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ORIGINAL PAPER

The impact of extreme rainfall and flash floods on the flood risk management process and geomorphological changes in small Carpathian catchments: a case study of the Kasiniczanka river (Outer Carpathians, Poland)

Tomasz Bryndal[1] · Paweł Franczak[2] · Rafał Kroczak[1] · Wacław Cabaj[1] · Adam Kołodziej[2]

Abstract Short-duration extreme rainfall and flash floods are the major natural hazards in small Carpathian catchments. Quantifying forcing rainfall, hydrological responses and geomorphological impacts is the key to mitigating the negative impacts of flash floods. This article focuses on the hydrometeorological aspects of a flood event, the geomorphological changes of hillslopes and the river valley, in the Kasiniczanka catchment— 48 km^2 (Outer Carpathians, Poland). Results revealed that the flood in 2014 was generated by 6-h rainstorm with a total of 95.2 mm, and the mean intensity ranging from 7.1 to 31.3 mm h^{-1}. The flood peak ranged from 60 to 171 m^3 s^{-1}, and it was approximately two times higher than an 0.1% flood. The unit peak flow ranged between 3.6 and 4.6 m^3 s^{-1} km^{-2}, and the K index (which is non-dimensional measure and allows the comparison of flood magnitudes in catchments of differing size), ranged from 3.9 to 4.1. These two measures revealed that this flood was among the worst, recorded in catchments ranging from 13 to 48 km^2 in the Carpathians as a whole. The most significant geomorphological changes were observed in unmanaged channel reaches (the upper and middle parts of the catchment), contrary to lower part, where the river channel was protected by a hydrotechnical infrastructure. Flood analysis enabled the evaluation of the flood risk management process, related to flash floods in small catchments. In this context, some proposals to reduce flood risk level are presented and discussed.

Keywords Extreme rainfall · Flash flood · Flood peak · Flood risk · The Carpathians

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1 Introduction

Flash floods are the most destructive phenomena among natural disasters in terms of people affected (Barredo 2007). In inland, continental Europe, typical flash floods result from locally restricted, heavy rainstorm zones. The zone is usually less than 100 km^2 and most frequently 25 km^2 (Lenart 1993; Bryndal 2015). Floods generated by this type of precipitation include local flash floods, and usually affect catchments smaller than 40 km^2 (Bryndal 2014a, b, 2015).

Although local flash floods are among the most destructive disasters, relatively little is known about these natural phenomena (Gaume et al. 2009). This is mainly because they develop in space and time scales that conventional measurement networks of rain and river discharges are not able to sample effectively (Creutin and Borga 2003). Consequently, the atmospheric, hydrological and geomorphic controls of these hydrogeomorphic processes are poorly understood, leading to highly uncertain warning and risk management processes (Borga et al. 2014). Therefore, the description and analysis of every flood event are extremely important. Quantifying forcing rainfall, hydrological responses and geomorphological impacts is the key to mitigating the negative impacts of flash floods.

On August 5–6, 2014, an extraordinary rainstorm occurred over the middle part of the Beskid Wyspowy (Outer Carpathian, Poland—see Fig. 1a for location). The rainfall generated flash floods in several tributaries (Kasiniczanka, the headwater of Stradomka and Krzyworzeka) of the Raba river system (Fig. 2b). This event created an opportunity to assess the impact of extreme rainfall and flash flood on the geomorphological changes of small flysch Carpathian catchment and flood risk management process.

The goals of this study were to describe: (1) the meteorological setting of the heavy rainfall and the hydrological response of the catchment (2) the geomorphological changes of hillslopes, floodplain terraces, and the river channel. Based on this research (3) certain aspects of the flood risk management process were analyzed and discussed.

2 Materials and methods
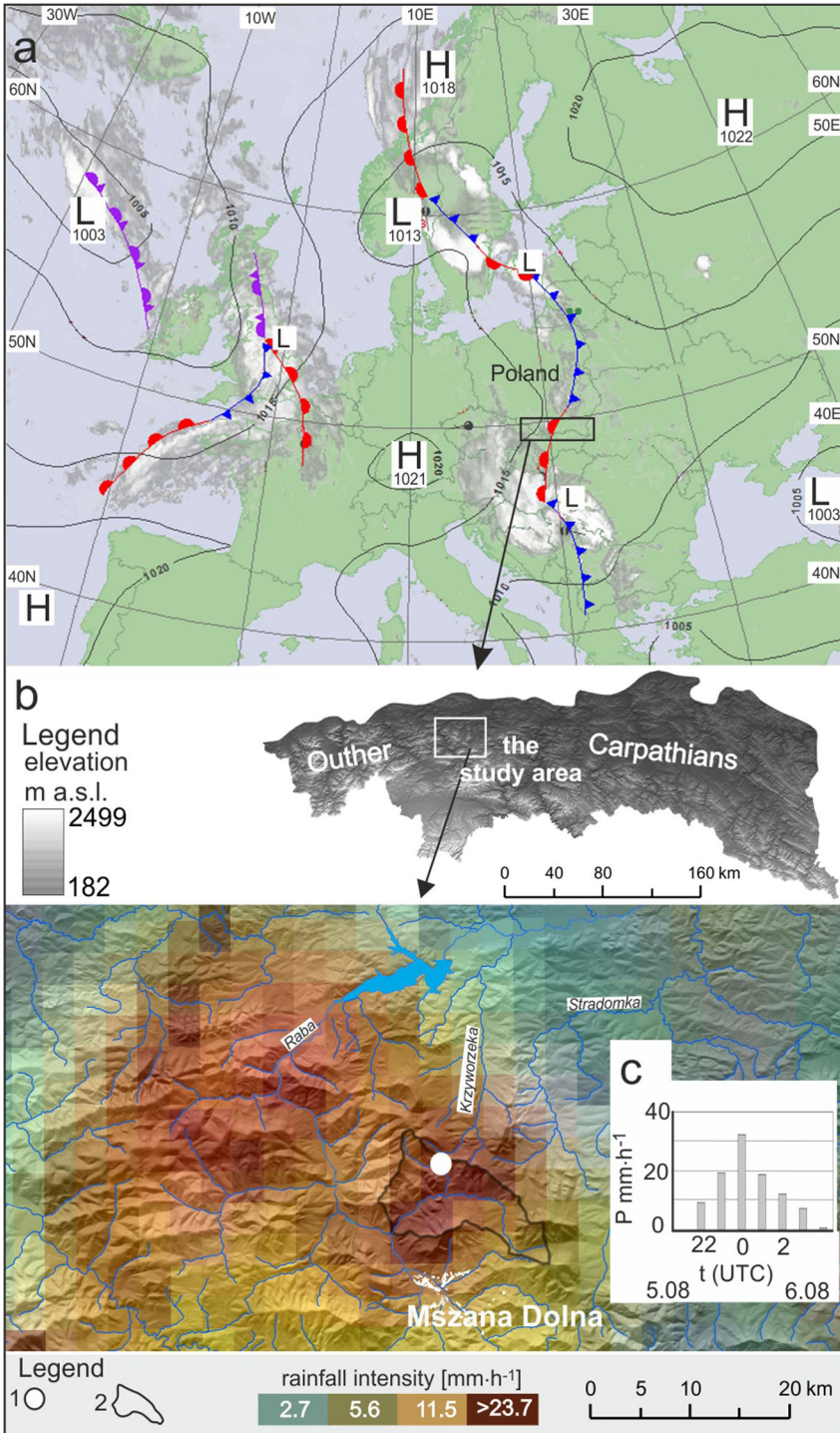
2.1 Meteorological settings

The meteorological settings were described using a synoptic map developed by the Institute of Meteorology and Water Management-Polish Research Institute (IMGW-PIB) and by daily commentary on the synoptic situation (Tomczuk and Dąbrowska 2014). The precipitation was reconstructed based on telemetry-type rainfall network stations managed by the IMGW-PIB. The rainfall data are presented in near real time on the IMGW-PIB official weather service Web site. The hourly rainfall intensity (mm h^{-1}) was downloaded directly from this Web site (http://monitor.pogodynka.pl, Accessed 06-08-2014).

