

Hydrological model analyses on the watershed of Bükkös Creek

by

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ABSTRACT

The exploration of runoff processes in small catchments located on mountainous terrain has become relevant in order to predict floods and runoff volumes.

This study purposes to describe the basin (39 km²) of Bükkös Creek through hydrological model simulations. Firstly a one-dimensional hydrodynamic model of the main creek was set up to determine the accurate rating curve at the outlet of the watershed obtaining reliable discharge time series from the water level measurements.

The lumped model of HEC-HMS was clarified with the catchment's digital elevation model and successfully calibrated and validated.

The conception of the spatially semi-distributed TOPMODEL has been also implemented on the watershed, achieving better results throughout calibration and validation. Sensitivity analyse of parameters made the performed calibration of TOPMODEL precise. Effects of resolution of the digital terrain model and the complexity of hydrological model were analysed. The results were quantified with well-known indices of goodness of fit.

Keywords: Hydrologic modelling, semi-distributed TOPMODEL, HEC-HMS, sensitivity analysis

1 INTRODUCTION

It has become basically relevant to get an appropriate introspection into hydrological processes of small and medium sized mountainous catchments, in order to predict floods and discharge volume or water surface level with different return probability in significant cross-sections in terms of water resources engineering or spatial planning.

This study has the main purpose to describe the watershed of Bükkös Creek through hydrological model simulations.

First, a one-dimensional hydrodynamic model was set up to determine a reliable rating curve at the outlet cross-section of the watershed which was the base of the used runoff time series during the calibration and validation of the hydrological models.

The already applied lumped model of HEC-HMS (Széles et al, 2012) was clarified with the use of digital elevation model and successfully recalibrated and validated against corrected runoff data.

The conception of the spatially semi-distributed TOPMODEL has been implemented on the watershed achieving better results throughout calibration and validation. Sensitivity study made the results even more precise. The effect of resolution of digital terrain model and the complexity of hydrological model regarding the number of free parameters with different physical content were analysed. The results were quantified with well-known parameters of goodness of fit.

2 DESCRIPTION OF THE STUDY AREA

The investigated area can be found to south from the Curve of Danube in Hungary. The creek flows into the Danube in Szentendre, it is the most remarkable permanent watercourse of the city (*Figure 1*).

The total area of the catchment is 39.2 km². The creek is 16 km long, having a constructed bed in the urban area, which is well protected by levees from floods.

It originates from the southern slopes of Dobogókő, nearly 600 m above the mean sea level, from where through a way varied with numerous mite waterfalls and making a level difference of 500 m, it arrives to the interior part of Szentendre.

The characteristic aquifers are andesite and andesite-tufa with a strongly watertight nature. The runoff volume fluctuates between great extremenesses, we managed to measure larger amount of discharge in spring, when snow melted and in summer when flash floods dominate. The creek along its way could not form ponds, because the evolving hollows are quickly filled up with alluvium (Dövényi, 2010).

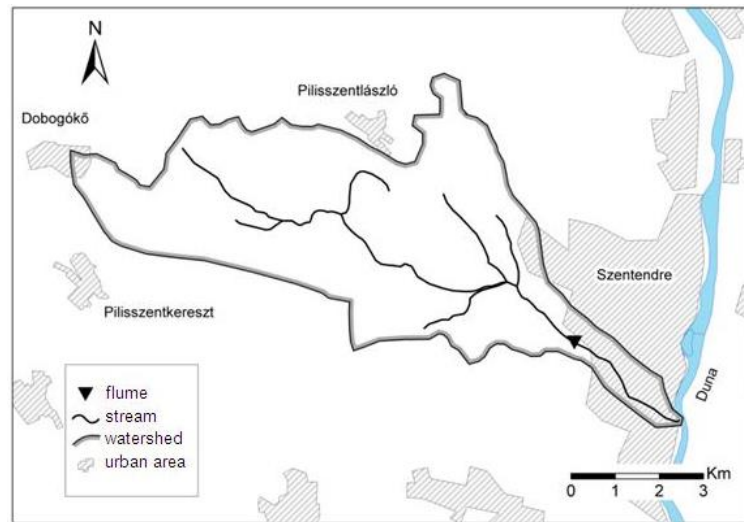


Figure 1 - Watershed of Bükkös Creek.

