Flood inundation mapping in small and ungauged basins: sensitivity analysis using the EBA4SUB and HEC-RAS modeling approach
Matej Vojtek, Andrea Petroselli, Jana Vojteková and Shahla Asgharinia

ABSTRACT
Flood mapping is an important part of flood risk analysis and management as its result is the visualization of flood hazard in terms of flood depth and extent. However, flood mapping strongly depends on the selected modeling approach. Furthermore, model input data usually incorporate uncertainties that may vary significantly in time and space. In this study, the EBA4SUB (Event-Based Approach for Small and Ungauged Basins) hydrologic model and the one-dimensional HEC-RAS (Hydrologic Engineering Center’s River Analysis System) hydraulic model were selected for evaluating their sensitivity, in terms of simulated flood area (FA) and volume (FV), to different combinations of input parameters. Results of hydrologic modeling highlight the great variation of design peak discharges which strongly influence the modeled FA and FV. The sensitivity of FA and FV to excess rainfall determination was several times larger than the sensitivity to the routing propagation for two assumed gross rainfall distributions (rectangular and Chicago), which highlights the importance of the correct estimation of soil and land use properties affecting the infiltration estimation. Moreover, the sensitivity of FA and FV to the roughness parameter was 1.5–2 times greater than the sensitivity to the cross-section parameter, yet, stressing the importance of input parameters for hydraulic modeling.

Key words | EBA4SUB, flood, HEC-RAS, inundation, sensitivity analysis, ungauged basin

INTRODUCTION
Flood mapping is a crucial element of flood risk management since it provides the delineation of flood depth and extent in flood-prone areas. The creation of flood maps is usually performed using a combination of hydrologic and hydraulic models that is particularly challenging in case of small and ungauged basins where the calibration of advanced hydrologic models is difficult due to lack of observed discharge data (Grimaldi et al. 2013a; Szymczak & Krążek 2018). In order to estimate the design peak discharge or the design hydrograph for ungauged basins, different hydrologic models are usually applied (Petroselli et al. 2019). In particular, simple conceptual models represent a reliable compromise between the physical representation of the investigated hydrologic processes and the limited number of adopted parameters (Mlyński et al. 2018).

Regarding the hydraulic part, the first important issue concerns the selection of the modeling approach to be used which mainly depends on the objective of the study and flow conditions. In general, one-dimensional (1D) and two-dimensional (2D) hydraulic models are commonly used allowing the simulation of steady or unsteady flow. 1D models consider discrete cross-section profiles for defining the channel and floodplain shape and assume that water moves only longitudinally along the river direction. However, the limitation of 1D hydraulic models is that they are not able to provide information on the character and direction of flow as well as the way of flowing off the obstacles.
Conversely, 2D models are mainly raster-based or use a continuous mesh to define the floodplain and the channel while water moves along all cardinal directions (Cook & Merwade 2009; Liu & Merwade 2018). 2D hydraulic models are rather recommended for complex urban settings, but they are usually highly demanding in terms of computational time and required data input (Teng et al. 2017). Moreover, they sometimes pose particular problems like the accurate estimation of river cross-section data and related characteristics like channel depth, top width and flow area (Peña & Nardi 2018). Therefore, the use of 1D hydraulic models is many times preferred.

Flood mapping may vary in terms of the complexity of modeling approaches that are used (Horritt & Bates 2001; Puech & Raclot 2002; Matgen et al. 2007). In recent years, considerable attention has been paid to the understanding and estimation of the modeling uncertainties in order to improve flood mapping procedures and thus flood risk analyses (Dimitriadis et al. 2016; Zeng et al. 2016; Liu & Merwade 2018; Petroselli et al. 2019). Separating single uncertainty sources allows a comparison of the contribution of different uncertainty sources to the overall predictive uncertainty in terms of derived flood products (Apel et al. 2008). The main sources of uncertainty in flood mapping can be divided into the following groups (Apel et al. 2004; Merwade et al. 2008; Bates et al. 2014):

- Uncertainties in the estimation of design discharges and/or design hydrographs with different return periods (Tr) in the hydrologic model. For instance, this group includes uncertainties related to annual maximum discharge estimation, measurement errors, selection of data and partial series, selection of the distribution function of annual maximum discharge, parameter estimation for distribution functions, etc.
- Hydraulic model selection (1D or 2D models) and the choice of flow conditions (steady or unsteady flow).
- Uncertainties in model input data (digital elevation model – DEM, channel bathymetry, roughness parameters, cross-section spacing, and hydraulic structures along the reach). For example, this group contains uncertainties related to changes in river channel over time, parameter estimations, levee failure estimation, etc.

Indeed, the aforementioned studies highlighted the role of DEM characteristics and topographic features (e.g. river–road intersections, bridges, culverts, etc.) in flood modeling.