2.2 Hydrological analyses

The largest flash flood event occurred in the Kasiniczanka river catchment. Therefore, it was selected for detailed investigation. The Kasiniczanka is an ungauged catchment. The nearest hydrological station (Kasinka Mała) is located on the Raba river, above the Kasiniczanka river outlet (Fig. 3). There are two hydrological stations located at tributaries of the Raba river (Lubień—Lubieńka river and Krzczonów—Krzyczonówka river) and one

Fig. 1 Study area. Location and hypsometry of the Kasiniczanka catchment (**a**), slope gradient (**b**) and land cover (**c**)
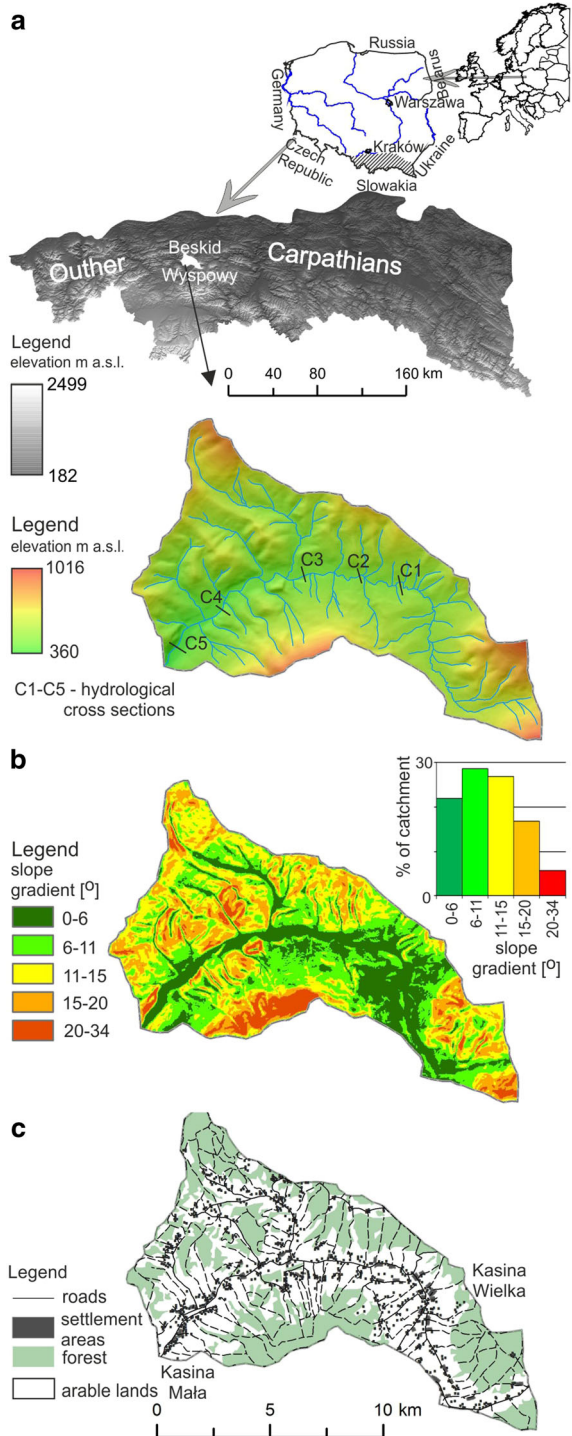
◄ **Fig. 2** Meteorological settings of a heavy rainstorm generating a flash flood in the Kasiniczanka catchment. The synoptic chart (2014-08-06 00:00 UTC) (**a**), rainfall intensity distribution (**b**), hourly rainfall in the Węglówka (*1*) telemetry-type rain gauge station (**c**), (*2*) boundary of the Kasiniczanka catchment. *Source*: Based on meteorological data obtained from the IMGW-PIB official weather service Web site www.pogodynka.pl; (Access 2014-08-06)

station (Stróże) located downstream on the Raba river (see Fig. 3—for location). The hourly flow data recorded on these gauges was obtained from the IMIGW-PIB monitoring Web site (http://monitor.pogodynka.pl, Accessed 06-08-2014) and used to assess spatial differences in flood wave magnitude.

The flood peak in the Kasiniczanka catchment was obtained after the flood event. The hydrological data obtained as a result of post-flood investigations is uncertain, and the sources of uncertainties were discussed in the literature many times (e.g., Gaume and Borga 2008; Lumbroso and Gaume 2012). In spite of the uncertainty, post-flood investigations are the primary source of hydrological data for flash floods in small catchments (Gaume and Borga 2008). In order to minimize uncertainties related to flood peak assessment, the field studies data verification process were performed in accordance with the flash flood post-flood field investigation guidance (Gaume and Borga 2008; Lumbroso and Gaume 2012). A field campaign was launched immediately after the flood event, and the highest floodwater stages were marked at 5 cross sections (Fig. 1a), where water flow had not been disturbed, and geomorphological changes of a channel and floodplain had not contributed to errors related, e.g., to flood cross-sectional area assessment. This allowed the use of the slope-area method for maximum flow calculation and reduced the errors related to flow calculation as much as it was possible. Geodesy measurements were taken 1 month later and included: the cross sections and the slope of the highest flood water stage. Flow water velocity was calculated using Manning's gravity flow formula (Lambor 1971), and the roughness coefficient was estimated based on field observations and tables (Chow 1959)—channel bed and riparian vegetation mainly. Flow velocity was verified by cross-check comparison with flow velocities reported by Marchi et al. (2010) and Lumbroso and Gaume (2012) for flash floods in Europe.

Flood peak calculated in 5 cross sections was compared to p-probable floods in order to evaluate the flood magnitude. The p-probable floods were calculated using the so-called *rainfall formula,* a regional type of equation used in Poland for catchments of up to 50 km^2 (Biernat et al. 1991).

The hydrological modeling approach complements the hydrological investigation in an ungauged catchment (Gaume and Borga 2008). Based on previous flash flood studies in the Polish Carpathians (Bryndal et al. 2010a, b, c), two hydrological models namely: Soil Conservation Service-Curve Number (SCS-CN) and Soil Conservation Service-Unit Hydrograph (SCS-UH), were used (Mistra and Singh 2003; Hydrologic Modeling System HEC-HMS 2015). These two models (in spite of their limitations and uncertainty discussed in the literature many times, e.g., Feldman 2000; Mistra and Singh 2003) have yielded the best results in terms of flood peak reconstruction (Bryndal et al. 2010a, b, c).