3 THE ONE DIMENSIONAL HYDRODYNAMIC MODEL OF BÜKKÖS-CREEK

The one-dimensional (1D) hydrodynamic model of the main creek was based on the geodesic survey of the stream. The average density of cross-sections is about 20 m in urban area and 100 m above the water level gauge in rural area. Manning's roughness coefficient was neither horizontally nor vertically varied throughout calibration, channel and banks could have the same value along the stream because calculated water surface levels are affected mostly by the great slope of the channel instead of its roughness. Sensitivity analysis performed with measured data verified this assumption.

The previously calculated rating curve based on a simple curve fitting method (Széles et al, 2012) used to be uncertain due to extrapolation in the range of high waters. The 1D hydrodynamic model of the main creek generates reliable discharge time series from the water level measurements which also fit the measured low discharge data of Central Danube Valley Environmental and Water Management Directorate. Figure 2 shows rating curves calculated by curve fitting and modelling. From the observed water levels at the cross-section of the compound flume discharge data of the flood event in May 2010 were recalculated with the new rating curve (Figure 3). This flood has been the greatest one measured by the floating instrument since its installation (2005) and as well the calibration period of model analysis.

Routing time of the watercourse was also calculated with the river model which meant to be an estimation of hydrologic response time of the watershed for severe thunderstorms.

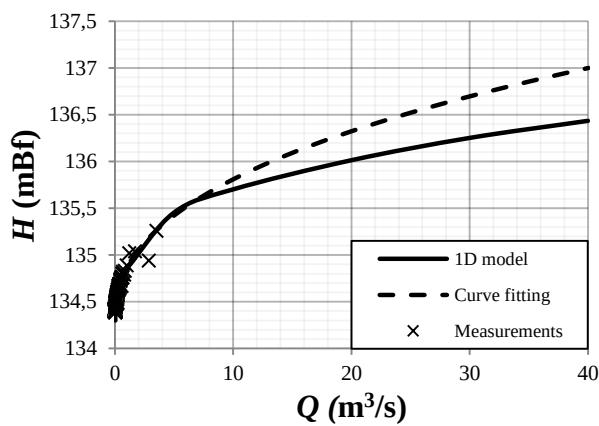


Figure 2 - Rating curves (calculated by 1D river model with solid line, simple curve fitting with dashed line, measured data with points).

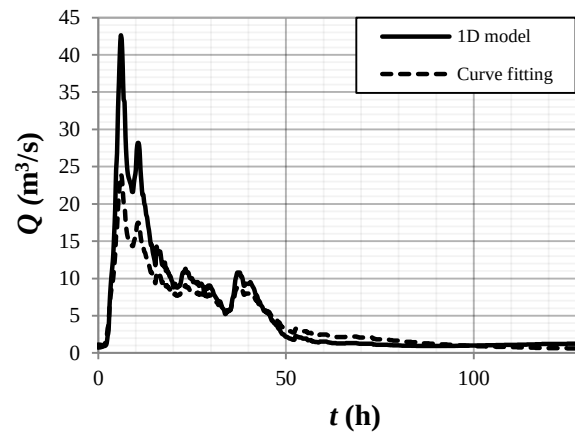


Figure 3 - Discharge data of the flood event in May 2010 (calculated by a rating curve of 1D model with solid line, with simple curve fitting with dashed line).

4 HYDROLOGICAL MODELS AND GOODNESS OF FIT CRITERIA

A lumped model (HEC-HMS) and a spatially semi-distributed (TOPMODEL) hydrological rainfall-runoff model were implemented on the watershed.