In this study, a particular modeling approach, represented by the recently developed hydrologic EBA4SUB (Event-Based Approach for Small and Ungauged Basins) model (Grimaldi & Petroselli 2015; Piscopia et al. 2015; Petroselli & Grimaldi 2018) and by the consolidated hydraulic 1D HEC-RAS (Hydrologic Engineering Center’s River Analysis System) model, was selected in order to test the sensitivity of flood mapping, in terms of flooded areas and volumes, to different combinations of input parameters. It is noteworthy that, at the moment, a sensitivity analysis of EBA4SUB input parameters with respect to flood mapping is not present in the literature. Several recent studies highlighted the critical role of hydrologic modeling with respect to flood products. For instance, Nardi et al. (2018) applied the EBA4SUB framework for evaluating extreme hydrologic forcing conditions at the basin scale in order to understand the rationale behind the observed increasing frequency of local urban inundations in the city of Rome. Moreover, it is well known in the literature that the use of the HEC-RAS model for flood mapping applications is strongly dependent on the quality of input data. For example, the DEM correction technique showed significant improvements in the quality of topographic data with a corresponding increase in the HEC-RAS model accuracy, as reported by Bhuyian et al. (2014).

The aims of this study are hence as follows:

1. To investigate the flood mapping sensitivity with respect to the following EBA4SUB input parameters: curve number (CN), concentration time ($T_c$) and gross rainfall distribution (GRD) for different Tr. The resulting design peak discharges were employed in 1D HEC-RAS model using the same hydraulic parameters.
2. To investigate the flood mapping sensitivity with respect to the following 1D HEC-RAS input parameters: roughness and cross-section spacing. Each 1D HEC-RAS application has been performed with the use of the same hydrologic parameters.
STUDY AREA

The Korytářka basin (Figure 1), representing a small and ungauged basin, was chosen as the study area. The total catchment area is equal to 25.25 km². The Korytářka stream, with the total length of 10.9 km, creates a left tributary of the Jablonka watercourse. The highest elevation point has 479 m a.s.l., while the lowest elevation point has 222 m a.s.l. The average slope is 14.1% and the maximum distance of the outlet from the watershed boundary is 9.9 km. The study area belongs to the following administrative units: Western Slovakia (NUTS II), Trenčín Region (NUTS III) and Myjava District (NUTS IV).

The urban area of the Krajné municipality was selected as the hydraulic domain which covers 2.07 km² and the length of the modeled river segment is 1.65 km. Moreover, the Krajné cross-section was chosen as the starting node for hydraulic modeling (Figure 1).

DATA AND METHODS

Data for hydrologic and hydraulic models

The basic input in hydrologic modeling was the DEM which was interpolated from contour lines and elevation points in the topographic map of 1:10,000. The resulting pixel size was 10 m × 10 m (Figure 1). Another important input in hydrologic modeling was the land cover data for which the CORINE Land Cover vector layer (2012) was used (European Commission 2000). As for the soil data, they were provided by the Soil Science and Conservation Research Institute in Bratislava and National Forest Centre in Zvolen. Based on the data, two soil texture types were identified. Medium-heavy loam soils cover the majority of the study area representing 97%. Moreover, heavy clay-loam soils are also found in the catchment covering 3% of the study area. The rainfall data were represented by the annual maxima of daily precipitation for the period 1981–2017 which were observed at the Krajné rain gauge station. Such data allowed the construction of the Intensity–Duration–Frequency (IDF) curves linking rainfall duration, cumulative rainfall depth and return period, as explained in the following. The IDF were determined starting from observed annual maxima daily precipitation values and employing the methodology described in Bara et al. (2010).

In order to create the input data for hydraulic modeling as well as to visualize the model results, the 2 m high-resolution airborne DEM, orthophotos from 2016, as well as vector cadastral map of the Krajné municipality, were used.
Hydrologic EBA4SUB model

Recently, a simple conceptual rainfall-runoff model named EBA4SUB has been developed (Grimaldi & Petroselli 2015; Piscopia et al. 2015; Petroselli & Grimaldi 2018). EBA4SUB consists of the following steps: design hyetograph estimation, excess rainfall estimation and design hydrograph estimation. Rainfall data, land cover and DEM represent the input data while the basin flood hydrograph constitutes the output data.

In the design hyetograph module, it employs the basin IDF curves and different design hyetographs, characterized by a desired rainfall duration, can be selected.

