Flood hazard and flood risk assessment at the local spatial scale: a case study

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With regard to minimizing flood damage, there are measures of different character each of which has its justification and plays an important role in flood protection. Implementation of traditional flood protection measures is still very important; however, an increasing role should be played particularly by flood prevention and flood risk management. The paper presents a case study on flood hazard and flood risk assessment at the local spatial scale using geographic information systems, remote sensing, and hydraulic modelling. As for determining flood hazard in the model area, which has 3.23 km², the estimation of maximum flood discharges and hydraulic modelling were important steps. The results of one-dimensional hydraulic modelling, which are water depth and flow velocity rasters, were the basis for determining flood hazard and flood risk. In order to define flood risk, the following steps were applied: determining flood intensity on the basis of water depth and flow velocity rasters, determining flood hazard using three categories (low, medium, and high) based on flood intensity, defining vulnerability for the classes of functional areas using three categories of acceptable risk (low, medium, and high), and lastly determination of flood risk which represents a synthesis of flood hazard and vulnerability of the model area.

1. Introduction

Floods are a natural part of the hydrological cycle. However, they have the potential to cause fatalities, displacement of people, and damage to the environment which may also severely endanger the economic development (EU Floods Directive 2007).

Furthermore, some human activities contribute to an increase in the probability of occurrence of flood events and their negative impacts. Anthropogenic impacts can cause the limited natural retention and transformation capabilities of basins (Fohrer et al. 2001; Wooldridge et al. 2001). Insensitive and careless actions in the basin often cause the multiplication of economic damage. Therefore, we are exposed, voluntarily or under the pressure of society development, to the risk of flooding.

We should realize that no protection against floods is absolute. It is necessary to think about the complex and integrated approach to the flood protection (Plate 2002; Pottier et al. 2005; Werritty 2006). With regard to minimizing flood damage, implementation of traditional flood protection measures is still very important. On the other hand, an increasing role should be particularly played by flood prevention and flood risk management (Schanze 2006; EU Floods Directive 2007).
Flood risk management can be basically divided into two parts: flood risk analysis and assessment on one hand and risk mitigation on the other. Broadly speaking, the purpose of flood risk assessment is to establish where the risk is unacceptably high and where mitigation actions are necessary. Risk mitigation means to propose, evaluate, and select measures to decrease risks in these areas. Therefore, the comprehensive analysis and assessment of flood risk is an essential part of the whole risk management concept (Meyer et al. 2009).

The most common approach to define flood risk is that it is the product of hazard, i.e. the physical and statistical aspects of the actual flooding (e.g. return period of the flood, extent and depth of inundation, and flow velocity), and the vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage (Sayers et al. 2003; Apel et al. 2009). This definition is adopted also in the EU Floods Directive (2007). Based on this definition, meteorological, hydrological, and hydraulic investigations to define the hazard and estimation of flood impact to define the vulnerability can be performed separately in the first place, but have to be combined for the final risk analysis (Apel et al. 2009).

In scientific literature, for both the hazard and vulnerability analyses, a number of approaches and models of different complexity levels are available on different scales — from local (e.g. Kourgialas & Karatzas 2011) to global (e.g. Barredo et al. 2007).

Examples of similar studies dealing with the flood hazard and flood risk assessment at the local spatial scale (Beffa 1998; Werner 2001; Baddiley 2003; Dutta et al. 2006; Kubal et al. 2009; Masood & Takeuchi 2012, etc.) suggest that there are several problems and tasks that need to be tackled (Merz et al. 2007).

One of the cardinal problems remains the estimation of maximum flood discharges for various return periods (Apel et al. 2004; Merz & Thieken 2009). Generally, methods for the estimation of N year maximum discharges can be divided into direct and indirect.

Direct methods are based on the field-observed data from gauging stations which are then evaluated by various statistical methods (Vojtek 2014). However, statistical methods and direct observations can have several uncertainties. According to Apel et al. (2008), these uncertainties stem e.g. from the inappropriateness of the extreme value function for the given data series, violation of the underlying assumptions of the extreme value statistics, i.e. stationarity and homogeneity of the data series, and shortness of the data series or large uncertainties in the extrapolation range. Another group of statistical methods is represented by the methods of regional frequency analysis (Zrinji & Burn 1994; Cannarozzo et al. 1995; Hoskings & Wallis 1997; Reed 1999). Regional frequency analysis is based on the idea that if the frequencies of events of a certain size in different river basins are similar, then a more accurate conclusion on their distribution can be achieved by the common analysis of data from basins with similar hydrological reaction than data from one river basin (Bohée et al. 1996).

