CN* is a function of hydrologic soil group, cover type, treatment, hydrologic conditions and impervious area in the watershed (*Feldman*, 2000). SCS method is simple and stable and it is widely used all over the world (*Feldman*, 2000). Parameters used in our study are presented in Tab. 3 and resulted hyetograph in Fig. 2.

Table 3. Estimated parameters of the SCS curve number loss model.
Tabuľka 3. Parametre určené pre SCS model.

Subbasin	149121	149122	149123
I_a [mm]	1.2	2.4	2.4
CN	88	89	89

Green and Ampt loss model

In 1911, Green and Ampt developed an analytical infiltration loss model (Eq. (4)) in which the wetting front moves vertically downwards from saturated soil to unsaturated soil. Their solution was based on one-dimensional vertical flow and was developed directly from Darcy's law (*Delleur*, 1999). The model computes the infiltration f in a time interval as

$$f = K\left[\frac{1+(\Phi-\Theta_i)\cdot S_f}{F_t}\right], \tag{4}$$

where K is saturated hydraulic conductivity, $(\Phi – Q_i)$ – volume moisture deficit, S_f – wetting front suction and F_t – cumulative loss at time t. The infiltration rate f decreases as t increases.

The Green and Ampt infiltration model in HEC-HMS is a conceptual model. It includes also an initial abstraction which represents surface ponding not otherwise included in the model (*Feldman*, 2000). Estimated input parameters used in HEC-HMS model are showed in Tab. 4 and results in Fig. 2.

Smith-Parlange model

The Smith-Parlange model is based on Richard's equation for infiltration. The potential infiltration rate f by *Smith*, *Parlange* (1978) is calculated as:

$$f = K_s \frac{\exp(f_{cum}/B)}{\exp(f_{cum}/B)-1}, \tag{5}$$

where K_s is effective saturated hydraulic conductivity in a time step, f_{cum} – cumulative infiltration since the start of rain and B is saturation deficit parameter combining the effective net capillary drive and the saturation deficit of the soil. Input parameters used in HEC-HMS model of Glinscica watershed are presented in Tab. 5 and results in Fig. 2.

Table 4. Estimated HEC-HMS input parameters of the Green and Ampt infiltration model.
Tabuľka 4. Vstupné parametre HEC-HMS pre Greenov a Amptov infiltračný model; 1 – časť povodia, 2 – počiatočný odtok, 3 – deficit obsahu vody, 4 – vodný potenciál na čele omáčania, 5 – hydraulická vodivosť.

Subbasin$^{1)}$	149121	149122	149123
Initial loss$^{2)}$ [mm]	14.10	10.17	5.62
Volume moisture deficit$^{3)}$	0	0	0
Wetting front suction$^{4)}$ [mm]	714	636	714
Hydraulic conductivity$^{5)}$ [mm h^{-1}]	0.6	1.2	0.6

Table 5. Estimated HEC-HMS input parameters of the Smith-Parlange infiltration model.
Tabuľka 5. Vstupné parametre HEC-HMS pre infiltračný model Smith-Parlange; 1 – časť povodia, 2 – počiatočná vlhkosť, 3 – reziduálna vlhkosť, 4 – vlhkosť nasýtenia vodou, 5 – tlak vzduchu potrebný pre jeho vstup do pórov, 6 – rozdelenie pórov, 7 – hydraulická vodivosť.

Subbasin$^{1)}$	149121	149122	149123
Initial content$^{2)}$	0.415	0.415	0.415
Residual content$^{3)}$	0.09	0.109	0.09
Saturated content$^{4)}$	0.475	0.43	0.475
Bubbling pressure$^{5)}$ [mm]	856	794,8	856
Pore distribution$^{6)}$	0.165	0.223	0.165
Hydraulic conductivity$^{7)}$ [mm h^{-1}]	0.6	1.2	0.6

