DOI: 10.2478/aslh-2014-0006 Acta Silv. Lign. Hung., Vol. 10, Nr. 1 (2014) 77–90

Applicability of Different Hydrological Model Concepts on Small Catchments: Case Study of Bükkös Creek, Hungary

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Abstract – This study aims to test and compare the applicability and performance of two different hydrological model concepts on a small Hungarian watershed. The lumped model of HEC-HMS and the semi-distributed TOPMODEL have been implemented to predict streamflow of Bükkös Creek. Models were calibrated against the highest flood event recorded in the basin in May, 2010. Validation was done in an extended interval when smaller floods were observed. Acceptable results can be achieved with the semi-distributed approach. Model comparison is made by means of sensitivity analysis of model parameters. For TOPMODEL the effect of spatial resolution of the digital terrain model, while for HMS the complexity of the model setup was further explored. The results were quantified with model performance indices.

rainfall-runoff modelling / small watershed / TOPMODEL / HEC-HMS / model intercomparison

Kivonat – Különböző hidrológiai modellkoncepciók alkalmazhatósága magyarországi kisvízgyűjtőkön: esettanulmány a Bükkös-patak példáján. A tanulmány célja, hogy két különböző hidrológiai modell koncepció alkalmazhatóságát teszteljük és vessük össze magyarországi kisvízgyűjtők esetén. A koncentrált paraméterű HEC-HMS modellt és a térben félig osztott TOPMODEL-t alkalmaztuk a Bükkös-patak vízgyűjtőjének kifolyási szelvényében kialakuló árhullámok számítására. A modelleket az eddig mért legnagyobb, 2010. májusi árhullámra kalibráltuk. A validációt egy rövid, kiterjesztett időszakra végeztük, amikor kisebb árhullámok alakultak ki. A térben félig osztott megközelítéssel elfogadható eredményeket kaptunk. A modellek összehasonlítását érzékenységvizsgálat segítségével végeztük. A paramétereken túl, a TOPMODEL esetében a digitális terepmodell felbontásának, míg a HMS esetében a modell összetettségének hatását vizsgáltuk. Az eredmények értékelése a közismert, illeszkedés jóságát leíró paraméterekkel történt.

csapadék-lefolyás modellezés / kisvízgyűjtő / TOPMODEL / HEC-HMS / modell összehasonlítás

INTRODUCTION

An appropriate introspection into hydrological processes of small and medium sized mountainous catchments (up to 1000 m a.s.l.) of Hungary has become necessary due to a recent increase in flash flood events (Hegedüs et al 2013). It is especially challenging to predict floods (stage levels and discharge volumes) in data-poor catchments. In such environments adaptation of hydrological models can only be useful if they are robust for

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streamflow estimation (Gumindoga et al 2011). Due to the huge number of available hydrological models it is difficult to select the most effective one. Different model classifications exist (e.g. deterministic or stochastic etc.), but the most basic one concerns spatial structure. Lumped models handle the basin as one unit while fully distributed models solve equations on a finite number of discrete cells that cover the basin. In the latter case parameter values may vary in each computational point. Semi-distributed models do not calculate hydrological processes by cells but take into account the spatial variation of some characteristics of the watershed by dividing it into smaller homogeneous units (Beven 2001).

Depending on their structural concept, rainfall-runoff (RR) models usually require at least half a dozen model parameters to be optimized. Robustness is difficult to ensure when a large number of parameters have to be defined. The optimization procedure requires as long a rainfall-runoff record as possible. With different parameter combinations, similar runoff values can be achieved meaning that a number of local minima exist in the parameter space with different interpretations of the modelled mechanisms (Duan et al 1992, Iorgulescu – Jordan 1994). Selection from these parameter combinations can be obtained with various hydrological and geographical analyses.

In Hungary little effort has been put into testing the applicability of different model concepts. Only a few studies report of successful applications of lumped RR models in small Hungarian watersheds (Hegedüs et al 2013, Koch – Bene 2013). This study aims to simulate streamflow during a large flood event in the small watershed of Bükkös Creek using two different RR models. The watershed of Bükkös Creek is data-poor, only a water level gauge has been in operation in it, which is typical in Hungary. The main goal is to test the applicability of two different model concepts and to estimate their robustness and sensitivity. A lumped (HEC-HMS) and a semi-distributed (TOPMODEL) models are implemented.

