SENSITIVITY OF THE HEC-HMS RUNOFF MODEL FOR NEAR-SURFACE SOIL MOISTURE CONTENTS ON THE EXAMPLE OF A RAPID-RESPONSE CATCHMENT IN SW HUNGARY

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Abstract. - Sensitivity of the HEC-HMS runoff model for near-surface soil moisture contents on the example of a rapid-response catchment in SW Hungary. Due to the global climate change, flash floods are one of the most significant natural hazards of today. To prevent, or at least mitigate flash flood triggered losses, numeric model based flood forecasting models are ideal tools to predict stream water levels. Model accuracy, nonetheless is profoundly influenced by input data quality. To obtain input data for the HEC-HMS distributed rainfall-runoff model, widely used for runoff forecasting, in present study we have regularly monitored ground precipitation, discharge and soil moisture in the Pósa Valley watershed (1.7 km^2) in SW Hungary and data was extrapolated and upscaled to the broader area of the Bükkösd Watershed (99 km^2). To test model applicability for flow time series reconstruction, the peak flow event of May 15 to 18, 2010 on the Bükkösd Stream was reproduced with the HEC-HMS. Model sensitivity was tested for various antecedent soil moisture values estimated from 2009, 2011 and 2012 *in situ* measured data. The output of the current research could be utilized for increasing the accuracy of rainfall-runoff model based flash flood warning systems for forested rapid response catchments that are representative for low-mountain environments under humid continental climates.

Keywords: Flash flood, soil moisture, runoff, monitoring system, HEC-HMS, model sensitivity

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1. Introduction

In the past few decades, temporal frequency of flash flood events has been increasing. This is likely to be one of the hydrological consequences of the global climate change, and also the more extreme behavior and variability of precipitation events. In one hand, the number of the weather extremities has been increasing; on the other hand, these events are usually concentrated on a small area (catchment) and are strongly influenced by topography (Sharif et al. 2005). Thus, the temporal and spatial distribution of precipitation is a major issue in flash flood forecasting and stormwater management. Prediction and analysis of these types of floods is a complex topic, as excess runoff is concentrated over a short period of time (Gaume et al 2009). Usually, the energy of a flux is also very high, thus both prevention and protection can be extremely important and challenging against floods (Yates et al. 1999). The changing frequency of torrential rainfalls not only alters streamflow characteristics, but may also carries nutrients, silts and hydrocarbons, chlorinated organics and heavy metals from surfaces of buildings directly into watercourses and other water bodies (Bathurst et al. 2012; Czigány et al. 2010).

Undoubtedly, precipitation is a very important condition for triggering flash floods, but other environmental factors, such as relief, land cover, and soil parameters must also be considered as well for runoff calculations (Georgakakos 2006). As the return time of the flood events are decreasing, the losses it causes are also become more relevant. The second reason for increased runoff and increased frequency of urban floods today is that the Earth's natural land cover and land use have been dramatically changed (Le Lay & Saulnier 2007, Fábián et al. 2009). Up to 95% of the ground surface in cities is now sealed due to urban development and this is ground space through which rainwater cannot be lost by permeation. This leads to up to 75% of rainwater becoming run-off in urban areas. To prevent localized flooding built-up areas need to be drained of excess rain water.

The objective of the current research paper is (a) to model a characteristic flood event that occurred in the drainage area of the Bükkösd Stream in the Mecsek Hills, SW Hungary between May 15 and 18, 2010 and (b) to test the sensitivity of HEC-HMS model for antecedent soil moisture values and (c) to test the applicability of the HEC-HMS for runoff forecast in rapid response catchments typical for the low-mountain areas of Central and Eastern Europe. To reproduce the flow time series, we used the 3.5 version of the HEC-HMS (US Army Corps of Engineers, 2009) rainfall-runoff model. Limited antecedent environmental data were available for the reconstruction of the flood event for the trunk river and the tributary streams. Antecedent near-surface (20 cm) soil moisture value was estimated based on soil moisture data measured for the same period in 2009, 2011 and 2012. Through the HEC-HMS numeric rainfall-runoff model we described the impact of soil moisture content (volumetric water content, hereafter VWC) and initial infiltration rate on surface runoff in the upper Bükkösd Stream drainage system (upstream form the village of Bükkösd). The studied watersheds cover a combined land area of 99 km^2.