3.3 Synthetic hyetographs

Synthetic hyetographs are often used in hydrological modeling to estimate the design discharge (maximum peak discharge) for a given rainfall recurrence interval. They are also used when the precipitation data are not available or the records are too short. Synthetic hyetographs are rainfall temporal patterns associated with a return period and often developed using intensity-duration-frequency (IDF) curves for rainfall events lasting from 30 minutes up to 24 hours. The Soil Conservation Service (SCS) 24-h hypothetical storm is example of synthetic design storm (*DeVries*, 1982). In synthetic hyetographs the maximum is usually placed in the middle of rainfall event regardless of rainfall duration. However, *El-Jabi*, *Sarraf* (1991) have proven for Moncton in Canada that the maximum rainfall intensity position should be considered in relation to the duration of the rainfall.

In the study, synthetic hyetographs of different probability and duration were used. Different positions of the maximum rainfall intensity were evaluated and also the constant intensity distribution of rainfall of different durations was applied and compared with typical rainfall distribution with the position of the maximum intensity at 50 %.

4. Results and discussion

4.1 The influence of loss model

In the study six different models of rainfall loss (Infiltration index model, Horton model, Initial and uniform method, SCS method, Green Ampt method and Smith-Parlange method) were compared (*Dirnbek*, 2009). Results are presented in Tab. 6, 7 and Fig. 3.

It was found that the SCS curve number loss model underestimates peak discharge by 7.6 %, but gives the best runoff volume and time-to-peak estimation (Tab. 6 and 7). In general, the SCS curve number loss method gave the best results with the lowest *RMSE* (0.27 m^3 s^{-1}).

All six loss methods gave applicable and comparable results with root mean squared error (*RMSE*) between 0.27 and 0.77 m^3 s^{-1} (Tab. 7). Comparisons carried out using available data show no essential deviations between methods. Similar finding was reported also by *Garklav*, *Oberg* (1986) comparing inital and uniform method with exponential loss method.

The initial and uniform loss model or SCS model are well established and used widely and successfully in Slovenian practice and abroad. The reason is simplicity of use. Both models used only one or two parameters.

T a b l e 6. Results of different loss models for each subbasin.
T a b u ľ k a 6. Výsledky výpočtu rozdielnymi modelmi odtoku pre jednotlivé subpovodia; 1 – subpovodie, 2 – strata zo zrážky, 3 – efektívna zrážka, 4 – max. prietok, 5 – odtečený objem.

	Subbasin[1)]	Precipitation loss[2)] [mm]	Efective precipitation[3)] [mm]	Peak discharge[4)] [m^3 s^{-1}]	Runoff volume[5)] [m^3]
F-index model	149121	16.82	33.58	4.3	241800
	149122	16.82	33.58	3.6	201100
	149123	16.82	33.58	2.2	122900
Horton's model	149121	14.88	35.52	4.2	255800
	149122	22.70	27.70	3.5	165900
	149123	14.88	35.53	2.1	130000
Initial and constant-rate loss model	149121	19.98	30.42	4.1	219100
	149122	19.78	30.62	3.3	183400
	149123	12.37	38.03	2.4	139200
SCS model	149121	18.81	31.59	3.7	227300
	149122	16.59	33.81	3.3	202400
	149123	16.59	33.81	2	123700
Green and Ampt model	149121	19.56	30.84	4.1	222000
	149122	19.13	31.27	3.3	187300
	149123	11.91	38.49	2.4	140900
Smith-Parlange model	149121	20.18	30.22	4	217600
	149122	14.98	35.51	3.7	212700
	149123	17.97	32.49	2.1	118900

Table 7. Comparison of the modeling results using different loss models with measured hydrograph at the outflow of the basin.
Tabuľka 7. Porovnanie výsledkov modelovania s použitím rôznych modelov odtoku s meranými hydrografmi v konečnom profile povodia; 1 – max. prietok, 2 – rozdiel, 3 – odtečený objem, 4 – čas dosiahnutia maxima.