First, a one-dimensional hydrodynamic model of the main creek was set up to derive a reliable rating curve at the outlet cross-section of the watershed to transform stage records into runoff time series for the calibration and validation of the hydrological models. The already applied lumped model of HEC-HMS (Széles et al. 2012) fitted with a digital elevation model was successfully recalibrated and validated against corrected runoff data. The semi-distributed TOPMODEL has also been implemented, achieving better results throughout calibration and validation. Sensitivity study made the results even more reliable. The effect of digital terrain model resolution and the complexity of the hydrological model regarding the number of free parameters with different physical content were analysed. The results were quantified with well-known model performance tests.

1 STUDY AREA

The catchment is found south of the Danube's Bend in Hungary. The creek flows into the Danube at Szentendre, it is the largest permanent watercourse of the city (*Figure 1*).

The total area of the catchment is 39.2 km^2. The creek is 16 km long, having a constructed bed in the urban area protected by flood levees. It originates in the southern slopes of Dobogókő, nearly 600 m above m.s.l., where from through various waterfalls traversing a level difference of 500 m, arrives to downtown of Szentendre (*Figure 2*).

The aquifer is made up of andesite and andesite-tufa with a strongly watertight nature (due to the secondary porosity its hydraulic conductivity coefficient is about 10^{-7}-10^{-8} m/s). Runoff fluctuates within a large range: enhanced discharge in spring when snow melts and in summer when flash floods dominate. The creek cannot form ponds along its course because the evolving hollows are quickly filled up with alluvium (Dövényi 2010).

As it is shown in *Figure 1* a water level gauge is operated at the border of the settlement. Water level is recorded in every 15 minutes since 2005 which is occasionally complemented with discharge measurement by the Water Directorate at low and medium waters. Hourly precipitation data were obtained from the Hungarian Meteorological Service. The rainfall gauge is operated about 10 km south from the watershed.

The basin is covered by forest above the gauge, the area of open fields is negligible. The topography of the catchment is displayed in *Figure 2*. Hydrological modelling tools require a structured grid, therefore from the manually digitalized contour levels a TIN model was created which was then interpolated onto structured grids. Digital terrain models were generated with four different horizontal resolutions: 25, 50, 100, 200 m.

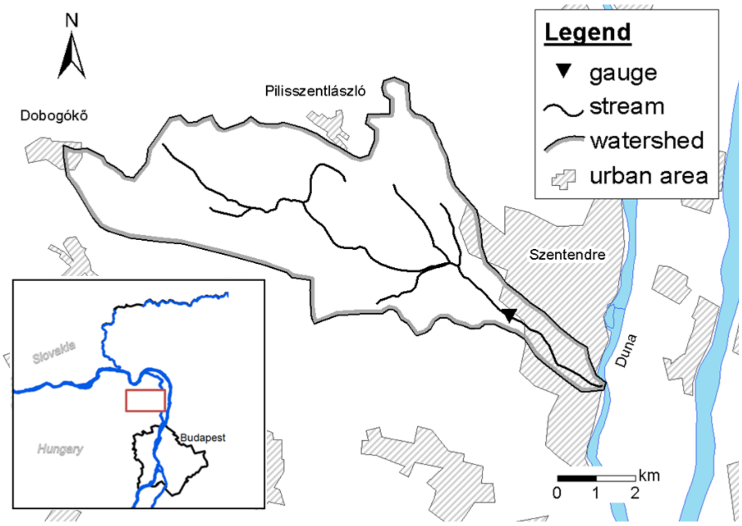

Figure 1. Location of the watershed of Bükkös Creek

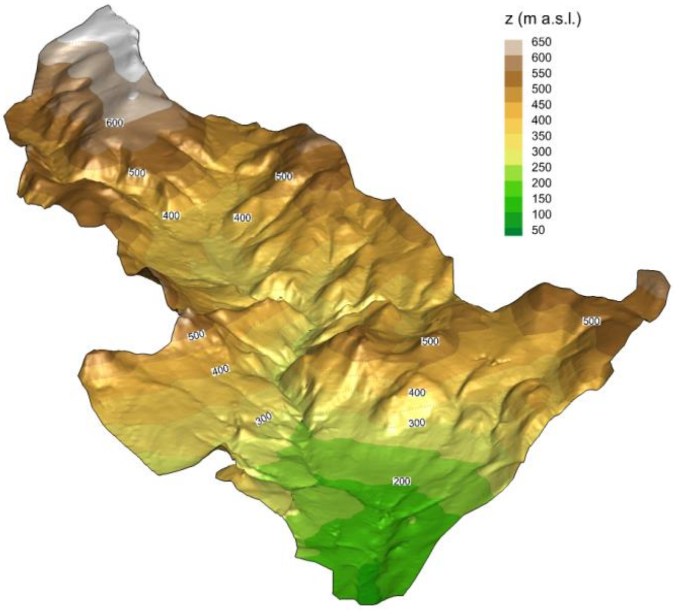

Figure 2. Digital elevation model of the Bükkös watershed derived from triangulation of contours