IDF curves allow one to estimate the cumulative gross precipitation value that can be distributed in time at sub-hourly resolution (here a 15-min time resolution has been adopted in order to ensure a minimum number of time steps for calculations). In this study, rectangular and Chicago hyetographs were investigated and the rainfall duration was set equal to the basin concentration time estimated thanks to the Giandotti formula (Giandotti 1934). Leclerc & Schakee’s (1972) areal reduction factor (ARF) was applied transforming the punctual rain gauge information in spatially uniform data occurring in the whole basin. Regarding the choice of setting the rainfall duration equal to the basin concentration time, it must be highlighted that this is an open topic. In the literature, we can find contributions following the theoretic assumption that this choice causes the maximum peak runoff at the outlet compared to shorter or longer rainfall durations. For instance, Šraj et al. (2010) showed that rainfall duration significantly longer than the concentration time can yield significantly different (more than 50% smaller) design peak discharges than design hyetographs with a rainfall duration approximately equal to the catchment concentration time. Conversely, other contributions usually assume rainfall durations 2–3 times larger than concentration time in order to maximize the peak discharge (Viglione & Blöschl 2009; Gaál et al. 2015; Sikoroska et al. 2017).

Excess rainfall is then estimated by applying the CN for Green–Ampt (CN4GA) procedure (Grimaldi et al. 2013b) consisting of two steps: the former step uses the empirical CN method (NRCS 2008) to determine ponding time and cumulative excess rainfall volume:

\[
P_e = \frac{P - I_a}{P - I_a + S} \quad \text{if} \quad P > I_a = \lambda S
\]

\[
P_e = 0 \quad \text{if} \quad P \leq I_a = \lambda S
\]

with \(P_e\) being the cumulative excess rainfall, \(P\) the cumulative gross rainfall, \(I_a\) the initial abstraction, \(\lambda\) the initial abstraction ratio and \(S\) potential retention depending on the CN value. The latter step distributes in time at sub-hourly resolution the cumulative excess rainfall volume employing the physically based infiltration scheme provided by the Green–Ampt equation (1911):

\[
q_0(t) = K_s \left( 1 + \frac{\Delta \theta \Delta H}{I(t)} \right) \quad \text{if} \quad t > t_p
\]

\[
q_0(t) = i(t) \quad \text{if} \quad t < t_p
\]

with \(q_0\) being the infiltration rate, \(i\) the gross rainfall intensity, \(I\) the cumulative infiltration, \(K_s\) the saturated hydraulic conductivity, \(t_p\) the ponding time, \(\Delta H\) the difference between the matric pressure head at the moving wetting front and at the soil surface and \(\Delta \theta\) the change in soil water content between the initial value of soil water content and the field-saturated soil water content. From a practical point of view, we first estimate cumulative excess rainfall with Equation (1) using \(\lambda = 0.2\) and the CN value obtained from look up tables linking CN and land cover. Therefore, by difference, the CN cumulative infiltration is quantified. Ponding time is assumed as the time when \(P(t) = I_w\), given that excess rainfall is zero until \(P(t) < I_w\). Then, literature values for the Green–Ampt (GA) equation parameters were assumed and Equation (2) was applied to compute the cumulative infiltration with GA. The estimated GA infiltration is compared with CN infiltration. If GA infiltration is higher than CN infiltration, Equation (2) is run again using a lower effective saturated hydraulic conductivity value that is the main parameter in Equation (2). The parameter is iteratively reduced until the GA infiltration becomes lower than CN infiltration. Conversely, if GA infiltration is lower than CN infiltration, Equation (2) is run again using a higher effective saturated hydraulic conductivity value. The parameter is iteratively increased until the
GA infiltration becomes higher than CN infiltration. At the end of the iterative procedure, an optimal value for the effective saturated hydraulic conductivity is quantified. According to the previous step, net rainfall is maintained at zero until \( P(t) < I_a \). Consequently, by applying Equation (2) with the estimated saturated hydraulic conductivity parameter, the CN4GA rainfall excess is obtained. This storm has the same cumulative rainfall excess value and the same initial abstraction value derived with the CN method, but it has a physically based temporal distribution.

The design hydrograph estimation is performed using the width function-based instantaneous unit hydrograph (WFIUH-1par) theory (Grimaldi et al. 2012a). WFIUH-1par is a kinematic model estimating the time distribution of all DEM cells to the outlet, thanks to the determination of the surface flow velocity:

\[
WFIUH(t) = \frac{L_c(x)}{v_c(x)} + \frac{L_h(x)}{v_h(x)}
\]

with \( L_c \) and \( L_h \) being the drainage path in the channel cell and along the hillslope cell, respectively, related to the DEM cell \( x \) of the watershed, and \( v_c \) and \( v_h \) the velocity values that are assumed in the channel and in the hillslope. In particular, DEM is first preprocessed in order to remove spurious points such as pits and flat areas in order to derive the flow routing (Petroselli & Fernandez Alvarez 2012). Second, runoff paths are determined for each location of the basin along the DEM-controlled flow direction. Third, the hillslope runoff velocity component is defined as in Grimaldi et al. (2010), employing a formula linking hillslope velocity to pixel slope and land cover. Fourth, the runoff paths are rescaled by associating them to their corresponding flow velocity to obtain the probability distribution of the time required for rainfall drops, not infiltrated or intercepted, to reach the basin outlet. Hillslopes are associated with the flow velocity defined as above, while for the channels a different approach was selected. Indeed, the drainage network velocity is calibrated, imposing that the WFIUH mass center is equal to the basin lag time, which is estimated as 60% of the concentration time. Finally, the design hydrograph is estimated by performing the convolution integral between WFIUH and excess rainfall determined by the CN4GA method:

\[
q(t) = A \int_0^t WFIUH(t - \tau) Pn(\tau)d\tau
\]

with \( A \) being the basin contributing area (\( \text{km}^2 \)), \( t \) the precipitation duration (h), \( \tau \) the time step in precipitation duration (h) and \( Pn(\tau) \) the excess rainfall determined applying the CN4GA method (mm).

EBA4SUB is characterized by two advantages. First, for excess rainfall estimation, it combines the simplicity of an empirical approach with the accuracy of a physically based infiltration scheme. Then, for design hydrograph estimation, it determines the IUH shape using detailed geomorphological information on every basin pixel avoiding the use of synthetic shapes.

Hydraulic 1D HEC-RAS model

The HEC-RAS, which was developed by the U.S. Army Corps of Engineers Center, is one of the most common hydraulic models used worldwide. In addition to the 1D model, the 2D model version was recently developed both allowing to work with steady and unsteady flow conditions.

In this study, the 1D HEC-RAS model and steady-state flow conditions with a downstream condition of normal depth (bed slope \( S = 0.003 \text{ m/m} \)) were applied (HEC-RAS 2010). The basic principle of the model is the determination of a set of cross-section profiles, which should be perpendicular to the direction of river flow, while the calculation of the water level in a given profile is based on the water level in the previous profile. The main input data are represented by the stream centerline, bank lines, cross-sections and land use with roughness coefficients which were manually prepared with the use of HEC-GeoRAS extension and ArcGIS software. Using the HEC-GeoRAS extension, the flood extent is generated through a semi-automated process in which the ground elevation is subtracted from the water surface elevations. The water surface extent points on each cross-section are then linearly joined producing the inundation extent. The channel geometry and floodplain features were modeled based on the 2 m high-resolution airborne DEM.
Investigated parameters and sensitivity analysis

In Table 1, the investigated parameters for hydrologic and hydraulic modeling sensitivity are reported. Fifty-four combinations for hydrologic parameters and 27 combinations for hydraulic parameters were tested to investigate the sensitivity of flood-prone area, in terms of extent and volume, to the input parameters. Different combinations of input parameters were used allowing quantification of the sensitivity of hydrologic and hydraulic modeling with respect to a reference condition. As for the hydrologic sensitivity of the EBA4SUB model, variations of the following input parameters were investigated (Table 1): CN, concentration time ($T_c$) and GRD (rectangular, Chicago) for three return periods (Tr 20, 50 and 100 years).

Reference values for CN and $T_c$ were assumed as 70 and 5 h, respectively, as determined by the EBA4SUB model, thanks to DEM, land cover and soil data, applying the Gandelli formula (1934) and considering the official NRCS look up tables (NRCS 2008) linking land use and CN (selecting AMC II). Regarding CN variation, a $\pm 15\%$ variation with respect to the reference value (determining a range 60–80 for CN) was determined starting from the official NRCS look up tables and associating CN and land cover. In these tables, indeed, the specific land use (e.g. urban areas, pasture, woods, herbaceous and so on) is assigned a CN depending on the poor, fair or good condition. The reported CN variation ranges on average between a 20% difference for hydrologic group soil A (sand) and 5% for hydrologic group soil D (clay). Regarding $T_c$ variation, its determination is subject to high uncertainty, with six computational definitions reported in McCuen (1998) and a number of available empirical formulas at the basin scale, leading to differences that can arrive up to 500% (Grimaldi et al. 2012b). In this study, the formulas reported in Grimaldi et al. (2012b) were applied and values ranging between 2 h (California Culvert Practice formula) and 7 h (KWF – Kirpich approach formula) were obtained. It was decided to remain in the interval 3–7 h with the reference value in the middle.