Spatial distribution of rainfall intensity was evaluated on the basis of hourly Surface Rainfall Intensity (SRI) products, distributed to the public by the IMGW-PIB monitoring Web site www.pogodynka.pl/radary (Accessed 06-08-2014). The hourly SRI products are developed based on 10 min of SRI radar images. The nearest radar station (Brzuchnia) is situated roughly 80 km from the Kasiniczanka catchment. The catchment is located in a medium–high-mountain region, and the distance from the radar antenna reached the threshold value for the SRI product usage. Therefore, it was decided that the hourly rainfall data from Węglówka telemetry-type rainfall station were used to provide the input data to

Fig. 3 Locations and
hydrographs recorded at flow
measurement stations: Kasinka
Mała (Raba river) (**a**),
Kasiniczanka—C5 cross section
(results of the hydrological
modeling) (**b**), Lubień (Lubieńka
river) (**c**), Krzczonów
(Krzczonówka river) (**d**) and
Stróża (Raba river) (**e**). SWQ—
multiannual mean high flow.
Source: Based on hydrological
data obtained from the
hydromonitor Web site of the
IMGW-PIB weather service
http://monitor.pogodynka.pl (access 2014-08-06)
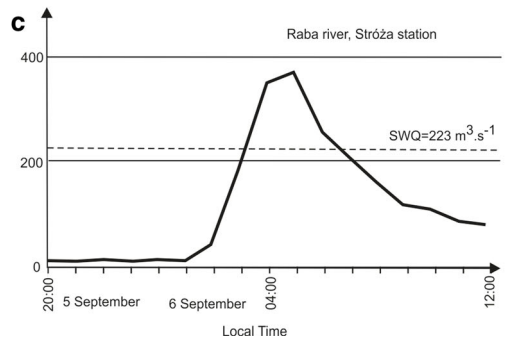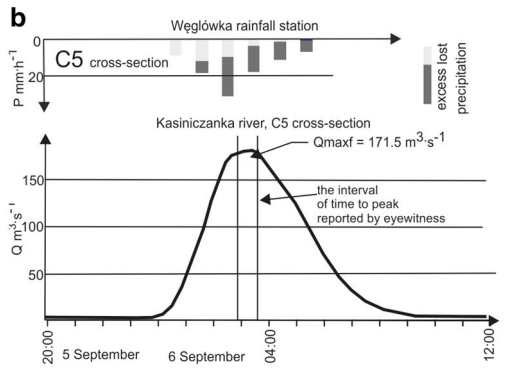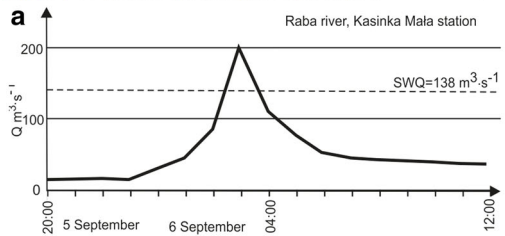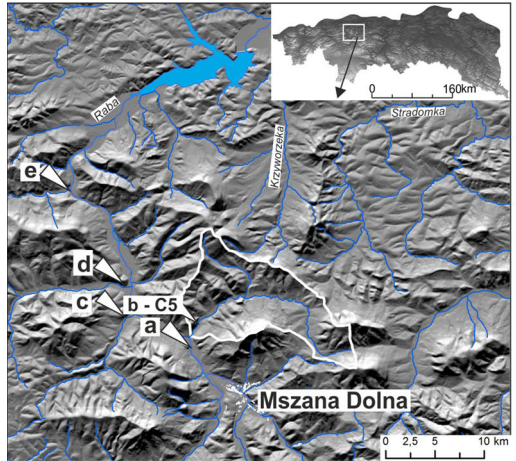
SCS-CN model. The station was located in the centroid part of the catchment, where the rainfall intensity was the highest (Fig. 2b). The small size of the catchment (48 km^2) and the spatial distribution of the rainfall were the reasons that uniform rainfall distribution was assumed. The CN curve was calculated according to Antecedent soil Moisture Conditions (AMC), evaluated on the basis of a 5-day period (Mistra and Singh 2003). In this case, the III AMC level and a 0.15 coefficient of initial loss were assumed. The lag time (T_{lag}) required for the SCS-UH model was calculated according to the equation (National Engineering Handbook 2010):

$$T_{lag} = \frac{(L \times 3.28 \times 10^3)^{0.8} \times \left(\frac{1000}{CN} - 9\right)^{0.7}}{1900 \times \sqrt{I}} \qquad (1)$$

where L—length of the longest drainage path (km), I—the average catchment slope ($I\%$), CN—the CN parameter (–).

The quality of the hydrological data obtained as results of hydrological modeling and post-flood field investigation was verified by cross-check comparison. Hydrologically simulated flood peak (Q_{fs}—m^3 s^{-1}) was compared to the flood peak calculated using the slope-area method (Q_f—m^3 s^{-1}), and percentage difference (%) was calculated. The quality of the hydrological data was also verified by comparison between the runoff depth (mm h^{-1}) and the precipitation depth (mm h^{-1}) for the time when the rainfall intensity was the highest (Gaume and Borga 2008). The ratio between these two values should not lead to the runoff rate greater than one. A higher value may suggest that model-computed flood peak/post-flood surveyed flood peak is overestimated. The errors may result from hydrological modeling or field-surveys. For example, in catchments heavily impacted by geomorphic changes, post-flood surveys are more uncertain and finally, may lead to larger errors in flood peak calculations. If calculations of peak flow are correct, the runoff rate higher than one, may result from hydrotechnical infrastructure destruction, e.g., reservoirs, dams, etc., release a massive amount of stored water (Gaume and Borga 2008). However, it was not a case of this study; therefore, cross-check comparison should lead to the runoff rate lower than one. The input data required for the hydrological models were obtained from a geodatabase consisting of a raster-type digital elevation model (20 × 20 m), a land cover map 1:50,000 and a soil cover map 1:25,000 in scale. The parameters required for hydrological models (catchment size, relief conditions, the CN parameter, variable of Eq. (1), a percentage of unpaved areas), were calculated using Arc-GIS 9.3 software, whereas hydrological modeling was performed in HEC-HMS software (Hydrologic Modeling System HEC-HMS 2015).

Flood magnitude recorded in the Kasiniczanka river catchment was compared to other local flash floods in the Carpathians. The K flood index developed by Françou and Rodier (1969) was used as a first measure. The authors, on the basis of flood peaks recorded on the rivers extending over the entire globe, developed a set of envelope curves, characterized by the equation:

$$\frac{Q_{max}}{Q_0} = \left[\frac{A}{A_0}\right]^{\left(1 - \frac{K}{10}\right)} \qquad (2)$$

where Q_{max}—the flood peak (m^3 s^{-1}), Q_0—the threshold flow (10^6 m^3 s^{-1}), A—the catchment area (km^2), A_0—the threshold catchment area (10^8 km^2). Adaptation of this formula allows for the calculation of the K variable according to the equation:

$$K = 10 - \left[1 - \frac{\text{Log}Q_{\max} - 6}{\text{Log}A - 8}\right] \tag{3}$$

The K variable is known as the Françou–Rodier index or the K flood index.