	Peak discharge[1)] [$m^3 s^{-1}$]	Difference[2)] [%]	Runoff volume[3)] [m^3]	Difference [%]	Time of peak[4)]	Difference [%]	RMSE [$m^3 s^{-1}$]
F-index model	10.1	3.7	566000	1.9	18:20	–1:50	0.77
Horton's model	9.76	0.2	551800	–0.6	19:00	–1:10	0.58
Initial and constant-rate loss model	9.6	–1.4	541600	–2.5	18:40	–1:30	0.47
SCS model	9.0	–7.6	553400	–0.3	20:00	–0:10	0.27
Green and Ampt model	9.8	0.6	550200	–0.9	18:40	–1:30	0.49
Smith-Parlange model	9.7	–0.4	549200	–1.1	18:40	–1:30	0.52
Measured hydrograph	9.74	0	555290	0	20:10	0	0

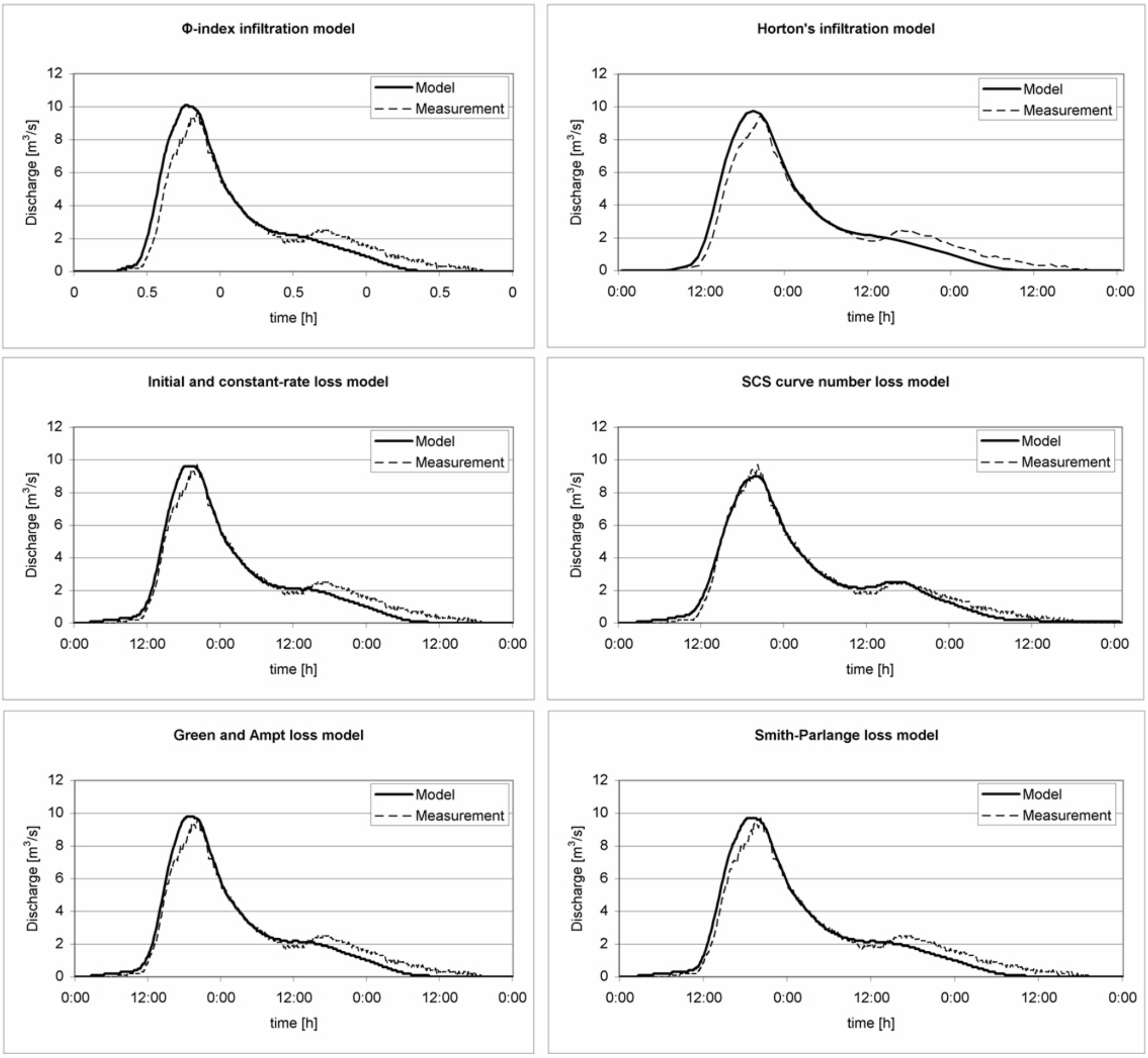


Fig. 3. Comparison of modeled hydrographs using different loss models with measured one.
Obr. 3. Porovnanie modelovaných hydrografov vypočítaných rozdielnymi modelmi s meraným hydrografom.

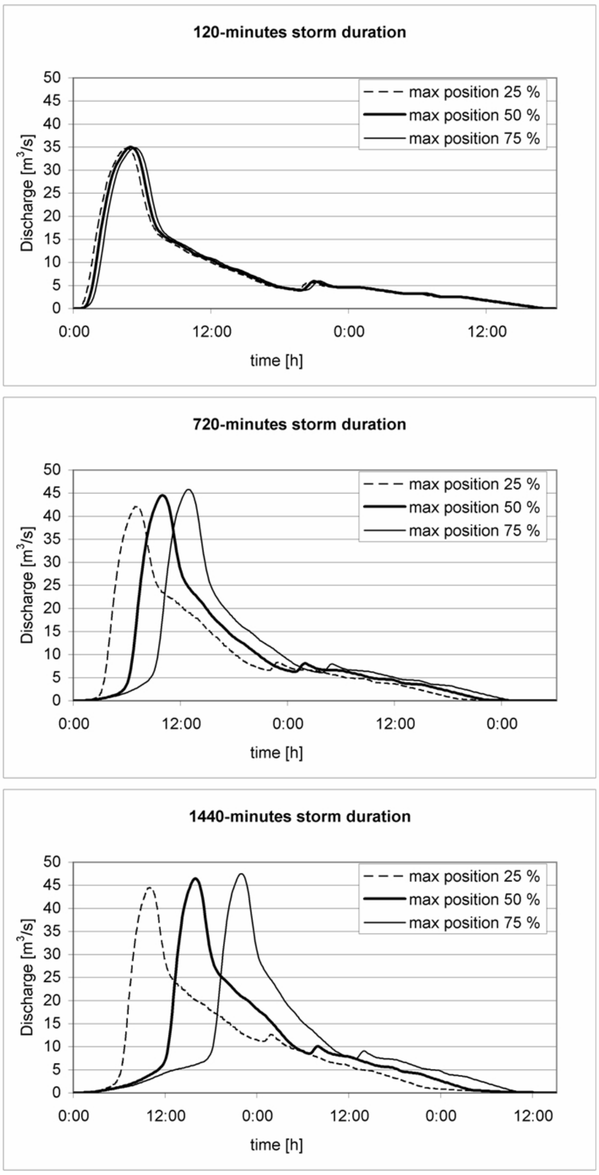


Fig. 4. Comparison of modeled results using different maximum rainfall intensity position and duration of synthetic hyetograph with the return period of 100 years.
Obr. 4. Porovnanie výsledkov modelovania s použitím rozdielnych rozdelení intenzít zrážok a ich trvania syntetického hyetografu s opakovaním raz za 100 rokov.

4.2 The influence of maximum rainfall position of synthetic hyetograph

Three positions of the maximum rainfall intensity at 25, 50 and 75 % of the rainfall duration were applied in the study. The rainfall durations were chosen in such a way that they were equal to, less than and more than the time of concetration of the watershed (the time needed for water to flow from the most remote point in a watershed to the watershed outlet). Initial and uniform loss method was applied and the same unit hydrograph as in previous cases.

