

# Flood mapping in small ungauged basins: a comparison of different approaches for two case studies in Slovakia

Andrea Petroselli, Matej Vojtek and Jana Vojteková

## ABSTRACT

Flood mapping is a crucial element of flood risk management. In small and ungauged basins, empirical and regionalization approaches are often adopted to estimate the design hydrographs that represent input data in hydraulic models. In this study, two basins were selected in Slovakia and different methodologies for flood mapping were tested highlighting the role of digital elevation model (DEM) resolution, hydrologic modeling and the hydraulic model. Two DEM resolutions (2 m and 20 m) were adopted. Two hydrologic approaches were employed: a regional formula for peak flow estimation and the EBA4SUB model. Two hydraulic approaches (HEC-RAS and FLO-2D) were selected. Different combinations of hydrologic and hydraulic modeling were tested, under different spatial resolutions. Regarding the DEM resolution, results showed its fundamental importance in the low relief area while its effect was secondary in the moderate relief area. Regarding the hydrologic modeling, results confirmed that it affects the results of the flood areas in the same way independently of DEM resolution and that when using event-based models, the hydrograph shape determination is fundamental. Regarding the hydraulic modeling, this was the step where major differences in the flood area estimation were found.

**Key words** | EBA4SUB, FLO-2D, flood mapping, HEC-RAS, ungauged basins

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## INTRODUCTION

Flood mapping is a crucial element of flood risk management, producing flood hazard maps which show the extent and expected water depths of flooded areas for various scenarios. However, reliable flood mapping is difficult in small ungauged basins due to the lack of observed discharge data that are needed for calibrating the adopted hydrologic and hydraulic models. Indeed, the primary methodology for estimating flood frequency would be fitting a theoretical statistical distribution to available measurements of flood peak discharges, but in the case of ungauged basins the most preferred approaches are the empirical and regional ones, since they do not require calibration.

In Slovakia, the most common approach for estimating design peak discharges in catchments without gauging stations is the regional method by [Dub \(1957\)](#), which is

based on the basin morphometric properties and regional parameters derived for individual regions of Slovakia. This regional method is simple and needs minimum input data; however, it has some drawbacks. For instance, it estimates the peak flow but not the whole design hydrograph, which is usually needed for sophisticated hydraulic models.

On the other hand, conceptual models trying to represent in a simplified form the mechanisms governing the formation of the design hydrograph were developed in many scientific studies. Particularly, one of the recently developed conceptual models is the Event Based Approach for Small and Ungauged Basins (EBA4SUB) ([Grimaldi & Petroselli 2015](#); [Piscopia \*et al.\* 2015](#)).

In order to create a flood map, a hydrologic model must be combined with a hydraulic model. As for the hydraulic

model, the complexity of models ranges from one-dimensional (1D) to two-dimensional (2D) (Apel *et al.* 2009).

1D models can be used for steady and unsteady flow analysis (Mark *et al.* 2004). However, one disadvantage of 1D hydraulic models is that they do not provide information about the character and direction of the flow field or the way of flowing off the obstacles (such as buildings) which is most prominent in urban areas (Horritt & Bates 2002). Although advanced 2D hydraulic approaches are more demanding in terms of computational resources, they are recommended for detailed local spatial scale areas and complex urban settings where the 1D hypothesis is often not applicable (Grimaldi *et al.* 2013a; Ignacio *et al.* 2015).

Nevertheless, inherent uncertainties are present in multiple aspects of the hydrologic-hydraulic (h&h) approaches involving the model structure, model parameters, boundary conditions or input data. These uncertainties may be surprisingly large, even in small basins (Dimitriadis *et al.* 2016). According to Grimaldi *et al.* (2013a), three main issues characterize the current h&h modeling procedure for flood mapping: (1) availability of a detailed topographic information digital elevation model (DEM); (2) impact of the hydrologic modeling; (3) impact of the hydraulic model.

This study investigates all of the three issues in two selected small ungauged basins in Slovakia and focuses on the related uncertainties. Regarding the first issue and its associated uncertainty, it compares a 2 m high-resolution airborne DEM with a resampled 20 m resolution DEM. As for the second issue and its associated uncertainty, the study analyzes the impact of hydrologic modeling on the flood mapping procedure, adopting both the regional method and the EBA4SUB model. In terms of the last issue and its associated uncertainty, this study compares 1D steady flow analysis performed by the HEC-RAS hydraulic model and 2D analysis using the FLO-2D hydraulic model.

The aims of this study are as follows:

- (1) To test EBA4SUB for the first time in two small ungauged basins in Slovakia. The obtained design hydrographs are compared with the corresponding one obtained by the regional method.
- (2) To determine flood prone areas employing different h&h modeling approaches in order to understand which step of the employed methodology affects the results more.

Furthermore, in this study an attempt is made to present an alternative approach to the current methodology adopted in Slovakia for flood mapping using the most recent h&h modeling.