Estimation of N year maximum flood discharges out of the gauging stations is generally based on the use of indirect rainfall–runoff methods. They include regional methods (Kohnová et al. 2005) which are based on physical-geographical parameters of the catchment. In Slovakia, the regional formula by Dub (1957) is widely used. Moreover, the transformation of rainfall to runoff may be applied e.g. using the method of unit hydrograph or deterministic models with spatially differentiated or non-differentiated parameters (Beven 2000). Eventually, the accuracy of the calculated extent of flooded area depends on the method which is chosen to estimate the maximum flood discharges.

Hydraulic modelling is another crucial step in determining flood hazard and flood risk at the local spatial scale. First, the selection of mathematical model is important. Depending on the scale of the hazard or risk analysis, the complexity of models applied range from simple interpolation methods to sophisticated and spatially detailed models solving the water equations in two dimensions (Apel et al. 2009). Second, it is the acquisition or creation of necessary input data (orthophotos, digital elevation model (DEM), hydrological data, etc.). Especially, the role of digital elevation model (DEM) is important since its accuracy can significantly affect the resulting quality of flood maps (Moore et al. 1991).
The use of one-dimensional (1D) or two-dimensional (2D) hydraulic models is preferred at the local spatial scale. On the other hand, modelling tools incorporated in geographic information systems (GIS) are also powerful (Zerger 2002; Kourtigialas & Karatzas 2011). The comparison of different 1D and 2D models is presented e.g. in the works of (Horritt & Bates 2002; Alho & Aaltonen 2008) or Leedal et al. (2010). Findings of these works suggest that 1D hydraulic models are preferred for the steady flow analysis. Moreover, most of them are compatible with GIS where pre-processing and post-processing tasks are carried out (De Roo et al. 2000; Maidment & Djokic 2000; Zerger & Wealands 2004; Cesur 2007). Two-dimensional hydraulic models are rather used for solving unsteady flow tasks which are more demanding for input data. On the other hand, they are able to simulate the extent of flooded area at different time intervals (Bates & De Roo 2000; Horritt & Bates 2001). All in all, the question of what model should be used in order to give reasonable results is often answered pragmatically given the characteristics of the study area, available resources, and data.

In this paper, the aim is to present a case study on flood hazard and flood risk at the local spatial scale. As a whole, the methods used propose an integrated approach to their assessment using GIS, remote sensing and hydraulic modelling. The important steps in determining flood hazard were the estimation of maximum flood discharges \( Q_{1000}, Q_{100}, Q_{50} \) using indirect regional methods and 1D hydraulic modelling. In order to define flood risk for each flood scenario \( Q_{1000}, Q_{100}, Q_{50} \), the method consisting of four interconnected steps was applied. The proposed steps aimed at determining flood intensity, hazard categories, vulnerability of the model area, and flood risk as the synthesis of hazard and vulnerability. By this study, we try to introduce universal methods which could be applied to other similar flood-prone areas at the local spatial scale.

2. Study area

The study area is represented by the catchment of Vyčoma stream (99.9 km\(^2\)) which is located in the Nitra River Basin in Slovakia. Geographic coordinates of the Vyčoma catchment are 48°29’N, 48°35’N, and 18°12’E, 18°26’E. The Vyčoma stream forms a left tributary of the Nitra River and has a length of 25.2 km.

The catchment is a part of two geomorphological units — Podunajska pahorkatina (hills) and Tribeč (mountain). The highest point has an altitude of 715 m a. s. l. and it is located near Javorový vrch (730 m a. s. l) in the southern part of the catchment. The lowest point has an altitude of 168 m a. s. l. and it is located in the confluence of the Vyčoma stream and Nitra River (figure 1).

The study area lies in the temperate climate zone. Average annual rainfall is 600–700 mm and towards the mountains rises to 800 mm (Lapin et al. 2002).

From the administrative point of view, the catchment belongs to the Western Slovakia (NUTS II), Trenčín Region (NUTS III), and Partizánske District (NUTS IV).

For the purposes of flood hazard and flood risk modelling, a smaller model area was chosen from the Vyčoma catchment. The model area is represented by the built-up area of the Klátova Nová Ves municipality through which Vyčoma stream directly flows (figure 1). The model area covers 3.23 km\(^2\) and the main reasons for its selection were:

- The occurrence of several flood events in the municipality of Klátova Nová Ves (e.g. in April and June 1994, June 1995, June 1999, June 2010, and the last in April 2013),
- It represents the local spatial scale which allows detailed elaboration of flood hazard and flood risk maps,
- The presupposition of the occurrence of flood situations in the future.

3. Methods

Given the aim of the paper, the methods used required the application of different data or specialized software.
3.1. Methods for calculating maximum discharges (flood scenarios)

Since there is no gauging station in the model area, indirect rainfall-runoff methods, which are based on empirical formulas, were used to estimate maximum flood discharges with return periods of 1000, 100, and 50 years.

