AKADÉMIAI KIADÓ

Rainfall duration and parameter sensitivity on flash-flood at a steep watershed

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ABSTRACT

The common feature of streams in steep sloping watersheds is that there is a significant change from base-flow to flash-flood; sometimes two or three orders of magnitude. In Hungary, these streams are usually ungauged, with lack of available data, and models. The watershed features both urban and natural land use conditions, but the main area is quite homogenic.

This paper evaluates the impact of different model parameterizations, and rainfall duration on flash-flood events in the Morgó-creek watershed. The goal is to find the main parameters that can represent the uncertainty of a flash-flood sensitive area, and how the calibrated and determined parameters take effect on a model if these values are shifted on given intervals.

KEYWORDS

numerical modeling, watershed hydrology, parameter sensitivity, flash-flood, sensitivity study

1. INTRODUCTION

Flash-flood events are a considerable natural hazard that will intensify in the future due to climate change and expansion of the built environment. In the last 10–15 years, these rainfall events have become more frequent throughout Hungary, with higher peak intensities [1]. This trend in rainfall patterns would induce flash-flood events in certain areas of Hungary. They are most likely to occur in watersheds with relatively steep slopes, low infiltration capacity, and high levels of antecedent soil moisture. To forecast a flash-flood, hydrologists may use different numerical models, and then compare their predictions to field performance data. Unfortunately, the watersheds within Hungary that are prone to flash-flooding are generally un-gauged [2, 3].

Hydrologic models that predict stream flow out of a watershed may consist of a set of parameters that are either lumped or spatially distributed over the watershed or rely heavily on previous performance data from similar watersheds. Lumped models require less data input and computational effort; however, they require more modification or fine tuning to improve their predictive capability [4]. Distributed models require more data at high temporal and spatial resolution. The initial data gathering effort results in more accurate predictions with some analyses capable of making predictions in real-time [4]. The choice of model may also depend on ease of use, available data, and past experiences. This study used semi-distributed and lumped models, where uncertainties are reduced through sensitivity studies and comparisons to other models.

Flash-floods often have a serious environmental impact on the watershed and models do exist to evaluate the damage [5], peak flow was chosen as the predictive indicator.

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2. AVAILABLE DATA AND THE WATERSHED DESCRIPTION

The Morgó Creek watershed is in northern Hungary about 60 km directly north of Budapest. The creek flows directly into the left bank of the Danube River at about rkm 1,689, near the

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town of Kismaros, Fig. 1. The watershed area is 52.63 km^2. Land use is mostly woodlands (~70%) with agriculture use in the southern region (~25%), and 4–5% urban area near the outlet, the soil is volcanic, Fig. 2. The watershed has a high average slope with upper regions 4.6–9.1%; conducive for flash-floods. Urban areas along lower regions average 0.5–1%. The only existing data came from a previous study where outlet flow from a 50-year return period (2% frequency) rainfall was $Q_{2\%}$ = 53.3 cm. Since then, no further high-water data was measured or calculated on the creek [6].

