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A METHOD FOR IDENTIFICATION OF SMALL CARPATHIAN CATCHMENTS MORE PRONE TO FLASH FLOOD GENERATION. BASED ON THE EXAMPLE OF SOUTH-EASTERN PART OF THE POLISH CARPATHIANS

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Abstract:. The European Union has obligated all Members States, to perform a preliminary assessment to identify the catchments at risk of flooding. Usually, hydro-meteorological data and historical information about flooding are used to determine whether a catchment is at risk of flooding or not. Such information is missing for many small Carpathian catchments. Therefore, a method, enabling identification of small catchments more prone to flash flood generation, was proposed. The method focused on physiographic parameters of catchment. Eighty-five catchments where flash floods were well-documented, were described by physiographic parameters. The parameters described dimension, shape, relief, hydrological and geological conditions and land use. Then, the influence of those parameters on flash flood formation process was studied. The results revealed that physiographic parameters of those catchments made them more sensitive to flash flood generation. On the basis of these parameters, types of the Carpathian catchments more prone to flash flood generation were created. The method was tested in south-eastern part of the Polish Carpathians. Catchments resembling the types were identified within a group of 366 catchment located in this area. The results revealed that many flash flood events recorded in the study area, had taken place within catchments identified by use of the method. This fact suggests that the method enable to identify catchments more prone to flash flooding in the geographical space. Therefore, the method may be a valuable tool in the process of flood risk management in the Carpathians.

Keywords: flash flood, small catchments, physiographic parameters, flood risk management, the Carpathians

1. INTRODUCTION

Flash floods are the most destructive phenomenon among natural disasters in terms of people affected and damage (Barredo, 2007; Gaume et al., 2009). Scientific evidences show an increase in mean precipitation and extreme precipitation events, which implies that extreme flood events might become more frequent (Christensen & Christensen, 2003), what may increase in flood damage. Therefore, the European Union had obligated all Members States, to perform a preliminary assessment to identify catchments at risk of flooding (Directive 2007/60/EC). Flood hazard, flood risk maps and flood risk management plans should be prepared for these catchments. Those actions are supposed to limit negative effects of flooding in the future and should be reviewed every six years. Usually, hydro-meteorological data and historic information about flooding are the basis for the identification of catchments at risk of flooding. However, small catchments are usually ungauged and hydro-meteorological and historical data is missing. Scientific reports mainly describe the largest flood events. The local flash floods are usually not investigated. Some information about local flash flood events is delivered by newspapers, parish chronicles and insurance agencies. On the basis of this data, it is difficult to assess whether a catchment is at risk of flooding. In the context of the European Flood Directive the question arises: is it possible to identify catchments more prone to flash flooding, even when hydro-meteorological and historical data is limited?

Many works suggest that flash flood may occur in almost every catchments and any region. However, a flash flood results from combinations of meteorological and hydrological conditions, as well as catchment characteristics (Collier, 2007; Collier & Fox, 2003; Marchi et al., 2010). Heavy rainfall accumulation is necessary but not sufficient condition for inducing flash floods. Apart from heavy rainfall, soil moisture conditions and catchment physiographic parameters such as: dimensions, shape, geology, relief, hydrography and land use, strongly influence on flood wave parameters and determine flash flood triggering (Norbiato at al., 2008). Taking into account, that physiographic parameters of a catchment have a large influence on time to peak and flood magnitude, we may assume, that analysis of those parameters may be a valuable tool for the assessment of predisposition to flash flood formation and identification of catchments more prone to flash flood formation in the geographic space. Catchments more prone to flash flood generation may be considered as at risk of flooding.

In this study a conception of a method for identification of small catchments more prone to flash flood generation was presented. The method was tested and evaluated in the south-eastern part of the Polish Carpathians.

2. METHODOLOGY

The idea for creation of the method, had arisen from post-flooding investigations carried out by the author. Physiographical parameters of 84 catchments affected by flash flooding in Poland, were investigated in context of flash flood formation process. The parameters described dimensions, shape, hydrological and geological conditions and land use. Analysis of fourteen cartographically derived, physiographic parameters indicated considerable similarities among those catchments (Bryndal, 2008). Moreover, analysis of the influence of those parameters on flood wave formation revealed, that they accelerate the transformation from rainfall into runoff, and in this way, make catchments more sensitive to flash flood generation. This statement was confirmed by analysis of hydrological response of catchments on heavy rainfall. The catchments reacted to a heavy rainfall almost immediately (Bryndal, 2010; Bryndal et al., 2010), what was confirmed by: time to peak (usually lower than 2 h); high value of the maximum specific flow (usually $q_{max}>3\ m^3 \cdot s^{-1}$) and the runoff coefficient (usually Rc>0.3). The results suggest that if a catchment with characteristic values of physiographic parameters is affected by heavy rainstorm then probability of a flash flood to occur is higher. Therefore, in this study an attempt to create a method enabling identification of catchments more prone to flash flood generation in the Carpathians was undertaken.

2.1. Characterization of the method

The method focuses on physiographic parameters, with a well-documented influence on flash flood formation process. This approach allowed to emphasize the geographical features of the region, and made the method more transferable to other parts of the Carpathians. The role of precipitation and soil moisture conditions was omitted. On the one hand, those two factors are considered as a driving for flash flood inducing (Gaume et al., 2009; Marchi et al., 2009, 2010), on the other hand, it is difficult to include those factors, because of their spatial and temporal variability. Those two factors are usually use for short-term evaluation of a catchment potential for flash flood inducing, to produce flood alerts (Georgakakos, 2006; Norbiato et al., 2008).

The method includes five stages:
1) selection of catchments with a well-documented flash flooding events,
2) selection of physiographic parameters describing the catchments,
3) calculation of the physiographic parameters for each catchment,
4) statistical analysis of the physiographic parameters and evaluation of the catchments' predisposition to flash flood generation,
5) typology of catchments,

The stages of the method were discussed in details below.

2.1.1. Selection of catchments with a well-documented flash flooding events

In inland part of the continent, flash floods usually result from short-term, isolated precipitation events. The area covered by heavy precipitation zone, is usually smaller than 50 km^2. The rainstorm time duration is usually shorter than three hours and sum of precipitation often exceeds 20 mm (Ostrowski at al., 2012). This precipitation generates flash floods in catchments usually smaller than 40 km^2 (Bryndal, 2008). Sometimes flash floods occur as a result of short-term precipitation events which appears during a long-term and low-intensive precipitation periods. Such precipitation generates flash floods in larger catchments (a few hundred km^2 in area), because the flood wave created by a short-term heavy rainfall, overlays the flood wave generated by long-term, low-intensive precipitation.

Those types of flash floods significantly differ in terms of: 1) dimensions of catchment affected by flooding, 2) precipitation parameters, and 3) hydrological processes generating flood wave.