The K flood index is a non-dimensional measure, and therefore it allows the comparison of flood magnitudes in catchments that differ in terms of area. According to Françou and Rodier (1969), this method of envelope curves can be considerably useful for the study of exceptional floods in regions, where observation data are insufficient, especially for rivers with very heavy floods. The second measure, used for flood magnitude comparisons, was the unit flood peak ($m^3 \ s^{-1} \ km^{-2}$).

2.3 Mapping of geomorphological changes

The most significant geomorphological changes occurred on the valley floor; therefore, detailed geomorphological mapping was performed in this part of the catchment. Field investigations were performed during two campaigns. Photographic documentation was made on 6 August immediately after the flood event, whereas detailed geomorphological mapping was performed between 10–18 August 2014.

A methodology developed by the Department of Physical Geography of Jagiellonian University in Cracow (Kamykowska et al. 1999) was adapted for geomorphological mapping. The methodology allows for the collection of quantitative and qualitative data derived from fieldwork mapping, which is then complemented by analyses of thematic (topographical, geological, etc.) maps and aerial photographs. The data, among others, include information about: (1) river channel (e.g., geology, morphometry, hydrotechnical infrastructure, types and dimensions of landforms); (2) hydrological and meteorological settings during fieldwork; (3) morphometry of a catchment.

The field measurements were taken with a GPS receiver and laser rangefinder. Landforms such as river bars and cut banks, developed in the river channel and floodplain, were characterized by: area, length and width (river bars), and length (cut banks). Apart from previously mentioned measurements, the width of the river channel was also measured (one measurement per approximately 100 m).

Landforms mapped after the flood event were loaded onto topographical maps (using ARC-GIS software) and then, reaches of the river channel (15 reaches) were established on the basis of the number and dimensions of river bars and cut banks. This enabled the characterization of morpho-dynamic (erosive, and accumulation) type of a reach. The mean and the maximum width of the river channel were then calculated for these reaches, allowing for an evaluation of geomorphological changes of the river channel and flood-plain terrace after the 2014 flood.

Comparative analysis was performed to evaluate the spatial and temporal geomorphological changes of the river channel. The analysis was carried out within 15 reaches, determined after the 2014 flood. The number and dimensions of the river bars and cut banks, as well as the width of the river channel before the flood event (in 2014), were reconstructed on the basis of ortho-photomaps (from 2009), developed by the Head Office of Geodesy and Cartography. Comparison analyses were performed using ARC-GIS software.

The impact of flood water on river channel was also expressed quantitatively by stream power Ω (W m^{-1}) and unit stream power ω (W m^{-2}) indexes. The first measure, which represents the rate of energy expenditure per unit channel length, was computed as:

$$\Omega = \gamma \times S \times Q_f \tag{4}$$

where γ (9810 N m^{-3}) is the specific weight of water, S (m m^{-1}) is the energy slope of a channel and Q_f (m^3 s^{-1}) is a flood peak.

The second measure, which represents the energy expenditure per unit area of a channel bed, was computed as:

$$\omega = \gamma \times S(Q_f/w) \tag{5}$$

where w (m) is a channel width corresponding to flood water stage.

2.4 Flood hazard assessment

In order to evaluate flood hazard in the catchment, 1.0, 0.5 and 0.2% probable flood inundated areas marked on the flood risk maps 1:10 000 in scale (Flood risk maps 2014) were analyzed and compared to an inundated area mapped after the 2014 flood event. The inundated area was delineated after the flood using a GPS receiver. The mapping area extended from the Kasiniczanka river outlet to the boundary of Kasinka Wielka village (5.67 km from the Kasiniczanka river outlet).

2.5 The study area

The Kasiniczanka catchment is 48.5 km^2 in area. The bedrocks are composed of flysch sandstones and shales of Magurska Naple, and they are covered by a 0.3–1.5 thin mantle rich in clay minerals—usually exceeding 30%. The valley bottom is terraced and consists of fluvial deposits (usually composed of gravel mixed with clay).

The catchment has short and steep hillslopes. Average hillslope length is 0.2 km, and over 49% of the catchment has a slope gradient exceeding 11%. The width of the Kasiniczanka valley floor usually ranges between 100 and 400 m, with several small basins, where the width reaches up to 700-800 m (Fig. 1b).

The river channel is incised (1–4 m) into alluvial terraces and flysch bedrocks are usually uncovered. Numerous grade-control and hydraulic drop structures prevent bed erosion of the river. Some reaches of the river bank, especially in the middle and lower parts of the catchment, contain gabions and rip-rap. The tributaries of the Kasiniczanka river are deeply incised into hillslopes and their density reaches 1.8 km km^{-2}.

Land cover is predominantly arable land (58.5%). Pastures and meadows prevail in the headwater part of the catchment, as well as in the valley floor. The upper parts of the hillslopes are covered by forest areas (41%). Croplands usually cover the middle and lower parts of hillslopes (Fig. 1c). There are two villages located in the catchment, namely: Kasinka Mała and Kasinka Wielka, with a total population c.a. 3400 citizens. The built-up areas (0.5%) cover the bottom part of the valley and are located on fluvial terraces which should not be over-flooded. Several dozens of farmsteads are scattered on the slopes (Fig. 1c). The predominance of arable land and scattered farmsteads results in a high density of road network (on average 3.8 km km^{-2}).

3 Results

3.1 Meteorological settings

On 5 August, a trough of low pressure between anticyclones developed over northern Russia and the Azores Anticyclone, with a cold front system was spreading over Poland (Fig. 2a). This created dry and hot continental tropical air in the eastern part of Poland and cold, humid, maritime air in the western part. The cold front moved slightly eastward, leading to good weather conditions in western Poland, but full cloud cover and rainstorms in eastern Poland. In the Carpathians, the highest precipitation was recorded in the Beskid Wyspowy, near the town of Mszana Dolna. Taking into account the spatial distribution of rainfall intensity (mm h^{-1}) presented on the radar-derived picture (Fig. 2b), the Węglówka telemetry-type rainfall station, located in the middle of the heavy rainstorm zone, is the most representative for rainfall field characteristics.

The first rainfall event was recorded between 12:00 and 14:00 UTC (local time LT in summer: UTC + 2 h), and the mean rainfall intensity was 7 and 21 mm h^{-1}, respectively. The second rainfall event occurred between 22:00 (5.08.2014) and 04:00 (6.08.2014) UTC and the mean rainfall intensity reached: 8.6, 18.6, 31.3, 18.3, 11.3, 7.1 mm h^{-1} (Fig. 2c). A total of 95.2 mm of precipitation was recorded during the second heavy rainstorm.

3.2 Hydrological response

The largest flash flood was observed in the Kasiniczanka catchment. According to eye-witnesses from the Kasina Mała village, located in the lower part of the catchment (Fig. 1c), the bank-full stage was reached 1 h after the heavy rainstorm started (c.a. 01:00 LT). Between 02:30 and 03:30 LT, the water stage rose quickly and flood water overflowed the valley floor (Fig. 7). The inundated areas ranged between 120 and 220 m, with a maximum of c.a. 260 m. The flood water stage reached an elevation of about 2.5 m above the floodplain terrace, and more than 5 m above the bottom of the river channel. Two hours later (c.a. 05:00 LT), the water did not exceed bank-full stage.