2. Materials and Methods

Overview of the pilot area

The studied catchment of the Bükkösd Stream is part of the river Drava's drainage system and drains the streams and waters of the Mecsek Hills in SW Hungary (Fig. 1). The headwaters of the Bükkösd Valley are situated upstream from Szentlőrinc (SW Hungary) and cover a total area of 137 km^2 although we only focused on the catchment segment located upstream of the village of Bükkösd. The studied area here covers a land are of 99 km^2 and primarily characterized by high relief.

The Bükkösd Stream has a variable, primarily rainfall-affected flow regime with high flow peaks occurring usually over the period of May to July. The Bükkösd Stream is fed by several tributary streams, namely the Sormás, Kán, Gorica, Sás and Megyefa Streams. Flood events on the Bükkösd Stream and its tributaries inundated the adjacent floodplains at multiple times, indicating a higher frequency of flood related losses in the Mecsek Hills and its immediate vicinity in SW Hungary.

Over the last 50 years, 7 major flash flood events were reported from broader drainage area of the Bükkösd Stream (Vass 1997; Eszéky 1987). Weather patterns in the studied area for this period of the year are typically characterized by torrential, monsoon-like rainfalls, when, since the beginning of regular meteorological measurements, a maximum rainfall intensity of 114 mm/day was observed. Highest discharge of the Bükkösd Stream at Hetvehely, reached 8.8 m^3/s between January 1, 2000 and December 31, 2009 with an increasing temporal frequency of flood-level and bankfull stages in the second half of the period of observation. By comparison, peak flow reached 18 m^3/s during the May 6, 1987 flood event, 25 m^3/s at 4-m stage during the July 10, 1967 event, and 35 m^3/s at 3.7-m stage during the June 27, 1987 event (Eszéky, 1987, 1992; Vass, 1997). About 68.9% of the entire catchment is covered by either forests of intermittent clear cuts, 28.6% is agricultural land, while the remaining 2.3% is under urban development and various artificial (paved) surfaces and about 0.15% is covered by surface water. Villages located in the upper narrow part of the valley have been inundated by flash floods several times since records are available, causing significant economic losses. For instance, during the July 10, 1967 flash flood, 10 and 4 buildings collapsed in Hetvehely and Okorvölgy, respectively. With a few exceptions, reliable inundation data is unavailable for the period prior to 1900. Notable (*i.e.*, when properties were damaged) flash-flood events were reported on July, 1 1954, July 31, 1959, July 10, 1967, May 6, 1987, June 27, 1987 and May 16, 1996.

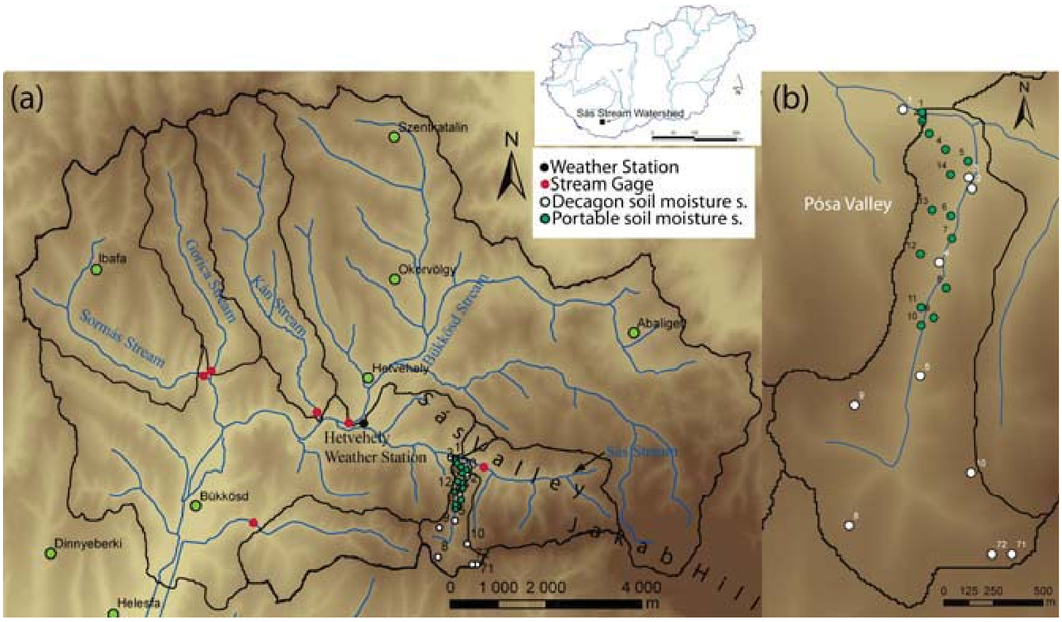

Fig. 1. Location of the monitored area (Pósa Valley)