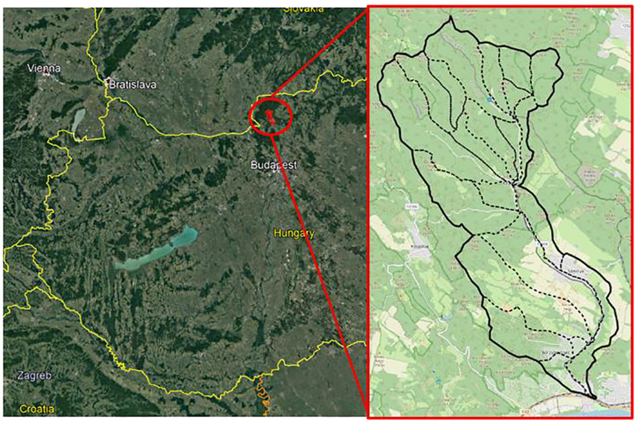

Fig. 1. Watershed location at the northern-Hungarian region

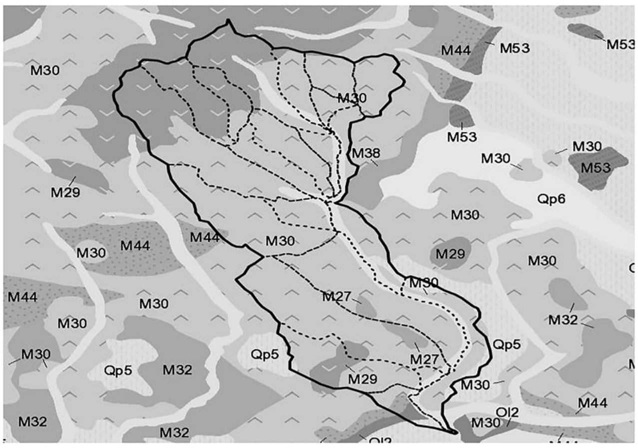

Fig. 2. Hungarian surface parent rock map, M30: dacite-pyroclastite; subvolcanic dacite, andesite, M29: andesite, -pyroclastics, M27: shallow-marine foraminiferal, mollusc-bearing clay marl (*Source*: https://map.mbfsz.gov.hu)

3. MODEL DEVELOPMENT

The HEC-HMS modeling software [7, 8], analyzed the system of 21 sub-watersheds with similar terrain usage, soil, and slope parameters [6]. The event-based runoff process starts with precipitation, then reaches ground surface. At the ground surface, if infiltration and surface storage capacities are exceeded, runoff is generated. The runoff of the event-based model structure is shown in Fig. 3.

The surface storage module was left out because the number of uncertain parameters. The module defines an amount of stored water on the surface, and is recommended for only continuous simulations [7]. Base-flow was left out because the watershed initially is dry.

The Green and Ampt method [9–11] was selected to calculate infiltration. The method is a combination of mass conservation and the unsaturated form of Darcy's law,

$$f_t = K\left(1 + \frac{(\varphi - \theta_i)S_f}{F_t}\right), \tag{1}$$

where f_t is the loss during time interval t; K is the saturated hydraulic conductivity; φ is the soil porosity; θ_i is the volumetric moisture content at time interval; φ-θ_i is the moisture deficit; S_f is the wetting front suction; and F_t is the cumulative loss at time t. Relation between K and S_f is showed in Fig. 4.

The Green and Ampt model also includes an initial removal that represents interception in the canopy or surface depressions not otherwise included in the model [7]. This interception is separate from the time to ponding that is an integral part of the model. The Green and Ampt method uses an initial loss parameter, and it is defined as the moisture deficit of the soil. For the sensitivity analyses, 75% saturation was assumed, moisture deficit was 25% given as volumetric ratio. Based on land use conditions, 10% impervious area was assumed.

The Clark-Unit hydrograph model was used to determine surface runoff [12, 13]:

$$\frac{A_t}{A} = f(x) = \begin{cases} 1.414\left(\dfrac{t}{t_c}\right)^{1.5}, t \le \dfrac{t_c}{2}, \\ 1 - 1.414\left(1 - \dfrac{t}{t_c}\right)^{1.5}, x \ge 0, \end{cases} \tag{2}$$

where A_t is the cumulative watershed area contributing at time; A is the total watershed area and t_c is the time of