2 MODELS AND METHODS

2.1 1D hydrodynamic creek model

The one-dimensional (1D) hydrodynamic model of the main channel was based on the geodesic survey of the stream. The average density of cross-sections is about 20 m in the urban area and 100 m above the gauge in the 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 large slope of the water surface instead of friction caused by the channel's 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), was inaccurate due to extrapolation in the range of high waters. The 1D hydrodynamic model of the main channel generates reliable discharge time series from the water level measurements which also fit the measured low discharge data of the Central Danube Valley Environmental and Water Management Directorate. *Figure 3* displays the rating curves obtained by curve fitting and modelling. From the observed water levels discharge data of the flood event in May 2010 were recalculated with the new rating curve (*Figure 4*). This flood has been the greatest one measured since 2005, the calibration period of model analysis. The peak flow according to the rating curve derived from the 1D model is almost twice as large as the earlier extrapolated value.

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.

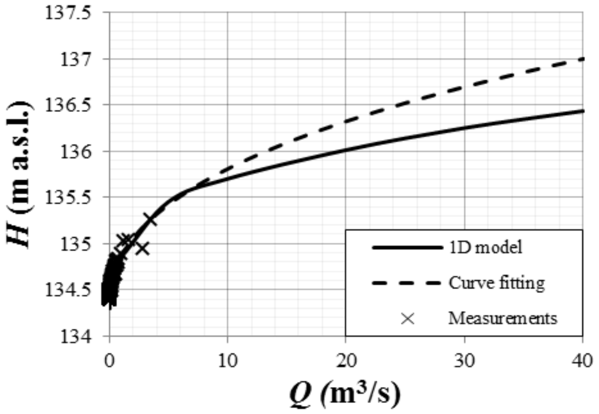

Figure 3. Rating curves calculated by 1D stream model and simple curve fitting

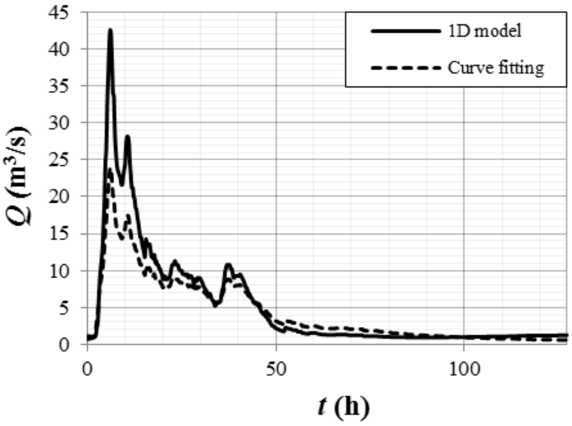

Figure 4. Discharge time series of the flood event in May 2010 derived by the rating curve of the 1D model as well as by simple curve fitting

2.2 Lumped model

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

The basin model represents the physical watershed by adding and connecting hydrological elements. Three of them were used by us: watershed, reach and junction (USACE 2010). *Figure 5* shows the basin model of Bükkös Creek with three subbasins created by HEC-GeoHMS.

The 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 station was 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 optimized: 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 in channels (*Routing*). The total runoff time of the main creek was calculated by the 1D model and divided between branches in proportion of the length of each reach elements during the calibration of lag routing. The time between the centroid of precipitation mass and the peak flow of the resulting hydrograph was divided between each watershed in proportion of watersheds' area during the calibration of the *Transform* method.

Figure 5. Basin model of Bükkös watershed with three (left) and with five (right) sub-basins in the lumped model

2.3 Semi-distributed model

The geomorphology of the catchment plays an important role in runoff generation, especially in hilly terrains. Various approaches focus on different topographic characteristics. The geomorphologic unit hydrograph theory and the geomorphologic nonlinear-cascade (Szilágyi – Parlange 1999) concepts identify physical parameters from the drainage network, while in the concept of TOPMODEL by Beven and Kirkby (1979), topographic derivatives are the responsible hydrological drivers.