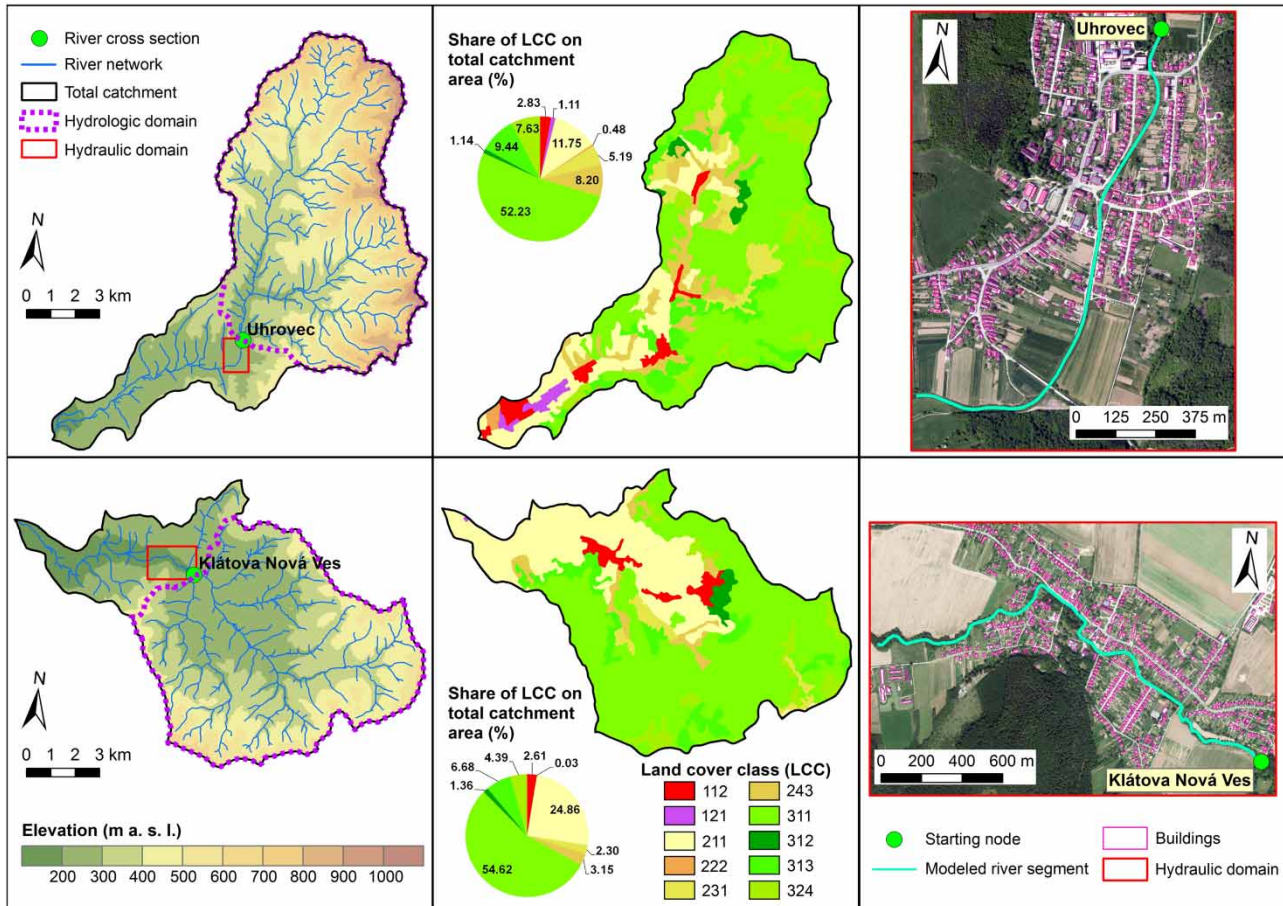
## STUDY AREA AND DATA

The main reasons for the selection of two similar small ungauged basins (i.e. case studies) were the following: first, several flood events occurred in both areas, so the two basins are indeed sensitive zones where anthropic structures are at risk. Second, both case studies have a comparable catchment area, but, on the other hand, they have different topographic (morphometric) and land cover characteristics: testing different h&h methodologies on such basins can help to determine how the differences in attributes affect the flood mapping results.

### Radiša and Vyčoma case studies

Radiša catchment (total catchment area: 110.33 km<sup>2</sup>, selected catchment area with the Uhrovec River cross section as the final outlet for hydrologic modeling: 87.9 km<sup>2</sup>) drains into the main channel of the Bebrava River as its left tributary. Elevations range from 195 to 1,028 m a. s. l., average slope is 27.8% and the maximum hydrologic distance of the outlet from the watershed boundary is 25.1 km. The catchment belongs to Western Slovakia (NUTS II), Trenčín Region (NUTS III) and Bánovce nad Bebravou District (NUTS IV). The selected hydraulic modeling domain is represented by the urban area of the Uhrovec municipality. The Uhrovec River cross section was selected, on the one hand, as the final outlet for hydrologic modeling and, on the other hand, it represents the starting point for hydraulic modeling (Figure 1). The area for hydraulic modeling is 1.4 km<sup>2</sup>.

Vyčoma catchment (total catchment area: 99.94 km<sup>2</sup>, selected catchment area for hydrologic modeling with the Klátova Nová Ves River cross section as the final outlet: 82.7 km<sup>2</sup>) drains into the main channel of the Nitra River as its left tributary. Elevations range from 167 to 712 m a. s. l., average slope is 16.4% and the maximum hydrologic distance of the outlet from the watershed boundary is



**Figure 1** | Case studies DEM and drainage network (left), land cover (center), detail of hydraulic domain (right). Radiša case study: first row. Vyčoma case study: second row.

25.7 km. The catchment belongs to Western Slovakia (NUTS II), Trenčín Region (NUTS III) and Partizánske District (NUTS IV). The selected hydraulic modeling domain represents the urban area of the Klátova Nová Ves municipality. The Klátova Nová Ves River cross section was selected as the final outlet for hydrologic modeling as well as the starting point for hydraulic modeling (Figure 1). The area for hydraulic modeling is 2.7 km<sup>2</sup>.

#### Available data for hydrologic and hydraulic modeling

The DEM used for hydrologic modeling was derived from the interpolation of 1:10,000 contour lines and elevation points using a specific interpolation method for the creation of hydrologically sound DEMs (Hutchinson 1988). The spatial resolution was set to 10 m. Land

cover was derived from the CORINE vector layers for the year 2012 (European Commission 2000) (Figure 1). Soil data for both case studies were provided by the Soil Science and Conservation Research Institute (VÚPOP) in Bratislava and National Forest Centre (NLC) in Zvolen.

The rainfall data included the observed annual maxima of daily precipitation, which were derived from the Slovak Hydrometeorological Institute covering the period 1981–2012 (Vyčoma catchment – Klátova Nová Ves rain gauge station) and the period 1981–2015 (Radiša catchment – Uhrovec rain gauge station).

For the hydraulic modeling, the 2 m high-resolution DEM, current orthophotos (provided by the company GEO-DETICCA, s.r.o.) and vector cadastral maps were used to prepare input data for the hydraulic models.

## METHODS

### Regional formula for peak flow estimation

The employed regional method was introduced by Dub (1954, 1957). This method is based on basin morphometric properties and regional parameters which were derived for different regions of Slovakia. The method was already used for the estimation of maximum discharges in the Vyčoma case study by Vojtek & Vojteková (2016). However, in the present work different river cross sections were determined for the estimation of peak discharges, and revised regional parameters (Makeř et al. 2003) were used instead of original regional parameters.

In this study, the following procedure for estimating design peak discharges ( $Q_T$ ) was applied:

1. The necessary morphometric properties were calculated: catchment area ( $A$ ), forested area ( $A_f$ ), watercourse length ( $L$ ) and catchment shape ( $\alpha$ ).
2. The design discharge with 100-year return period ( $Q_{100}$ ) was calculated:

$$Q_{100} = q_{max} \cdot A \quad (1)$$

where:  $Q_{100}$  – design discharge with 100-year return period ( $m^3/s$ ),  $q_{max100}$  – maximum specific discharge with 100-year return period ( $m^3/s/km^2$ ),  $A$  – catchment area ( $km^2$ ).