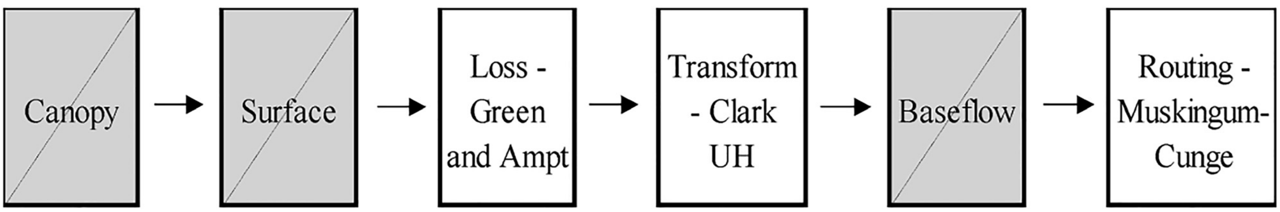

Fig. 3. HEC-HMS modules for the flash-flood model

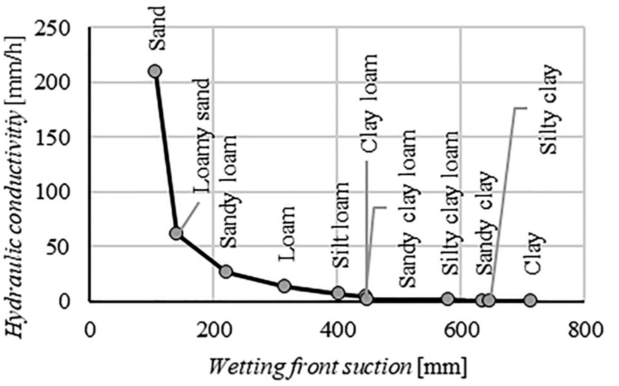

Fig. 4. Relation between wetting front suction and hydraulic conductivity in HEC-HMS [7]

concentration. Concentration was determined using the equations suggested by the HEC-HMS manual [7]:

$$t_c = 1.54 \cdot L^{0.875} \cdot S^{-0.181}; \; R = 16.4 \cdot L^{0.342} \cdot S^{-0.79}, \quad (3)$$

where t_c is the time of concentration; R is the storage coefficient; L is the longest route on the watershed; S is the average slope.

4. MODEL PARAMETERS, AND PARAMETER CALIBRATION

Some initial analyses were run to ensure the model was performing within acceptable limits. Since the only field verification was an estimate of peak flow from a rainfall event with 2% frequency of occurrence, it was adopted for a calibration analysis. The intensity/duration corresponded to a 2% event with uniform intensity and 1 h duration. Further input for the calibration check came from topographic and soil maps, as well as ortho-photos to estimate slope, infiltration, and roughness factor. The soil parameters were estimated via soil texture information and HEC-HMS Technical Reference Manual Tables 5–2 in [7]. It was assumed that the volcanic soil in Fig. 2 corresponds to sandy loam soil characteristics. The results of the calibration analysis are shown in Fig. 5 together with the field estimate of peak flow [6].

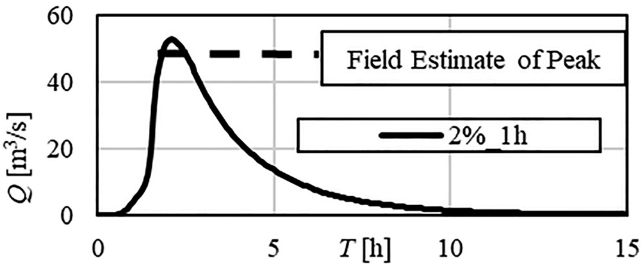

Fig. 5. Flow vs. time from calibration analysis compared to field estimate

5. SENSITIVITY ANALYSES

5.1. Rainfall duration

To better quantify the impact of uncertainty from input parameters, a sensitivity analysis of the watershed was conducted. A model rainfall was set to reflect a 1% frequency of occurrence and event durations from 1 to 12 h. Storm duration and time of concentration has a high impact on the magnitude of the flood peak, usually the highest floods occur due to storm duration, that are closest to the time of concentration. For the sensitivity analyses storm duration were selected that are close the calibrated around 2 h time of concentration of each sub-watershed. 1% frequency event was chosen to better represent possible impacts of climate change and comply with Hungarian design standards [14, 15]. The intensity vs. time function was defined with a triangular distribution. The resulting intensity function increased linearly to a peak that is double the uniform intensity value. The peak was set to 0.375 times the event duration [16]. A summary of rainfall parameters is included in Table 1.