Hydrologic data

Discharge flow time series were measure at multiple locations on the trunk stream and the tributaries. Gauging stations on the tributary streams are predominantly located at the immediate proximity of the confluences between the trunk and the tributaries (Fig. 1). Figure 4 shows the yearly flow peaks for the period of 2000 to 2010 for the Bükkösd Stream measured at the Hetvehely gauging station. The highest flow in this period was measured in 2005. The second highest flow was measured during the May 15 to 17, 2010 flood event. Peak flows for the 2005 and 2010 flood events have a return period of about 9 years. The studied flood event of May 15 to 18, 2010 was triggered by a long-lasting, but low-intensity rainfall event generated by the Sophia Mediterranean Cyclone between May 15 and 18, 2010. This flood event was ranked 2nd in 2010 with a peak flow value of 8.23 $m^3 s^{-1}$ at the Hetvehely gauging station. Additional details of the studied flood events are shown in Table 1. Highest flow was measured on June 1, when peak flow reached 8.8 $m^3 s^{-1}$ at Hetvehely, due to the substantial presaturation of the soils and the Angela Cyclone that produced approximately 100 mm rainfall over large areas of Hungary.

Rainfall Data

Model input rainfall data were obtained from an automated weather station (coordinates: N46^{o}07’30.67’’, E18^{o}02’51.18’’) located at the western edge of the Sás Valley, a left side tributary of the Bükkösd Stream (Fig. 1). 10-minute meteorological data were obtained from this station. The model simulation runs were based on the May 15-18, 2010 rainfall event, when on average 155 mm of rain fell from the Angela Cyclone (Bartholy-Pongrácz in press, Czigány et al. in press).

Table 1 General characteristics for 15 May, 2010 flood event at the Bükkösd Stream's catchment

Duration of rainfall event	63h 10 min
Beginning time of rainfall event	2010. May 15. 7:55
Maximum rainfall intensity	2010. May 15. 16:05 and 2010. May 16. 1:05, (both 1,6 mm/10 min (9.6 mm/h)
Elapse time between beginning of rainfall event and peak discharge time	8h 10 min to maximum intensity
Ending time of rainfall event	2010. May 17, 22:05
Peak discharge	8.23 m^3 s^{-1}, Bükkösd Stream, Hetvehely
Beginning of base flow rising	2010. May 15. 2010 19:00

Soil Data

Soil textural groups were determined by laboratory analyses for 14 surface soil samples and two borehole samples at depth intervals of 10 cm taken at the central catchment of the Sás Valley (Pósa Valley, see on Fig. 1).

Soil moisture measurements were not taken in the area during the modeled period. For comparison, soil moisture values measured in the Sás Valley during 2009, 2011 and 2012 were available as regular measurement were taken during these time periods, with a portable (in 2009) and point source datalogger equipped automated soil moisture sensors (in 2011 and 2012). Soil moisture values measured in 2009 were taken with a Time Domain Reflectrometry-type (TDR) soil moisture sensor (Spectrum TDR-300, Planfield, Illinois, US) between September 5 and December 5, 2008 and March 6, 2009 and September 5, 2009 in 5 to 15 day time intervals. The sensor was calibrated *a priori* in the Soil physics laboratory of University of Pécs, for the soil physical types found in the Pósa Valley (loam and clayey loam soils). Soil moisture sensors were equipped with 20-cm long stainless-steel electrodes. Measurements were taken at 14 monitoring stations located in the downstream (north) part of the Pósa Valley (Fig. 1). Measurements at each monitoring stations were carried out randomly with 3 to 5 repetitions in a circle of 1.5 meter radius. At each monitoring stations, due to the large spatial heterogeneity of understory vegetation and litter cover, measurements were repeated three times, however at measurement stations 7, 8 and 9 where a large proportion of coarse rocky fragments is present, 5 repetitive measurements were carried out.

The 2011 and 2012 soil moisture values were measured with datalogger (Decagon EM50) equipped TDR-type 5-TM sensors (all components were manufactured by Decagon Devices Inc., Pullman, WA, United States). Sensors were buried at a depth of 20 cm.

