Rainfall distribution as a main factor influencing flood generation in the eastern Slovakia

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Abstract

This paper aims to geographically assess the flood occurrence in eastern Slovakia by using a geographically based multi-criteria analysis for flood risk assessment. Flood risk assessment in this study is conducted in three specific cases: the long term period 1989–2009, the extremely wet 2010 year, and the extremely dry 2011 year. In the analyses, some of the causative factors for flooding in a basin area are taken into account. We use set of causative factors concerning mostly hydrological and physio-geographical characteristic of the target area that can be measured and evaluated such as soil type, daily precipitation (for the years 1989-2009, 2010, 2011), land use, catchment area and basin slope. For recommendation which causative factors should be preferred we use the multicriteria analysis – ranking method. In the ranking method (RM), every factor/criterion under consideration is ranked in the order of the decision-maker's preference. Geographic approach to flood risk assessment provides a descriptive presentation of the results obtained. Geographic information systems as a visualization tool is presented in a manner that aids understanding in a user friendly way.

Regarding our task of flood risk assessment, the partial results are three composite maps, which present the comparison of flood risk zones in percentage of the area in years 1989-2009, 2010, and 2011. The composite maps are background for risk assessment of the impact of rainfall on flood generation. This study of hydrological data and physio-geographical characteristic was carried out with the purpose of the identification of flood risk occurrence in eastern Slovakia. Results from our study shows, that rainfall distribution has high influence on flood risk of the area. Area percentage with very high flood risk index was calculated for "wet" year 2010 as 11.73 %, for "dry" year 2011 as 0.01 % and for period 1989 – 2009 as 0.28 %.

Keywords: Geographic information systems, rainfall, flood risk

1. Introduction

Floods are natural phenomena causing adverse conditions in the flood-prone areas by extensive inundation. The consequences of floods can be direct or indirect, and can cause loss of lives, economic damages, damages on the environment and the cultural heritage (Korytárová *et al.*, 2007). They can also influence the life and activities of large populations within and adjacent the flooded zone (Messner and Meyer, 2006; Tsakiris, 2010). Multicriteria analysis (MCA) methods have been applied in several studies in flood risk assessment. Chandran and Joisy (2009) introduced an efficient methodology to accurately delineate the flood hazard areas in Vamanapuram river basin in a GIS environment. Yalcin and Akyurek (2004) applied a GIS-based multicriteria evaluation in order to analyse the flood vulnerable areas in south-west coast of the Black Sea. The ranking method and pairwise comparison method were introduced and applied in this study. Tanavud *et al*. (2004) assess the risk of flooding and identified efficient measures to reduce flood risk in Hat Yai Municipality, southern Thailand using GIS and satellite imagery. Yahaya *et al*. (2010) identified flood vulnerable areas in Hadejia-Jama'are river basin Nigeria by using a spatial multicriteria evaluation technique. Pairwise comparison method, analytical hierarchy process and ranking method were applied in the study. Scheuer *et al*. (2011) present an approach to modeling multicriteria flood vulnerability which integrates the economic, social and ecological dimension of risk and coping capacity (Pintilii *et al*., 2016). Many studies have shown that flood properties are influenced by a combination of precipitation characteristics including volume, intensity, duration and spatial distribution (see among others Bracken *et al*., 2007; Şerban *et al*., 2016).

River floods in Slovakia have proven devastating for communities and individuals for centuries. Their risk is spatially variable, however floods have generally been well documented where and when they take place. The most complex situation has been in Bodrog and Hornad river basins in the eastern part of Slovakia in the recent years, mainly in 2010.

The present study develops a hybrid approach to identify flood risk zones and assess the impact of rainfall by integrating multicriteria analysis and GIS technologies.

2. Material and Methods

2.1. Study area

We are interested in the eastern part of Slovakia, particularly in the Bodrog and Hornád river basins, which have faced severe floods. The morphological type of terrain in the Hornád valley is dominated by rolling hills, higher and lower uplands. The southern sub-basin is part of the Slovakian Karst plain and is formed by moderately higher uplands. The geological structure of the territory determines the hydro-geological conditions of the basin. The sub-basin of the Hornád valley has strong predominance of impervious (or at least poorly permeable) rock. Well-drained rock with high permeability exists only in Spiš and Gemer areas and in the Slovakian Karst near Košice.