For comparison, the six different 1% frequency events are shown with cumulative rainfall vs. time in Fig. 6. While the 1 h event shows the highest intensity, longer events generate more cumulative rainfall and may generate higher outflows from the watershed.

Table 1. Scenario for calibration and modeling, where i is the uniform rainfall event intensity; Peak is the triangular peak rainfall intensity; T_p is the elapsed time to peak intensity; h is the total cumulative rainfall; S_f is the wetting suction front rom Fig. 4 and *Imp* is the impervious area

Event	i [mm h^{-1}]	*Peak* [mm h^{-1}]	T_p [min]	h [mm]	S_f [cm]	*Imp* [%]
2%, 1h	51.48	102.96	22.5	51.48	19	10
1%, 1h	60.48	120.96	22.5	60.48	19	10
1%, 2h	35.72	71.44	45.0	71.44	19	10
1%, 4h	21.09	42.18	90.0	84.36	19	10
1%, 6h	15.50	31.00	135.0	93.00	19	10
1%, 8h	12.46	24.92	180.0	99.68	19	10
1%, 12h	9.15	18.30	270.0	109.80	19	10

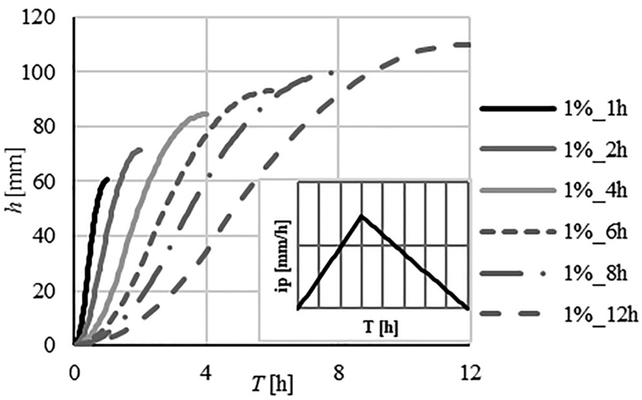

Fig. 6. Cumulative rainfall vs. time 1% frequency event triangular intensity 1–12 h duration

For the sensitivity studies two types of result values was chosen to compare scenarios: 1) peak outflow, 2) runoff ratio: runoff flow volume/rainfall event volume. To serve as a baseline for comparison, calibrated watershed parameters were set to the values shown in the second column of Table 2. The six different rainfall events were applied to the baseline configuration, generating outflow vs. time plots as shown in Fig. 7.

The figure clearly shows the effects of the very high peak rainfall intensity for the 1 h event. Listed in Table 2 is a summary of further results from the baseline scenario and the six chosen rainfall events.

Table 2 shows the dominant influence of rainfall duration on flow values for this watershed. Peak flow, runoff volume, and ratio are more than double for the 1 h rainfall compared to longer durations. The lowest outflow volume was produced by the 4 h event, and then slowly increased for longer duration rainfalls. The watershed is mostly covered with woodland areas which, according to Hungarian standards, should produce a runoff ratio around 10%. Table 2 shows that all model results are close to 10% value except for the 1 h event it can be suggested that the behavior of the watershed is not only a function of rainfall intensity and duration.

5.2. Watershed characteristics

The first parameter is hydraulic conductivity (*K*). During sensitivity analyses sandy loam, and loamy sand soils were investigated. Once the saturated hydraulic conductivity was determined for the watershed, the wetting front suction was adjusted, based on the relationship determined in Fig. 4. The other one is the parameter which defines the ratio of the watershed area which is impervious. Table 3 shows the intervals of the sensitivity calculations.