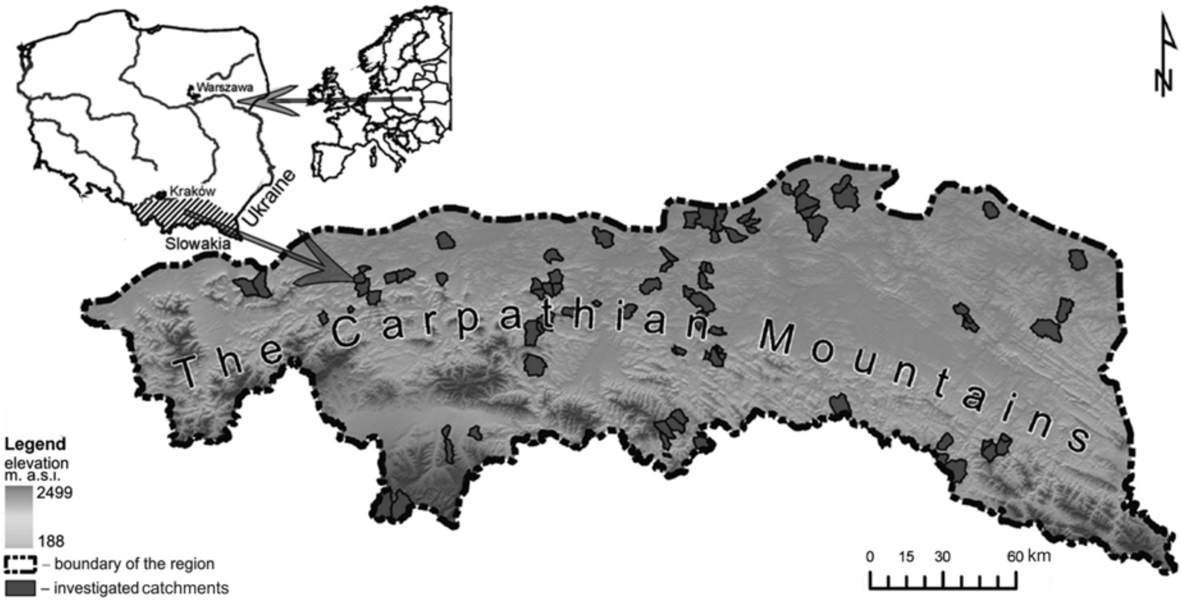

Figure 1. Spatial distribution of the investigated catchments

Therefore, in this study only flash flood events generated as a result of short-term, isolated precipitation events were taken into account. In this way, the sample of catchments was uniform in terms of mechanisms generating flash flood event. The catchment was selected if the following criteria were fulfiled: 1) flood wave overflowed entire valley bottom and 2) flood stage was 0.5 m or higher. Flood stage higher than 0.5 m may be interpreted as dangerous for human and property. The criteria proposed are important in context of flood risk and allowed to select catchments where the local extraordinary flash flooding occurred. Finally, eighty-five Carpathians catchments, were selected (Fig. 1).

No rainfall-threshold criterion was used, because of lack of detailed data. On the one hand, we have huge general knowledge about rainfall generating flash floods. On the other hand, there is lack of detailed data related to a given flood event, because this phenomena develop in time and space that regular measurement network are not able to monitor (Creutin & Borga, 2003). Many times there was an evidence for flash flooding (e.g. diagnosed during field-studies), but the nearest rainfall gauges recorded a few mm of rainfall. The maximum flow, for most of the recorded flood events ranged from 10 to 67 $m^3 \cdot s^{-1}$, and the maximum specific flow were included in the range of 1.9 to 9.1 $m^3 \cdot s^{-1} \cdot km^2$. Time to peak was lower than 3 h.

2.1.2. Selection of physiographic parameters describing catchments

The influence of a catchment physiographic parameters on flood wave formation process is widely discussed in hydrological literature (Brown et al., 1999; Etzenberg et al., 1997; Kroczak, 2010; Liu et al., 2004, 2011; Merz & Plate, 1997; Naef et al., 2002; Peschke et al., 2000; Shakya & Chander, 1998; Słupik 1972, 1973). On the basis of the literature, selection of the physiographic parameters was performed. A parameter was entered when three of the following criteria were fulfiled: 1) parameters had well documented influence on flash flood formation process, 2) parameters allowed to evaluate predisposition of a catchment to flash flood formation, 3) parameters were easy to calculate on the basis of typical, wide-available cartographical materials. These assumptions guarantee that the method may be tested in other parts of the Carpathians.

Finally, 16 physiographic parameters describing: dimension, shape, relief, hydrological conditions, structure of land use and geological settings were chosen. The names of parameters and short explanation for the selection are presented below.

Dimension of catchment was characterized by the catchment area (A). Size of the catchment is one of the major factors affecting the occurrence of flash flood (Flash flood..., 2010). Generally accepted view is that smaller catchments are more sensitive to flash flood, because they are usually completely covered by heavy precipitation zone.

Shape of a catchment was characterized by the shape index (Ck). Catchment shape influence on magnitude and timing of the peak flow at the catchment outlet. The runoff in more round catchment will arrive more quickly at the catchment outlet, producing higher peak flow (Flash flood…, 2010).

Relief condition was characterized by average slope gradient (Ψ) and the average slope of the main valley bottom (Ψv). Slope gradient affects the timing of runoff and the infiltration process (Flash flood…, 2010; Weingartner et al., 2003), whereas the valley bottom gradient affects channel retention capacity and flood wave velocity (Marchi et al., 2010). The steeper the slope and the steeper the drainage channels, the quicker the flow response and the higher the peak flow (Flash flood…, 2010).

Hydrological conditions were characterized by the stream network density (Sn). This parameter is one of the most important characteristics for evaluating potential runoff. Higher stream density allows the landscape to drain more efficiently. More efficient drainage means that water moves into streams faster, causing peak flows to be larger and to occur sooner (Flash flood…, 2010). Stream network, in the context of this investigation, should be described by Horton's ratios (Horton, 1945). Those parameters provide a quantitative characterisation of stream network structure. However, the analysis showed that the bifurcation ratio (R_b) was constant in each catchment affected by floods, whereas the length (R_l) and the area (R_a) ratios were invariable only within 26 of them. Therefore, the stream network was described by bifurcation ratio (R_b), average length of the first order stream (LI), average catchments area of the first order stream (AI) and the highest stream order (Ω_{max}).

Structure of land use influences on the runoff formation process. Three types of land use were distinguish: arable lands – where delayed overland flow is generated (Aa); forest areas – where slow subsurface flow is generated; impermeable areas, which were composed from high (Hh) and low (Lh) density housing. On these areas, fast surface runoff is generated.

Geological settings were characterized by coefficient of soil permeability (k) which corresponds to pedotransfer values.

Moreover, road network density (Rn) was included as a factor which plays significant role during flash flood formation (Froehlich & Słupik, 1986). The road network, during rainstorm events, complements the natural drainage network and acts similar to river drainage system.

2.1.3. Calculation of the physiographic parameters

Parameters of catchments were calculated according to typical methods described in hydrological literature or they were obtained directly from modules of a GIS software (ArcGis 9.x).

The geodatabase prepared for this study consisted of raster layer of digital elevation model (DEM) 20x20 m in resolution. The DEM layer was used to obtain parameters that characterized dimension, shape, relief, and hydrological condition of the catchments. Vector data 1:50 000 was the basis for creation of the layers contained types of land use and road network. Vector data (1:25 000 and 1:100 000) was applied to create soil layers. The vector data was converted into raster with the same resolution as DEM. This process allowed to compare the data, which differed in terms of the scale.

2.1.4. Statistical analysis of the physiographic parameters and evaluation of the catchments' predisposition to flash flood generation

The physiographic parameters, calculated for 85 catchments were tabulated and then, descriptive statistics were computed. This allowed for characterization of the Carpathians' catchments affected by flash flooding.