The concept of TOPMODEL (Beven – Kirkby 1979, Beven et al. 1984) was implemented in the watershed to model rainfall-runoff processes. Topography is represented in the model through the so-called topographic index, defined as $\ln(a/\tan\beta)$, where a is the total upslope contributing area, and $\tan(\beta)$ is the local downslope angle. The topographic index is used to estimate water table depths in any point of the catchment. Its distribution for the basin of Bükkös Creek is shown in *Figure 6*.The concept is based upon three main assumptions

(Beven 2001): (i) saturated zone is in equilibrium state due to the draining of the upslope contributing area, (ii) hydraulic gradient of the saturated zone is assumed to be equal with the topographic slope, (iii) the transmissivity with depth of the saturated zone is an exponential function of storage deficit. The semi-distributed feature arises from the assumption that areas with the same index value behave in the same hydrological manner. Originally TOPMODEL was developed for humid watersheds with thin soil but it has been used successfully in highly different circumstances, for instances in the Mediterranean (Candela et al 2005) or at the tropics (Plesca et al 2012). Topographic index can be derived from digital terrain models. GRASS, the free and open source GIS software was used to calculate index distribution in the catchment and as the run environment of TOPMODEL (GRASS 2012).

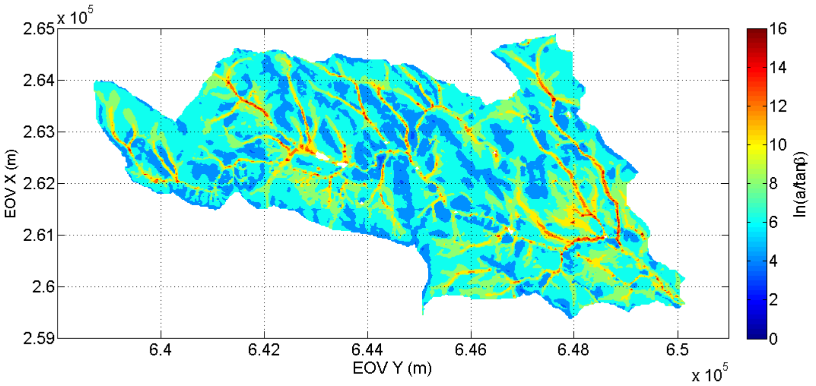

Figure 6. Topographic index distribution in the watershed with 25 m DEM resolution

2.4 Goodness of fit criteria

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

1) *Nash-Sutcliffe coefficient* (R_m^2):

$$R_m{}^2 = 1 - \frac{\sum_{i=1}^{N}(Q_s(t_i) - Q_0(t_i))^2}{\sum_{i=1}^{N}(Q_0(t_i) - Q_{0,a})^2}$$

where $Q_o(t_i)$is the observed, $Q_s(t_i)$ is the simulated discharge at time step t_i, $Q_{o,a}$ is mean observed discharge and N is the number of time steps.

2) *Relative bias*:

$$Rel_{bias} = \frac{\sum_{i=1}^{N} Q_s(t_i) - Q_0(t_i)}{\sum_{i=1}^{N} Q_0(t_i)}$$

3) *Peak error*:

$$Peak\ error = \frac{Q_{s,max} - Q_{0,max}}{Q_{0,max}}$$

where $Q_{s,max}$ is the simulated and $Q_{o,max}$ is the observed peak discharge.

4) *RMSE (Rout mean squared error)*:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} Q_s(t_i) - Q_0(t_i)}{N}}$$

3 RESULTS

3.1 Rainfall-runoff simulations

The same flood event was simulated with the two RR models providing comparability. The highest water levels ever recorded occurred during the flood event in May 2010 and caused significant damage in the town of Szentendre. Both models were calibrated against the observed discharge time series determined by the rating curve derived from the 1D model. To validate the models the calibration period was extended from April to June, when smaller flood-waves were observed.

Figure 7 illustrates observed runoff time series at the outlet with the simulation result of HEC-HMS lumped model for May 2010. The measured and simulated flood waves are in moderately good agreement. The magnitude and the phase of the peak are captured well, but the modelled wave is long-drawn, therefore the simulated runoff volume is remarkably overestimated (*Figure* 13). The model was validated on the extended interval for which a similar statement can be made (*Figure 8*). Calibration and validation accuracy was quantified with goodness of fit indices in *Table 2*.