The flood peak and the unit flood peak calculated after flood event are presented in Table 1. Flow velocity calculated using Manning's equation ranged between 1.6 and 2.0 m s^{-1}, what is comparable to flow velocities reported for other flash floods in Europe (Marchi et al. 2010; Lumbroso and Gaume 2012).

The flood peaks were compared to p-probable floods (i.e., the 1% probable flood corresponds to the 100 year return period), in order to evaluate flood magnitude (Table 1). The flood peak in the headwater part of the catchment (Fig. 1a, C1–C2 cross sections) ranged between 60.1 and 72.2 m^3 s^{-1}, and it was about 1.3 times higher than the 0.1% (44.8 m^3 s^{-1}—C1; 54.4 m^3 s^{-1}—C2) flood (Table 1). In the middle part of the catchment (Fig. 1a, C3 cross section), the flood peak reached 105.5 m^3 s^{-1} and was about double the 0.1% flood (Table 1). In the lower part of the catchment (Fig. 1a, C4–C5 cross sections), the flood peak ranged between 163.9 and 171.5 m^3 s^{-1}, and it was almost double the 0.1% flood (Table 1). The unit flood peak ranged between 3.6 and 4.8 m^3 s^{-1} km^{-2} (Table 1).

The spatial diversity of the flood magnitude was evaluated by looking at the flood peaks recorded at the flow measurement stations. It was the Raba river (Fig. 3, sites a, e) and its tributaries: Lubieńka (Fig. 3, site c) and Krzczonówka (Fig. 3, site d). The flood peak recorded at the Kasina Mała flow measurement station (the Raba river Fig. 2, site a), located above the Kasiniczanka river outlet, reached approximately 201 and was 63 m^3 s^{-1}

Table 1 The flood peak (Q_f) and the unit flood peak (q) on the background of *p-probable* floods. *Source*: this study

Cross-sectional number	Area (km²)	Q_f (m³ s⁻¹)	q (m³ s⁻¹ km⁻²)	*p-probable* flood (%)						
				0.1 (m³ s⁻¹)	0.2 (m³ s⁻¹)	0.5 (m³ s⁻¹)	1.0 (m³ s⁻¹)	10 (m³ s⁻¹)	50 (m³ s⁻¹)
C1	13.1	60.1	4.6	44.8	39.8	33.7	29.1	14	4.2
C2	17.9	72.2	4.0	54.4	48.4	41.0	35.3	17	5.1
C3	22.2	105.5	4.8	55.6	49.5	41.9	36.1	17.4	5.2
C4	41.1	163.9	4.1	84.2	74.9	63.4	54.7	26.4	7.9
C5	48.0	171.5	3.6	88.4	78.7	66.6	57.4	27.7	8.3

higher than the multiannual mean high flow (138 m^3 s^{-1}). The flood peak recorded at Lubieńka and Krzczonówka rivers (tributaries of the Raba river) did not exceed 2.9 m^3 s^{-1}. The flood peak recorded at the Stróża flow measurement station (several kilometers downstream), reached 370 m^3 s^{-1} and was 147 m^3 s^{-1} higher than the multiannual mean high flow (223 m^3 s^{-1}). Taking into account the spatial diversity of the flood magnitude, the value calculated at the C5 cross section (171 m^3 s^{-1}) seems to be correct.

Hydrological modeling was performed in order to complement the post-flooding investigations and to verify the hydrological data by cross-check comparison. The input data required for hydrological models and the results of the modeling process are presented in Table 2. The flood peak simulated with the SCS-CN and SCS-UH hydrological models (Q_{fs}), is similar to the data obtained during the post-flooding investigation (Q_f). The differences ranged from 4% (C1, C4 cross sections) to 13% (C3—cross section)—Table 2. It is notable, that time to peak simulated by hydrological models (3 A.M. L.T.—Fig. 3b) for the C5 cross section located in Kasina Mała (Fig. 1a), is comparable to eyewitness reports. The comparison of the runoff depth (21.3 mm h^{-1}) and the precipitation depth (31.3 mm h^{-1}) for the time, when the rainfall intensity was the highest, amounted to 0.68. This runoff rate is comparable to values reported during flash flood events in Europe (Gaume and Borga 2008; Surian et al. 2016). Taking into account that: (1) hydrologically simulated (Q_{fs}) and flood survived (Q_f) peaks are comparable (the differences are lower than 13%), and (2) the runoff rate is comparable to other flash flood events reported in the literature (Gaume and Borga 2008); the quality of hydrological data can be considered as "fair." Therefore, the magnitude of this flood can be compared/evaluated to other floods reported in the Carpathians.

3.3 Geomorphological changes of the catchment

The geomorphological changes of the flysch Kasiniczanka catchment were mainly related to a river channel and floodplain terrace. Changes observed on hillslopes were moderate.

3.3.1 Erosional changes of the river channel

Erosional changes of the river channel were related to the development and rejuvenation of cut banks. Landforms resulting from bed erosion were rarely observed. The general tendency observed after the 2014 flood event was an increase in the number of cut banks, in relation to 2010 (Fig. 4a). The highest number of cut banks (>15) occurred in the middle part of the catchment (reaches 5–8) where the river channel is not managed—not modified

Table 2 Input data required to hydrological models and results of modeling process. *Source*: this study

Cross section number	A (km^2)	I (%)	L_{max} (km)	CN (–)	Q_f (m^3 s^{-1})	Q_{fs} (m^3 s^{-1})	Percentage differences between flows (%)
C1	13.1	16.9	7.1	85	60.1	57.6	4
C2	17.9	17.2	8.4	85	72.2	77.7	−8
C3	22.2	17.3	10.3	85	105.5	91.9	13
C4	41.1	20	13.3	85	163.9	157.6	4
C5	48.0	20.0	15.2	85	171.5	179.9	−5

A, catchments area; I, mean catchments slope; L_{max}, maximum length; CN, curve number; Q_f, flood peak calculated by slope-area method; Q_{fs}, hydrologically simulated (SCS-CN and SCS-UH) flood peak

by hydrotechnical infrastructure (Fig. 4a). In lower part of the catchment (reaches 9–15), where some reaches of the river channel were protected by gabions, rip-rap, and grade-control structures, several newly developed cut banks (up to 5), appeared after the 2014 flood (there were no diagnosed cut banks in 2010)—Fig. 4a.

The mean and cumulative lengths of cut banks enable quantitative assessment of the river channel changes. A higher number of cut banks, generally corresponds to the increase in mean and cumulative lengths of these landforms (Fig. 4b, c). The highest values occurred in reaches 5 and 6 (Fig. 4c) and resulted from significant changes of unmanaged parts of the river channel (Fig. 5b). In the lower part of the catchment (9–15 reaches), a few newly formed and several dozen meter long cut banks were developed after 2014 flood. The mean length of these landforms exceeded 70 m (Fig. 4b), with the highest value reaching 135 m (reach 13). This increase resulted from extensive lateral erosion, which occurred over rip-rap (Fig. 5c). As a result of lateral erosion, after 2014 flood, the river channel was widened (Fig. 5a). The highest increases were observed in the middle and lower parts of the catchment and may be explained by erosional effects, quantified by the number and length of cut banks (Figs. 4, 5). The erosional effects correspond to higher values of unit stream power index. The reaches 5–7, 12 (Fig. 4), where the geomorphological changes were the most intense, have higher values of the unit stream power index (Table 4).