Then, the predisposition of the catchments studied, for flash flood formation was evaluated. The evaluation was preformed by use of three methods.

In the first method, descriptive statistics of physiographic parameters of catchments were discussed in the context of the literature that characterizes the influence of catchment parameters on flood wave formation process. This analysis allowed to evaluate predisposition of a catchment for flash flood formation qualitatively. Therefore, in two remaining methods, parameters, which enable evaluation of the predisposition quantitatively, were studied.

In the second method, two characteristics, namely: the CN parameter and the lag time (Tlag) were calculated. The physiographic parameters of a catchment strongly influence on those two measures.

The CN parameter, originates form SCS-CN method (SCS, 1972), and it was calculated on the basis of soil cover maps and land use map. The average level of soil moisture condition was assumed. This measure enabled to assess predisposition of a catchment in terms of transformation of rainfall into runoff. The parameter ranges from 0-100. Higher value of the parameter denotes that more precipitation will be transformed into excess rainfall (direct runoff), generating flood wave.

The Tlag [h] parameter, allowed to evaluate hydrological reaction of a catchment on a rainfall. This parameter, was calculated according to equation (SCS, 1972):

$$\text{Tlag} = \frac{(L \cdot 3.28 \cdot 10^3)^{0.8} \cdot \left(\frac{1000}{CN} - 9\right)^{0.7}}{1900 \cdot \sqrt{I}} \quad (1)$$

where:
L – length of the longest drainage path [km],
I – the average catchment slope [%],
CN – the CN parameter [-].

The lower value of the Tlag denotes faster response of a catchment. In context of the evaluation of a catchment potential for flood formation, higher value of CN parameter and lower value of the Tlag, may be interpreted as a catchment is more prone to flash flood generation.

In the third method, hydrological reaction of a catchment to heavy precipitation was studied. This process was analysed in relation to sub-catchment affected and unaffected by flash flooding. More dynamic response of sub-catchment affected by flash flooding, suggests higher vulnerability to flash flood generation.

Four catchments, where flash flooding were recorded in the source part of a catchment, and it was possible to include the neighboring catchments were studied in terms of transformation form rainfall into runoff (time to peak, maximum specific flow, runoff coefficient). It was assumed, that catchments were affected by rainstorm of 100 $mm \cdot h^{-1}$. This value corresponds to sum of precipitation that generated extraordinary flash floods in small catchments in Poland. Flood wave parameters were calculated by two models namely, SCS-CN and SCS-UH. (Soil…, 1986). Those two models fairly well reconstructed flash flood events in small Carpathian catchments (Bryndal et al., 2010). A weighted value of CN parameter, related to average antecedent moisture condition and the uniform spatial distribution of a rainfall, were assumed.

2.1.5. Typology of catchments

Typology of catchments was performed by use of the multidimensional analysis. In this way types (models) of the Carpathians' catchments more prone to flash flood generation, were created. Cluster analysis was used for classification process. First, on the basis of correlation analysis, parameters with coefficient of correlation higher than |0.7| were eliminated. Then, the input data was standardized in order to minimize its influence on a distance measure. The Euclidean distance was used as a measure of similarity and agglomeration was performed using Ward's Method. Division of the hierarchical tree led to the creation of subsets, which were treated as types. Analyses of the screeplot combined with evaluation of agglomeration distance were applied to the division of the hierarchical tree. Differences between the types were investigated by Kruskall-Wallis statistical test and multiple-comparison analysis (Siegel & Castellan, 1988). Only those parameters where the differences were statistically valid (p_{level}=0,05) were used in further investigation.

The types were characterized by descriptive statistics. Mean values enabled characterization of the types, whereas the diversity measures and percentiles enabled to perform identification of catchments similar to types. The identification process was performed by use of the values such as: min-max, Q_5-Q_{95}, Q_{10}-Q_{90}. If physiographic parameters of a catchment were within the range determined by those threshold-values then the catchment was included to a given type.

First, the identification process was performed on the control group. The control group, was composed of 43 catchments, randomly selected from the group of 85 catchments, which reacted with flash floods. The identification process, performed on the control group, allowed to evaluate if the types were able to identify catchments affected by flash flooding.

The threshold-values calculated for each type, have created the ranges, that were not fully-disjunctive. Therefore the quality of the classification was evaluated by three measures: the effectiveness of the classification index (I_E), the disjunctive of the classification index (I_H) and the accordance of the classification index (I_A).

The first measure (I_E) informs about the percentage of catchment which were identified within the testing group. It was computed as:

$$I_E=(Ci/Cc)\cdot 100 \quad (3)$$

where: Ci – number of catchments identified within the control group, Cc – number of catchments within the control group. The index ranges from 0-100. The higher value of the index denotes that effectiveness of the classification is higher and more catchments was identified within the control group. It also allowed to evaluate the percentage of catchment which might be omitted during the identification process in the geographical space.

The disjunctive of the classification index (I_D) informs whether catchment identified had been assigned to one or more than one type. It was calculated according to the equation:

$$I_D=(Ct/Cc)\cdot 100 \quad (4)$$

where: Ct – number of catchments assigned to more than one type. The index ranges from 0-100, where 0 denotes that each catchment was assigned to one type only.

The accordance index (I_A) informs whether the catchments identified within the control group, had been included to the same type like in the typology. It was computed as:

$$I_A=(Cp/Ci)\cdot 100 \qquad (5)$$

where: Cp – number of catchments identified, included to the same type during the typology. The index ranges from 0-100, where 100 denotes that each catchment was included to the same type like in the typology.

Higher values of I_E and I_A and lower value of I_H denotes that the identification process is more accurate.

2.2. Identification of the catchments similar to the types in the geographical space

The last stage was the practical use of the method and identification of catchments similar to the types in the geographical space. The method was tested in the south-eastern part of the Polish Carpathians. The identification was performed by use of the ArcGis 9.x software. First, on the basis of DEM, catchments smaller than, the largest Carpathian catchment affected by flash flooding, were found. Next, the physiographic parameters were calculated and as the attribute data was attached to each catchment. Finally, the attribute data was searched by use of the Structural Query Langue. In this way catchments with physiographic parameters similar to created types were identified in the geographical space. At this stage, the quality of the identification process was evaluated by Kolmogorov-Smirnov two-sample test.

At the end the study, information about flash flooding recorded in the south-eastern part of the Polish Carpathians was related to spatial distributions of the catchment, identified by use of the method. This comparison allowed to evaluate the usefulness of the method and potential for the practical usage.

3. RESULTS

3.1. Characteristics of the catchments affected by flash flooding and the evaluation of their predisposition towards flash flood generation

Descriptive statistics of catchments are presented in table 1. On average, the catchment area amounted to 10 km^2. Eighty per cent of the catchments were larger than 4 and smaller than 26 km^2. The largest catchment had 35.2 km^2. Most of catchments had slightly elongated shape (Ck–0.6). Those values of parameters indicate vulnerability to of a catchment to flash flood generation. During a rainstorm, such a catchment is completely covered by heavy precipitation zone what leads to a rapid response of the catchment. The shape of catchment indicates that the runoff will arrive more quickly at the catchment outlet, producing higher peak flow.