The values of maximum flood discharges \( Q_{\text{max}} \) were calculated for the profile in the municipality of Klášťová Nová Ves in the confluence of Vyčoma stream and Turčiansky potok stream and also for final profiles of Hradský potok stream, Turčiansky potok stream, and unnamed stream which are tributaries of the Vyčoma stream within the model area.

According to Makel’s et al. (2003), in Slovakia the most widespread and in practice used method for estimating maximum flood discharges \( Q_{\text{max}} \) in profiles without gauging stations and catchments having more than 20 km\(^2\) is a method using exactly derived regional dependence of maximum specific discharge with 100-year return period \( q_{\text{max100}} \) on the catchment area. It is called the regional formula which is based on morphometric and morphological characteristics and regional parameters which were derived on the basis of regression analysis of peak discharges for individual regions of Slovakia (Dub 1957).

First, the calculation of maximum flood discharges was based on determining morphometric and morphological characteristics such as catchment area \( S_p \), forested area \( S_f \), stream length or valley line \( L_v \), and catchment shape \( \alpha \).

The maximum flood discharge with 100-year return period \( Q_{\text{max100}} \) was calculated as the multiplication of the maximum specific discharge with 100-year return period \( q_{\text{max100}} \) and catchment area \( S_p \) according to equation (1) (Dub 1957):

\[
Q_{\text{max100}} = q_{\text{max100}} \cdot S_p
\]  

(1)

The maximum specific discharge with 100-year return period \( q_{\text{max100}} \) was calculated according to equation (2) (Dub 1957):

\[
q_{\text{max100}} = \frac{A_o}{S_p^n \cdot (1 \pm o_1 \pm o_2)}
\]  

(2)
Equation (2) includes regional parameters $A_0$ and $n$ which characterize the impact of a specific area on drainage conditions. The Vyčoma catchment was assigned into the area no. 4 (see Dub (1957)) where the parameter $A_0$ has a value of 4.8 and parameter $n$ has a value of 0.415.

To make the formula flexible and to account the local runoff-forming conditions in more detail, different correction factors from the average type were developed (Kohnová et al. 2005). Correction factor of afforestation ($o_1$) reflects the impact of forested area or percentage of forested area ($S_f$) on drainage conditions and was calculated based on equation (3) (Mosný 2002):

$$o_1 = 0.5 \cdot \left(0.5 - \frac{S_f}{S_p}\right)$$

Correction factor of catchment shape ($o_2$) is characterized by the catchment shape coefficient ($\alpha$) which was calculated according to equation (4), where $S_p$ is catchment area and $L_p$ is the catchment length:

$$\alpha = \frac{S_p}{L_p^2}$$

Then, the correction factor of catchment shape can have the following values (Mosný 2002):

- $o_2 = 0.05 - 0.1$ for fanlike catchment shape, $\alpha = 1$,
- $o_2 = 0.0$ for moderately protracted catchment shape, $\alpha = 1/3$,
- $o_2 = -0.1$ for strongly protracted catchment shape, $\alpha = 1/10$.

A regional frequency factor $a_N$ is used to calculate other maximum flood discharges ($Q_{\text{max}N}$) with a return period of $N$ years based on the maximum flood discharge with 100-year return period ($Q_{\text{max}100}$). Its values for differently forested catchments are provided by Dub (1957) or Mosný (2002). The resulting values were calculated based on equation (5):

$$Q_{\text{max}N} = a_N \cdot Q_{\text{max}100}$$

### 3.2. Hydraulic modelling

As for hydraulic modelling, 1D hydraulic model HEC-RAS version 4.1.0 was used. The decision to choose this 1D model was influenced by the possibility of two-way conversion of formats between GIS and the model and its free availability. In the case of hydraulic modelling, the model area is represented by the built-up area of the Klášťová Nová Ves municipality through which Vyčoma stream (3802.62 m) flows as the main watercourse with the right tributaries of Turčiansky potok stream (782.00 m) and unnamed stream (812.86 m) and left tributary of Hradský potok stream (338.17 m) (figure 2).

#### 3.2.1. Data preparation

The work with HEC-RAS model was preceded by the preparation (pre-processing) of geometric input data using HEC-GeoRAS extension which is compatible with ArcGIS software. The bases for their creation were orthophotos from the year 2011 and DEM.

Geometric data entering into the model were represented by the stream centrelines, bank lines, flow paths, cross-sections, bridges, culverts, and land use with the Manning’s roughness coefficients. A total of 14 cross barriers were identified in the model area (bridges, culverts, and footbridges). Basic geometric input data (stream centrelines, bank lines, flow paths, cross barriers — bridges, culverts and footbridges) are shown in figure 2.

Hydraulic modelling requires a quality DEM (Vojtek et al. 2013). Therefore, photogrammetrically measured data from aerial images in the form of 5360 field points and also breaklines
(lineamental edges) were used as input data. From these input data, the DEM in the form of triangulated irregular network (TIN) was created where elevations range from 189 to 400 m a. s. l. (Figure 3).