3.3.2 Accumulation changes in the river channel

Geomorphological changes of river bars were observed both in the river channel and on the floodplain terrace. Generally, a significant increase in the number and area of river bars, after 2014 flood, was observed (Fig. 4d–f).

In a river channel, the number of bars usually corresponded to the number of cut banks, because the mineral material eroded from the river banks was usually deposited in the vicinity of cut banks. Before 2014 flood, river bars were usually observed in the upper, unmanaged reaches of the river channel. The cumulative area covered by these landforms (reaches 5, 6) amounted c.a. 9500 m^2 in 2010. After the 2014 flood, this value increased approximately fourfold (37,200 m^2). Before the 2014 flood, in the lower, managed part of the channel, river bars occurred rarely and the cumulative area of these landforms (reaches 12–15) reached 1530 m^2. After 2014 flood, many newly developed river bars were observed. The cumulative area covered by river bars increased approximately 11 times, reaching 15,400 m^2. Taking into account the whole river channel, after 2014 flood the area covered by river bars increased from 13,900 to 65,625 m^2—about 5 times (Fig. 4e).

3.3.3 Erosional/accumulation changes on the floodplain terrace and hillslopes

Evaluation of temporal changes related to bars accumulated on the floodplain terrace was hampered. Before 2014 flood, these landforms were not identifiable on ortho-photomaps, because they were covered by grass. Therefore, only geomorphological changes after 2014 flood were analyzed. Fieldwork revealed that many bars were formed (Fig. 6b) and the cumulative area amounted 8000 m^2 (reaches 8, 10–11, 15)—Fig. 4f. Many bars were composed of coarse-grained material mixed with organic substances, including tree logs. A relationship between the morphometric characteristics of the floodplain, the distribution of these bars and erosional changes of the floodplain terrace, was observed. If a bar was located in a wider part of the floodplain, flood water flowed next to this bar, and erosional changes in the floodplain terrace did not occur. However, if a bar was located in a narrow

Fig. 4 The geomorphological changes of the Kasiniczanka river channel in 2010 and 2014. Number (**a**), mean width (**b**) and cumulative length (**c**) of cut banks. Number (**d**), cumulative area of bars (**e**). Area of bars deposited on terrace over floodplain (**f**). *1* river, *2* cut banks, *3* grade-control structures, *4* river channel, *5* bars, *6* numbers of investigated reaches

part of the valley, flood water overflowed this bar, and huge plunge pools (up to 1.5 m) were developed (Fig. 6a).

Heavy rainfall resulted in the moderate geomorphological changes of hillslopes. The changes were mainly related to the unpaved road network system where concentrated overland flow incised (even up to 0.7 m) and widened some sections of roads. Eroded material was deposited at the outlets of roads, as a debris fan composed of coarse-grained mineral material. The largest fan reached 750 m^2 (Fig. 6c).

3.4 Flash flood and its economic impact

The 2014 flood extent is presented in Fig. 7. The maximum flow was nearly double the 0.1% and resulted in huge economic damage. They were estimated at approximately 5 million euro. More than 164 buildings, including 75 residential buildings, 15 production and trading buildings, and 4 service public buildings, were flooded. Flood damage was reported in approximately 70 farm buildings. Seven bridges, several dozen culverts, water supply systems and roads were partially or completely destroyed (Fig. 6d, f, g).

4 Discussion

4.1 Meteorological and hydrological aspects

The flash flood in the Kasiniczanka catchment occurred as a result of heavy rainstorms that developed in the cold front zone. The front separated the polar maritime air from the Atlantic Ocean and continental tropical air. Many local flash flood events reported in Poland have been recorded under similar synoptic conditions (Parczewski 1960; Bryndal 2015). In authors' opinion, they can be considered as likely to trigger local flash floods in this geographical region.