The mentioned hydrological modelling tools require structured grid, therefore from the manually digitalized contour levels a TIN model was created which was then interpolated onto a structured grid. Digital terrain models were generated with four different resolutions: 25, 50, 100, 200 m (Figure 4).

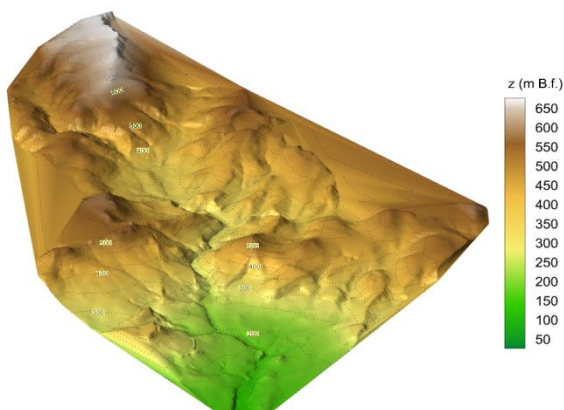


Figure 4 - Digital terrain model of Bükkös watershed.

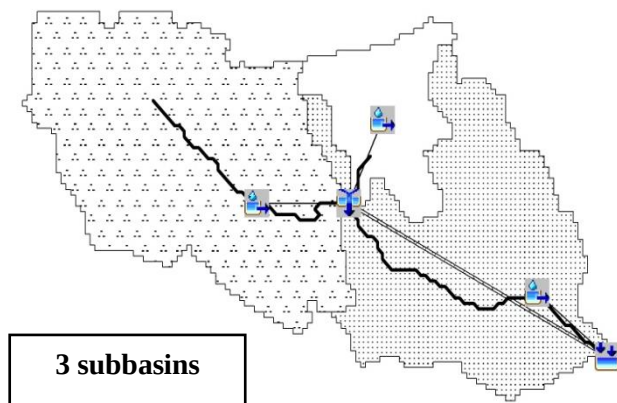


Figure 5 - Basin model of Bükkös watershed with three subbasins.

Quantifying goodness of fit between simulated and measured data during the procedure of calibration, validation and sensitivity studies is basically important. Four statistical indices were used which are described in details in Das et al, 2008:

- 1) Nash-Sutcliffe coefficient (R_m^2),
- 2) Relative bias,
- 3) Peak error,
- 4) RMSE (Rout mean squared error).

5 SIMULATING RAINFALL-RUNOFF PROCESSES WITH HEC-HMS

HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. The main components of the program are: basin model and meteorological model, input data and control specifications.

The basin model represents the physical watershed developed by adding and connecting hydrologic elements. Three of them were used by us: watershed, reach and junction (see HEC-HMS User's Manual). *Figure 5* shows the basin model of Bükkös Creek with three subbasins created by HEC-GeoHMS.

Meteorological model calculates the frozen or liquid precipitation and evapotranspiration. We dealt with only liquid precipitation. We assumed a homogeneous spatial distribution of rain in the meteorological model, because only one precipitation gauge's data were available.

Hourly measured precipitation data and discharge data with a temporal resolution of 15 minutes constituted the input data pairs.

Models with three and five subbasins were calibrated and validated. Altogether ten free parameters were calibrated: a specified amount of water remaining on the leaves of trees (*Canopy*), the sum of infiltration and precipitation left on the surface (*Loss*), surface runoff calculation (*Transform*), subsurface processes (*Baseflow*) and parameters of runoff time (*Routing*). The total runoff time of the main creek was calculated by HEC-RAS and divided between branches in proportion of the length of each reach elements during the calibration of lag routing. The length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph was divided between each watershed in proportion of each watershed's area during the calibration of the *Transform* method.