HEC-HMS model setup

The HEC-HMS 3.5 model was setup with 7 subbasins for the Bükkösd Stream, namely the Sormás, Gorica, Kán, Sás, Megyefa, Bükkösd Upper and Bükkösd Lower subcatchments. To account for loss (retention) of rainfall during the simulation runs (*i.e.* due to interception, surface storage and infiltration) the Simple Canopy, Simple Surface and Deficit and Constant models of HEC-HMS 3.5 were used. Parameterization scheme for the best fit between the observed and simulated flow time series and employed measurement techniques are shown in Table 2. Static (time-independent) relevant data were not changed for the two selected unit hydrograph (UHG) events while dynamic, time-dependent boundary conditions, like antecedent soil moisture values were different for the two selected UHG events.

Table 2 Measurement techniques, and the parameters used for best fitting in the three loss method modules (Simple Canopy, Simple Surface and Deficit and Constant) and the hydraulic parameters (Clark Unit Hydrograph) of the HEC-HMS for the two simulated UHG events for the studied, adjacent and entire watershed

Input parameter	**Bükkösd**	**Sor-más**	**Kán**	**Gorica**	**Megyefa**	**Sás**
Max. canopy storage (mm)	4	4	4	4	4	4
Initial canopy storage (%)	0	0	0	0	0	0
Surface storage (mm)	5	5	5	5	5	5
Initial surface storage (%)	0	0	0	0	0	0
Initial deficit (mm)	40	50	29	70	45	20
Maximum deficit (mm)	100	100	70	100	70	70
Infiltration rate (mm h^{-1})	2	3	2	2	2	2
Impervious surf. (%)	0	0	0	0	0	0
Time of concentration (h)	7	3	3	2	2,2	4
Storage coefficient (h)	20	20	20	4	10	6
Base flow (m^3 s^{-1})	0.160	0.032	0.035	0.025	0.068	0.032
Lag time (min)	50	36	47	36	10	50

3. Results and Discussion

Soil moisture pattern and behavior in the Bükkösd Valley

In general, soil moisture contents in the Bükkösd Valley, besides the localized effects of soil texture and coarse rocky fragments, were primarily influenced by topography and elevation. Based on the interpolation among the measurement points, highest soil moisture contents were measured in the immediate vicinity of the floodplain, while with increasing elevation above the floodplain, decreasing soil moisture contents were observed.

Usually, the lowest soil moisture content was observed at monitoring station located on steep slopes with shallow topsoils and sandy or sandy-loam texture. The high fraction of coarse rocky (sandstone) fragments also likely contributed to the low soil moisture values of high spatial stability. These findings were confirmed by the infiltration experiments carried out with Decagon mini disk infiltrometers (data are not shown here). The crumbly soil structure may also contribute to the high infiltration rate at this location. Monitoring stations deployed on clear cut sites also indicated a substantial temporal soil moisture behavior. Nonetheless, the behavior of soil moisture regime compared to each other at each measurement time, was relatively consistent, i.e. the spatial ranking of each soil moisture monitoring stations was quite stable, corroborating the findings of e.g.: Brocca et al. (2012).The soil moisture regime clearly reflected the orographic effects, soil physical types (texture and structure) and the land use type of the given location. All these factors significantly contributed to the large spatial heterogeneity and mosaic pattern of soil moisture contents in the Bükkösd Valley.

On average, highest soil moisture values were detected in 2009 (Fig. 2). However, due to the lack of adequate data homogenization, the difference cannot be considered statistically reliable. As previously mentioned, the 2009 soil moisture data were collected with a portable TDR soil moisture meter at irregular time intervals of about 1 to 3 weeks. Data in 2011 and 2012, on the other hand, were collected with automated datalogger equipped TDR sensors, where collection time intervals were 10 minutes, and for the period May 15 to July 15, 2011 collection intervals were decreased to 1 minute. This way, data collected in 2011 and 2012 could be inter-correlated with each other. On average, 2012 data were significantly higher than the mean soil moisture values for all monitoring station for the period of February 21 to May 15 in 2011. This is explained by the low total cumulative precipitation of this period in 2011.