Ninety per cent of catchments had the coefficient of soil permeability lower than 0.36 m·h^{-1} (Table 1). The soil permeability is very low what create favorable conditions for rapid flood wave formation and flash flooding. Low value of this parameter is mainly determined by soil's structure and texture. Soil's maps indicate, that the weathered mantle of the flysch bedrocks, typical for wide part of the Carpathians, is characterized by high clay minerals content – usually higher than 35%. A soil cover rich in clay minerals accelerates overland flow formation process, due to restriction of the infiltration, caused by swelling of the soils during the wetting (Léonard et al., 2006).

Structure of land use is one of the most important factors that influences flood wave formation. This parameter determines the runoff formation process. Impermeable surfaces such as high-density housing, road surface generate fast surface runoff (Liu et al., 2004). The runoff coefficient for such terrain usually ranges from 0.75 to 1. Moreover, those areas reduce the surface roughness and therefore shorten the overland flow detention time (Liu & De Smedt, 2005). Generally, higher impermeable surface content results in higher vulnerability of catchment to flash flood generation. Impermeable areas covered only small part of the studied catchments (Table 1). For ninety per cent of catchments, the sum of the high-density and the low-density housing content, was lower than 9%. However, it should be emphasized that exactly those areas determine rapid catchment response at the beginning of a rainstorm event (Froehlich & Słupik, 1986). Fast surface runoff from impermeable areas quickly reaches the watercourse and significantly reduces channel retention. This in turn, creates favorable conditions for flooding.

Apart from impermeable surfaces, arable lands are considered to create preferable conditions for overland flow formation (Liu et al., 2004; Ludwig et al., 1995; Naef et al., 2002). In this type of land use, the sheet and the concentrated overland flow is generated, a few minutes after the onset of the rain event. It is worth to emphasis that in the catchments of 10 km^2 in area, the arable land content was found as a driving factor for runoff response (Cerdan et al., 2004). In the investigated catchments, arable lands dominated. More than 50% of catchments had the arable land content higher than 62.3% (Table 1), what may be interpreted as the fact that this dominant content makes them more vulnerable to flash flood formation.

The influence of forest areas on flash flood wave formation is still the matter of discussion (e.g. Bathurst et al., 2011; Beschta et al., 2000; Weingartner et al., 2003). A generally accepted view is that forest, reduce the maximum flow, due to higher retention capacity and reduction of the quick overland flow. Most of the catchments studied were substantially deforested (Table 1). Fifty per cent of catchments had the forest content lower than 31.3%, what suggests preferable conditions for fast response of a catchment and higher predispositions to flash flood inducing. However, there were a few catchments where forest occupied more than 78.6% of their area. Generally accepted view is that more forested catchments are less sensitive to flash floods occurrence than deforested ones, because forest may reduce small and moderate rainstorms (Beschta et al., 2000; Sikka et al., 2003). However, high forest content does not guarantee that flash floods will not occur. The relationship between rainstorm volume and the influence of forest on the flash flood formation is a threshold type (Bathurst et al., 2011). In small Carpathian catchment, precipitation of 100 mm is considered as threshold value that restricts the influence of forest on flood wave reduction completely (Figuła, 1955). This fact indicates that "there are no safe catchments" and heavy torrential rainfall may generate flash floods, even when a large part of a catchment is covered by forest areas.

Rainfall water transformed into the overland flow is delivered from slopes to main valley floor via natural and artificial network mainly. The catchments had well-developed natural and artificial draining networks.

The stream network density reached 2.4 $km \cdot km^{-2}$ and the bifurcation ratio amounted to 3.9. Average value of the first order stream reached 0.6 km and each first order stream drained on average sub-catchment 0.4 km^2 in area. Natural drainage system is complemented by man-made system of roads and ditches. It should be emphasized that artificial network, created as the result of human activity significantly modifies water circulation on a slope and accelerates delivery of rainstorm water from the slopes to rivers (Kroczak, 2010). Road and dishes network, during rainstorm, acts as water collectors in which high-speed concentrated flow occurs. It is worth to mention, investigation in which the surface flow velocity, was studied (Figuła, 1955). The surface flow velocity on the 10-17^o steep slope may reach 8–9 $cm \cdot s^{-1}$ on the grassland field, 13 $cm \cdot s^{-1}$ on the ploughed field, but more than 100 $cm \cdot s^{-1}$ on the road (Figuła, 1955).

Table 1. Physiographic parameters of the catchments affected by flash flooding – descriptive statistics

Parameter	$\bar{x}$	V	min	max	Q_{10}	Q_{25}	Q_{50}	Q_{75}	Q_{90}
Catchment's dimensions and relief									
A [km^2]*	12.3	69.3	1.1	35.2	3.6	6.4	10.4	16.0	25.9
Ck*	0.6	15.5	0.4	0.8	0.5	0.5	0.6	0.7	0.7
ψ [°]*	9.5	39.2	3.2	26.5	6.2	7.2	8.6	10.5	13.3
Ψv [‰]	22.2	63.3	5.2	63.4	8.4	11.7	19.2	26.7	45.7
Hydrological and geological settings									
Rn [$km \cdot km^{-2}$] *	2.4	19.8	1.2	3.8	1.9	2.1	2.4	2.7	3.0
Ls [km]	0.2	24.2	0.1	0.5	0.2	0.2	0.2	0.3	0.3
Rb	3.9	38.7	1.0	11.0	2.5	3.0	3.7	4.5	5.1
Ωmax	3.2	24.9	1.0	5.0	2.0	3.0	3.0	4.0	4.0
LI [km]	0.6	46.7	0.2	2.1	0.3	0.4	0.5	0.6	0.8
AI [km^2]	0.4	66.3	0.1	2.1	0.2	0.3	0.3	0.4	0.6
k [$m \cdot h^{-1}$]	0.158	104.1	0.0	0.36	0.0	0.004	0.036	0.36	0.36
Structure of land use									
F [%]*	37.6	61.3	1.6	92.9	12.6	17.7	31.3	52.1	78.6
Lh [%]*	2.5	65.3	0.1	6.3	0.3	1.3	2.6	3.7	5.0
Hh [%]*	1.6	116.7	0.0	9.5	0.0	0.2	0.9	2.7	3.6
Aa [%]	53.3	48.0	0.3	93.8	11.3	35.2	62.3	75.4	79.8
Rdn [$km \cdot km^{-2}$] *	4.1	20.0	1.7	6.2	3.0	3.6	4.2	4.7	5.0

A – catchment area, Ck – the shape index, ψ – average slope gradient, Rn – river network density, ψv – average slope of the main valley bottom, Ls – average slope length, Rb – bifurcation ratio, Ωmax – the highest order stream, LI – average length of the first order stream, AI – average watersheds area of the first order stream, k – soil's permeability coefficient k (after Pazdro and Kozerski, 1990), F – forest content, Lh – low-density housing, Hh – high-density housing, Aa – arable area, Rdn – road network density, $\bar{x}$ - mean, V – coefficient of variability (%), min, max – minimum and maximum values, , Q10-Q90 – percentiles. * – parameters applied to cluster analysis. Source: This study.