In terms of the investigated HEC-RAS input parameters, different variations of roughness parameters and cross-section spacing were used for the same return periods. Roughness parameters are represented by Manning’s values. Manning’s values were assigned to different types of a detailed land use of the hydraulic domain based on the work of Chow (1959). Manning’s values range from a minimum to maximum while the normal value represents a sort of averaged state. In this study, the normal values refer to the reference condition. Maximum spacing between two

<table>
<thead>
<tr>
<th>Parameters for hydrologic model sensitivity</th>
<th>Reference condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve number (CN)</td>
<td>60, 70, 80</td>
</tr>
<tr>
<td>Concentration time ($T_c$)</td>
<td>3, 5, 7 h</td>
</tr>
<tr>
<td>Gross rainfall distribution (GRD)</td>
<td>Rectangular, Chicago</td>
</tr>
<tr>
<td>Return period (Tr)</td>
<td>20, 50, 100 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters for hydraulic model sensitivity</th>
<th>Reference condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section spacing</td>
<td>5, 20, 80 m</td>
</tr>
<tr>
<td>Roughness parameters</td>
<td>Normal channel + normal floodplain Normal (Chow 1959) Built-up area: 0.02 Backyard garden: 0.04 Forest: 0.15 Arable land: 0.035 Grassland: 0.035 Orchard: 0.04 Road (asphalt): 0.015 Channel: 0.035</td>
</tr>
<tr>
<td>Return period (Tr)</td>
<td>20, 50, 100 years</td>
</tr>
</tbody>
</table>
cross-sections was estimated by applying Samuel's (1989) formula:

\[ \Delta x \leq 0.15D/S_0 \]  

(5)

where \( \Delta x \) is the maximum cross-section spacing, \( D \) is the average bankfull depth of the channel (m) and \( S_0 \) is the average bed slope (m/m). Based on this formula, the maximum cross-section spacing is 80 m.

**Performed analysis and the use of the dimensionless sensitivity index**

Each hydrologic or hydraulic simulation is characterized by different input parameters and produces, as output, a flood area (FA) map where each pixel is assigned the maximum flow depth obtained during the entire simulation. From this map, the total FA and total FV are calculated by summing the flooded pixel areas (FA) and summing the flooded pixel areas multiplied by the corresponding flow depth (FV), respectively. In order to quantify and compare the obtained results, we make reference to the total values of FA and FV for each simulation, and we also consider a dimensionless sensitivity index (SIULs) that expresses the relative change in the selected output, compared to the reference solution, divided by the relative change in the input for a specific input variable (Grimaldi et al. 2016b).

The sensitivity index is expressed using the following relation:

\[ S_{IUL} = \frac{O_U - O_L}{O_0} \times \frac{P_0}{P_U - P_L} \]  

(6)

where \( \Delta P \) is the change in the parameter vector \( P \) due to a change in the single \( i \)th parameter \( p_i \). \( P_U \) and \( P_L \) are the parameter extreme values defined by selected upper and lower bounds of the generic parameter \( p_i \), while the other input parameters are held constant at their nominal values; \( O_0 \) is the output variable of interest obtained when using the nominal values for the parameter set \( P_0 \), and symbols \( O_U \) and \( O_L \) represent the model output corresponding to the parameter set with the selected upper and lower bounds of parameter \( p_i \). For example, parameter vector \( P1,U \) is equal to \( \{p1,U; p2,0; p3,0; \ldots\} \), with \( p1,U \) being the upper bound for parameter \( p1 \) and \( p2,0, p3,0 \ldots \) being the nominal values for parameters \( p2, p3; \) and so on.

A dimensionless local measure of the sensitivity, as expressed by SIUL, is particularly efficient for comparison purposes. In particular, one advantage of using SIUL is that the parameters are values by accounting for the entire range of their plausible values and not only by a fixed percentage of their respective reference values. In the following analysis, FA and FV will be expressed as selected output variables, while the specific input parameters will be CN and \( T_c \) (both for Chicago and for rectangular GRD) for the hydrologic sensitivity and cross-section spacing and roughness for hydraulic sensitivity.

**RESULTS**

**Determination of design peak discharge for the hydrologic sensitivity**

Figure 2 (left) shows the IDF curves in terms of the relationship between rainfall duration, cumulative rainfall depth

![Figure 2](https://iwaponline.com/hr/article-pdf/50/4/1002/584687/ihr0501002.pdf)
and return period. In Figure 2 (right), the case study WFIUHs are reported. Each combination of $T_c$, CN and GRD furnishes a design hydrograph characterized by a peak discharge. The ensemble of the obtained peak discharges is reported in Table 2.

As it can be seen from Table 2, a great variation for design peak discharges is found. This variation is expected to strongly influence the flooded areas and volumes, as shown in the next paragraph. For Tr 100 years, the calculated peak discharges range from 2.73 m$^3$/s to larger than 40 m$^3$/s.

Regarding the variation of peak discharge with CN, an expected increasing behavior was found for all combinations of $T_c$ and the design hyetograph.

Regarding the variation of peak discharge with $T_c$, two different behaviors emerge. In case of high CN, the increase of $T_c$ causes an increase in cumulative rainfall depth, but this increase is counterbalanced by a lower peak in the WFIUH, and this effect is predominant in the convolution integral, so peak discharges decrease. In case of low CN, the increase of $T_c$ causing an increase of cumulative rainfall depth is predominant with respect to the decrease of the WFIUH peak, so peak discharges increase.