Precipitation total for this period, i.e. preceding the studied high peak event of May 15 to 18 was 127.8 mm, which was the highest value for the period of 2009 to 2012. The differences in the rainfall totals for the February 21 to May 15 period, nonetheless, do not exactly reflect the observed soil moisture values in the pilot area (2009: 97.6 mm; 2010: 127.8 mm; 2011: 33.2 mm; 2012: 98.7 mm).

By using soil moisture values available for this period and especially for May 15 to 18, we could estimate initial soil moisture deficits for the studied peak flow event of May, 2010. Best matches were found for the estimated soil moisture deficits at 40 to 70 mm for most subcatchments of the Bükkösd Stream (see later in details) which would correspond to a volumetric soil moisture content of 0.14 to 0.35 m^3 m^{-3}. This would agree with the expected soil moisture range of the area based on the 2009, 2011 and 2012 soil moisture data.

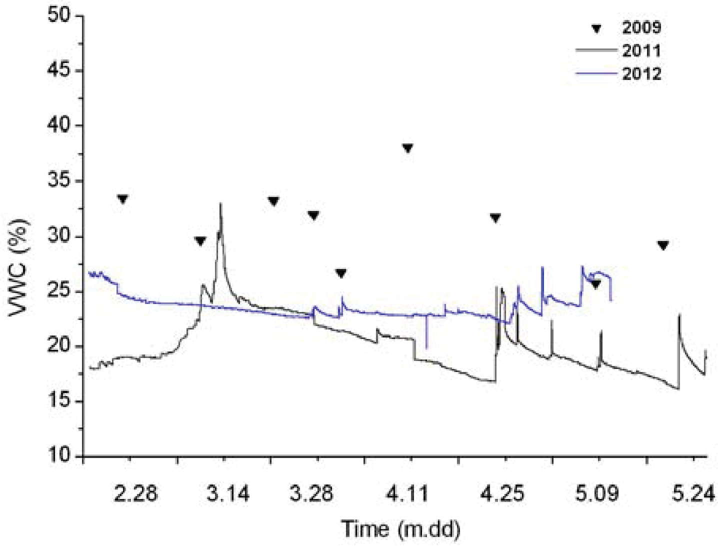

Fig. 2. Volumetric water contents in the Pósa Valley in 2009, 2010 and 2011. Soil moisture data were unavailable for 2010

Maximum moisture storage values also significantly influenced model output. Best matches were found at initial soil moisture storage values of 70 to 100 mm. These values are much lower than expected based on the soil depth measurements carried out in the Pósa Valley and published formerly (mean for boreholes: 2.66 m, mean for VES measurements: 2.76 m, see in further details in Keresztény et al. 2011). The low value of storage depth is explained by the fact, that immediately following a torrential high-intensity rainfall, interflow processes only occur in the shallow, near-surface part of the soils, thus the deeper soil profiles and horizons do not contribute to soil moisture within the time frame of time of concentration values typical for rapid-response catchments of small land area.

HEC-HMS model results

Flow time series for the selected flood events were reproduced and simulated using the HEC-HMS (Hydrological Modeling System) runoff hydrological program (developed in Davis, CA, United States). Measured initial and boundary conditions, and in certain cases modeled values were used as input data for the model. For comparative purposes, observed data were available for the above listed tributary valleys and for the Bükkösd Valley at Hetvehely as an outflow point. However, no data were available for the Bükkösd Stream at Bükkösd. Model simulations reproduced the observed flow time series with a relatively high accuracy for both single-peak and multi-peak hydrographs. However, in certain cases temporal shift is detectable between the observed and the modeled curves. This shift is likely caused by the single-point precipitation measurement within the watershed. Peak discharge could not be reproduced with sufficient accuracy for the Megyefa and Sás Streams. This discrepancy was caused by the failure of the stream gage measurements above 0.9 $m^3 s^{-1}$ and 1.55 $m^3 s^{-1}$ for the Megyefa and Sás Streams, respectively. To overcome of this shortcoming in peak flow detection and quantification, simulation runs were used for peak flow determination for the two aforementioned streams. In the case of the Sás Stream, the tailing of the falling limb was also poorly reproduced (Fig. 3f). Percentage of modeled cumulative outflow compared to the observed values ranged between 87.6 and 107.3%, while peak outflows, due to the failure of the stream gages for detecting high flows, ranged between 89.9 and 215.3%. Model runs were carried out using the Initial and Constant loss methods to account for infiltration into the subsurface and the vadose zone. We also attempted to employ the Soil Moisture Accounting Loss Model of the HEC-HMS, however, reconstruction efficiency was worse for this model than for the Initial and Constant Loss model.