Cross-sections are very important input data and they were chosen in the way they best characterize the terrain. Therefore, they were created in the places with changing flow direction because the model tends to linearize segments between the cross-section profiles. A total of 214 cross-sections were created on the Vyčoma stream, Hradský potok stream, Turčiansky potok stream, and unnamed stream with the average distance of 26 m among them.
Another input layer was the polygon layer of land use with Manning’s roughness coefficients which were assigned to different types of land use based on the work of Chow (1959). They are listed in Table 1 and land use of the model area is presented in Figure 4. The lowest value of Manning’s roughness coefficient was assigned to asphalt roads (0.016) and built-up area (0.020). On the other hand, the highest roughness value was assigned to forests (0.150) followed by landscape and residential vegetation (0.060).

In the final phase of data preparation, an export file, was created for the HEC-RAS model consisting of the geometric data and DEM.

### 3.2.2. 1D hydraulic modelling

The first step in creating the hydraulic model was to import geometric data which were prepared in GIS using HEC-GeoRAS extension.

In order to perform the steady flow analysis, the next important step was to specify the values of upper and lower boundary conditions for the stations in the model area. The maximum flood discharges for high ($Q_{50}$), medium ($Q_{100}$), and low probability of occurrence ($Q_{1000}$) were used as upper boundary conditions.

For the lower boundary condition, which defines the streamflow characteristics at the lower part of the created model, the presupposition of a uniform streamflow was chosen where the slope of the

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**Table 1.** Manning’s roughness coefficients for different land use (modified according to Chow 1959).

| Land use                        | Manning’s roughness coefficient |
|---------------------------------|--------------------------------|
| Roads (asphalt)                 | 0.016                          |
| Landscape and residential vegetation | 0.060                      |
| Forest                          | 0.150                          |
| Meadows                         | 0.040                          |
| Arable land                     | 0.035                          |
| Water bodies                    | 0.035                          |
| Stream (natural channel)        | 0.035                          |
| Stream (modified channel)       | 0.027                          |
| Built-up area                   | 0.020                          |

**Figure 4.** Land use in the model area from the viewpoint of Manning’s roughness coefficients.
energy line, water level, and stream bed is identical since there is not any defined object in the watercourses.

Outputs from the model were processed in GIS using the HEC-GeoRAS extension. Post-processing was aimed at processing of water levels for individual cross-sections and generating a surface model of water levels in TIN format. Intersection of TIN terrain model and TIN model of water levels generated the water depth. In addition to water depth rasters, flow velocity rasters were created from the field of cross-cutting velocities in individual cross-section profiles or their parts.

3.3. Determination of flood hazard and flood risk

When determining the flood hazard and flood risk, as a basis the risk matrix method was used (Beffa 1998; Říha et al. 2005; Drbal et al. 2008, 2009). However, it was modified to a wider context introducing new approach. The proposed approach thus consists of four main steps:

1. determination of flood intensity,
2. determination of flood hazard (in categories),
3. determination of vulnerability, and
4. determination of flood risk.

3.3.1. Determination of flood intensity

Input data for the calculation of flood intensity (FI) were the rasters of water depth ($d$) and flow velocity ($v$) for each flood scenario ($Q_{50}$, $Q_{100}$, $Q_{1000}$) using the equation (6):

$$FI = \begin{cases} 
0 \rightarrow d = 0 \text{ m} \\
\rightarrow d > 0 \text{ m}, v \leq 1 \text{ m/s} \\
\rightarrow v > 1 \text{ m/s}
\end{cases}$$

(6)

3.3.2. Determination of flood hazard

When defining flood hazard in the model area, the flood intensity for each flood scenario was used. We assumed that if the flood intensity is greater within the flooded area, the flood hazard is also greater. In terms of the works of Beffa (1998), Říha et al. (2005) and Drbal et al. (2009), we created hazard categories which were modified from the stated four to three (table 2).

In addition to the number of hazard categories, the sizes of their corresponding flood intensities were also adjusted. From the viewpoint of the model area and its characteristics, the size of flood intensity for each category was reduced. In the case of high hazard, the flood intensity was adjusted from $FI > 2$ to $FI > 1$, for medium hazard the value changed from $0.5 < FI \leq 2$ to $0.3 < FI \leq 1$, and low hazard value changed from $FI < 0.5$ to $FI < 0.3$. Moreover, table 2 provides the description
of each hazard category in the form of proposed recommendations and restrictions from the field of spatial (urban) planning and construction.

3.3.3. Determination of vulnerability and determination of flood risk

To determine vulnerability, information on functional land use was used. It was obtained from the cadastral maps, orthophotos from the year 2011, and field research. Each area was assigned an attribute about how it is currently used. The functional areas were then categorized into the classes of functional areas according to the methodology of spatial planning and local development plan of municipality (URBION 2012).