### Table 2 | Design peak discharges for each combination of parameters

<table>
<thead>
<tr>
<th>Design peak discharges (m$^3$/s)</th>
<th>Rectangular GRD</th>
<th>Chicago GRD</th>
</tr>
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<tbody>
<tr>
<td><strong>Tr 20 (years)</strong></td>
<td>$T_c$</td>
<td>$T_c$</td>
</tr>
<tr>
<td>CN 60</td>
<td>0.09</td>
<td>0.74</td>
</tr>
<tr>
<td>CN 70</td>
<td>5.90</td>
<td>6.58</td>
</tr>
<tr>
<td>CN 80</td>
<td>19.03</td>
<td>15.92</td>
</tr>
<tr>
<td><strong>Tr 50 (years)</strong></td>
<td>$T_c$</td>
<td>$T_c$</td>
</tr>
<tr>
<td>CN 60</td>
<td>1.14</td>
<td>2.45</td>
</tr>
<tr>
<td>CN 70</td>
<td>10.29</td>
<td>10.24</td>
</tr>
<tr>
<td>CN 80</td>
<td>25.89</td>
<td>21.21</td>
</tr>
<tr>
<td><strong>Tr 100 (years)</strong></td>
<td>$T_c$</td>
<td>$T_c$</td>
</tr>
<tr>
<td>CN 60</td>
<td>2.73</td>
<td>4.15</td>
</tr>
<tr>
<td>CN 70</td>
<td>13.86</td>
<td>13.28</td>
</tr>
<tr>
<td>CN 80</td>
<td>31.65</td>
<td>25.28</td>
</tr>
</tbody>
</table>

Regarding the variation of peak discharge with the GRD, the obtained results confirm that the Chicago hyetograph has the tendency to overestimate the peak discharge because it represents the critical rainfall for all partial durations of the event, circumstance that could be positive from a precautionary point of view.

The aforementioned statements are true for the majority of combinations, and it is noteworthy that non-monotonic trends could be attributed to the approximation of the computational codes inherent in the solution of the GA equation (that has no exact solution) present in the CN4GA approach.

## Sensitivity of flood mapping to hydrologic modeling

The results of the hydrologic modeling sensitivity in terms of flooded areas (FA) and flooded volumes (FV) are shown in Table 3 and Figure 3. The trends of FA and FV with respect to the input parameters such as CN, $T_c$ and GRD follow what was expressed in the previous paragraph. The monotonic increasing relationships between peak discharge and FA and between FA and FV are both caused by the HEC-RAS modeling approach.

The difference in FA and FV between the CN 70 + $T_c$ 3 h combination and CN 70 + $T_c$ 7 h combination with respect to the reference condition for Tr 100 and Chicago GRD is 1.3% and 3.1% for FA, while for FV it is 2.4% and 6.1% (Table 3). The largest negative and positive differences in FA and FV, in case of Tr 100 and with respect to the reference condition for Chicago GRD, are represented by the CN 60 + $T_c$ 3 h combination (−51.1% difference for FA and −65.2% for FV) and CN 80 + $T_c$ 3 h (46.8% difference for FA and 105.2% for FV) (Table 3 and Figure 4).

With decreasing Tr (50 and 20 years), the differences in FA and FV with respect to the reference condition for Chicago GRD are larger. In case of Tr 50, the largest difference was 56.3% for FA and 123% for FV. Regarding the Tr 20, the largest difference was 72.7% for FA and 136.7% for FV (Table 3).

The results for the SIUL are shown in Figures 5 and 6, respectively, for FA and FV. Considering the $T_c$ parameter, a decreasing trend with the increase in Tr is found with differences in the range of 4.4% to −16.7% for FA and in the range of 6.3% to −24.6% for FV for rectangular GRD.
and in the range of 35.8–4.6% for FA and in the range of 49% to 9.1% for FV for Chicago GRD. Considering the CN parameter, again a decreasing trend with the increase in Tr is found, but with bigger differences in the range of 320–241% for FA and in the range of 463–384% for FV for rectangular GRD and in the range of 387–294% for FA and in the range of 624–503% for FV for Chicago GRD.

### Sensitivity of flood mapping to hydraulic modeling

The results of hydraulic modeling sensitivity are presented in Table 4 and Figure 7, which show the FAs and FVs for different combinations of input hydraulic parameters.