In general, for the best fit case, cumulative outflow reproduction efficiency was better than the reproduction of peak flow. Relative cumulative outflow ranged between 0.877 and 1.073 for the six studied catchments. Closest match was observed for the Sás Stream where modeled cumulative outflow exceeded the measured one by 0.2%. Worst match was found for the Gorica Stream where relative cumulative outflow (i.e. the ratio of modeled and measured outflow) was only 0.877, *i.e.* the model significantly underestimated the observed cumulative outflow. Modeled peak flow values showed a larger deviation compared to the observed values than in the case of cumulative outflow. Peak flow for all tributaries usually ranged in the probability ranges of 5 to 10% based on the log-Pearson probability distribution of peak discharges. Peak flow values showed the best match for 60 mm initial deficit with the exception for the upper Bükkösd Drainage System and the Kán Stream. In the latter two cases best match was found at 40 mm initial soil moisture deficit.

With higher initial soil moisture contents, peak flow values showed a significant increase. This is explained by the decreasing pore volume capacity available for water storage. The match between the timing of the modeled and measured peak flow was relatively good in most cases with the exception of the Gorica Stream when both the entire length and the falling limb of the observed flow series was longer than for the modeled data of the best fit (60 mm initial soil moisture (deficit) (Fig. 3c). Also, for the Gorica Stream, the peak flow values for the best fit significantly exceeded that of the modeled flow time series (50% difference at 60 mm initial deficit). Worst relative peak flow value of 2.153 (calculated/measured) was observed for the Sás Stream. Here, the large difference is likely caused by the malfunction of the stream gage, which also indicated by the long 'plateau' of the observed flow data for the both Megyefa and Sás Stream (Fig. 3a and 3b). Best match was observed for the upper catchment of the Bükkösd Stream where the relative peak flow totaled 1.067 (Table 3). Largest sensitivity for the antecedent soil moisture contents was observed at the Gorica Stream. When initial soil moisture deficit was decreased from 60 mm to 10 mm (60 mm being the best match), peak flow value increase by 2.5-fold.