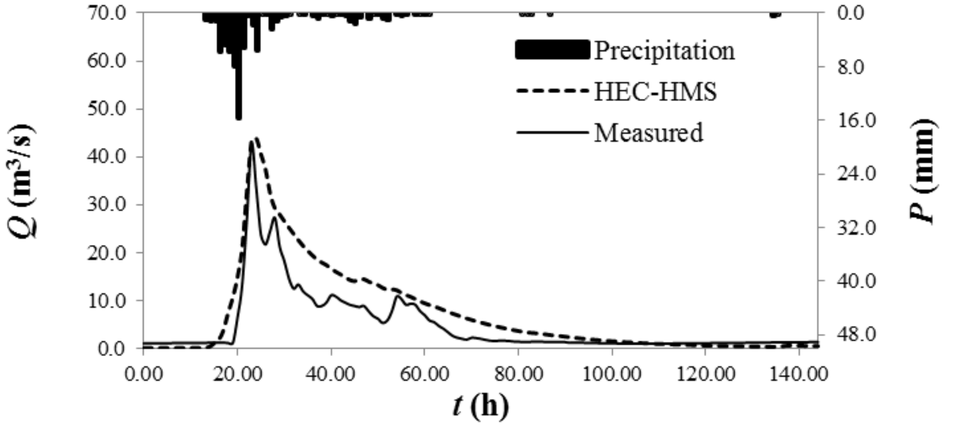

Figure 7.Observed and simulated runoff with HEC-HMS using three sub-basins for the calibration period

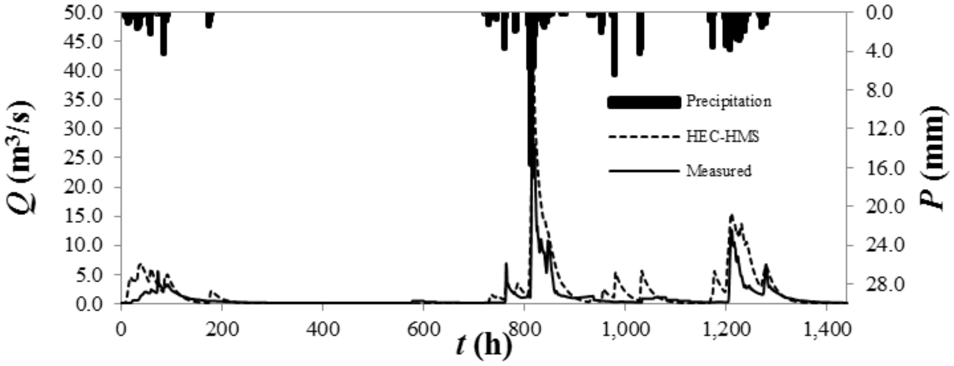

Figure 8.Observed and simulated runoff with HEC-HMS using three sub-basins from April to June 2010.

The results of the runoff simulation for TOPMODEL is shown in *Figure 9*. The calibration and validation periods correspond to the time intervals used before. The free model parameters are displayed in *Table 1*, although many of these were explicitly determined. *Figure 10* shows the result of the validation (from April 2010 to June 2010).

Table 1 – Model 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 sub-catchment routing velocity
nch	(-)	Number of sub-basins
d	(m)	Distance from outlet
Ad_r	(-)	Cumulative area ratio of sub-catchment

Table 2 demonstrates that prominently good results were achieved with TOPMODEL. Nash-Sutcliffe coefficient is close to 0.9 also for the validation period. Peak error for the calibration is of the order of two decimal places. Furthermore, the second peak is also appearing on the times series, although it is overestimated and occurs earlier. The simulated cumulative runoff volume is also approximated more accurately than in case of the lumped model.

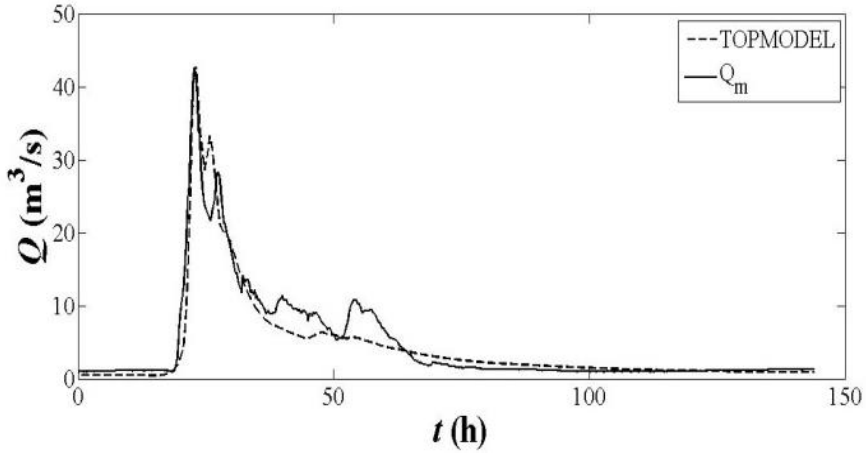

Figure 9. Observed (Q_m) and simulated runoff with TOPMODEL for the calibration period