Regarding the cross-section spacing, the difference in FA and FV between the 5 m cross-section spacing and the 80 m...
cross-section spacing with respect to the reference situation for Tr 100 and normal roughness values is 18.9% and 13.3% for FA, while for FV it is 49.4% and 21.1% (Table 4). However, when comparing FA and FV for the combinations of 5 m cross-section spacing + maximum channel/floodplain roughness and 80 m cross-section spacing + minimum channel/floodplain roughness with the reference condition for Tr 100, the difference is greater (27.3% and 26.1% for FA; 63.3% and 35.4% for FV) (Table 4 and Figure 8). With decreasing Tr (50 and 20 years), the differences in FA and FV with respect to the reference condition are even larger. In case of Tr 50, the largest difference was 36.9% for FA and 81.4% for FV. Regarding Tr 20, the largest difference was 52.4% for FA and 105.9% for FV (Table 4).

Regarding the roughness parameter, the differences are similar; however, the values are higher ranging from 18.0% (Tr 100) to 24.1% (Tr 20) for FA and from 28.0% (Tr 100) to 32.0% (Tr 20) for FV. The results for the SIUL and hydraulic sensitivity are shown in Figure 9. As for the cross-section parameter, the values of SIUL range from −8.5% (Tr 100) to −15.8% (Tr 20) for FA, while for FV, the range is from −18.8% (Tr 100) to −30.5% (Tr 20).

**DISCUSSION**

**Sensitivity of flood mapping to hydrologic modeling**

A first comment derives from the concept of \( T_c \). The recent literature (Kjeldsen *et al.* 2016; Michailidi *et al.* 2018; Papaioannou *et al.* 2018) is trying to redefine the concept of concentration time, in particular, toward the application of the so-called varying concentration time, the function of return period and rainfall intensity. In this context, although not performed here for simplicity, it would be convenient to consider different ranges for \( T_c \) for the three examined return periods. As previously mentioned, the concentration time was estimated here for all return periods equal to 5 h for the reference condition and the range of 3–7 h was obtained by applying the formulas used in Grimaldi *et al.* (202b).

A second comment concerns the choice of the time resolution that could affect the results, in particular, for the Chicago hyetograph. From a theoretic point of view, the peak discharge should be higher for a shorter time resolution because the IDF shape provides higher rainfall...
intensity. However, such a circumstance could be limited because the convolution between IUH and rainfall data reduces the expected amplification of the peak discharge. The IUH frequencies should be smaller for shorter resolution times and thus the greater impulse will be convoluted by lower IUH values. Petroselli & Grimaldi (2018), who investigated the time resolution effect, found that the differences in the peak discharge estimation for

Figure 4 | Flood-prone areas for Tr 100: (a) CN 60, $T_c$ 3 h, Chicago GRD, (b) reference condition (CN 70, $T_c$ 5 h, Chicago GRD), and (c) CN 80, $T_c$ 3 h, Chicago GRD.

Figure 5 | SIUL (%) for FA varying $T_c$ and with CN as a reference value (left) and varying CN and with $T_c$ as a reference value (right). Black bars for Tr 20, gray bars for Tr 50, white bars for Tr 100.
time resolutions between 15 and 60 min were limited (maximum 6%).

A third comment concerns the influence of CN selection on peak discharges. CN selection appears of paramount importance, probably, greater than the influence of $T_c$ selection. This aspect is well known in the literature. For instance, Moghadasi et al. (2017) performed a sensitivity analysis on an arid watershed characterized by forest and rangeland degradation and found that a 5% change in CN (from 74 to 78) can cause up to 60% of variation in peak flow estimation. Furthermore, Banasik et al. (2016) indicated high sensitivity of peak discharge to the CN value, with a single increment in the CN value that could change the flood flow up to 6%.

A fourth comment concerns the influence of GRD selection on peak discharges. The obtained results are in line with other studies. For instance, Gong et al. (2016) determined fluctuations in the peak discharge estimation increasing the
rainfall duration and adopting different GRDs (Chicago, alternating block systems, Pilgrim and Cordery distribution). Banasik et al. (2016) determined a similar behavior adopting the rectangular GRD, describing the effect of simultaneous increase in runoff volume and a decrease in rainfall (and runoff) intensity. Such a behavior is in agreement with other
studies. For example, Walega (2016) investigated the GRD effect on the peak discharge, concluding that the hyetograph shape has a significant impact on differences in peak discharges (up to 20%). Moreover, Oliveira & Stolpa (2005) determined that gross rainfall rectangular distribution with duration equal to the basin concentration time generates significantly lower peak flows compared to other hyetograph shapes.

Concerning the simulated flood maps, it is evident that the sensitivity of FA and FV to the parameter CN is several times larger than the sensitivity to the parameter $T_c$. This circumstance is valid for both the GRD and highlights the importance of a correct estimation of soil and land use parameters affecting the excess rainfall estimation. The obtained results were also confirmed by other previous studies. Mosquera-Machado & Ahmad (2007) performed a sensitivity analysis of FAs on peak discharge determining a 50% variation of flood extent for a 25% variation of peak flow. A significant increase in flow depths and flooded areas with the increase in CN was also reported by Tahmasbinejad et al. (2012) and Taghi Dastorani et al. (2011) who state that CN and initial loss are the main parameters affecting the results.