The essential differences in time to peak of resulted hydrographs and also differences in peak discharge were established. The results demonstrate that the differences in time to peak increase considerably with the increasing of the rainfall duration (Fig. 4 and Tab. 8).

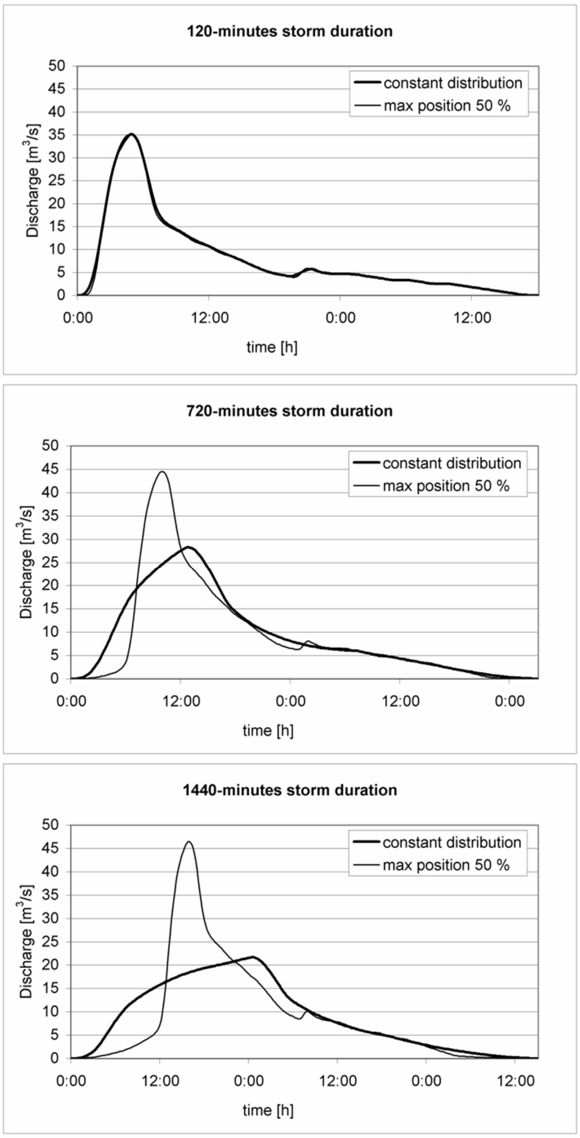


Fig. 5. Modeled results using constant rainfall distribution and typical rainfall distribution with maximum rainfall intensity position at 50 % of the synthetic hyetograph with different durations and the return period of 100 years.
Obr. 5. Výsledky modelovania s použitím konštantného rozdelenia intenzity zrážok a s ich typickým rozdelením s polohou maximálnej intenzity na 50 % trvania syntetického hyetografu s rozdielnym trvaním a s opakovaním raz za 100 rokov.

Danil et al. (2005) have reported that the same discharge value can be derived from different combinations of storm duration and return period. They affirmed that the position of maximum rainfall intensity can be essential. Also, *El-Jabi*, *Sarraf* (1991) have established necessary to consider variable position of the maximum rainfall intensity position in relation to the duration of the rainfall.

4.3 The influence of rainfall pattern of synthetic hyetograph

Finally, the constant intensity of rainfall of different durations was applied. The results were compared with those obtained with typical rainfall distribution with the position of the maximum intensity at 50 %. There was no significant influence on runoff hydrograph by short rainfall durations, but extending of the rainfall duration caused the increasing of the difference in peak discharge and time to peak (Fig. 5 and Tab. 9). Furthermore, time to peak is shorter by temporaly variable pattern. Peak discharge of resulted hydrograph by 24-h constant rainfall intensity distribution was more than 100 % lower than the one calculated with typical rainfall distribution.

We can conclude that temporal variability of rainfall produces greater peak discharge than does constant rainfal distribution. The same finding was established also by other authors (*Ball*, 1994; *Singh*, 1997; *Maca*, 2003).