Figure 6 illustrates the result of calibration, the measured and calculated flood waves are in good agreement. The model was validated on an extended but independent time interval from April 2010 to June 2010, without changing the values of parameters. The preciseness of calibration and validation were quantified with goodness of fit indices found in *Table 2*. Remarkable differences in the results of models with three or five subbasins did not occur.

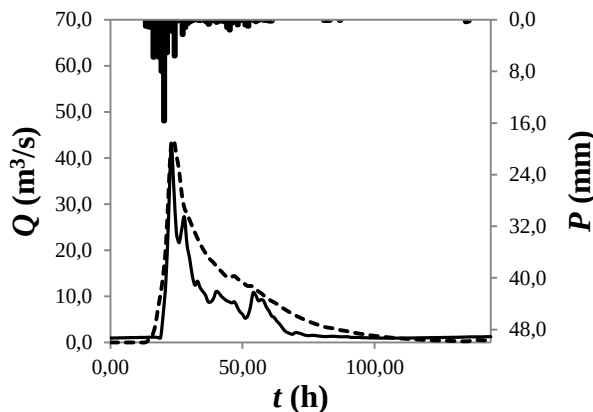


Figure 6 - Calibration period: May 2010, HEC-HMS with three subbasins (Simulated runoff with dashed line; measured runoff with solid line; precipitation with bar graph).

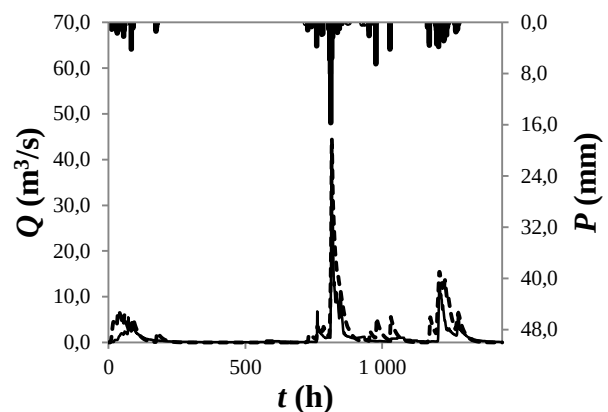


Figure 7 - Validation period: from April to June 2010, HEC-HMS with three subbasins (see notation at *Figure 6*).

6 SIMULATING RAINFALL-RUNOFF PROCESSES WITH TOPMODEL

The conception of TOPMODEL (Beven and Kirkby, 1979; Beven et al, 1984) was implemented on the watershed to model rainfall-runoff processes. “The model is based on a spatially distributed topographic index (defined as $\ln(a/\tan\beta)_i$, where a is the total upslope area which drains through point i and $\tan\beta$ is the local downslope topographic gradient which is used to predict local variations in water table depths. Areas of the catchment with approximately equal values of the topographic index may be assumed to behave in a hydrologically consistent manner” (Beven, 2001). Topographic index can be obtained from digital terrain models. GRASS, free and open source GIS software was applied as the run environment of TOPMODEL.

The calibration and validation period correspond with the time intervals used before (Figure 9), to be able to compare a lumped hydrological model with a semi-distributed one. The number of calibrated free parameters was eleven (Table 1), although many of these were explicitly determined. Figure 10 shows the result of validation (from April 2010 to June 2010).

Table 1 – Calibrated parameters of TOPMODEL.

Parameter	Dimension	Physical meaning
Q_0	[m/h]	Initial subsurface flow per unit area
$T_e = T_0$	(m ² /h)	Transmissivity of saturated soil
m	[m]	Transmissivity decline rate
Sr_0	[m]	Initial root zone storage deficit
Sr_{max}	[m]	Maximum available root zone storage deficit
t_d	[h]	Unsaturated zone time delay per unit storage deficit
v_{ch}	[m/h]	Main channel routing velocity
v_r	[m/h]	Internal subcatchment routing velocity
nch	[-]	Number of subbasins
d	[m]	Distance from outlet
Ad_r	[-]	Cumulative area ratio of subcatchment

Table 2 shows that prominently good results were achieved with TOPMODEL simulations. Nash Sutcliffe Coefficient is close to 0.9 also for the validation period. Peak error is for the calibration is of the order of two decimal places.