The sensitivity analyses compared the Percentage Change in RUNoff ratio (PCRUN) and the Percentage Change of Peak flow (PCQP) where

$$PC = \frac{(Sensitivity\ value - Baseline)}{Baseline} \cdot 100\%. \qquad (4)$$

Table 2. Peak flow, precipitation and outflow volumes, and runoff ratio for baseline watershed and six rainfall events

Rainfall event	Q_{max} (m^3 s^{-1})	Volume Precipitation (1,000 m^3)	Volume Outflow (1,000 m^3)	Ratio Runoff Flow/ Precipitation
1%, 1 h	**93.35**	3160.37	934.27	**29.56%**
1%, 2 h	43.68	3758.76	478.04	12.72%
1%, 4 h	30.91	4439.26	**444.18**	10.01%
1%, 6 h	27.42	4894.50	489.53	10.00%
1%, 8 h	24.54	5461.84	524.48	**9.60%**
1%, 12 h	20.36	5778.66	578.01	10.00%

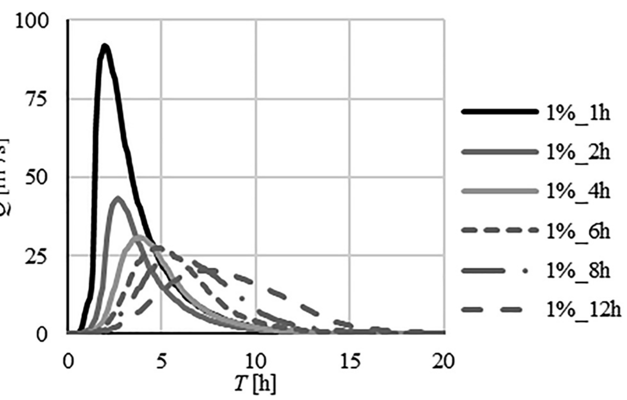

Fig. 7. Outflow vs. time for baseline scenario and six different rainfall events

5.3. Results of sensitivity analysis

In each group, only one parameter was changed, while the other two remained set to the baseline values shown in Table 3 within the group six rainfall events were analyzed as it is summarized in Table 2.

K had a significant influence on both output quantities as shown in Fig. 8. A higher *K* value decreased runoff ratio, while a lower *K* value significantly increased runoff ratio (Fig. 8a). In a similar manner, higher *K* values reduced peak flow for only the shortest duration events while lower *K* values significantly increased peak flow for all events (Fig. 8b).

Changes are not symmetric when comparing higher vs. lower *K* values. This is partially due to the baseline *K* values that drain faster than average soils. Analyzing a higher *K* will not allow for much more infiltration; it is already high and will only affect the short duration/high intensity events (1 h, 2 h duration). However, as *K* is reduced, infiltration rates become significantly less, so even the lower intensity/longer duration events will surpass infiltration rate capacity and produce significantly more runoff. In nature, conductivity values may vary between 0.001 and 100 + mm h^{-1}. Even smaller *K* values possible, but at those values they are essentially impervious from the perspective of runoff prediction during rainfall events. To get a more detailed appreciation for the effect of *K*, runoff ratios and peak flow values are listed in Table 4. The runoff ratio values increase significantly for most of the events as peak flow as well. An additional factor that influences both results is the change in soil suction values that automatically occur when K changes. As *K* is reduced, HEC-HMS interprets this as a change in soil type; therefore, wetting front suction values change. Increasing *K* did not trigger a change in soil type and suction value. This contributed to the asymmetrical results as well.