Table 8. Modeled results using different maximum rainfall position and duration of the synthetic hyetograph with the return period of 100 years.
Tabuľka 8. Výsledky modelovania s rozdielnymi polohami maximálnej intenzity zrážky počas jej trvania a času trvania syntetického hyetografu s časom opakovania 100 rokov; 1 – poloha maximálnej intenzity zrážky, 2 – trvanie, 3 – max. prietok, 4 – odtečený objem, 5 – čas dosiahnutia maxima.

	Maximum rainfall intensity position[1)]		
	25 %	50 %	75 %
120-min duration[2)]			
Peak discharge[3)] [$m^3 s^{-1}$]	34.7	35.0	34.9
Runoff volume[4)] [m^3]	1167700	1180200	1181700
Time of peak[5)]	4:30	5:00	5:20
720-min duration			
Peak discharge [$m^3 s^{-1}$]	42.1	44.5	45.8
Runoff volume [m^3]	1678700	1697300	1702500
Time of peak	7:00	9:50	12:50
1440-min duration			
Peak discharge [$m^3 s^{-1}$]	44.5	46.5	47.5
Runoff volume [m^3]	2027600	2041700	2046900
Time of peak	9:50	15:50	21:50

Table 9. Comparison of the modeling results using constant rainfall distribution and typical rainfall distribution with maximum rainfall intensity position at 50 % of the synthetic hyetograph with different durations and the return period of 100 years.
Tabuľka 9. Porovnanie výsledkov modelovania pre konštantné rozdelenie intenzity zrážky a typického rozdelenia s maximom intenzity zrážky pri 50 % trvania syntetického hyetografu s opakovaním raz za 100 rokov; 1 – trvanie zrážky s opakovaním raz za 100 rokov, 2 – rozdelenie zrážky, 3 – maximálny prietok, 4 – odtečené množstvo, 5 – čas dosiahnutia maxima.

	Storm duration of 100-year return period[1)] [min]					
	120		720		1440	
Rainfall distribution[2)]	constant	50 %	constant	50 %	constant	50 %
Peak discharge[3)] [$m^3 s^{-1}$]	35.2	35.0	28.3	44.5	21.7	46.5
Runoff volume[4)] [m^3]	1209500	1180200	1689500	1697300	2025800	2041700
Time of peak[5)]	4:50	5:00	12:50	9:50	24:30	15:50

5. Conclusions

The overall aim of the study was to evaluate the effect of effective rainfall on modeled hydrograph. We could expose three essential conlusions. (1) In our study all used loss models gave applicable and comparable results. The differences in peak discharge, time-to-peak and runoff volume have not varied in a great range. (2) On the other hand, it was found that the maximum rainfall position of the synthetic hyetograph has essential influence on runoff hydrograph, especially on time-to-peak. With the increasing of the rainfall duration the differences in time-to-peak increse considerable. (3) Rainfall pattern distribution has a great impact on runoff hydrograph. Constant rainfall intensity distribution produces essentially lower peaks than typical temporal rainfall distribution, especially by longer rainfall durations.

We can conclude that the pattern of precipitation excess can have a significant influence on the runoff hydrograph. Results of the model clearly refer to the importance of the excess hyetograph on runoff prediction. The influence is evident in peak discharge, time-to-peak and volume of the runoff hydrograph.

List of symbols

B – saturation deficit parameter [mm],
CN – curve number [–],
F_t – cumulative loss at time t [mm],
f – infiltration rate [mm h^{-1}],
f_c – constant capacity [mm h^{-1}],
f_{cum} – cumulative infiltration since the start of the rain [mm],
f_0 – initial infiltration capacity [mm h^{-1}],
I_a – initial abstraction [mm],
K – saturated hydraulic conductivity [mm h^{-1}],
K_s – effective saturated hydraulic conductivity in a time step [mm h^{-1}],
k – constant representing the rate of decrese in capacity [h^{-1}],
P – accumulated rainfall depth [mm],
S – potential maximum retention [mm],
S_f – wetting front suction [mm],
t – time [h],
$(\Phi – Q_i)$ – volume moisture deficit [–].