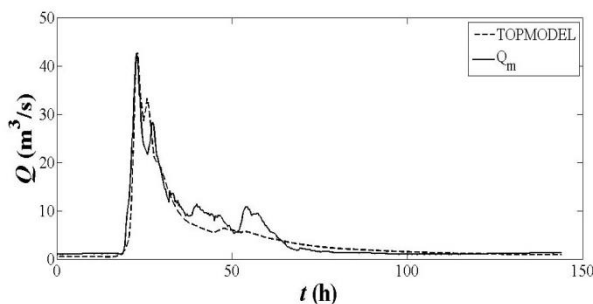


Figure 9 - Calibration period: May 2010, TOPMODEL (Simulated runoff with dashed line; measured runoff with solid line).

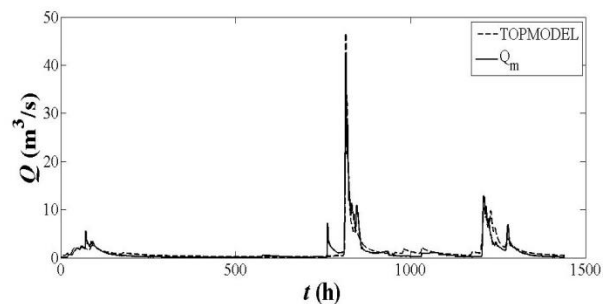


Figure 10 - Validation period: from April to June 2010, TOPMODEL (see notation at Figure 9).

Table 2 - Goodness of fit indices, calibration and validation of TOPMODEL and HEC-HMS.

Model	Type of simulation	Rel.Bias	R_m^2	Peak error	RMSE
HEC-HMS (3 subbasins)	Calibration	0.51	0.60	0.05	4.35
	Validation	0.75	0.38	0.06	2.22
HEC-HMS (5 subbasins)	Calibration	0.51	0.54	0.03	4.64
	Validation	0.75	0.36	0.05	2.26
TOPMODEL	Calibration	-0.0821	0.9077	0.0016	2.0841
	Validation	0.1653	0.8797	0.0978	0.9790

Sensitivity of the model parameters was analysed: the values were perturbed with $\pm 10\%$ (changing only one at a time) and there effects were measured through goodness of fit indices. According to Table 3 the most sensitive parameters were primarily m which controls the rate of decline of transmissivity with increasing storage deficit, and it is followed by T_e representing the transmissivity of the soil in the saturated state.

Table 3 - Results of sensitivity analyses.

Parameters	Rel. Bias	R_m^2	Peak	RMSE
Calibration	-0.0821	0.9077	0.0016	2.0841
$m-10\%$	-0.0658	0.8653	0.3535	2.5169
$m+10\%$	-0.0994	0.8759	-0.2538	2.4162
$\ln T_e-10\%$	-0.0818	0.9146	0.0251	2.0043
$\ln T_e+10\%$	-0.0824	0.9006	-0.00075	2.1629
$Sr_0-10\%$	-0.0786	0.9083	0.0204	2.0768
$Sr_0+10\%$	-0.0857	0.9067	-0.0133	2.0955
$Sr_{max}-10\%$	-0.0821	0.9077	0.0016	2.0841
$Sr_{max}+10\%$	-0.0821	0.9077	0.0016	2.0841
$t_d-10\%$	-0.082	0.9131	0.023	2.0216
$t_d+10\%$	-0.0822	0.9006	-0.0114	2.1627

Further sensitivity analyses were performed with the two most sensitive parameters (m and T_e) in order to find those parameter pairs when the value of Nash Sutcliffe Coefficient has a local maximum (Figure 11). The results show that the calibrated parameters are not the optimal data pairs in this aspect, however they are close to these and the aimed agreement is reached. Furthermore this method could be used to optimize model parameters.