The effects of impervious areas on runoff ratio and peak flow are shown in Fig. 9. Note that the *x*-axis is percentage *change* of impervious area from a baseline of 10%. This

Table 3. Baseline and varied parameters for sensitivity analysis

Parameter	Value	Change [%]			
Hydraulic conductivity, *K* (mm h^{-1})	35	−75	−50	+50	+75
Impervious area [%]	10	−100	−50	+50	+100

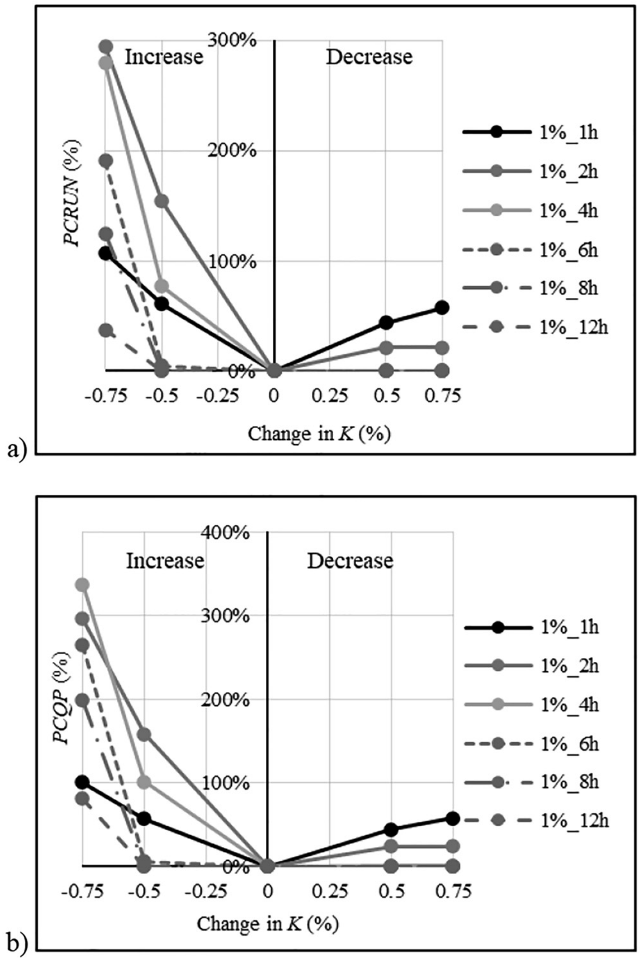

Fig. 8. Effect of hydraulic conductivity, *K*, on a) runoff ratio and b) peak flow

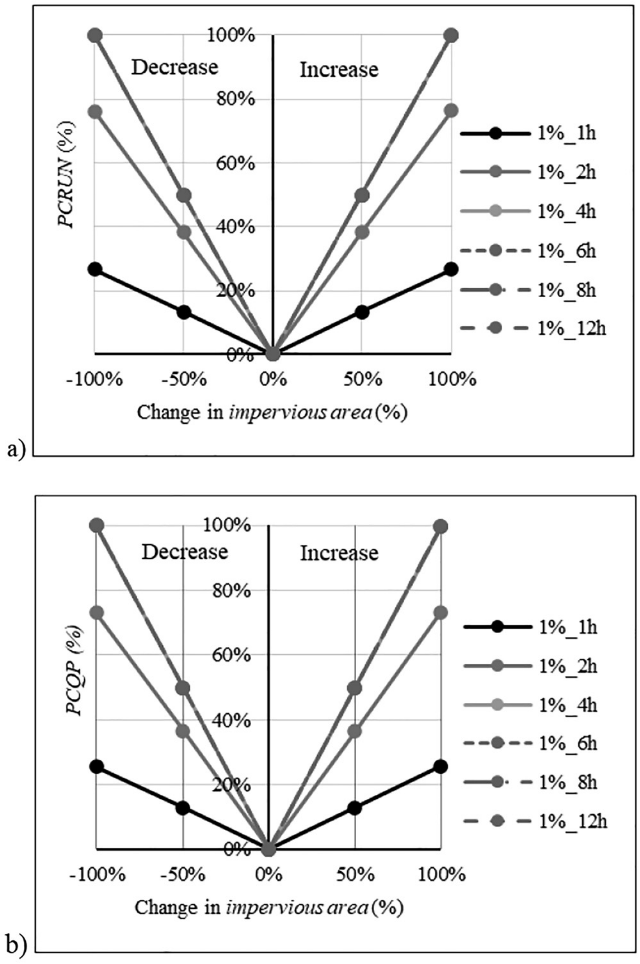

Fig. 9. Effect of changing impervious area on a) runoff ratio and b) peak flow

Table 4. Runoff ratio and peak flow values for reduced conductivity, *K*, for all events