Maximum specific discharge with 100-year return period ( $q_{max100}$ ) was calculated:

$$q_{max100} = \frac{B}{A^n} \cdot (1 + c_1 + c_2) \quad (2)$$

where:  $c_1$  – correction factor of afforestation,  $c_2$  – correction factor of catchment shape,  $B$  and  $n$  – revised regional parameters published by Makeř et al. (2003) which characterize the impact of specific region on drainage conditions. The regionalization principle was based on the fact that the selected regions should have similar vegetation cover, land use, topography, geology or hydrologic regime. In the case of Radiša catchment, parameter  $B$  has a value of 5.70 and parameter  $n$  has a value of 0.521, while in the case of Vyčoma catchment, the parameter  $B$  is 6.25 and parameter  $n$  is 0.520.

Correction factor of afforestation ( $c_1$ ), which reflects the impact of forested area ( $A_f$ ) on drainage conditions, was calculated:

$$c_1 = 0.5 \cdot \left( 0.5 - \frac{A_f}{A} \right) \quad (3)$$

where:  $c_1$  – correction factor of afforestation,  $A$  – catchment area ( $km^2$ ),  $A_f$  – forested area ( $km^2$ ).

Correction factor of catchment shape ( $c_2$ ) is characterized by the catchment shape coefficient ( $\alpha$ ), which was calculated according to:

$$\alpha = \frac{A}{L^2} \quad (4)$$

where:  $A$  – catchment area ( $km^2$ ),  $L$  – watercourse length (km).

The values of correction factor of catchment shape ( $c_2$ ) range from  $-0.1$  to  $0.1$  (Mosný 2002):

$c_2 = 0.05$ – $0.1$  fanlike catchment shape ( $\alpha = 1$ ),

$c_2 = 0.0$  moderately protracted catchment shape ( $\alpha = 1/3$ ),

$c_2 = -0.1$  strongly protracted catchment shape ( $\alpha = 1/10$ ).

3. Design discharges ( $Q_T$ ) with  $Tr$ -year return periods were calculated according to:

$$Q_T = a_N \cdot Q_{100} \quad (5)$$

where:  $Q_T$  – design discharge with  $Tr$ -year return period ( $m^3/s$ ),  $a_N$  – regional frequency factor for differently forested catchments (see e.g. Čerkařin (1964) or Mosný (2002)),  $Q_{100}$  – design discharge with 100-year return period ( $m^3/s$ ).

The design hydrographs, needed for hydraulic modeling in order to determine the flood prone areas, were reconstructed synthetically using the SCS (Soil Conservation Service, now NRCS, National Resources Conservation Service) Dimensionless Unit Hydrograph (SCS 1972). Within the framework of the ungauged basin perspective, the standard curvilinear hydrograph shape was adopted and the design hydrograph was determined starting from the



calculated peak discharge values and from the estimated basin concentration time that was calculated with the [Giandotti \(1934\)](#) formula.

### Event-based EBA4SUB model

EBA4SUB is a rainfall-runoff model consisting of three modules: (a) gross rainfall estimation, (b) net rainfall determination, and (c) rainfall-runoff transformation.

In module (a) synthetic design rainfall based on Intensity-Duration-Frequency (IDF) curves can be determined and different design hyetographs can be selected. In this study, the Chicago hyetograph was selected. Rainfall duration was assumed equal to the concentration time ( $T_c$ ), which is estimated from DEM thanks to the [Giandotti \(1934\)](#) formula. An areal reduction factor (ARF) was applied to extend to the whole basin the punctual rain gauge information ([Leclerc & Schaake 1972](#)). Regarding the IDF parameters, they were determined starting from annual maxima daily precipitation values employing the methodology described in [Bara et al. \(2010\)](#).

In module (b) net rainfall is calculated with the CN4GA (Curve Number for Green-Ampt) scheme ([Grimaldi et al. 2013b](#)) consisting of two steps: the first step estimates ponding time and cumulative net rainfall volume thanks to the Curve Number (CN) method ([NRCS 2008](#)).

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{if } P > I_a = \lambda S \quad (6)$$

$$P_e = 0 \quad \text{if } P \leq I_a$$

where  $P_e$  is the total net rainfall,  $P$  is the total gross rainfall,  $I_a$  is the initial abstraction,  $\lambda$  is the initial abstraction ratio and  $S$  is the potential retention related only to the CN value. The second step distributes within the rainfall event the cumulative net rainfall volume according to the physically based [Green & Ampt \(1911\)](#) equation, calibrating the equation parameters automatically:

$$q_0(t) = i(t) \quad \text{for } t < t_p \quad (7)$$

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

where  $q_0$  is the infiltration rate,  $i$  is the gross rainfall intensity,  $I$  is the cumulative infiltration,  $K_s$  is the saturated hydraulic conductivity,  $t_p$  is the ponding time,  $\Delta H$  is the difference between the matric pressure head at the moving wetting front and at the soil surface, and  $\Delta\theta$  is the change in soil water content between the initial value of soil water content and the field saturated soil water content.

The previous equation is implemented assuming that the ponding time is reached when the total precipitation  $P(t)$  is equal to  $I_a$ . The calibration of parameters is automatically performed, matching the cumulate net rainfall values computed by applying Equation (7) and Equation (6). It is noteworthy that this approach combines the accuracy of a physically based infiltration scheme with the simplicity of an empirical approach employing only one parameter (CN). CN was assigned here thanks to [NRCS \(2008\)](#) official tables starting from the land cover data. Hydrologic soil group B was selected for both case studies based on available soil maps, while the initial abstraction ratio ( $\lambda$ ) was fixed at a value of 0.2 as proposed in the original method. Antecedent moisture conditions for wet soil (AMC III) were chosen. It is well known in literature ([Papaioannou et al. 2018](#)) that flood generation is strongly influenced by the soil moisture at the moment of rainfall, and in the present work we decided to adopt an approach favoring safety.