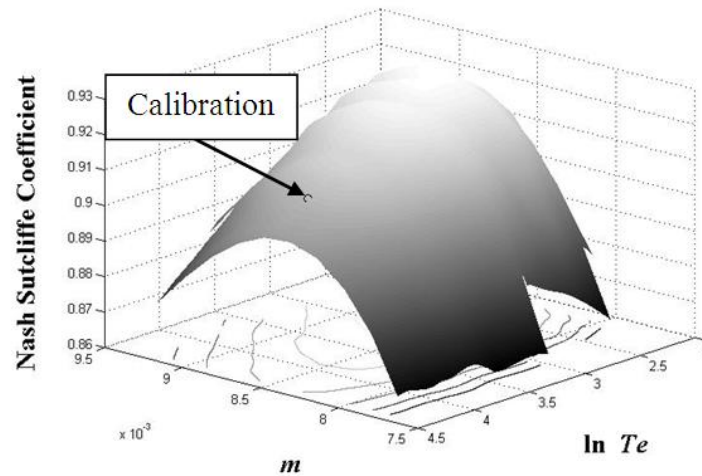


Figure 11 - Sensitivity analysis of the two most sensitive parameters of TOPMODEL, a circle shows the applied parameter pair of calibration.

Effects of spatial resolution on model performance were analysed applying different grid size: 25 m, 50 m, 100 m, 200 m. Spatial resolution has a great influence on the distribution of topographic index (γ) and the number of its classes. Figure 12 shows the distributions of topographic index under different spatial resolution. The distribution of γ begins to converge over 50 m. Our aim was to find the mesh independent solution which is almost reached.

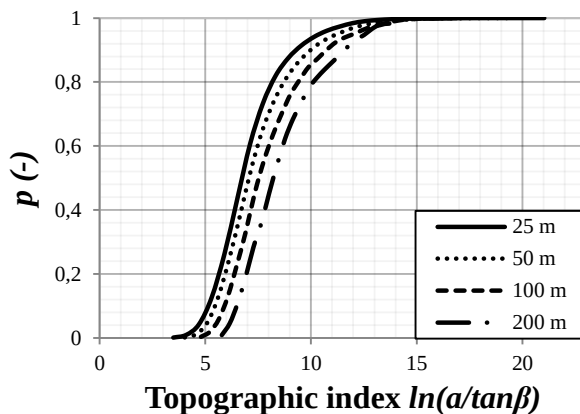


Figure 12 - Topographic index distributions under different spatial resolution.

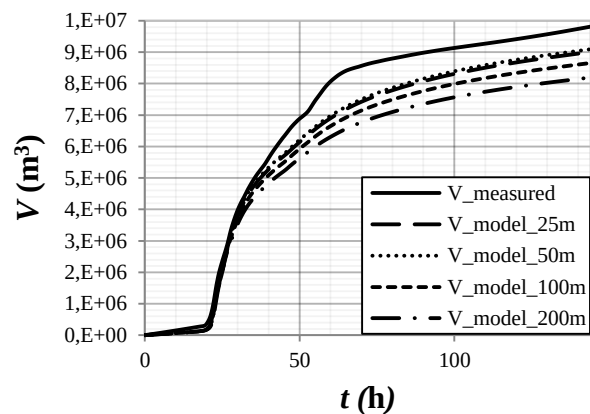


Figure 13 - Cumulative discharge volumes in May 2010, under different DEM resolution (25, 50, 100, 200 m).

Recognizable differences occurred during summing up discharge volumes using digital terrain models with different spatial resolutions (Figure 13). Cumulative discharge volumes with 25 m x 25 m and 50 m x 50 m grid size were almost the same, however differences were evident with coarser resolution (100 m and 200 m). Changing spatial resolution of DTM influenced primarily the magnitude of peak flow, the flood itself was not shifted in time.