Rainf. event	Runoff Ratio (%)			Q_{max} ($m^3\ s^{-1}$)		
	$K =$ 35 mm h^{-1}	$K =$ 17.5 mm h^{-1}	$K =$ 8.25 mm h^{-1}	$K =$ 35 mm h^{-1}	$K =$ 17.5 mm h^{-1}	$K =$ 8.25 mm h^{-1}
1%, 1 h	29.56	47.6	61.2	93.35	146	187
1%, 2 h	12.72	32.3	50.2	43.68	113	172
1%, 4 h	10.01	17.7	37.9	30.91	63	135
1%, 6 h	10.00	10.5	29.1	27.42	29	100
1%, 8 h	9.60	9.6	21.6	24.54	26	73
1%, 12 h	10.00	10.0	13.7	20.36	20	37

means the full range of percent impervious area shown on the *x*-axis ranges 0%–20%. On both Figs 9a and 9b, the results for 4, 6, 8, and 12 h events give the same results. Changes in runoff ratio and peak flow in absolute values are symmetrical, which means increasing or decreasing the impervious area produces a proportional change in runoff ratio or peak flow. Increasing impervious area increases both results and decreasing area decreases both. Changes to impervious area impacts results from the 1 h duration rainfall event the least (27% difference, for 100% change). For events longer than 2 h duration rainfall, the impact is the same: for a 100% impervious area change PCRUN and PCQP are both 100%. This indicates 4–12 h rainfall events are more sensitive to change in impervious area.

6. SUMMARY

The results of the sensitivity analyses are shown in Table 5.

Runoff ratio, and peak flow became more sensitive to hydraulic conductivity, as the values were lowered. Although in this study the hydraulic conductivity was changed in a

Table 5. Summary of results

Parameter	Results of sensitivity study	
	Runoff ratio	Peak flow
Hydraulic conductivity	Highly sensitive if under-calibrated on grainy soil (asymmetrical)	Highly sensitive if under-calibrated on grainy soil (asymmetrical)
Ratio of impervious area	Symmetrically sensitive	Symmetrically sensitive highly

way that they became different soil types, underestimation of hydraulic conductivity has the risk of resulting much higher peak flow than will occur.

The percentage of impervious area shows a symmetrical, similar percent of change both ways for each sensitivity study. The change is higher at longer duration events for both runoff ratio, and peak flow.

7. CONCLUSION

The result of the sensitivity analyses show that the peak flow of the 1 h event is much greater than the other peak flows on the investigated stream. Possible reasons for this:

1. the effect of infiltration rate is significantly smaller than the rainfall intensity;
2. the higher slopes;
3. size and shape of the watershed. In the interval between 1 and 2 h rainfall duration the infiltration capacity of the soil starts to increase thereby significantly decreasing the peak flow.

For events longer than 2 h, runoff ratio, and runoff volume did not change very much. The runoff ratio significantly decreased after the 1-h event and stabilized around 10%. Also the 1 h rainfall causes higher peak flow than expected.

Change in percentage of impervious area had an inversely proportional effect on the peak flow and runoff ratio. The impervious area during flash-flood events is defined as constant, but it's possible that the area changes during short duration rainfall events since small depressions and ponds on a watershed could temporarily increase the impervious area. Further research connecting hydrologic and hydro-dynamical models can help to determine how this parameter affects the surface flow processes.

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