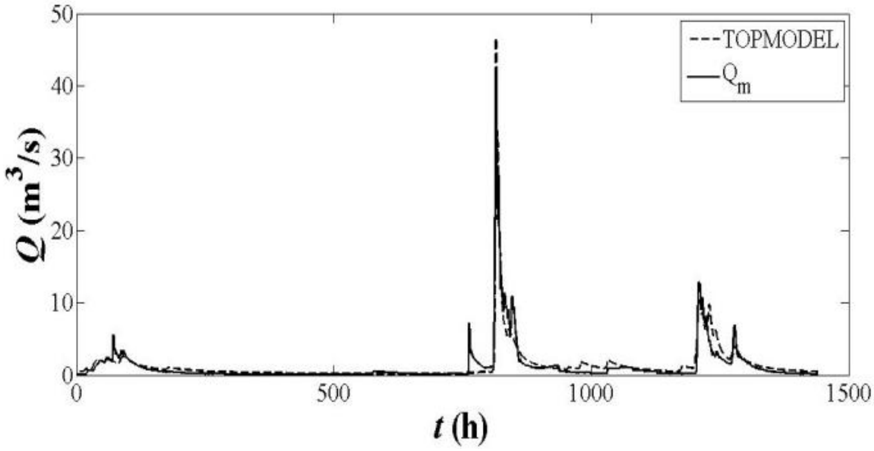

Figure 10. Observed (Q_m) and simulated runoff with TOPMODEL from April to June 2010

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	Calibration	0.51	0.60	0.05	4.35
(3 subbasins)	Validation	0.75	0.38	0.06	2.22
HEC-HMS	Calibration	0.51	0.54	0.03	4.64
(5 subbasins)	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

3.2 Sensitivity analysis

One of the main goals of this study is to explore robustness of model concepts. To this end, sensitivity analysis was performed. As it clearly seen from *Table 2* and from the runoff time series, TOPMODEL performs considerably better. In the international literature many researchers work with HEC-HMS and even the previously mentioned Hungarian studies applied this lumped model (Széles et al 2012, Hegedüs et al 2013, Koch – Bene 2013), thus the sensitivity analysis focuses on TOPMODEL.

With HMS the modeller has to adjust the level of model's complexity during model building. In practice the number of sub-basins and consequently the number of side streams have to be decided. The amount of model parameters increases rapidly with sub-basins. In order to check the sensitivity of HMS for complexity, simulations were performed by delineating three and five sub-catchments. Remarkable differences in the results did not occur as it can be seen by the indices of *Table 2*. It was not possible to model the second peak of the main flood event of May by the more sophisticated structure.

In case of TOPMODEL, a more detailed investigation was performed. Sensitivity of the model parameters was analysed: the values were perturbed with ±10% (changing only one at a time) and the effects were measured through goodness of fit indices. The list of model parameters and their physical interpretation is specified in *Table 1*. According to *Table 3*, the most sensitive parameter was m which controls the rate of decline of transmissivity with increasing storage deficit, followed by T_e representing the transmissivity of the soil in saturated state.

Table 3 Results of the sensitivity analysis

Parameters	Rel. Bias	R_m^2	Peak error	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$\mathbf{T_e}$-10 %	–0.0818	0.9146	0.0251	2.0043
ln$\mathbf{T_e}$+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 %	–0.0820	0.9131	0.0230	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 the NS coefficient has a local maximum (*Figure 11*). The results show that the calibrated parameters are not the optimal data pair in this aspect, however they are close to it and the aimed agreement is reached. Furthermore this method could be used to optimize model parameters.

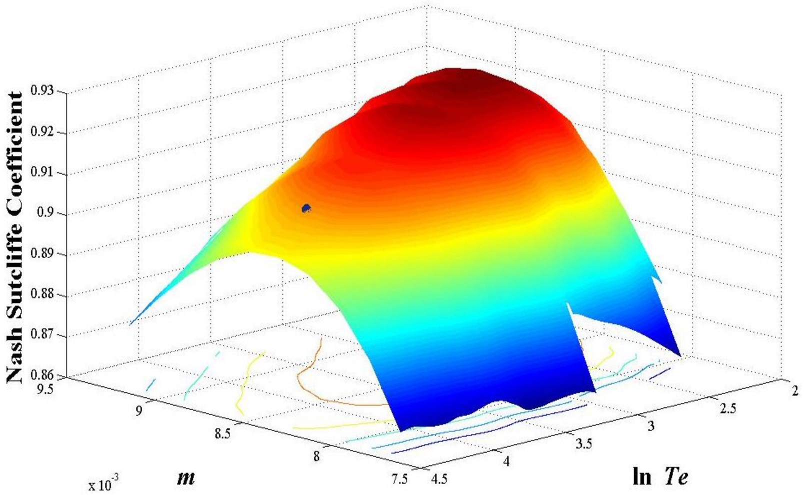

Figure 11. Sensitivity analysis of the two most sensitive parameters of TOPMODEL, a circle shows the applied parameter combination at calibration