Module (c) performs the transformation of net rainfall in discharge thanks to the WFIUH-1par (monoparametric width function based instantaneous unit hydrograph) ([Grimaldi et al. 2012](#)). WFIUH-1par estimates the surface flow velocity both in river network cells and in hillslope cells, determining the time distribution of all DEM cells to the outlet:

$$WFIUH(t) = \frac{L_c(x)}{v_c(x)} + \frac{L_h(x)}{v_h(x)} \quad (8)$$

where  $L_c$  and  $L_h$  are the drainage path in the channel and along the hillslope, respectively, related to the DEM cell  $x$  of the watershed, while  $v_c$  and  $v_h$  are the assumed velocity values in the channel and along the hillslope. Hillslope cell velocities are different from cell to cell and are determined based on the generic pixel slope and land cover data ([NRCS 1997](#)). Conversely, river velocity is constant in the whole drainage network and is calibrated by imposing

that the center of the WFIUH mass is equal to the basin lag time ( $T_L$ ), which is estimated proportionally to the concentration time ( $T_c$ ) according to the relation  $T_L = 0.6T_c$  (Grimaldi *et al.* 2012). This approach is a peculiarity of EBA4SUB and it allows consideration of the geomorphologic properties in determining the catchment IUH shape.

### Hydraulic models and the employed analysis

Two hydraulic models were employed: one-dimensional HEC-RAS (<http://www.hec.usace.army.mil/software/hec-ras/>) and two-dimensional FLO-2D (<http://www.flo-2d.com/>).

HEC-RAS can employ 1D flood routing in both steady and unsteady flow conditions. Because of its 1D nature, the discharge is distributed within the whole cross section in the longitudinal direction, which may, however, create inconsistencies when multiple flow directions occur or when the flow exchange between the channel and the floodplain cannot be ignored. On the other hand, it is able to sufficiently represent the topography and it has quite low computational demands. The steady flow analysis is based on the solution of the 1D energy equation (used for gradually varied conditions) or momentum equation (used for rapidly varied conditions) between individual cross sections (HEC-RAS 2010). In the investigated case studies, the original 2 m grid resolution DEM was used in the elaborations. Moreover, in order to investigate the effects of topography and to compare the results with the elaborations of FLO-2D, the resampled 20 m grid resolution DEM was also used. The main geometric data influencing the channel geometry in the HEC-RAS model were represented by the stream centerline and cross sections. The channel geometry, which in both cases has a trapezoidal shape, was modeled using the 2 m high-resolution DEM.

FLO-2D is based on the dynamic wave momentum equation solved on a numerical grid of square cells, where resolution depends on the adopted hydrograph peak discharge and on computational limits (O'Brien *et al.* 1993; FLO-2D 2012). In the investigated case studies, the original 2 m DEM was resampled at 20 m grid resolution in order to avoid computational instability problems. In FLO-2D applications, detailed aerial photos and images allowed the hydraulic parameters such as floodplain roughness coefficient, shape and dimensions of channel section to be taken

into account and also allowed simulation of the flow obstruction due to buildings or other floodplain features. In this study, in particular, Manning's roughness coefficients of 0.02, 0.04 and 0.12 were assigned respectively for channel, floodplain-pasture and floodplain-trees. Regarding the channel cross sections, they were approximated, starting from HEC-RAS data, to a trapezoidal shape (45° side slope) with bottom width of 6 m and 10 m for Radiša and Vyčoma, respectively, and a maximum depth of 2.5 m for both case studies. It is noteworthy to consider that the channel geometry can be slightly different from HEC-RAS to FLO-2D, depending on local morphological conditions, and hence it can be a source of uncertainty in the results. Anyway, in our opinion, this uncertainty is inherent in the choice of the adopted hydraulic modeling approach selected by the user.

Both investigated hydraulic models were used to propagate the design hydrographs on the topography, leading to a number of combinations of methodologies for the h&h modeling. For each combination, the flood prone area, in terms of extent, flow depths and flow volumes, was determined. It is noteworthy to highlight that, in FLO-2D elaborations, the flood prone area was determined considering both the channel area and the floodplain area.

The analysis was performed for the following Tr: 2, 5, 10, 20, 50 and 100 years.

## RESULTS AND DISCUSSION

### Flood frequency estimation by different methods

Results of the hydrologic modeling are summarized in Table 1 showing the peak discharge values for different Tr and the total volumes of the design hydrographs. In Figure 2, the design hydrographs are shown in detail and two considerations can be stated.

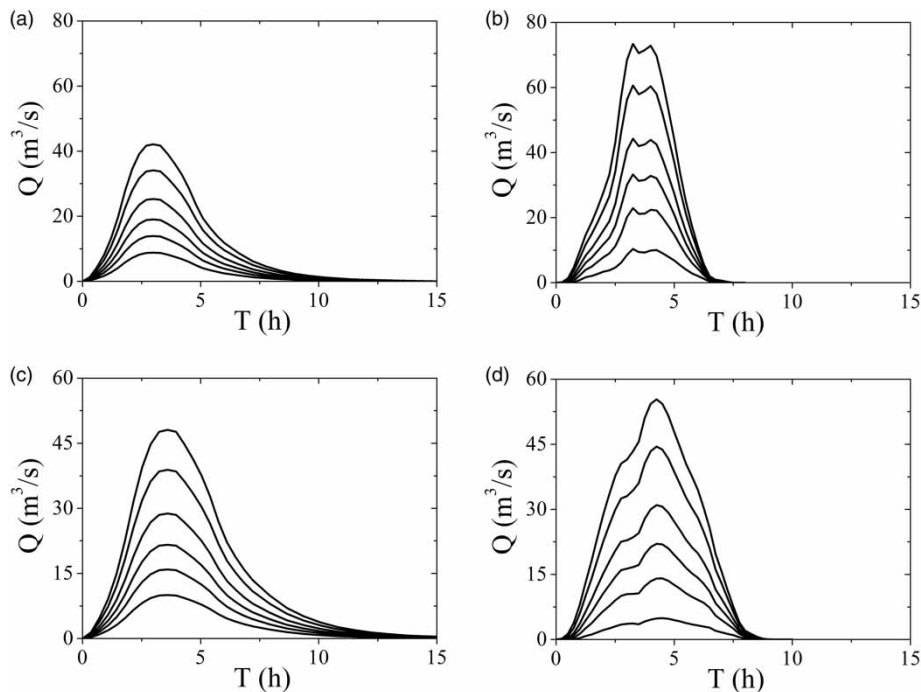
First, peak discharges and total volumes are quite different for the Radiša case study considering the regional method as compared with the EBA4SUB approach. EBA4SUB provides larger values than the regional method, with a difference on average greater than 60% for peak discharges and on average greater than 25% for total volumes, highlighting the importance of hydrologic modeling. Conversely, for the Vyčoma case study, the differences are minor (strongly limited from