The Bodrog watershed area, consisting of the Cirocha, Laborec, Latorica, Ondava, Topľa and Uh river basins, is located in two orographic subassemblies, which are the Carpathian Mountains and the Pannonian Basin. The morphological type of the relief is predominantly flat in the southern part and hilly in the northern part. The Bodrog river valley has variable climatic conditions. The annual precipitation is higher in the eastern border mountains and Vihorlat (1000 mm), and reduces at the south (800 mm) (Zeleňáková and Gaňová, 2011).

2.2. Data

Modeling the complex interaction of river flow hydraulics with topographical and land use features of the floodplains is usually required to map flood risk zones.

We use data from the Atlas of the Slovakian Landscape, provided by Slovak Water Management Enterprise, s.c. Košice, Soil Science and Conservation Research Institute, Slovak Hydrometeorological Institute, to compute index of flood risk based on multicriteria analysis. We use set of causative factors concerning hydrological and physio-geographical characteristic of the target area that can be measured and evaluated.

2.3. Hydrological analysis

Daily rainfall records from 19 rain gauges stations concerning Bodrog and Hornad catchment during the period 1989 – 2011 (Table 1) were used. The lowest and highest average daily rainfall is 0.7 and 3.2 mm in year 2011 and 2010, respectively. The period 1989-2011 was divided as: extremely wet year 2010, extremely dry year 2011 and the long time period 1989 – 2009 (see Table 1).

Table 1. Rain gauge stations and their average daily rainfall for the 3 periods.

ID	Station	Period		
		1989-2009	2010	2011
		average daily rainfall (mm)		
ST 1	Streda nad Bodrogom	1.6	3.0	1.3
ST2	Horovce	1.8	2.7	0.7
ST3	Hanusovce	1.8	2.6	1.4
ST4	Bardejov	2.0	2.6	1.4
ST5	Stropkov	2.0	2.7	1.3
ST6	Svidnik	2.2	2.9	1.4
ST7	Izkovce	1.8	2.6	1.3
ST8	Velke Kapusany	1.8	2.6	1.3
ST9	Michalovce	1.9	2.5	1.5
ST10	Humenne	2.1	3.1	1.5
ST11	Snina	2.1	2.9	1.9
ST12	Krasny Brod	2.4	3.2	2.0
ST13	Kosicke Olsany	1.7	2.7	1.4
ST14	Presov	1.9	2.4	1.3
ST15	Jakubovany	1.9	2.5	1.2
ST16	Cana	1.8	2.7	1.3
ST17	Kysak	1.9	3	1.5
ST18	Spisske Vlachy	1.9	3	1
ST19	Spisska Nova Ves	1.8	2.8	0.7
average		1.9	2.8	1.3

Figure 1 presents the spatial distribution of rainfall for all three periods. The inverse distance weighting method was used to spatially interpolate the raingauge-based records.

2.4. Analyses of physio-geographical characteristic

Physio-geographical characteristic for this study were selected due to their relevance for flood occurrence in the study area. The selected causative factors of floods are listed below (note that other factors could cause flooding, i.e. antecedent catchment conditions, but are not considered in here):

- Soil type
- Slope
- Land use
- Catchment area

Antecedent catchment conditions are also another factor of floods (Pechlivanidis *et al*. (2016) although we did not consider this factor in our study.