As it was described in section 2.3, runoff generation in TOPMODEL is principally controlled by topography, hence the accuracy of the DEM has primary importance. Many researchers analysed grid size dependency of this concept (e.g. Lin et al 2010). Brasington and Richards (1998) showed that cell-size-independent results can be reached with about 100 m resolution. When using a finer DEM resolution, accuracy can be maintained by recalibration of the model. Effects of spatial resolution on model performance were analysed applying different grid size: 25 m, 50 m, 100 m and 200 m. Spatial resolution has direct influence on the topographic index (γ). *Figure 12* shows the distribution of the topographic index under different spatial resolutions. Our aim was to find a mesh independent solution which has almost been achieved. The distribution of γ does not differ significantly using 25 m or 50 m resolution.

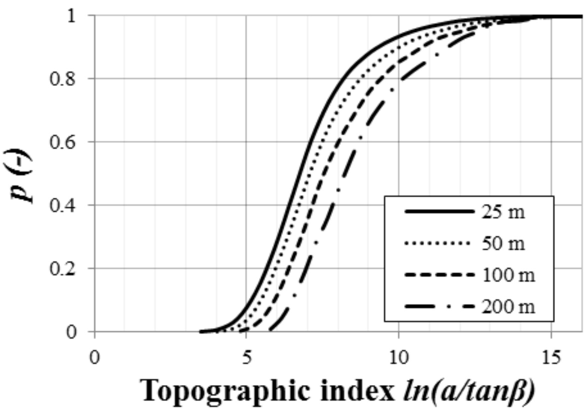

Figure 12.Topographic index distributions under different spatial resolution

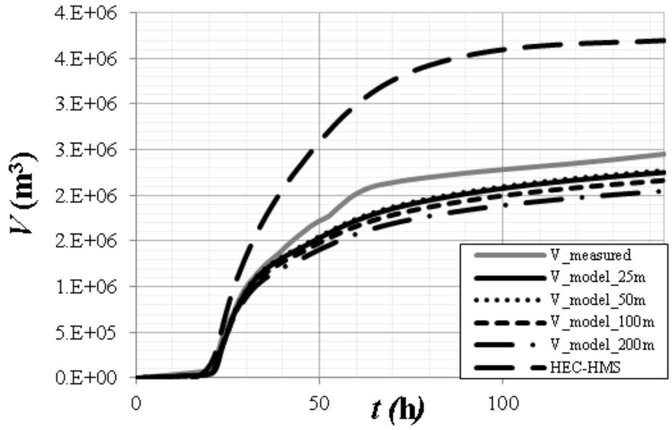

Figure 13.Cumulative discharge volumes in May 2010, under different DEM resolution (25, 50, 100, 200 m)

Recognizable differences can be discovered in the cumulative discharge volumes using digital terrain models with different spatial resolutions (*Figure 13*). Volumes with 25 m x 25 m and 50 m x 50 m grid sizes were almost the same, however differences were evident with a coarser resolution (100 m and 200 m). Changing spatial resolution of DTM influenced primarily the magnitude of the discharge peak value, the flood itself was not shifted in time.

3.3 Model comparison

One of the main purposes of this study is to compare the lumped and semi-distributed approaches as to their accuracy and applicability.

Probably the most important item in the comparison is model performance. It is clearly shown that TOPMODEL simulated the chosen flood wave with more accuracy. Not only its shape and the peak flow were well estimated, but the runoff volumes were also acceptable, which is not the case for HMS.

TOPMODEL uses only one hydrological approach, whereas HMS offers a broad range of hydrologic and hydraulic methods to describe watershed processes properly. This can be even disadvantageous if a robust tool is looked for since it is already challenging to select among the different approaches possessing parameters with different physical meaning.