Another investigation revealed, that rapid increase in flood stage at the beginning of a storm event was produced by a delivery of rainfall water mostly via the road network (Słupik, 1981). As was noticed by Froehlich & Słupik (1986) during the storm event almost 60% of the rainfall water was delivered to the river by the road network. These facts emphasize very important role of the road network in flash flood formation process. For the 75% of catchments, the road network density was higher than 3.6 km·km^{-2} (Table 1). It should be emphasized that, road network density was almost twice as high as natural stream network density. The sum of artificial and natural networks density, where fast, concentrated type of flow occurs, reached almost 6.5 km·km^{-2}. Dense and well-developed natural and artificial networks within the catchments studied, accelerate delivery of rainfall water from the slopes, and in this way predispose a catchment to flash flood formation.

The relief condition is considered as one of the most important factors favoring triggering of flash floods (Flash flood…, 2010). Heavy convective precipitation may occur also in plain areas, but the ensuing flood generally lack the kinematic component, which characterises the propagation and the hazard potential of flash floods (Marchi et al., 2010). The majority of catchments had steep slopes (Table 1). The average slope gradient was higher than 7.2º for 75% of catchments. Steeper slopes accelerate overland flow velocity. As was mentioned before, the overland flow velocity on the slope of this gradient, is higher than 8 cm·s^{-1} on the arable lands and higher than 100 cm·s^{-1} on the road (Figuła, 1955). The slope gradient determines also the main valley bottom gradient, this in turn, mainly influences on flood wave velocity. The main valley bottom gradient was higher than 11.7‰, for 75% of the catchments (Table 1). High value of this parameter predisposes fast propagation of a flood wave. Summarizing, parameters describing relief condition also suggest that investigated catchments have predisposition to flash flood formation.

The analysis, where the influence of the basic physiographic parameters of catchments on flash flood formation process was considered, clearly indicated that the catchments have predisposition for flash flood generation. A typical Carpathian catchment where flash flooding appeared is small in area (A≈10 km^2), with slightly extended shape (Ck≈0.6) and steep slope gradient (ψ≈9°). River network is dense (Rn≈2.4 km·km-^{2}) and well-develop (Rb≈3.9). Usually, the river network is developed to fifth order stream and slope length reach on average 0.2 km. On average, first order streams has 0.6 km, and they drain 0.4 km^2 of the catchments' area. The catchment is considerably deforested (L≈31%), and arable areas slightly dominate (Ur≈60%). The road network, which plays crucial role in flood wave generation (Froehlich & Słupik, 1986), is very well-developed. The road network density (D≈4.1 km·km^{-2}) is almost twice as high as the river network. The soil cover permeability is very low.

Small dimensions, impermeable soil cover, steep slopes, structure of land use, and dense and well-developed river and road systems, create favorable conditions for fast response of a catchment. In order to assess this predisposition quantitatively, the CN and the lag time parameters were calculated (Table 2).

Table 2 The CN and the lag time parameters of the catchments affected by flash flooding – descriptive statistics

	$\bar{x}$	V	min	max	Q_{10}	Q_{25}	Q_{50}	Q_{75}	Q_{90}
CN [-]	82	3	75	88	78	80	82	84	86
Tlag [-]	0.9	38	0.3	1.9	0.5	0.6	0.9	1.2	1.4

Labeled like table 1. Source: This study.

Table 3 The input data of the SCS-CN and the SCS-UH hydrological models within part of catchment affected and unaffected by flash flooding.

A [km^2]	Lmax [km]	I [%]	CN [-]	Tlag [h]
Ryjak				
14.5*	10.7	10.9	77.0	1.8
26.9*	13.2	11.4	79.7	1.9
47.9	18.6	11.8	81.5	2.4
Łużanka				
9.7*	6.4	8.1	85.7	1.1
28.9*	7.0	9.4	83.7	1.1
54.9	22.9	10.5	83.5	2.8
Wolanka				
13.3*	8.7	12.8	82.9	1.2
22.5*	9.1	13.0	83.4	1.2
32.7*	9.9	12.3	83.1	1.3
44.8	14.9	12.5	83.3	1.8
Rzepianka				
10.6*	6.2	13.0	82.3	0.9
24.2*	6.9	13.3	81.9	1.0
34.5	11.7	13.5	82.1	1.5
42.9	15.1	13.6	82.3	1.8

*sub-catchment affected by flash flooding. Lmax – the maximum length of a catchment, I – average slope of a catchment. Labeled like table 1. Source: This study.

The mean value of the CN parameter reached 82. All catchments had this parameter higher than 75 and lower than 88. The lag time parameter, reached on average 0.9 h, and almost 90% of catchments had this parameter higher than 0.5 and lower than 1.4 h. It is worth to mention, that similar values were recorded in other catchments affected by flash flooding (Creutin et al., 2009). High value of the CN parameter denotes that during the rainstorm, a large part of a rainfall will be transformed into runoff. Low value of the lag time suggests rapid hydrological response of a catchment. These results also confirmed that investigated catchment may be considered as more prone to flash flood generation.

In order to evaluate if predisposition to flash flood formation may arise from the specific features of sub-catchment affected by flash flooding, hydrological parameters, derived as the result of the simulation of P=100 mm·h^{-1} rainstorm event, were studied. The input data of hydrological models is presented in table 3.

The cross-sections were located inside (*) and outside of the sub-catchment affected by flash flooding. The increase in a catchment area, between the cross-sections was similar, what allowed to compare changes in hydrological response within sub-catchment affected and unaffected by flash flooding. The cross-sections closed the sub-catchments from 9.7 to 54.9 km^2 in area. The maximum length ranged from 8.1 to 22.9 km and slope gradient was usually higher than 8%. The CN parameter was higher than 77 and Tlag ranged from 0.9 to 2.8 h.

The values of the time to peak (Tp), the maximum specific flow (q_{max}) and the runoff coefficient (Rc) are presented in figure 2. The Rc had comparable values within sub-catchment affected and unaffected by flash flooding. This may suggest that the potential for transformation from rainfall into runoff is similar. However, sub-catchments affected and unaffected by flash flooding differed in terms of reaction to rainfall. In each catchment significantly lower values of the time to peak and significantly higher values of the maximum specific flow were recorded within sub-catchment affected by flash flooding (signed by arrow) in contrast to unaffected ones (Fig. 2). Sub-catchment affected by flash flooding reacted to heavy rainfall more dynamically than unaffected ones. This is another fact that confirmed that the investigated catchments are more prone to flash flood generation.