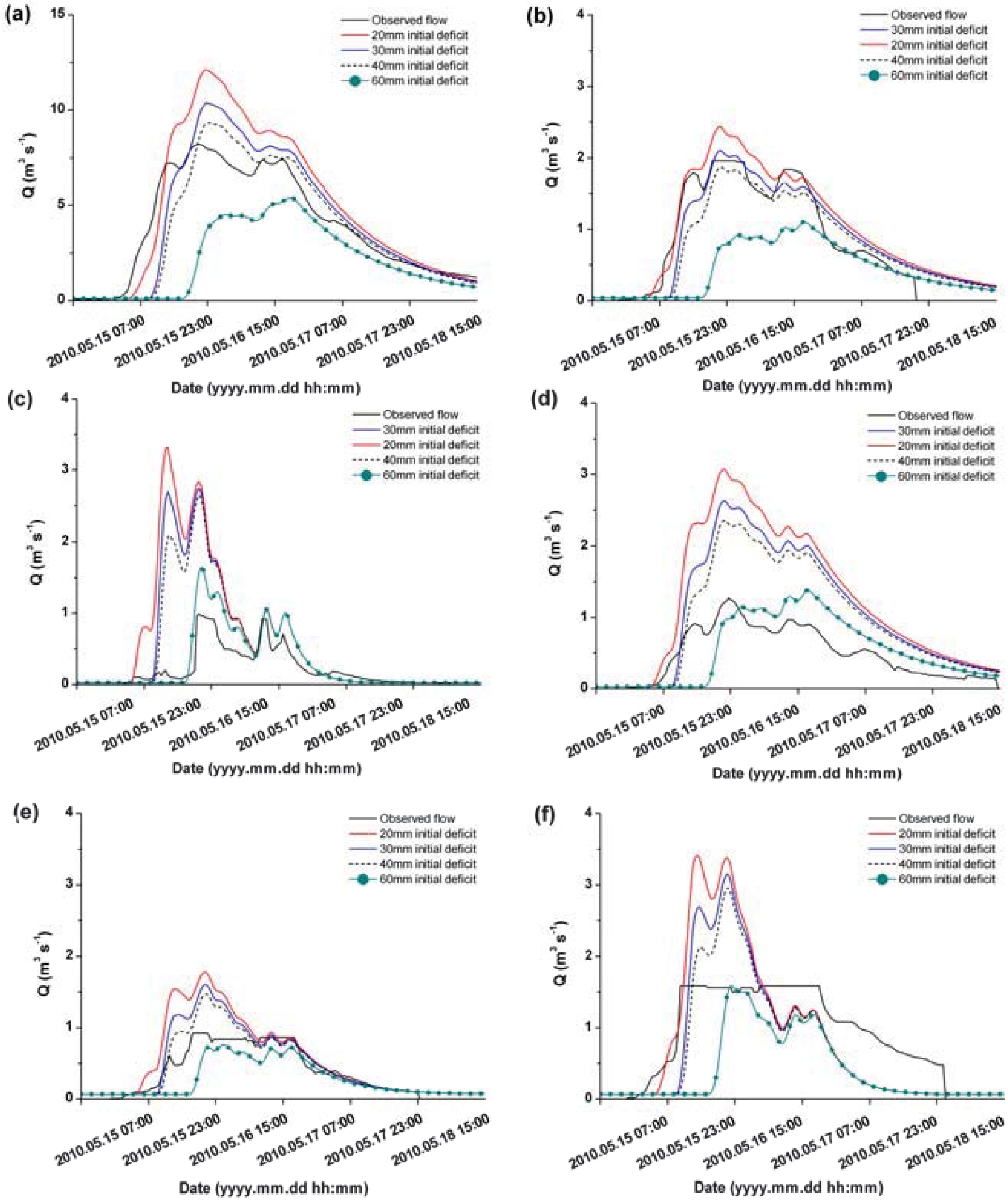

Fig. 3. Observed and simulated discharge values for various initial deficit values for the 15 May 2010 flood event for the 6 studied watersheds of the Bükkösd Stream: (a) Upper-Bükkösd, (b) Kán Stream, (c) Gorica Stream, (d) Sormás Stream, (e) Megyefa Stream, (f) Sás Stream

4. Conclusions

The ratio of runoff to infiltration is profoundly influenced by antecedent soil moisture contents, soil texture and hydraulic conductivity, thus awareness of watersheds-scale soil properties is also essential stormwater management. Understanding soil moisture variability across spatial-temporal scales is of great interest in many scientific and operational hydrologic applications (Brocca et al. 2012). Both antecedent soil moisture and infiltration rate are important runoff-influencing factors; however, they are highly variable both spatially and temporally; consequently their exact values are hard to predict in sufficient spatial resolution at a given location. The findings of the present study pointed out the considerably sensitivity of the HEC-HMS for input antecedent soil moisture values when the flow peak of the May 15 to 18, 2010 event was reconstructed. However, the sensitivity greatly varied among the tributary catchments and were influenced by land use types (clear cuts to canopy cover ratio), area (time of concentration and storage coefficient) and soil storage capacity (pore space).

However, if soil moisture values obtained at regular measurement intervals are unavailable, then spatial interpolation of the measured soil moisture points may help in the estimation of soil moisture contents at given parts of the watershed or for the entire watershed if no measured values are available for the watershed of importance. Temporal interpolation may also be suitable tool for the hydrologic characterization and determination of water balance of a given watershed. However, such a procedure may require the thorough hydrometeorological analysis and monitoring of the area of interest. Such hydrometeorological monitoring may include the measurement and subsequent analysis of air and soil temperature, relative humidity, soil moisture potentials, rainfall totals and intensity, wind speed and several other weather parameters.

Table 3 Observed and modeled peak discharge and cumulative outflow values at various initial deficit values for the 15 May, 2010 flood event for the Bükkösd Stream's subcatchments

	Cumulative outflow (1000 m^3)		Peak flow ($m^3\ s^{-1}$)		Relative cumulative outflow (Calc./Meas.)	Relative peak flow (Calc./Meas.)
	Meas.	Calc.	Meas.	Calc.		
Gorica S.	79.8	69.9	1.06	0.989	0.877	0.933
Kán S.	296.1	299.5	1.96	2.104	1.017	0.107
Sormás S.	180.1	160.8	1.412	1.27	0.893	0.899
Bükkösd S.	1437.6	1299.6	8.23	8.782	0.904	1.067
Sás Stream	290.4	290.9	1.58	3.403	1.002	2.153
Megyefa S.	123.2	132.3	0.922	1.36	1.073	1.475

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