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VPLYV EFEKTÍVNYCH ZRÁŽOK NA MODELOVANÝ HYDROGRAF ODTOKU

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Presné simulovanie zrážkoodtokového procesu je ťažké. Koncepcia použitých modelov využíva tzv. efektívne zrážky; hyetograf zrážok je rozdelený na stratovú zložku a efektívnu zrážku. Efektívna zrážka je použitá ako vstup do modelu na výpočet hydrografu odtoku. Presné určenie efektívnej zrážky je pre zrážkoodtokové modely podstatné (*El-Jabi*, *Sarraf* 1991; *Ball*, 1994; *Faures* et al., 1995).

Cieľom štúdie je výpočet vplyvu efektívnych zrážok na modelovaný hydrograf odtoku. Pre tieto účely bol vytvorený model experimentálneho povodia Glinscica s využitím nástroja U.S. Army Corps of Engineers hydrograph package HEC-HMS 3.2, ktorý bol kalibrovaný a verifikovaný v tomto povodí.

Povodie Glinscica je jedno z troch experimentálnych povodí v Slovinsku (*Rusjan* et al., 2008; *Šraj* et al., 2008a; b). Je lokalizované v centrálnej časti Slovinska a zasahuje do východnej časti areálu hlavného mesta Ljubljana. Jeho plocha je 16,85 km^2. Tok Glinscica pramení pod svahmi pohoria Polhograjsko hribovje v madmorskej výške 590 m a tečie na plošinu Ljubljana. Vteká do toku Gradascica v nadmorskej výške 209 m v južnej časti povodia. Horná časť povodia je hornatá, južná rovinatá. Hlavným prítokom Glinscice je tok Przanec. Povodie sa delí na tri subpovodia (*Šraj*, 2001). Povodie Glinscica je vybavené zrážkomerom (Onset RG2-M), vodomerná stanica ultrasonickým Dopplerovým prístrojom (Starflow Unidata 6526 model) a multisondou na meranie kvalitatívnych charakteristík. Údaje o využívaní krajiny boli získané z databázy CORINE (*Heymann*, 1993). Väčšia časť povodia je zalesnená (48,6 %), poľnohospodárska pôda zaberá 22,9 % (*Brilly* et al., 2006). Urbanizovaná plocha zaberá 19,6 % povodia Glinscica. Pôdy sú typu C a D (SCS klasifikácia) (*Feldman*, 2000) s prevažne nízkou intenzitou infiltrácie.

Simulovaný hydrograf bol vypočítaný pomocou jednotkového hydrografu, odvodeného z meraných hodnôt. Model bol kalibrovaný na vybraných nameraných odtokových hydrogramoch, boli použité merania z novembra 2003. Vybrané zrážkové udalosti trvali 40 hodín s maximálnou intenzitou 6 mm h^{-1}. Zrážkový úhrn bol 50,4 mm. Táto zrážka spôsobila odtok, jeho nameraná hodnota bola 9,4 m^3 s^{-1}. Model bol úspešne verifikovaný na meranom hydrografe v januári 2004. Na tento kalibrovaný model bolo aplikovaných šesť rozdielnych modelov efektívnych zrážok. Tie modely, ktoré nie sú zahrnuté v balíku HEC-HMS (Hortonov model a Φ-index model), boli počítané manuálne. Porovnali sme čas maximálneho prietoku, maximálny prietok a odtečený objem. Z porovnania nevyplynuli podstatné rozdiely medzi modelmi. Všetkých šesť metód určenia efektívnych zrážok dalo porovnateľné výsledky s (*RMSE*) medzi 0,27 a 0,77 m^3 s^{-1}. Najlepšie výsledky s najmenším RMSE v danom prípade poskytla metóda SCS.

Syntetické hyetografy sa v modelovaní hydrologických javov často používajú na určenie návrhového prietoku (maximálnych prietokov) pre zrážku s daným časom opakovania. Používajú sa syntetické hyetografy rôznych pravdepodobností a trvania.