**Table 1** | Design hydrographs main properties: peak values ( $Q_T$ ) and total volumes ( $V$ )

		Tr (years)					Case study: Radiša
		2	5	10	20	50	100
Regional method	$Q_T$ ( $m^3/s$ )	8.8	13.9	19.0	25.3	34.1	42.1
	$V$ ( $m^3$ )	125,481	198,203	270,926	360,759	486,240	600,314
EBA4SUB	$Q_T$ ( $m^3/s$ )	10.3	22.9	33.3	44.3	60.6	73.4
	$V$ ( $m^3$ )	110,777	250,004	367,930	492,973	678,993	824,258
		Tr (years)					Case study: Vyčoma
		2	5	10	20	50	100
Regional method	$Q_T$ ( $m^3/s$ )	10.0	15.9	21.6	28.8	38.9	48.1
	$V$ ( $m^3$ )	171,111	272,066	369,600	492,799	665,621	823,043
EBA4SUB	$Q_T$ ( $m^3/s$ )	4.9	14.1	22.1	31.0	44.5	55.4
	$V$ ( $m^3$ )	73,237	210,776	331,249	465,125	670,076	836,749

Tr 10), with EBA4SUB presenting lower values for low return periods and higher values for high return periods, as compared with the regional method. This particular behavior was also not expected, because the two case studies are quite similar in terms of the catchment area (87.9 km<sup>2</sup> vs 82.7 km<sup>2</sup>), IDF parameters (71 mm vs 73.3 mm for 24 h rainfall and for Tr 100) and CN values (78.7 vs 77.8 for AMC III). The explanation of such behavior could be found in different regional parameters ( $B$  and  $n$ ), i.e.

regionalization uncertainty reported, for example, by Szolgay et al. (2003) or Solín (2005), as well as in the geomorphological basin properties, such as the catchment shape and basin slope (27.8% for Radiša case study and 16.4% for Vyčoma case study). This last circumstance causes slower surface flow velocities for the Vyčoma case study, so that its response to rainfall is slower and produces hydrographs characterized by minor peak discharge and greater base time as compared with the Radiša case study.

**Figure 2** | Design hydrographs for different return periods (2, 5, 10, 20, 50, 100 years). (a) Radiša, Regional method; (b) Radiša, EBA4SUB; (c) Vyčoma, Regional method; (d) Vyčoma, EBA4SUB.

Indeed, the WFIUH framework provides an instantaneous unit hydrograph with a base time of 9 hours for Vyčoma catchment and 7 hours for Radiša catchment. Apparently, the regional method is not so able to take into account the basin geomorphological properties. A similar opinion is presented by [Efstratiadis \*et al.\* \(2014\)](#), who also recommend a substantial revision of different flood engineering procedures including the empirical and regionalization formulas as well as the modeling concepts themselves.

Second, a tendency is confirmed for the EBA4SUB framework to overestimate the peak discharge, as compared with the use of the classic rational formula or other empirical formulas, for high return periods and to underestimate it for low return periods ([Młyński \*et al.\* 2018](#); [Nardi \*et al.\* 2018](#); [Petroselli & Grimaldi 2018](#)). These circumstances may be a consequence of the Chicago hyetograph selection and initial abstraction value of the SCS-CN approach that reduces the net hyetographs for low return periods.

### Measurement of flood prone areas' differences

Results of h&h modeling are summarized in [Table 2](#) showing the total flood prone areas and total flood volumes. Before commenting on the differences, it is noteworthy to point out that volumes reported in [Table 2](#) cannot be compared with the corresponding ones reported in [Table 1](#). Indeed, the flood volumes determined employing HEC-RAS are obtained automatically, extending the channel flow depth horizontally until the DEM topography is reached, while the volumes determined employing FLO-2D are based on an asynchronous flow depth map that gives, for each cell, the maximum value of flow depth for the entire simulation.

In the following, the effects of topography, hydrologic modeling and hydraulic modeling are discussed separately in order to highlight which step of the procedure influences the flood areas' delineation more. In particular, the comparison was performed by comparing pairs of approaches reported in [Table 2](#) according to the formula:

$$\frac{X - Y}{Y} * 100 \quad (9)$$

where:  $X$  and  $Y$  are two separate modeling approaches reported in [Table 2](#).

### Differences in flood prone areas due to DEM resolution

The effect of topography on the flood areas' estimation is shown in [Figure 3](#), where the comparison of approaches RFA1 vs RFA3 (and VFA1 vs VFA3) and RFA2 vs RFA4 (and VFA2 vs VFA4) is reported. Comparing RFA1 vs RFA3 (and VFA1 vs VFA3) allows understanding of how much the DEM resolution affects the flood areas using the h&h modeling regional method + HEC-RAS. On the other hand, comparing RFA2 vs RFA4 (and VFA2 vs VFA4) allows understanding of how much the DEM resolution affects the flood areas using the h&h modeling EBA4SUB + HEC-RAS.

The following considerations can be made. Both h&h modeling approaches are sensitive to DEM resolution ([Bates \*et al.\* 2003](#); [Horritt 2006](#)) with differences always being negative and diminishing when the peak discharge increases. This could mean that a high-resolution DEM is able to provide a smaller (in theory more realistic) flood area as compared with a coarser resolution DEM, in particular when the peak discharge is low, a circumstance that implies the beginning of the floodplain inundation. Although this behavior may not be general, such a finding, i.e. the flood inundation area reduces with improved resolution and vertical accuracy in topographic data, was also confirmed by [Cook & Merwade \(2009\)](#). Conversely, when the peak discharge increases, the floodplain begins to be filled, the effect of the flat area begins to cease, and DEM resolution may not be so effective in determining variations of the flood area. Such a finding is in agreement with recent literature (e.g. [Werner 2001](#); [Bhuiyan \*et al.\* 2015](#)). The behavior is confirmed both for the regional method and EBA4SUB, with the change in hydrologic modeling being not significant when using HEC-RAS (FLO-2D was not tested in this analysis since it cannot run with a 2 m resolution DEM for computational limits). It is noteworthy that differences between the RFA1 vs RFA3 (and VFA1 vs VFA3) and RFA2 vs RFA4 (and VFA2 vs VFA4) are greater for the Vyčoma case study. Indeed, following the aforementioned assumptions, DEM resolution has more impact in low relief areas, as confirmed by recent literature ([Petroselli 2012](#); [Petroselli & Fernandez Alvarez 2012](#)). Moreover, [Casas \*et al.\* \(2006\)](#) especially recommend using airborne laser scanning as an input DEM, which produced, in their study, a variation