In the final stage, each class of functional areas was assigned three categories of acceptable risk. The categories of acceptable risk were assigned to the classes of functional areas primarily on the basis of their sensitivity to the flood hazard or potential damage. The model area thus contains areas where the minimum flood risk is tolerated such as residential areas, areas of civic amenity, areas of agricultural and forestry production, areas of technical amenity, areas of transport amenity, and areas of specific amenity. Furthermore, there are areas with medium acceptable risk such as recreational areas and areas of residential greenery. Areas with high acceptable risk are represented by agricultural land, forest areas, areas of landscape greenery, and areas of watercourses and reservoirs (figure 5).

In terms of determining vulnerability of the model area, a polygon layer of buildings was created characterizing every building in the model area. Moreover, a point layer of address points was also created representing postal addresses of each building in the model area. They are defined by attributes such as ID, name of the region, district, and municipality, building number, type of building, number of flats, land parcel, x, y coordinates, etc. The address points were classified into family houses, apartment houses, and other buildings (figure 5).

Within the classes of functional areas, there are also objects that need increased attention regarding the assessment of acceptable risk. These sensitive objects were identified in the model area (particularly ambulatory care centre, energetics facility, immovable cultural monuments, and primary school) and localized by point signs in the vulnerability map (figure 5). Its content also includes classes of functional areas with defined acceptable risk and buildings with corresponding address points.

![Figure 5. Vulnerability map of the model area.](image-url)
Creation of flood risk maps was based on the overlay of the vulnerability map and flood hazard maps for the defined flood scenarios ($Q_{50}$, $Q_{100}$, $Q_{1000}$).

4. Results

4.1. Maximum flood discharges (flood scenarios)

Regional formula by Dub (1957) was applied to calculate the maximum flood discharges of $Q_{1000}$, $Q_{100}$, $Q_{50}$ for the streams in the model area. The resulting values along with the maximum specific discharge with 100-year return period ($q_{\text{max}100}$) and parameters entering into their calculation are shown in table 3. The maximum flood discharges for the Vyčoma stream, as the main watercourse in the model area, are 49.00 m$^3$/s ($Q_{50}$), 60.50 m$^3$/s ($Q_{100}$) and 102.84 m$^3$/s ($Q_{1000}$). Regarding the other streams in the model area, the maximum flood discharges are substantially lower as compared to the main watercourse (table 3).

The calculated maximum flood discharges for high ($Q_{50}$), medium ($Q_{100}$), and low probability of occurrence ($Q_{1000}$) represent the upper boundary conditions for the specified stations in the model area. They define the course of water level or discharge at the upper edge of the created hydraulic model. Values of the upper boundary conditions are shown in table 4.

4.2. Hydraulic modelling

Results of the steady flow analysis had to be verified in the model. The illogical inundations, which are produced with a tendency of the model to place water into the lowest parts within the cross-section profiles, were manually removed. Corrected results of the steady flow analysis were exported into GIS which allows to further work with them.

The resulting rasters of water depth and flow velocity for the maximum flood discharges of $Q_{1000}$, $Q_{100}$ and $Q_{50}$ have the resolution of 1 $\times$ 1 m.

Water depth for the flood scenario of $Q_{1000}$ (figure 6(a)) reaches the maximum value of 3.15 m which is mostly in the stream channel. As for the flood discharge of $Q_{100}$ (figure 6(b)), the water depth ranges from 0.01 to 2.64 m while for the flood scenario of $Q_{50}$ (figure 6(c)) it is from 0.01 to 2.58 m.

Table 3. Maximum flood discharges according to the regional formula by Dub (1957).

| Stream name          | $A_0$ | $n$  | $S_1$ (%) | $S_o$ (km$^2$) | $a_1$ | $\alpha$ | $a_2$ |
|----------------------|-------|------|-----------|-----------------|-------|----------|-------|
| Vyčoma stream        | 4.8   | 0.415| 60.8      | 82.7            | -0.12 | 0.709    | 0.07  |
| Hradský potok stream| 4.8   | 0.415| 18.4      | 20.5            | -0.20 | 0.326    | 0.00  |
| Turčiansky potok stream| 4.8  | 0.415| 1.7       | 4.3             | 0.05  | 0.233    | -0.05 |
| Unnamed stream       | 4.8   | 0.415| 0.4       | 2.3             | 0.16  | 0.294    | 0.00  |

| Stream name          | $q_{\text{max}100}$ (m$^3$/s km$^2$) | $a_n (Q_{50})$ | $a_n (Q_{100})$ | $Q_{50}$ (m$^3$/s) | $Q_{100}$ (m$^3$/s) | $Q_{1000}$ (m$^3$/s) |
|----------------------|-------------------------------------|----------------|-----------------|-------------------|-------------------|----------------------|
| Vyčoma stream        | 0.599                               | 0.81           | 1.70            | 49.00             | 60.50             | 102.84               |
| Hradský potok stream| 1.041                               | 0.81           | 1.70            | 18.23             | 22.51             | 38.27                |
| Turčiansky potok stream| 2.934                              | 0.81           | 1.70            | 7.91              | 11.30             | 19.20                |
| Unnamed stream       | 4.746                               | 0.81           | 1.70            | 6.31              | 9.02              | 15.33                |