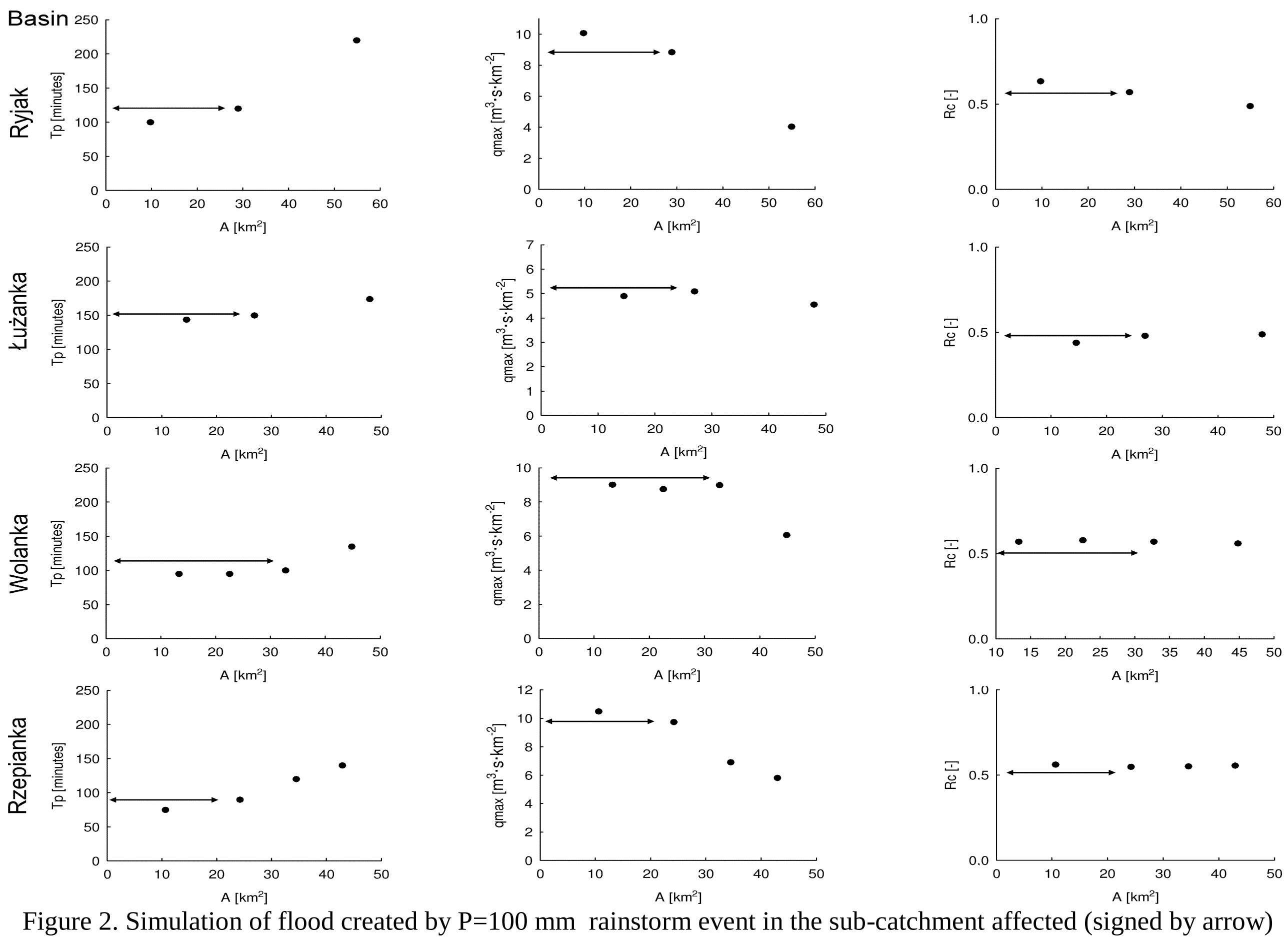

Figure 2. Simulation of flood created by P=100 mm rainstorm event in the sub-catchment affected (signed by arrow) and unaffected by flash flooding – selected hydrological parameters. Tp – time to peak, q_{max} – the maximum specific flow, Rc – runoff coefficient

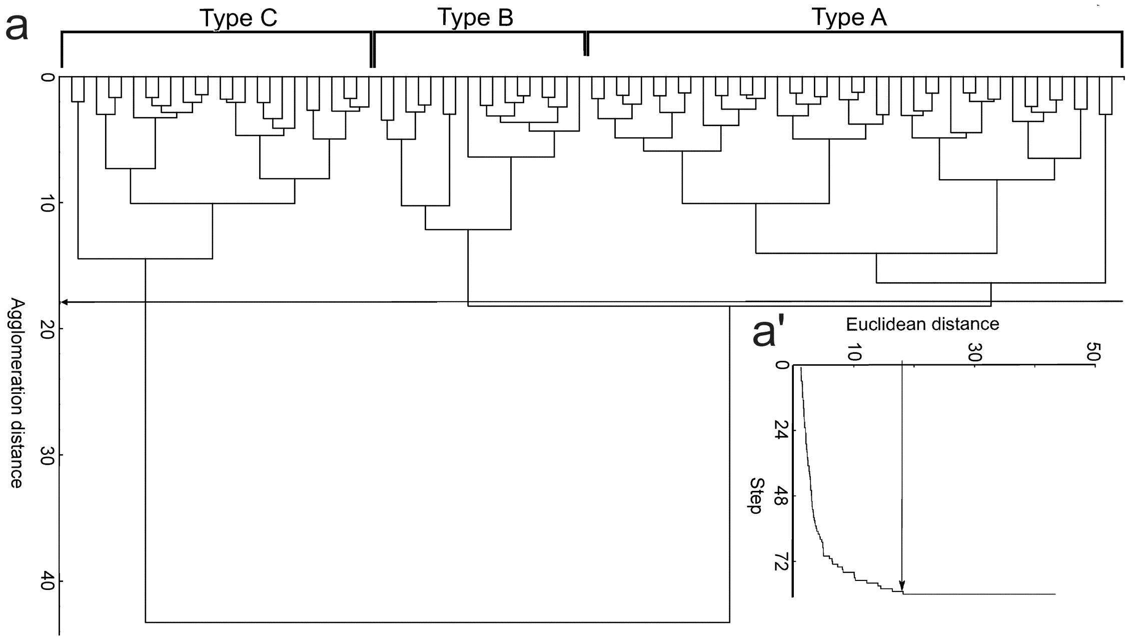

Figure 3. Agglomeration of catchments – a, screeplot with the point of division of the agglomeration tree – a'

3.2 Typology of catchments

The evaluation of a catchment predisposition to flash flood formation, suggests that investigated catchments have parameters, which make them more sensitive to flash flooding. Therefore types of the Carpathian's catchments more prone to flash flood generation were created.

Correlation analysis allowed to distinguish eight physiographic parameters, that were the input data to the cluster analysis (Table 1). The results of agglomeration process are presented in figure 3. Low level of linkage value during the agglomeration deserves special emphasis. This may be interpreted as the fact, that catchments were similar to each other in terms of physiographic parameters. Evaluation of the agglomeration process on the basis of hierarchical tree and screeplot (Fig. 3), supported by Kruskall-Wallis and multiple-comparison tests allowed for creation of three subsets (Table 4), which were treated as the types (models).

The area of catchment (A) and the shape index (Ck), had not diversified types statistically valid, therefore they were not taken into account when characterization of the types and identification were conducted. Remaining physiographic parameters diversified the types more significantly, but the differences were not so large, even though high value of the similarity measure was applied in division of the hierarchical tree (Fig. 3a). Therefore, created types (Table 4) are very similar. The main differences occurred in structure of land use and in the road network density. The mean values of the physiographic parameters enabled to characterize the types.

Table 4. Types (models) of the Carpathians' catchments more prone to flash flood generation – descriptive statistics.