Trvanie zrážky bolo vybrané tak, aby bolo kratšie alebo rovnaké ako čas koncentrácie v povodí (je to čas potrebný pre prítok vody z navzdialenejšieho miesta povodia do miesta výtoku z povodia). V tejto štúdii boli použité tri polohy maximálnej intenzity zrážky pri 25, 50 a 75 % rozdielnych trvaní zrážky. Z výsledkov vyplývajú značné rozdiely vo vrcholoch výsledných hydrografov a tiež rozdiely v maximálnych prietokoch. Rozdiely v časoch dosiahnutia maxím sa významne zvyšujú so zvyšujúcim sa trvaním zrážky.

Napokon boli použité konštantné intenzity zrážok s rôznym trvaním. Výsledky modelovania boli porovnané s tými, ktoré boli získané s typickým rozdelením zrážok, keď bola poloha maxima pri 50 % času trvania zrážok. Pri krátkych časoch trvania zrážok neboli zistené významné rozdiely v hydrografoch, ale zvyšujúc trvanie zrážok zvyšovali sa rozdiely medzi maximálnymi prietokmi a časmi po ich dosiahnutie. Napríklad, maximálny prietok vyvolaný 24 h zrážkou s konštantnou intenzitou bol podhodnotený o viac ako 100 %. Záverom môžeme konštatovať, že časová variabilita zrážkok spôsobuje vyšší maximálny prietok ako zrážka s konštantnou intenzitou. Také isté výsledky uvádzajú aj iní autori (*Ball*, 1994; *Singh*, 1997; *Maca*, 2003).

Cieľom tejto práce je vyhodnotiť vplyv priebehu zrážok na modelovaný hydrograf. Výsledky možno vyjadriť tromi základnými závermi: (1) Všetky modely, použité v našej štúdii viedli k aplikovateľným a porovnateľným výsledkom. Rozdiely v maximálnych prietokoch, v časoch po ich dosiahnutie sa významne nemenili. (2) Na druhej strane bolo zistené, že poloha maximálnej intenzity zrážok na syntetických hyetografoch má zásadný vplyv na hydrografy odtoku, hlavne na čas dosiahnutia maximálneho odtoku. Tieto časy sa významnen zvyšujú so zvyšujúcim sa trvaním zrážok. (3) Rozdelenie intenzity zrážok má významný dopad na hydrograf odtoku. Zrážky s konštantnou intenzitou v zásade spôsobujú nižšie maximálne prietoky ako typické rozdelenie intenzít zrážok, hlavne pre dlhotrvajúce zrážky.

Môžeme zhrnúť: neštandardné rozdelenia intenzity zrážok môžu zásadným spôsobom ovplyvniť hydrograf odtoku. Výsledky modelovania poukazujú na vplyv neštandardného priebehu intenzity zrážok na predpoveď odtoku. Tento vplyv je evidentný v maximálnom odtoku, v čase po jeho dosiahnutie a na objeme hydrografu odtoku.

Zoznam symbolov

B – parameter nedostatku nasýtenia [mm],
CN – číslo krivky [–],
F_t – kumulatívna strata v čase t [mm],
f – infiltračná rýchlosť [mm h^{-1}],
f_c – stála kapacita [mm h^{-1}],
f_{cum} – kumulatívna infiltrácia od začiatku zrážky [mm],
f_0 – počiatočná rýchlosť infiltrácie [mm h^{-1}],
I_a – počiatočný odtok [mm],
K – nasýtená hydraulická vodivosť [mm h^{-1}],
K_s – efektívna nasýtená hydraulická vodivosť v danom časovom kroku [mm h^{-1}],
k – konštanta, vyjadrujúca rýchlosť znižovania infiltrácie [h^{-1}],
P – akumulovaná vrstva zrážky [mm],
S – potenciálna maximálna retencia [mm],
S_f – vodný potenciál na čele omáčania [mm],
t – čas [h],
$(\Phi – Q_i)$ – vlhkostný deficit v jednotkách objemu [–].