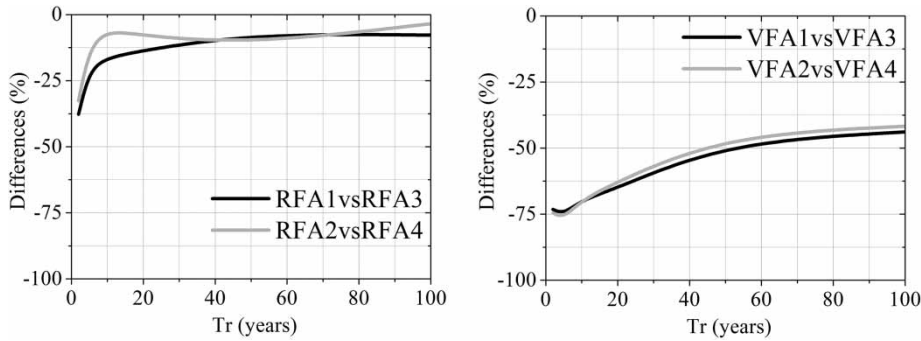
**Table 2** | Flooded areas and volumes

Code	DEM res. (m)	Flood areas (m <sup>2</sup> ) h&h modeling	Tr (years)					Case study: Radiša 100
			2	5	10	20	50	
RFA1	2	Regional method + HEC-RAS	33,644	50,112	60,952	68,148	79,776	89,312
RFA2	2	EBA4SUB + HEC-RAS	37,500	67,032	81,012	90,184	101,896	120,464
RFA3	20	Regional method + HEC-RAS	54,000	63,200	72,800	78,800	86,000	96,800
RFA4	20	EBA4SUB + HEC-RAS	55,600	76,400	86,000	98,000	114,800	124,800
RFA5	20	Regional method + FLO-2D	30,000	30,000	30,000	30,400	31,600	58,800
RFA6	20	EBA4SUB + FLO-2D	30,000	30,000	31,200	69,200	262,400	359,200
Code	DEM res. (m)	Flood volumes (m <sup>3</sup> ) h&h modeling	Tr (years)					Case study: Radiša 100
			2	5	10	20	50	
RFV1	2	Regional method + HEC-RAS	13,058	17,707	22,570	27,517	34,401	40,507
RFV2	2	EBA4SUB + HEC-RAS	14,274	25,944	34,165	41,656	51,951	62,036
RFV3	20	Regional method + HEC-RAS	18,220	22,651	26,981	31,714	37,811	43,915
RFV4	20	EBA4SUB + HEC-RAS	19,561	29,996	37,260	45,212	57,116	65,094
RFV5	20	Regional method + FLO-2D	33,200	43,900	52,320	63,716	79,992	93,492
RFV6	20	EBA4SUB + FLO-2D	36,520	59,252	78,672	96,304	135,120	167,208
Code	DEM res. (m)	Flood areas (m <sup>2</sup> ) h&h modeling	Tr (years)					Case study: Vyčoma 100
			2	5	10	20	50	
VFA1	2	Regional method + HEC-RAS	32,384	39,120	51,872	67,308	107,812	126,368
VFA2	2	EBA4SUB + HEC-RAS	25,964	36,572	53,492	75,160	119,120	140,096
VFA3	20	Regional method + HEC-RAS	120,800	156,800	170,400	193,200	206,400	225,200
VFA4	20	EBA4SUB + HEC-RAS	102,000	156,000	176,400	200,800	216,800	240,400
VFA5	20	Regional method + FLO-2D	42,800	43,600	43,600	44,000	50,400	112,400
VFA6	20	EBA4SUB + FLO-2D	42,800	44,800	45,200	46,000	74,000	219,600
Code	DEM res. (m)	Flood volumes (m <sup>3</sup> ) h&h modeling	Tr (years)					Case study: Vyčoma 100
			2	5	10	20	50	
VFV1	2	Regional method + HEC-RAS	23,392	30,473	37,507	45,331	59,872	69,758
VFV2	2	EBA4SUB + HEC-RAS	15,390	28,401	38,080	48,059	65,526	77,127
VFV3	20	Regional method + HEC-RAS	35,639	46,627	55,569	67,518	80,646	92,523
VFV4	20	EBA4SUB + HEC-RAS	26,465	44,483	57,093	71,099	88,215	102,985
VFV5	20	Regional method + FLO-2D	40,968	54,304	65,768	79,284	93,944	113,284
VFV6	20	EBA4SUB + FLO-2D	27,048	51,572	68,840	86,148	111,188	143,432

of up to only 1% in the modeled flood area of the floodplain, compared with contour-based DEM (50%) and global positioning system (GPS)-based DEM (8%). The same conclusions can be drawn for flood volumes, which are reported only in Table 2 and not shown in figures for brevity. Their values are in the range –30% to –5% for the Radiša case study and in the range –40% to –25% for the Vyčoma case study (for all the investigated approaches and for an increasing Tr).

### Differences in flood prone areas due to flood frequency estimation

The effect of hydrologic modeling on the flood areas' estimation is shown in Figure 4, where the comparison of approaches RFA1 vs RFA2 (and VFA1 vs VFA2), RFA3 vs RFA4 (and VFA3 vs VFA4), and RFA5 vs RFA6 (and VFA5 vs VFA6) is reported. Comparing RFA1 vs RFA2 (and VFA1 vs VFA2) and RFA3 vs RFA4 (and VFA3 vs VFA4) allows



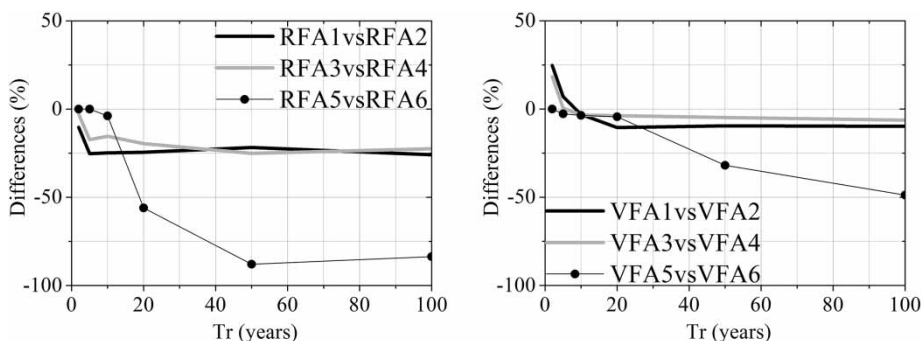
**Figure 3** | Differences in the flood areas due to the topography. Nomenclature as in Table 2.

understanding of how much the hydrologic modeling affects flood areas using 2 m and 20 m resolution DEM and HEC-RAS as the hydraulic model. Moreover, comparing RFA5 vs RFA6 (and VFA5 vs VFA6) allows understanding of how much the hydrologic modeling affects flood areas using the 20 m resolution DEM and FLO-2D as the hydraulic model.