Types	*N*	$\bar{x}$	min	max	Q_5	Q_{10}	Q_{50}	Q_{90}	Q_{95}
ψ [°]									
A	42	8.2	3.2	15.6	5.2	5.9	7.6	11.2	13.3
B	17	9.8	5.9	15.5	5.9	6.9	10.2	12.4	15.5
C	26	11.4	6.2	26.5	6.4	7.0	10.0	16.6	25.7
R [km•km^{-1}]									
A	42	2.3	1.3	3.4	1.6	1.9	2.3	2.6	2.6
B	17	2.6	1.9	3.8	1.9	2.0	2.7	3.3	3.8
C	26	2.5	1.2	3.3	1.3	1.4	2.7	3.0	3.3
L [%]									
A	42	25	5	80	9	12	25	35	51
B	17	33	2	63	2	9	36	57	63
C	26	62	14	93	40	41	59	85	85
Lh [%]									
A	42	3.2	0.4	5.3	1.7	1.8	3.0	4.8	5.1
B	17	3.3	1.4	6.3	1.4	1.5	2.8	6.0	6.3
C	26	1.0	0.0	5.9	0.0	0.1	0.7	1.8	2.9
Hh [%]									
A	42	1.4	0.0	5.2	0.0	0.0	1.1	3.2	3.4
B	17	4.0	0.8	9.5	0.8	1.8	3.2	8.0	9.5
C	26	0.4	0.0	4.1	0.0	0.0	0.1	1.1	1.4
Rn [km•km^{-1}]									
A	42	4.1	2.3	5.0	3.0	3.3	4.1	4.9	4.9
B	17	4.9	3.7	6.2	3.7	3.8	4.9	5.7	6.2
C	26	3.6	1.7	5.7	2.4	2.6	3.6	4.6	4.9

N – number of catchments, $\bar{x}$ – mean value, $x_{min.}$ x_{max} – maximum and minimum values, *me* – median, Q_{10}-Q_{90} – percentiles. Labeled like table 1. Source: This study.

Types A and B, have grouped the catchments, where arable lands dominated, they were significantly deforested, with steep slopes and dense road network, where low-density housing occupied significant part of the watershed. Moreover, high value of high-density housing was characteristic for type B.

Type C, has grouped the catchments more forested, with steeper slopes, dense and well-developed river network, where impermeable areas occupied small part of the catchment (Table 4).

The identification of catchments within the control group, allowed to assess if the created types were able to find catchments affected by flash flooding. The evaluation of the typology was performed by effectiveness of the classification index (I_E), the disjunctive of the classification index (I_H) and the accordance of the classification index (I_A). The measures are presented in table 5.

Table 5 The assessment of the identification process within the control group.

	Q_{10}; Q_{90}	Q_5; Q_{95}	min; max
I_E	48	80	86
I_H	6	10	67
I_A	71	88	91

Labeled like table 1. Source this study.

Identification by use of the minimum and maximum values, allowed to recognize 86% of catchments from the control group, however 67% of them, were classified to more than one type. Use of the Q_{10} and Q_{90} percentiles allowed to identify only 48% of catchment from the control group. The most satisfactory outcomes were obtained when the values of Q_5 and Q_{95} percentiles were applied. Almost 80% catchments from the control group ware identified, only 10% of catchments ware classified to more than one type and 88% of identified catchments were included to the same type as in the typology.

Based on these results, we may suspect that c.a. 20% of catchments may be omitted during identification in the geographical space.

3.3. Identification of catchments in the geographical space

Identification of catchments resembling the types was performed in the south-eastern part of the Polish Carpathians. The study area (Fig. 4a) consists of mid-mountain (the Beskid Niski, the Bieszczady Mts., and the Turczańsko-Sanockie Mts.), foothills (Jasielskie Foothills and Bukowskie Foothills) and intra-mountain basin regions (Jasielsko-Krośnieńska Basin). Folded flysch bedrocks of several Napples affect the relief. More resistant sandstones outcrops form the main mountain ridges with steep slopes incised by deep small valleys. Low-resistant shales separated and thick-bedded sandstones form more gentle foothills areas. The bedrocks are covered with 0.1–1.5 m thick weathered mantle, changed by pedological processes. Lithosols, Rancers and Cambisols form the soil cover. Forest areas occupy southern part of the study area, whereas, northern part is mainly covered by arable lands.

On the basis of digital elevation model, catchments smaller than 35.2 km^2 were delineated (Fig. 5b). This value corresponds to the dimension of the largest Carpathians' catchments, affected by flash flooding (Table 1). The group of 366 catchments where described by the same physiographic parameters as the types were (Table 4). Then, the group was searched in order to identify catchments similar to the types.

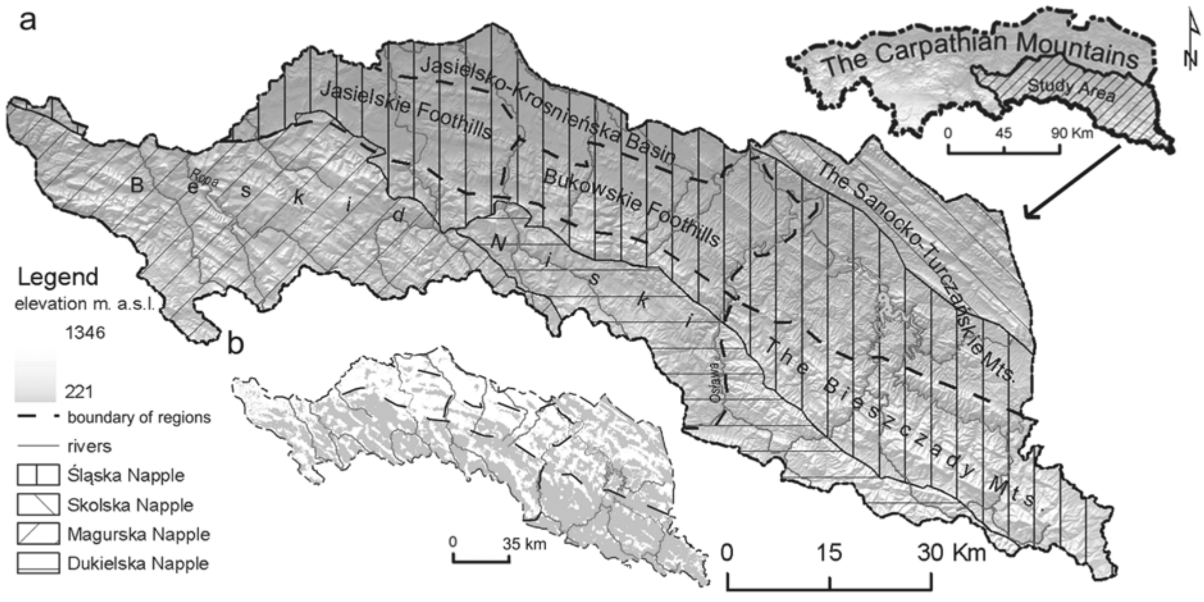

Figure 4. The study area. Geographic regions on the background of geological units – a, spatial distribution of the forested area – b