Table 4. Maximum flood discharges in profiles (stations) — upper boundary conditions.

| Stream name          | Stationing (m) | $Q_{50}$ (m$^3$/s) | $Q_{100}$ (m$^3$/s) | $Q_{1000}$ (m$^3$/s) |
|----------------------|----------------|--------------------|---------------------|----------------------|
| Vyčoma stream        | 3802.62        | 16.55              | 17.67               | 30.04                |
| Vyčoma stream        | 3271.07        | 22.86              | 26.69               | 45.37                |
| Vyčoma stream        | 2578.18        | 41.09              | 49.20               | 83.64                |
| Vyčoma stream        | 2016.39        | 49.00              | 60.50               | 102.84               |
| Unnamed stream       | 812.86         | 6.31               | 9.02                | 15.33                |
| Hradský potok stream| 338.17         | 18.23              | 22.51               | 38.27                |
| Turčiansky potok stream| 782.00       | 7.91               | 11.30               | 19.20                |
Regarding the flow velocity for the flood discharge of $Q_{1000}$ (figure 7(a)), its values range from 0.01 to 3.77 m/s. As for the flow velocity during the flood scenario of $Q_{100}$ (figure 7(b)), the maximum is represented by the value of 3.37 m/s while for the flood discharge of $Q_{50}$ (figure 7(c)) it is 3.32 m/s.

Figure 6. Water depth in the model area for the flood scenario: (a) $Q_{1000}$ (b) $Q_{100}$ (c) $Q_{50}$. 
4.3. Flood hazard and flood risk in the model area

Flood hazard and flood risk were assessed for each modelled flood scenario separately. It is clear that the overall size of inundations is larger with increasing maximum flood discharge.

Figure 7. Flow velocity in the model area for the flood scenario: (a) $Q_{1000}$ (b) $Q_{100}$ (c) $Q_{50}$.
Table 5. Size of flood hazard categories for flood scenarios of $Q_{1000}$, $Q_{100}$, and $Q_{50}$.

| Category of flood hazard | $Q_{1000}$ Area (ha) | $Q_{100}$ Area (ha) | $Q_{50}$ Area (ha) |
|--------------------------|-----------------------|---------------------|-------------------|
| Low                      | 15.03                 | 14.18               | 11.49             |
| Medium                   | 20.95                 | 9.98                | 6.70              |
| High                     | 5.44                  | 4.10                | 3.75              |
| Total                    | 41.42                 | 28.26               | 21.94             |

Figure 8. Flood hazard in the model area for the flood scenario: (a) $Q_{1000}$; (b) $Q_{100}$; (c) $Q_{50}$.
Flood hazard maps show areas with their corresponding hazard categories and flooded buildings for each flood scenario.

The total inundated area for the maximum flood discharge of $Q_{1000}$ has 41.42 ha (table 5). Flood hazard is mostly medium (20.95 ha) or low (15.03 ha). High flood hazard occurs primarily within the stream channels except a few minor inundations outside them (5.44 ha) (figure 8(a)).

As for the maximum flood discharge of $Q_{100}$, the total inundated area has 28.26 ha (table 5). Flood hazard is mostly low (14.18 ha) or medium (9.98 ha). High flood hazard occurs in the stream channels with the exception of some other minor inundations (4.10 ha) (figure 8(b)).

Regarding the maximum flood discharge of $Q_{50}$, the total inundated area has 21.94 ha (table 5). Flood hazard is mostly low (11.49 ha) or medium (6.70 ha) while high flood hazard remains mostly in the stream channels (3.75 ha) (figure 8(c)).

Flood risk was determined in terms of the flood risk definition which says that it is the synthesis of information on flood hazard and vulnerability of the model area. Flood risk maps thus present flooded classes of functional areas with corresponding acceptable risk along with flooded buildings within each flood scenario ($Q_{1000}$, $Q_{100}$, $Q_{50}$).

As for the flood scenario of $Q_{1000}$, the largest flooded area is represented by the category of low acceptable risk where mostly residential areas (16.67 ha) with more than 120 houses are flooded. Moreover, areas with high acceptable risk such as agricultural land (10.26 ha) or watercourses and reservoirs (7.86 ha) are also endangered by this flood scenario (table 6; figure 9(a)).