Comparison of the flood magnitude is important from the cognitive and practical point of view. Table 3 presents the flood peak, the unit flood peak, and flood index K reported for 10 greatest flash flood events in the Carpathians. The floods occurred in catchments comparable to Kasiniczanka in terms of area (13–48 km^2). These hydrological data have been published in the literature (Bryndal 2010; Bryndal et al. 2010a, b, c; Zoccatelli et al. 2010) and the Hydrate flash flood data center (www.hydrate.tesaf.unipd.it, Accessed on 01-09-2012). The data were refined, and only one cross section, representing the highest value in terms of the K index, was selected for each flood. The unit flood peak in the Kasiniczanka catchment was enclosed between 3.6 and 4.8 $m^3\ s^{-1}\ km^{-2}$, and reached the top position in the Polish Carpathians. The unit flood peak was usually higher compared to the values reported for the Slovak and Romanian Carpathians (Table 3). Only three values in the Slovak Carpathians and two values in the Romanian Carpathians exceeded the highest unit flood peaks recorded in the Kasiniczanka catchment. It is worth noting that the unit flood peak in smaller catchments can reach significantly higher values. The highest values published in the literature for the Carpathians (Bryndal 2014a, b; Bryndal et al.
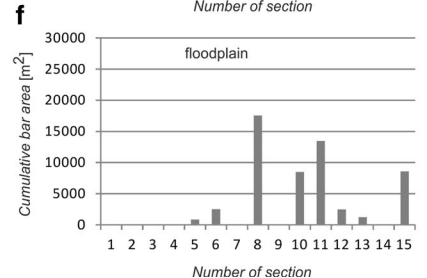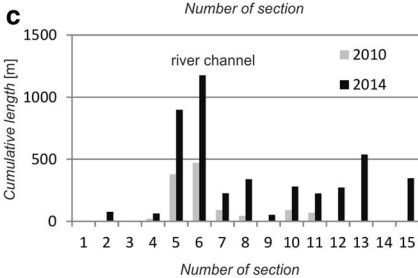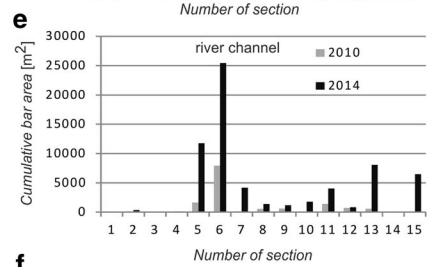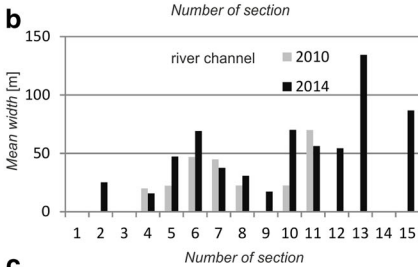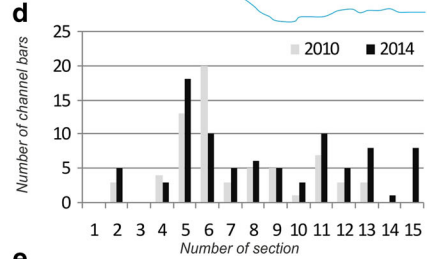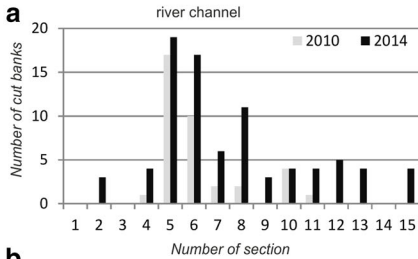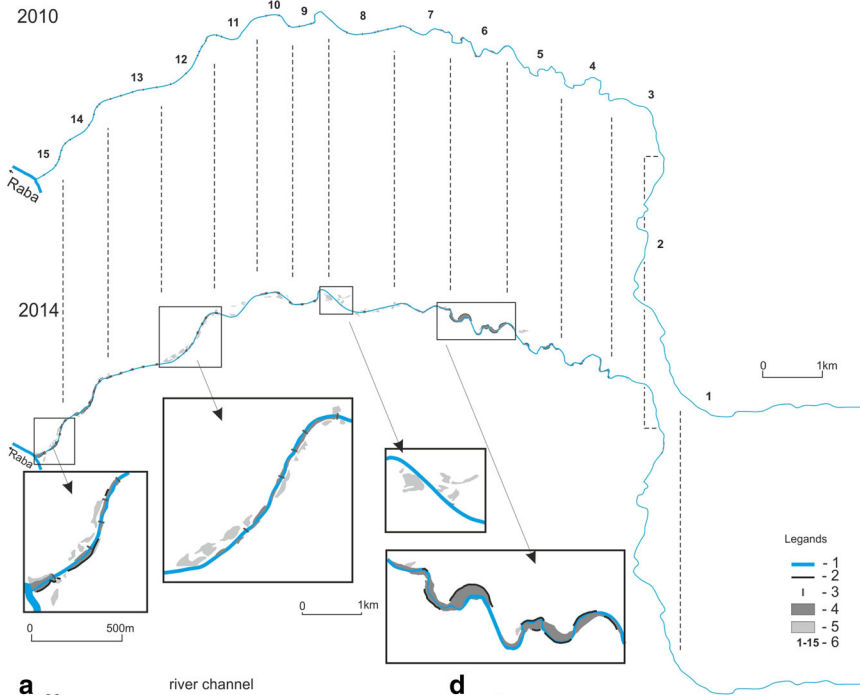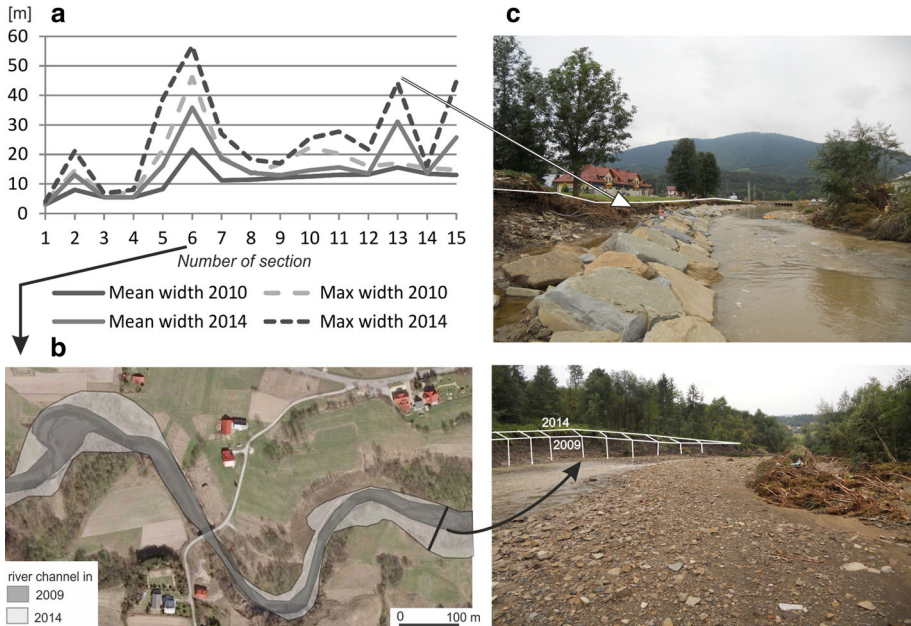
Fig. 5 Changes in the mean and maximum width of the Kasiniczanka river channel in 2010 and 2014 (**a**), modifications of the river channel not protected (**b**), and protected by hydrotechnical infrastructure (**c**). The number of reaches corresponds to Fig. 4

2010a, b, c) and the Hydrate database are enclosed in the range 12.9–15 m^3 s^{-1} km^{-2}, and were recorded in catchments ranging from 4 to 6 km^2.

The flood index K developed by Françou and Rodier (1969) allows the comparison of flood magnitude regardless of catchment area. This measure calculated for the Kasiniczanka river was enclosed between 3.9 and 4.1. It reached the highest position for the local flash floods in the Polish Carpathians, in catchments ranging from 13 to 48 km^2 in area. In the Slovak and Romanian parts, the K index was usually enclosed between 2.5 and 3.6 (Table 3). The value 4.1 was exceeded during four flash floods (Slovakia—2; Romania—2). The K index also enables the evaluation of a river to flood formation. The higher the index, the more susceptible is a river to a large-scale flood occurrence (Bartnik and Jokiel 2015). Taking into account the values reported in Table 3, and comparing them with world records (Bryndal et al. 2015), the susceptibility of small Carpathian catchments to flood generation may be evaluated as "an average."

4.2 Geomorphological changes

Extreme rainstorms in headwater catchments may trigger liquid floods, debris floods or debris flows (Borga et al. 2014). The type of process triggered depends on several characteristics, including (1) the hydrologic, geomorphometric and geotechnical features of the hillslopes, (2) the source materials and the availability of sediments, and (3) the frequency-magnitude characteristics of the precipitation event (Borga et al. 2014). In the Polish Carpathians, rainfall exceeding 20 mm h^{-1} is considered a threshold value triggering liquid flash floods (Parczewski 1960; Ostrowski et al. 2012). However, such rainfall and flooding generally result in the moderate geomorphological changes of a catchment.