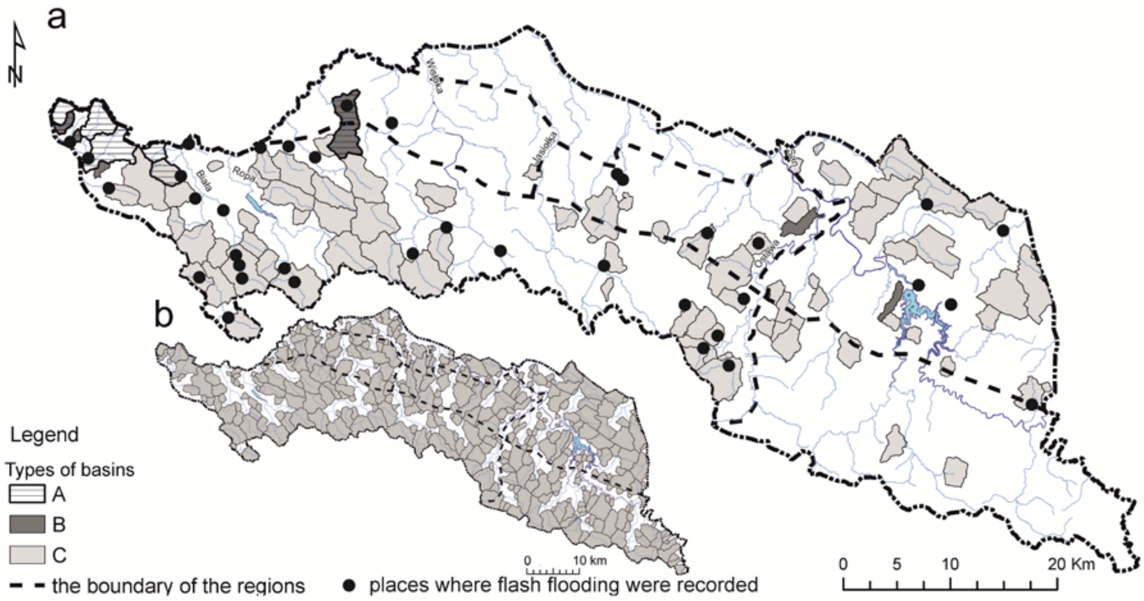

Figure 5. Distribution of catchments more prone to flash flood generation – a, catchments smaller than 35.2 km^2, where the identification process was performed – b

Table 6 Parameters of catchments identified in the geographical space and catchments included to given type.

Parameter	p_{level}	x_{ident}	x_{type}	std_{ident}	std_{type}
	Type A				
ψ [°]	p > 0.10	8.8	8.2	1.9	2.5
R [km·km^{-2}]	p >0.10	2.2	2.3	0.2	0.4
F [%]	p > 0.10	24.7	24.6	10.4	13.7
Lh [%]	p > 0.10	2.7	3.2	0.7	1.2
Hh [%]	p > 0.10	1.1	1.4	0.7	1.2
Rn [km·km-^{2}]	p < 0.10	3.9	4.1	0.5	0.6
	Type B				
ψ [°]	p > 0.10	7.9	9.8	2.0	2.5
R [km·km^{-2}]	p > 0.10	2.6	2.6	0.6	0.5
F [%]	p > 0.10	30.8	32.8	8.0	18.1
Lh [%]	p > 0.10	2.5	3.3	0.9	1.7
Hh [%]	p < 0.10	2.4	4.0	1.9	2.3
Rn [km·km-^{2}]	p > 0.10	4.4	4.9	0.5	0.7
	Type C				
ψ [°]	p > 0.10	9.8	11.4	1.7	5.1
R [km·km^{-2}]	p > 0.10	2.7	2.5	0.4	0.6
F [%]	p > 0.10	61.3	61.8	11.6	19.1
Lh [%]	p < 0.06	0.7	1.0	0.4	1.2
Hh [%]	p > 0.10	0.2	0.4	0.3	0.8
Rn [km·km-^{2}]	p < 0.10	3.3	3.6	0.6	0.9

Labeled like table 1. x_{type}, std_{type} – mean value and the standard deviation of catchments included to the types, x_{ident}, std_{ident} – mean value and the standard deviation of the catchment identified. Source this study.

Identification of catchments, where the values of Q_5 and Q_{95} were applied, led to identification of 91 catchments. The quality of the identification process in the geographical space was evaluated by Kolmogorov-Smirnov two-sample test (Table 6). Two groups of catchments namely, the group identified in the geographical space, and the group included to given type (A, B, C) during typology, were compared. The mean values and the standard deviations indicated that the two groups of catchment were similar. This fact indicates that the identification process allowed to find, in the geographical space, catchments similar to created types (models), and those catchments may be considered as more prone to flash flood formation.

Spatial distribution of the catchment identified is presented in figure 5a. Catchments similar to those in type A were represented by 8 catchments, which occupied the north-eastern part of the Beskid Niski region. Seven catchments were identified as those similar to type B. Catchments similar to those in type C were identified as the most abundant group - 76. Spatial distribution of this type deserves special emphasis. Majority of them were attributed to the western part of the Beskid Niski region. Several catchments were identified in the middle and the eastern part of this region. Some catchments were identified in the Turczańsko-Sanockie Mts.. Only a few catchments were indentified on the Jasielskie and Bukowskie Foothills, in Jasielsko-Krośnieńska Basin and in the Bieszczady Mts.. Foothills and intra-mountain basins are hilly or flat regions with gentle slopes, whereas catchments prone to flash flood generation have steeper slopes. The Bieszczady Mts., have favorable relief conditions for catchments prone to flash flood generation, however, structure of land use in which forest areas dominate (Fig. 4b) causes that the catchments were not identified.

At the end of the study information about flash flooding recorded in the south-eastern part of the Polish Carpathians, and spatial distribution of the catchments identified, were compared (Fig. 5a). Information about flash flooding was obtained from literature, Polish database of flash floods (Ostrowski et al., 2012) and past-flooding investigation, carried out by the author. In the study area, 36 flash flooding events, generated as a result of cloudburst, were found. It is worth to emphasis, that places where flash flooding were recorded, were located within catchments identified by the use of the method created in this study. This fact suggests that the method enable to identify catchments more prone to flash flooding in the geographical space.

4. DISCUSSIONS

Implementation of the European Flood Directive (Directive 2007/60/EC) requires identification of catchments at risk of flooding. Usually, hydro-meteorological data and historic information about flooding, were used to identify catchments at risk of flooding. In this way, the major flood events, recorded in larger, monitored catchments were the basis for evaluation if a catchment is at risk of flooding or not. Therefore, many small catchments, suffering from local flash flooding, were not taken into account, because of lack of appropriate data. Hence, in this study, the proposal for the method, enabling identification of small catchments more prone to flash flood generation, was presented.

The method, focused on physiographic parameters of a catchment, with a well-documented influence on flood wave formation process. The use of the physiographic parameters for evaluation of a catchments' predisposition to flash flood formation and application of those parameters for identification of catchments more prone to flash flood formation in the geographic space, was not studied in literature, before. Usually, a catchment potential for flash flooding was evaluated, in context of flood alert systems (Georgakakos, 2006; Norbiato et al., 2008), where soil moisture conditions and precipitation parameters are considered as driving factors for flash flood inducing.

Comprehensive characterization of a catchment by the use of relatively invariable in time physiographic parameters allowed to emphasize the potential for flash flood formation, that arisen from a catchment morphology, hydrological and geological conditions, relief and land usage. Types of the Carpathians' catchments more prone to flash flood formation, created as a result of typology, enabled to identify catchments similar to the types in the geographical space. Even though, only the basic parameters of a catchment were taken into account, the results obtained seem to be very promising. The agreement between the identified catchments and historic information about flash flooding confirmed, that the identification of catchments resembling those in theoretical types may be a valuable tool in the process of flood risk management. It seems that the method effectively identifies catchments, where probability of flash flooding, generated as a result of local, short-term precipitation rainstorms, is higher. The method has the potential for the practical use and should be tested in other parts of the Carpathians.

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