Flood risk for the flood scenario of $Q_{100}$ is mostly represented by the classes of functional areas having high acceptable risk with 14.13 ha of flooded area e.g. watercourses and reservoirs (7.32 ha) or agricultural land (6.52 ha). However, residential areas (11.03 ha) with more than 70 houses represent the most flooded class of functional area (table 6; figure 9(b)).

### Table 6. Size of flooded classes of functional areas for the flood scenarios of $Q_{1000}$, $Q_{100}$ and $Q_{50}$.

| Class of functional area | Flooded area (ha) | Category of acceptable risk | Flooded area (ha) |
|-------------------------|-------------------|-----------------------------|-------------------|
| **Size of flooded classes of functional areas ($Q_{1000}$)** |                 |                             |                   |
| Forest areas            | 0.37              | High                        |                   |
| Areas of landscape greenery | 0.03           | High                        |                   |
| Areas of agricultural land | 10.26          | High                        | 18.52             |
| Areas of watercourses and reservoirs | 7.86 | High                        |                   |
| Areas of residential greenery | 3.87           | Medium                      | 3.87              |
| Residential areas       | 16.67             | Low                         |                   |
| Areas of civic amenity  | 0.94              | Low                         |                   |
| Areas of transport amenity | 1.09           | Low                         | 19.03             |
| Areas of agricultural and forestry production | 0.33         | Low                         |                   |
| Total                   | 41.42             | Total                       | 41.42             |
| **Size of flooded classes of functional areas ($Q_{100}$)** |                 |                             |                   |
| Forest areas            | 0.27              | High                        |                   |
| Areas of landscape greenery | 0.02           | High                        |                   |
| Areas of agricultural land | 6.52           | High                        | 14.13             |
| Areas of watercourses and reservoirs | 7.32          | High                        |                   |
| Areas of residential greenery | 2.27           | Medium                      | 2.27              |
| Residential areas       | 11.03             | Low                         |                   |
| Areas of civic amenity  | 0.14              | Low                         |                   |
| Areas of transport amenity | 0.48           | Low                         | 11.86             |
| Areas of agricultural and forestry production | 0.21         | Low                         |                   |
| Total                   | 28.26             | Total                       | 28.26             |
| **Size of flooded classes of functional areas ($Q_{50}$)** |                 |                             |                   |
| Forest areas            | 0.04              | High                        |                   |
| Areas of landscape greenery | 0.01           | High                        |                   |
| Areas of agricultural land | 4.62           | High                        | 11.66             |
| Areas of watercourses and reservoirs | 6.99          | High                        |                   |
| Areas of residential greenery | 1.78           | Medium                      | 1.78              |
| Residential areas       | 8.14              | Low                         |                   |
| Areas of civic amenity  | 0.08              | Low                         | 8.50              |
| Areas of transport amenity | 0.28           | Low                         |                   |
| Total                   | 21.94             | Total                       | 21.94             |
Regarding the flood scenario of $Q_{50}$, residential areas are the most flooded class of functional area (8.14 ha) with more than 50 houses which are inundated during this flood scenario. On the other hand, the total flooded area (21.94 ha) is half the size compared to the flood scenario of $Q_{1000}$ (41.42 ha) (table 6; figure 9(c)).
5. Discussion

With regard to the results and methods used, e.g. determination of maximum flood discharges or hydraulic modelling, possible sources of uncertainty and improvements should be considered and discussed.

Regarding the regional formula by Dub (1957), it includes the regional parameters which were derived on the basis of regression analysis of peak discharges for individual regions of Slovakia. Other authors, who applied this formula in their works e.g. (Kohnová & Szolgay 1995), (Majercáková & Škoda 1998) or Szolgay et al. (2003), point to the regionalization uncertainty which arises from the use of spatial generalizations in the case of absence of direct observations such as selection of regional parameters for the studied catchment. Furthermore, Kohnová et al. (2005) compared several regional methods including regional formula by Dub (1957) to determine maximum discharge with 100-year return period in two different profiles. The results suggest that the traditional regional methods show higher discharges than other statistical methods such as regional frequency analysis.

On the other hand, regional formula by Dub (1954, 1957) forms the basis of the methodology for determining maximum flood discharges at the Slovak Hydrometeorological Institute (a specialized state organization providing hydrological and meteorological services at the national level) in catchments larger than 20 km². Regional parameters were revised, expanded, and published in the methodical guidance for determining N year maximum discharges (Makel’ et al. 2003). In Slovakia, this guidance represents a sectoral technical standard which is similar e.g. to the DVWK (1999) — German technical standard for determining design discharges. Despite the aforementioned, different methods can be used to estimate maximum discharges; however, each of these methods has certain pitfalls and uncertainties which need to be considered (Apel et al. 2004). As a consequence, the resulting N year value is chosen from a range of results of statistical methods which, however, can be even significantly different (Mitková et al. 2004). Therefore, national guides or technical standards can play a stabilization role by introducing certain conventions when deciding which method should be used to estimate maximum discharges.