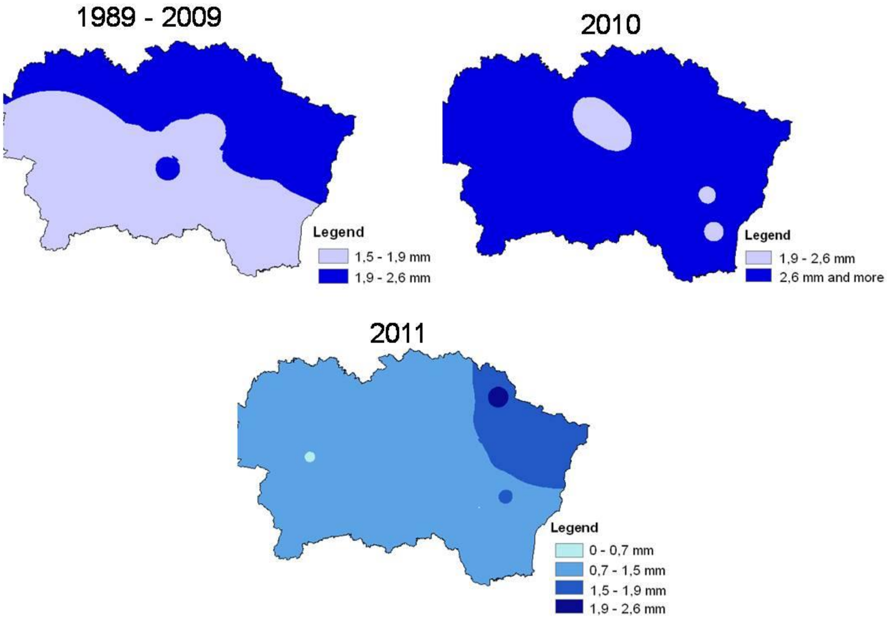

Figure 1. Maps of daily rainfall distribution for the periods 1989-2009, 2010, and 2011.

The soil data for the catchments were collected from the Soil Science and Conservation Research Institute. Soil types in the catchments were detected and soil map was digitized. Slope has a dominant effect on the contribution of rainfall to stream flow. It controls the duration of overland flow, infiltration and subsurface flow. The slope map was prepared from the Triangular Irregular Network (TIN) of the region. Slope in percentage was calculated using contour map. Land use was prepared using thematic map of the Slovak Republic (1:200 000). The map was digitized and the % area of each category was calculated. The catchment area map was also digitized and the size of each watershed was computed.

2.5. Ranking method

Ranking method (RM) is used if ordinal information about the decision makers' preferences on the importance of criteria is available. In the first step criteria are ranked in the order of their importance. In a second step, ranking method is used to obtain numerical weights from this rank order (Meyer, 2009).

Using the rank sum method normalized weights of the criterion were calculated as (1) (Yahaya *et al*., 2010):

$$W_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)} \qquad (1)$$

where: Wj is the normalized weight for the each criterion; n is the number of criteria under consideration (k = 1, 2, …, n); and rj is the rank position of the criterion.

$$W = n - r_j + 1 \qquad (2)$$

and then normalized by the sum of weights, that is (3)

$$\sum (n - r_k + 1) \qquad (3)$$

Resulting vulnerability was calculated using the following formula (4):

$$IV = \sum (IF_{1j} W_1 + IF_{2j} W_2 + IF_{3j} W_3 + IF_{4j} W_4 + IF_{5j} W_5) \qquad (4)$$

where: IV is index of vulnerability; IF_{1j}, IF_{2j}, IF_{3j}, IF_{4j}, IF_{5j} are importance of factor's class; and W_1, W_2, W_3, W_4, W_5 are the normalized weights for each criterion.

3. Results

After digitizing and plotting the maps, the rank of each factor was given on the basis of its significance in causing floods. The rank of each factor is as follows:

- Daily rainfall (D) = 1
- Slope (S) = 2
- Soil type (ST) = 3
- Land use (L) = 4
- Catchment area (C) = 5

The straight ranking was applied to these factors. "1" is the most important factor and "5" is the least important factor (Yahaya *et al*., 2010; Meyer, 2007). Each factor was divided into a number of classes and each class was weighted according to the estimated significance for causing flooding.

The inverse ranking (the least important = 1, next least important = 2, etc.) was applied on sub factors division (see Table 1). The rank sum method was used to identify the flood risk index (RI) after assigning weights to each factor; this weight is an index of sensitivity. Normalized weight to each main factors was assigned and normalization using the rank sum method and their computation is listed in Zelenakova *et al.* (2011). Resulting weights are listed in Table 2.

Table 2. The significance of flooding causative sub factors.