From Figure 4, the following considerations can be made. As expected, with the differences in the hydrologic modeling being greater for the Radiša case study as compared with the Vyčoma case study, RFA1 vs RFA2 and RFA3 vs RFA4 present higher values (on average  $-25\%$ ), as compared with VFA1 vs VFA2 and VFA3 vs VFA4 (on average  $-6\%$ ). It is interesting to note that for the reported modeling approaches, characterized by the use of HEC-RAS, such differences are not influenced by the peak discharges, both for 2 m and 20 m DEM resolution, for Tr greater than 5 years. It is also noteworthy that RFA1 vs RFA2 present the same values as compared with RFA3 vs RFA4 (the same happens for the Vyčoma case study). It is a sign that the choice of hydrologic modeling affects the results of the flood areas in the same way independently

of DEM resolution, which was confirmed and discussed also by Efstratiadis *et al.* (2014).

The situation changes when considering the employment of FLO-2D, i.e. RFA5 vs RFA6 (and VFA5 vs VFA6). In such application, the flood volume is as important as the peak discharge. For both case studies, the differences in flood area increase with the increase in peak discharge and flood volume, meaning that when using event-based models the hydrograph shape determination is also fundamental. Regarding flood volumes, the same conclusions can be stated. For the HEC-RAS modeling approaches, the differences are practically constant and around  $-30\%$  in value for the Radiša case study and around  $-10\%$  for the Vyčoma case study, for Tr greater than 5 years. As for FLO-2D applications, the difference increases with increasing peak discharge (Radiša case study in the range  $0\%$  to  $-84\%$  and Vyčoma case study in the range  $0\%$  to  $-49\%$ ). It is noteworthy to highlight the behavior of flood areas for the Radiša case study, with the difference between RFA5 vs RFA6 becoming quite large for Tr greater than 20 years. This behavior could be due to flood movement over



**Figure 4** | Differences in the flood areas due to the hydrologic modeling. Nomenclature as in Table 2.

the large flat area becoming significant for a particular threshold value of discharge.

### Differences in flood prone areas due to 1D and 2D hydraulic modeling

The effect of hydraulic modeling on the flood areas' estimation is shown in Figure 5, where the comparison of approaches RFA3 vs RFA5 (and VFA3 vs VFA5) and RFA4 vs RFA6 (and VFA4 vs VFA6) is reported. Comparing RFA3 vs RFA5 (and VFA3 vs VFA5) enables understanding of how much the hydraulic model affects the flood areas using the regional method for estimating design hydrographs. On the contrary, comparing RFA4 vs RFA6 (and VFA4 vs VFA6) enables understanding of how much the hydraulic model affects the flood areas using EBA4SUB for estimating design hydrographs.

Again, as expected, differences in the investigated approaches are greater for the Vyčoma case study due to the low relief area. In both case studies, a decreasing trend of such differences can be observed for high return periods. Differences are minor when considering the EBA4SUB application, as compared with the regional method; this is probably due to the often greater peak discharges provided by this method. In terms of absolute values, from a comparison of percentage differences shown in Figures 3–5, the hydraulic modeling is the step where major differences in the flood area estimation were found. This fact was also reported in recent studies on flood mapping issues (Pappenberger et al. 2005; Di Baldassarre et al. 2010; Dimitriadis et al. 2016). As a result, this issue should be carefully taken into account in flood risk studies. The inundation extent predicted by FLO-2D is smaller compared with predictions by HEC-RAS for the Vyčoma case study, while for the Radiša

case study, this tendency is confirmed, with the exception of RFA4 vs RFA6, Tr 50 and Tr 100. A similar finding was reported by Cook & Merwade (2009). Moreover, conceptual problems and poorer predictions performed by 1D models, as compared with 2D models, were reported by Tayefi et al. (2007). Regarding the flood volumes, RFA3 vs RFA5 (and VFA3 vs VFA5) showed that differences were quite stable with the return period (on average –50% for Radiša case study and –15% for Vyčoma case study). Conversely, RFA4 vs RFA6 (and VFA4 vs VFA6) showed a monotonic behavior with the increase in return period, from –45% to –60% for the Radiša case study and from –5% to –30% for the Vyčoma case study.

### Final comparison in flood prone areas

The flood areas' values are shown in Figure 6 for all the investigated methodologies, and visual comparison is provided in Figure 7 for Tr 100 limited to the approaches RFA1, RFA3 and RFA6. RFA1 represents 'standard' methodology for flood mapping in Slovakia, while RFA6 represents an alternative approach to the current methodology using the most recent h&h modeling. RFA3 highlights the role of DEM resolution.