With regard to the calibration or validation of the model result, it could have been improved if it had been possible to compare it to an actual flood event e.g. upstream and downstream flow hydrographs, mapped and recorded inundation extents, depths or flow velocities. Valuable calibration and validation data like these are in most cases scarce (Apel et al. 2009). Such data were not available for the model area. For that reason, we used as much accurate and quality input data as possible along with the field survey in order to provide reliable results.

As for the accuracy of input data, the crucial role was played by the DEM. To create the DEM, we used photogrammetrically measured field points along with breaklines which clearly delimitate river channels or road embankments. Such DEM allowed us to create quality rasters such as water depth or flow velocity with the resolution of 1 × 1 m. According to Werner (2001) and Sanders et al. (2007), it results in more reliable outcomes as compared to DEMs derived from satellite images with lower resolution such as ASTER GDEM (Wang et al. 2012), SRTM (Masood & Takeuchi 2012), LANDSAT (Demirkesen 2006), IFSAR (Sanders et al. 2005), or from topographic maps (Hazlinger 2008). The performed steady flow analysis in the HEC-RAS model worked well in our case, but during its final stage it needed to be verified because the model produced illogical inundations. They were created with a tendency of the model to place water into the lowest parts within the cross-section profiles. Such inundations had to be manually removed as reported also by Hazlinger (2008).

As for the risk method applied, the difficult task was to set hazard categories based on the water depth and flow velocity (i.e. flood intensity). The literature proposes several approaches for defining water depth—velocity hazard categories (e.g. Penning-Rowsell & Fordham 1994; Kourgialas & Karatzas 2011). In our case, hazard categories were modified according to Drbal et al. (2009). In addition to the number of hazard categories, we adjusted also the sizes of their corresponding flood intensity. Another similar approach with three hazard categories is presented by Beffa (1998, 2000).
On the other hand, Baldassarre et al. (2009) defined five hazard classes following the USBR ACER Technical Memorandum No. 11 (1988). These different approaches suggest that it is a challenging task which is related to the impact of flood event and characteristics of the study area and it seems that it needs to be resolved individually.

To define the vulnerability of the model area, classes of functional areas were created and each class was assigned the category of risk. Similar approach is presented by Kubal et al. (2009), Scheuer et al. (2011), or (Masood & Takeuchi 2012). However, these studies do not reflect to the requirements of spatial (urban) planning in particular area. In this paper, functional areas and its classes were created in correspondence with the methodology of spatial (urban) planning in Slovakia. This allows urban planners to incorporate flood risk maps directly into the process of creating local development plans of municipalities or towns. Moreover, these maps contain buildings and their address points which are located in the inundated areas. Such information is particularly interesting for insurance companies (Tariq et al. 2014). This paper can be further elaborated in terms of providing semiquantitative or quantitative analysis of the potential damage (Riha et al. 2005). However, these methods are more demanding for data and processing (Reiter 2000). On the other hand, they are used to quantify and assess potential direct and indirect damage in the inundated areas and also economic gain of flood protection measures.

6. Conclusion

In this paper, an attempt was made to improve the assessment of flood hazard and flood risk at the local spatial scale using GIS, remote sensing, and hydraulic modelling.

The flood hazard was determined using 1D hydraulic model HEC-RAS. Based on the water depth and flow velocity, the flood intensity was calculated and it was used to create three flood hazard categories (low, medium, and high). By this, zones with increased hazard were defined.

The basis for determining flood risk was the vulnerability of the model area. It was defined by the classes of functional areas which contained three categories of acceptable risk (low, medium, and high). Moreover, the vulnerability was defined by address points and sensitive objects which allows the definition of necessary measures for different types of objects and functional areas or restrictions of activities in certain parts of the model area. Flood risk thus represents the synthesis of information on flood hazard and vulnerability which actually enables to define the extent of areas that do not fulfil the requirement of acceptable level of risk.

To conclude, results of the paper can be applied especially in the areas of prevention, flood risk management, and crisis management. Its purpose should be primarily met in increasing public awareness of the flood risk and providing information on flood risk for the purposes of spatial (urban) planning and construction. By incorporating flood maps into the local development plan of the municipality, irresponsible expansion and densification of construction near the watercourse or in areas with medium and high degree of flood hazard could be prevented. Moreover, the results can be used in landscape planning, in the process of environmental impact assessment (EIA) or in insurance industry.

From the methodological point of view, the importance of the paper can be seen in universality of the proposed steps to assess flood hazard and flood risk which could be transferred to other similar flood-prone areas at the local spatial scale. However, further case studies in other regions should be undertaken to verify their general applicability.

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