The number of calibrated parameters was ten with HEC-HMS. By the lumped model the number of free parameters is increasing while the calibration process is getting more complicated by dividing the catchment into several sub-basins. In case of TOPMODEL, seven parameters have to be optimized, however we have found that the model was sensitive to only a few of them. This is partly due to the fact that some hydrological parameters are derived from the topography. For this reason this approach requires an accurate digital elevation model, but nowadays they are typically available. It can be stated that the semi-distributed model could be more easily calibrated.

Considering the availability of TOPMODEL and HEC-HMS, both can be legally and freely used. While for TOPMODEL model generation and simulations can be performed with the open-source GRASS-GIS software, the basin model preparation for HEC-HMS can only 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.

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

Another advantage of the semi-distributed TOPMODEL concept is that saturated zones can be calculated from the outputs of the model and topographic index raster. *Figure 14* illustrates the simulated saturated zones at the moment of peak. These calculations were not validated 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 incorrect on a terrain with a major depression or deeper valley where changes in the surface of groundwater occur. After the saturation map is validated, it can be used e.g., to delineate borders of riparian zones. Verification can be made by extensive groundwater surface level registering. Such measurements in Hungary take place in the Hidegvíz Valley Forest Experimental Watershed (Gribovszki et al 2011), which is also a small, hilly catchment, where TOPMODEL may work properly.

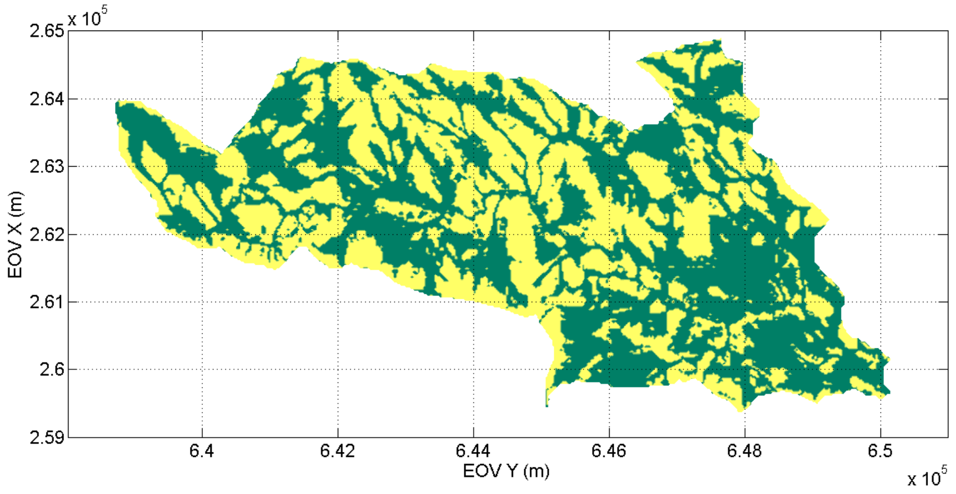

Figure 14. Snapshot of calculated saturated zones (dark green) at t=23 h, with 25 m spatial resolution

4 CONCLUSIONS

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

Two rainfall-runoff models with different stuctures and complexity were tested in our case study for the watershed of Bükkös Creek: the lumped model of HEC-HMS and the semi-distributed TOPMODEL. Better results were achieved with the latter concept. The principal reason is the fact that the basic assumptions of the TOPMODEL concept were realized in the catchment, owing to a hilly terrain with a thin soil layer and underlain by andesite as an aquifer. Detailed sensitivity analysis of parameters was performed as well as the effect of DTM's resolution was explored.

The main purpose of this study is a comparison of modelling approaches, aided by the watershed of Bükkös Creek, to narrow the list of hydrological models which can be used to predict streamflows of small Hungarian catchments. The models were investigated with respect to performance and robustness. The main conclusions are the followings:

The lumped HEC-HMS model performance is not satisfactory. It is challenging to apply it in poorly instrumented catchments due to its many optional modules and parameters.

In contrast, runoff simulations made by the semi-distributed TOPMODEL are in good agreement with observations. The model possesses less sensitive parameters and seems to be more robust. It can be explained by the fact that the model builds on topography as the main driver of hydrological processes. The semi-distributed approach (not only TOPMODEL) is more promising than the lumped description as a streamflow prediction tool in small watersheds. Nevertheless, care must always be taken if model assumptions are met in the given watershed. Further investigations are required in various basins of the country to verify a more extensive applicability of TOPMODEL or other geomorphologic semi-distributed approaches.

Methods adopted in this study for the catchment of Bükkös Creek could also be applied in better instrumented watersheds, allowing for drawing similar conclusions and generalizations that could be extended to other ungauged watersheds.

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