For the Radiša case study, approaches RFA1, RFA2, RFA3 and RFA4 obviously present differences, but they are not so prominent. Using HEC-RAS, the role of topography and hydrologic modeling is secondary. Conversely, the role of hydraulic modeling (RFA5 and RFA6) appears to be fundamental and amplifies the importance of choosing the correct hydrologic modeling. This means that when using a detailed 2D model, where the hydrograph shape and volume are taken into account, also the choice of hydrologic model is critical. For the Vyčoma case study,

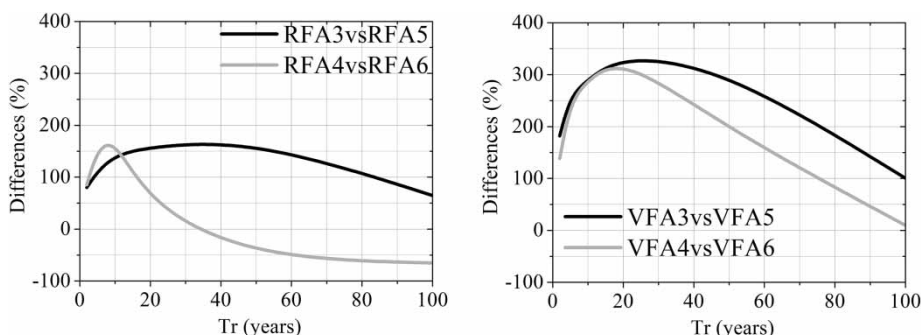
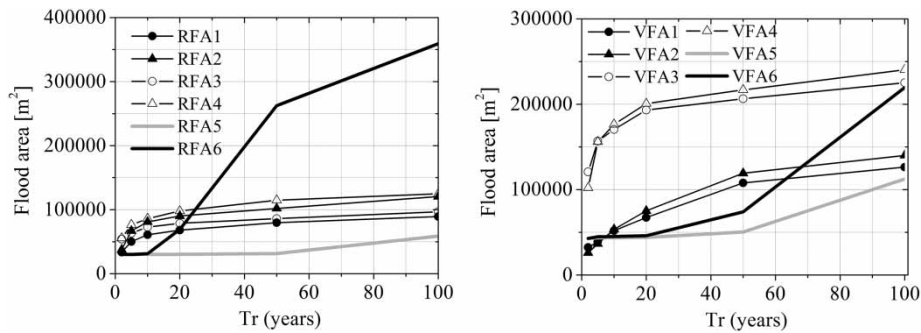


Figure 5 | Differences in flood areas due to hydraulic modeling. Nomenclature as in Table 2.



**Figure 6** | Flood prone areas' extent for all investigated approaches. Nomenclature as in Table 2.

representing a rather low relief area, the role of topography emerges and particular attention must be paid to the quality of DEM resolution. The importance of hydraulic modeling is confirmed also for the Vyčoma case study, where the almost flat area poses particular issues in the flood area estimation.

## CONCLUSIONS

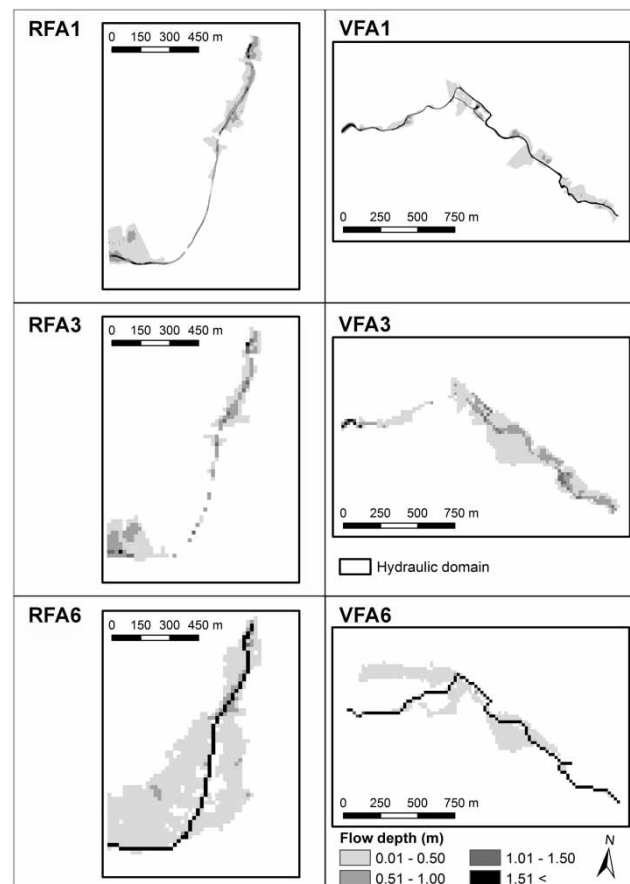
In this study, two small ungauged basins were selected in Slovakia and different methodologies for flood mapping were tested highlighting the role of DEM resolution and h&h modeling. Two DEM resolutions were adopted for determining the effect of topography on flood area estimation. Two hydrologic approaches were employed: regional method, representing the most applied procedure in Slovakia for ungauged basins, and EBA4SUB approach. Moreover, two hydraulic approaches (1D and 2D) were selected. Different combinations of topography and hydrologic and hydraulic modeling were tested in order to quantify the effect of the single step of the procedure on flood mapping.

Regarding the DEM resolution, results showed its fundamental importance in the low relief area, while its effect was secondary in the moderate relief area. Regarding the hydrologic modeling, differences emerged between the two case studies: apparently, the regional method was not able to take into account the basin geomorphological properties and provided different results in terms of peak discharges as compared with the EBA4SUB model. Results confirmed that the choice of hydrologic modeling affects the results of flood areas in the same way independently of DEM resolution and that when using event-based models, the hydrograph shape determination is also fundamental. Regarding the hydraulic modeling, this was the step where major differences in the

flood area estimation were found, so the practitioner should carefully choose the model to be employed.

The accuracy and quality of data as well as employed methodologies may introduce, obviously, sources of uncertainty in achieved results, which should be investigated.

One possible limitation may arise from the use of synthetic design rainfall in terms of hyetograph shape and its



**Figure 7** | Flood prone areas, Tr 100, RFA1-RFA3-RFA6, VFA1-VFA3-VFA6. Nomenclature as in Table 2.



characteristics, such as duration, here assumed equal to basin concentration time, but often assumed two or three times longer in order to maximize the peak discharge.

Furthermore, the quality of DEM is essential for h&h modeling. The best choice would be to use accurate photogrammetrical or LiDAR data, which provides the possibility to create high-resolution DEMs. This was the case in the presented HEC-RAS hydraulic modeling approach, where 2 m high-resolution DEM was used. Because of high demands for computational time needed by FLO-2D when using high-resolution DEMs, the original 2 m DEM was resampled to 20 m DEM.

Regarding the validation of the model results, they can be improved, especially in the case of their comparison to an actual flood event. According to [Apel et al. \(2009\)](#), such validation data are mostly rare, which was also the case for the presented case studies.

Finally, the EBA4SUB model, as the proposed approach for hydrologic modeling and estimation of peak discharges in small ungauged basins, along with 2D hydraulic modeling, can provide suitable alternatives for the review and updating of flood hazard maps in Slovakia, which should be implemented by 22 December 2019 ([European Parliament 2007](#)).

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