Criterion	Straight Rank	Weight (W)	Normalized Weight (Wj)	Weight (in %)
Rainfall	1	5	0.333	33.3
Slope	2	4	0.267	26.7
Soil type	3	3	0.200	20.0
Land use	4	2	0.134	13.4
Catchment area	5	1	0.066	6.60
SUM		15	1.00	100

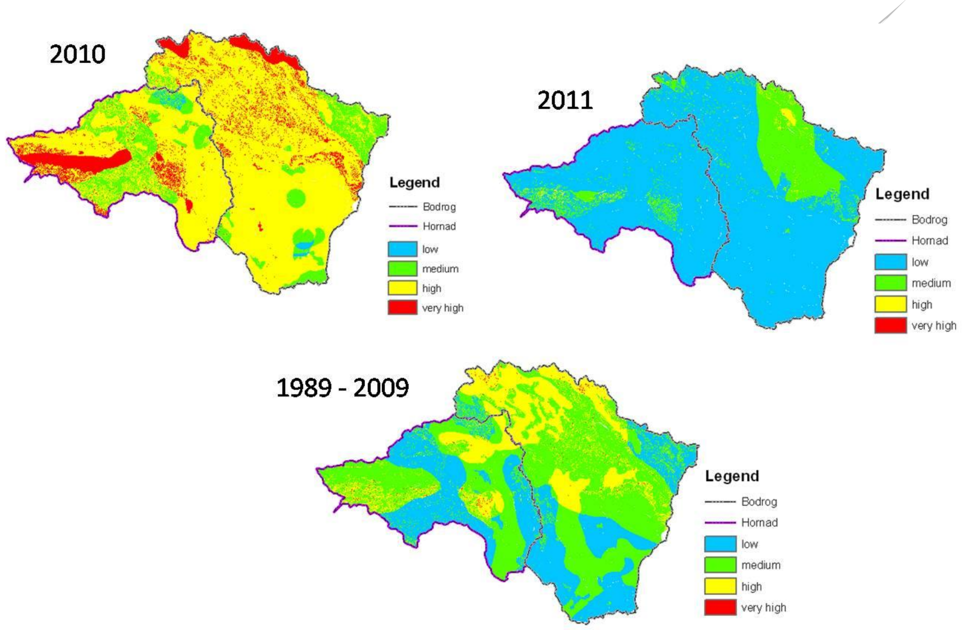

Figure 3. Maps of flood risk for the periods 2010, 2011 and 1989-2009.

The total weight (score) for estimating the flood risk in particular zone is equal to the sum of each causative factor. Finally composite flood risk maps were created using weighted overlay analysis and raster calculator in ArcGIS 9.3 software.

The values of risk index (RI) vary across the study area ranging for years 1989 -2009: 1.732 – 3.866, for the extremely wet 2010: 2.199 – 4.265 and for the extremely dry 2011: 1.399 – 3.456. These values were divided into four classes: very high (3.3 – 4.3), high (2.8 – 3.3), medium (2.4 – 2.8) and low (1.6 – 2.8). The flood risk maps of Bodrog and Hornad catchment for three time period are shown in Figure 3.

Results show that for the year 2010 the percentage of flood prone area was 0.64 % (low), 14.33 % (medium), 73.30 % (high) and 11.73 % (very high); for the year 2011 it was 83.40 % (low), 15.67 % (medium), 0.92 % (high) and 0.01 % (very high); and for the period 1989-2009 it was 29.87 % (low), 48.47 % (medium), 21.38 % (high) and 0.28 % (very high).

Results show that rainfall distribution has a very high impact on flood occurrence. The comparisons showed that there was a significant change in the extent of daily rainfall in years 2010 and 2011 and so significant differences in percentage area of flood risk between 2010 and 2011.

4. Conclusions

This paper presents work carried out in the Hornad and Bodrog catchment involving the use of GIS tools and multicriteria analysis method to generate maps of flood vulnerable areas. Analysis of the flood risk in the area was based on the ranking method. The level of flood risk was divided in four classes (low, medium, high and very high).

The Hornad and Bodrog catchment shows extreme variability in terms of flood risk due to the effect of rainfall distribution. During the extremely wet year (2010) the area has a risk index about 100% greater compared to the extremely dry year (2011) and the period 1989-2009.

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