Saturated zones can be calculated from the outputs of the model (topographic index statistical file, discharge time series) and topographic index raster. Figure 14 illustrates the calculated saturated zones

at the moment of the observed peak. These calculations were not checked with measured data. The results of model calculations can be correct in those areas where one of the preliminary simplifying assumptions of TOPMODEL is true: the downslope topographic gradient is assumed to be a good approximation of the downslope hydraulic gradient. This theory is certainly false on a terrain with major depression or deeper valley where changes in the surface of groundwater occur. This can be easily verified by registering groundwater surface levels.

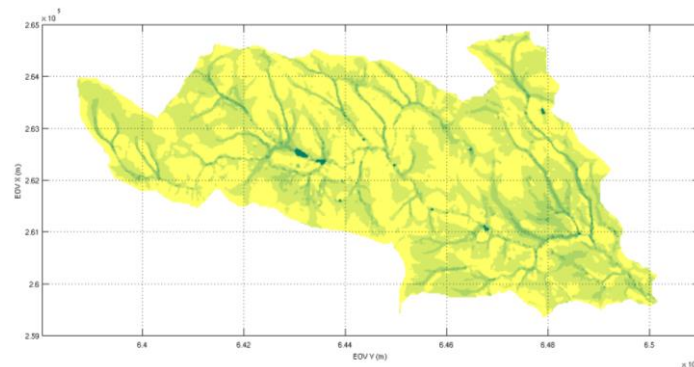


Figure 14 – Snapshot of calculated saturated zones with blue colour, $t=23$ h, with 25 m x 25 m spatial resolution.

7 COMPARISON OF THE MODELS

Considering the availability of the above performed TOPMODEL and HEC-HMS, both can be legally and freely used. As long as in case of TOPMODEL model generation and simulations can be performed with the open-source GRASS-GIS software, the basin model preparation for HEC-HMS can be realized with GeoHMS which is also free but works only as an extension of ArcGIS.

Input data format, data processing and run of TOPMODEL is similar to open source codes, results are not graphically displayed in GRASS, therefore separate scripts were coded for visualisation purposes. On the contrary HEC-HMS is more user-friendly with its graphical environment and detailed users' guides.

TOPMODEL uses only one hydrological approach, whereas HMS offers a broad range of hydrologic and hydraulic methods to describe watershed processes properly. The number of calibrated parameters was ten with HEC-HMS and seven with TOPMODEL, however we found the model was insensitive to some of the latter parameters. With a lumped model the number of free parameters is increasing by dividing the basin into more subbasins. Therefore the semi-distributed model could be more easily calibrated.

The complex HMS model can calculate with spatially inhomogeneous precipitation data. However the applied version of TOPMODEL was not able to use gridded precipitation data, this disadvantage can be easily eliminated throughout the open source nature of the tool.

8 CONCLUSIONS

However numerous empirical formulas exist to describe rainfall-runoff processes on watersheds, extreme circumstances of weather conditions and the lack of gauges on the numerous Hungarian watersheds mean an urgent need for a proper and reliable description of the small and medium sized catchments in order to predict floods and discharge volume.

Two rainfall-runoff models with different aspects and complexity were tested in our study on the watershed of Bükkös Creek: the lumped model of HEC-HMS and the semi-distributed TOPMODEL. According to the well-known goodness of fit indices better results were achieved with the latter throughout calibration and validation procedure, because the basic assumptions of the TOPMODEL

concept were realized on the catchment being hilly terrain with thin soil layer covering andesite as aquifer. Detailed sensitivity analyses of parameters was performed as well as the effect of DTM's resolution was explored. Furthermore we made an attempt to temporally describe the saturation process of the watershed.

Methods adopted on the catchment of Bükkös Creek could be also implied on better developed watersheds, giving an opportunity to draw such conclusions and generalizations which could be extended on other watersheds without gauges.

9 REFERENCES

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