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Regarding the roughness, FA and FV decrease with decreasing values of roughness parameters and vice versa. A similar finding was presented in the study by Dimitriadis et al. (2016). As for the cross-section settings, FA and FV decrease with the increasing cross-section spacing which was also reported by Ali et al. (2015). When cross-sections are placed far apart, the numerical damping of the flood wave (to low of a peak flow downstream) occurs causing the model to be less stable and thus decreasing the overall FA. On the other hand, too many cross-sections may lend great inaccuracies to the model, as reported by Castellarin et al. (2009). As a consequence, the placement (and number) of cross-sections as well as the channel and floodplain geometry have a considerable effect on the flood inundation mapping using the 1D HEC-RAS model (Pappenberger et al. 2005).

Based on the resulting SIUL for cross-section and roughness parameters, it can be stated that the sensitivity of the output variables FA and FV to the roughness parameter is 1.5–2 times greater than the one to the cross-section parameter. This finding is in line with the recent literature (Ali et al. 2015; Papaioannou et al. 2017; Lamichhane & Sharma 2018; Liu et al. 2019) and highlights the importance of a correct determination of roughness parameters as well as cross-section spacing.

**Comparison with the official flood hazard maps**

Regarding the uncertainty in hydraulic model selection and flow conditions, the results of the HEC-RAS model were compared with the official flood hazard maps for the study area produced by the Slovak Water Management Enterprise, a state-owned company. It is the institution responsible for applying the EU Floods Directive and creating the official flood hazard and risk maps for Slovakia. Steady-state flow conditions were used for creating the official flood hazard maps similarly as in this study. On the contrary, the MIKE Flood model was used to perform the analysis. Based on Figure 10, it can be seen that there is a difference in the FA as well as in the flow depth. The total flood extent calculated...
for the official flood hazard map (Figure 10(c)) is 137,095 m². When comparing it with the combination of 5 m cross-section spacing + maximum channel/floodplain roughness (Figure 10(a)), the difference is 14.3% while in case of the reference condition (Figure 10(b)), the difference is 32.6%.

Nevertheless, the reason why these maps are different lies mainly in the estimation of design peak discharges. In this study, the EBA4SUB model was applied while in case of the official flood hazard map, the Dub (1957) regional formula was applied. In Slovakia, this approach represents a sectoral technical standard for estimating peak flow in ungauged basins. The effect of employing the EBA4SUB approach and the regional formula by Dub (1957) on determining flood-prone areas was further investigated by Petroselli et al. (2019).

**CONCLUSION**

This study investigated the sensitivity of the combination EBA4SUB hydrologic model plus the 1D HEC-RAS hydraulic model, in terms of derived flooded areas (FA) and volumes (FV), to different combinations of their input parameters.

Results of the EBA4SUB hydrologic modeling point to the great variation of design peak discharge which strongly influenced the modeled FA and FV. The influence of CN value selection on the estimation of peak discharge appears to be more important and greater than the influence of the selection of correct concentration time ($T_c$).

Regarding the variation of FA and FV with respect to the hydrologic modeling, the sensitivity to CN parameter was
found to be several times larger than the sensitivity to $T_c$ parameter for both investigated GRDs (rectangular and Chicago). This finding highlights the importance of the correct estimation of soil and land use properties which affect the excess rainfall estimation.

As for the sensitivity of FA and FV to hydraulic modeling, the sensitivity to roughness parameter was found to be 1.5–2 times greater than the sensitivity to the cross-section parameter. However, the importance of both input parameters for hydraulic modeling should be highlighted because large differences in the investigated combinations of input parameters were found, as expressed in the Results section, with the differences being greater for smaller return periods.

To summarize, relatively large differences were found, for a short modeled river segment, in terms of flood extent and FV using different combinations of input parameters in the investigated hydrologic and hydraulic modeling approach. Moreover, the sensitivity of flood mapping to hydrologic modeling is greater than the one to hydraulic modeling, i.e. due to hydrologic modeling, larger differences were found in FA and FV with respect to the reference condition compared to hydraulic modeling. Nevertheless, the modeler should carefully estimate the input parameters for the hydrologic–hydraulic modeling approach since they can have a significant influence on determining flood-prone areas or designing flood mitigation structures, in particular for small and ungauged basins. Results of this study show that the most critical issues pertain to the hydrologic modeling and are related to the difficulty in the correct estimation of the CN parameter in order to determine the excess rainfall as well as in the correct estimation of $T_c$ affecting both the flow routing and the basin response to rainfall.

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