Fig. 6 Geomorphological changes of floodplain terrace (**a**, **b**, **d**) and hillslopes (**c**). Influence of hydrotechnical infrastructure such as grade-control (**d**) and hydraulic drop structures (**e**) on geomorphological changes of the river channel. Destruction of bridges (**f**) and culverts (**g**) as a result of erosional processes and organic material transportation. *1*—places where erosion occured

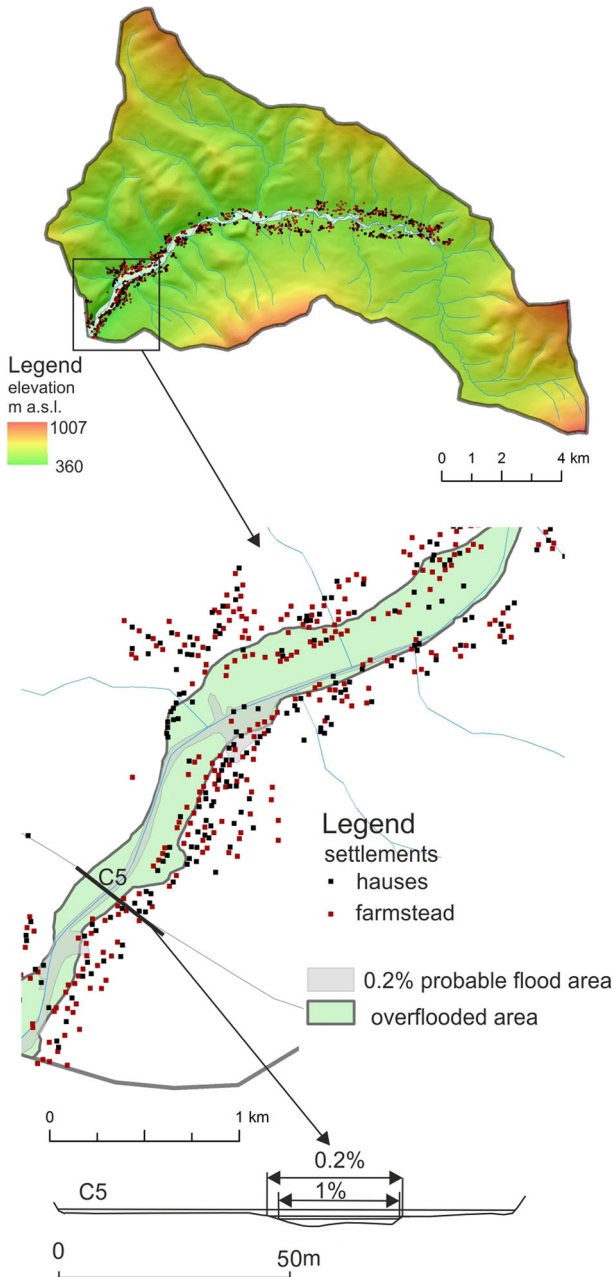**Fig. 7** Maximum extend of flooding in Kasiniczanka catchment after flood event in 2014, on the background of 0.2% flood inundate area

Significant changes usually resulted from rainfall exceeding this value many times over; often $P > 80$ mm (Izmaiłow et al. 2006; Gorczyca et al. 2013; Kowalczuk et al. 2013; Verez et al. 2013; Pekalova et al. 2015). The flood in the Kasiniczanka river catchment in

Table 3 The flood peak (Q_f), unit flood peak (q) and K indexes for local flash flood events in the Polish Slovakian and Romanian Carpathians (ordered according to the K index). *Source*: this study on the basis of Bryndal 2010, Hydrate flash flood data center (www.hydrate.tesaf.unipd.it) access at 2012-09-01; Zoccatelli et al. (2010)

Lp	River	Cross section	A (km^2)	Q_f (m^3 s^{-1})	q (m^3 s^{-1} km^2)	K (–)
	Poland					
1	Niedźwiedź	Porąbka Uszewska P3	18.1	28.0	1.5	3.2
2	Ryjak	Zabartówka	14.5	31.3	2.2	3.4
3	Targaniczanka	Targanice	23.0	43.0	2.0	3.4
4	Tarnawka	Kalnica	13.7	37.8	2.7	3.6
5	Wątok	Szynwałd P6	14.9	44.9	3.0	3.6
6	Niedźwiadka	Niedźwiada Dolna P2	13.7	43.3	3.2	3.6
7	Niedźwiedź	Porąbka Uszewska P2	14.4	47.0	3.3	3.7
8	Osława	Radoszyce	31.0	84.5	2.7	3.7
9	cbn	Brzeziny P1	26.8	81.5	3.0	3.8
10	Barbarka	Czystochorb	13.4	67.0	4.7	3.9
11	Kasiniczanka	C1	13.1	60.1	4.6	3.9
	Kasiniczanka	C2	17.9	72.2	4.0	3.9
	Kasiniczanka	C3	22.2	105.5	4.8	4.0
	Kasiniczanka	C5	48.0	171.5	3.6	4.0
	Kasiniczanka	C4	41.1	163.9	4.1	4.1
	Slovakia					
12	Sološnický potok	Sološnica	10.4	5.7	0.6	2.5
13	Osrblianka	Osrblie	27.8	12.8	0.5	2.5
14	Stupavka	Borinka	33.8	16.84	0.5	2.6
15	Chvojnica	Lopašov	31.1	24.6	0.8	2.9
16	Belá	Košická Belá	23.1	36.4	1.6	3.3
17	Hutná	Ľubietová	39.0	63.9	1.6	3.5
18	Biela	Ždiar	14.1	75.0	5.3	4.0
19	Biela	below Ždiarsky creek	22.1	100.0	4.5	4.0
20	Malá Svinka	Jarovnice	35.4	230.0	6.5	4.4
21	Dubovický potok (creek)	confluence	15.2	160.0	10.5	4.4
	Romania					
22	Crisul Negru	Poiana	29.9	20.5	0.7	2.8
23	Valea Grosenilor	Archis	29.2	29.0	1.0	3.1
24	Nimaiesti	Budureasa	23.0	24.8	1.1	3.1
25	Valea Galbena	Pietroasa	36.0	34.5	1.0	3.1
26	Teuz	Ignesti	17.0	28.1	1.7	3.3
27	Sacele	Sacele	32.0	45.0	1.4	3.3
28	Poicu	Vanatori	37.0	52.2	1.4	3.3
29	Valea Cerbului	Busteni	26.0	54.2	2.1	3.5
	Valea Cerbului	Busteni	26.0	62.3	2.4	3.6
30	Clit	Arbone	36.0	175.0	4.9	4.2
31	Hauzeasca	Orb Confluence	29.0	320.0	11.0	4.7

A, catchment area; K, the flood index

2014 is one such example. This was generally a liquid-type flood, however, high rainfall, and discharge exceeding the 0.1% flood, resulted in the significant geomorphological changes of the river channel and floodplain terrace.

4.2.1 Erosional type of changes and their reduction opportunities

Erosional changes of river banks and river bed were generally related to bank undercutting, rarely to plunge pools development. Lateral bank erosion was usually more significant in unmanaged, "more natural" reaches of the river channel, where river banks had retreated up to 30 m (reach 6, Fig. 5b). Significant geomorphological changes of a river channel, after flash floods, were reported in other small Carpathian catchments (e.g., Izmaiłow et al. 2006; Siwek et al. 2011; Gorczyca et al. 2013; Kowalczuk et al. 2013; Verez et al. 2013). The impact on flood water on river channel expressed by stream power index (Table 4) is comparable to this observed during flash floods in the inland continental part of Europe (Marchi et al. 2015). However, it is several times lower compared to the Mediterranean region (Surian et al. 2016; Rinaldi et al. 2016).

Managed reaches of the channel, allowed the assessment of a hydrotechnical infrastructure functioning, during flash floods events. In the catchment studied, the infrastructure includes bank protection, grade-control and bed reinforcement infrastructures that should prevent lateral and bed erosion of a channel. The flood in the Kasiniczanka catchment revealed that this hydrotechnical infrastructure could not eliminate erosion definitely, but it did slightly reduce the process. There was observed the relationship between structural design and the functioning of this infrastructure during a flash flood event. Lateral erosion of river banks was reduced effectively in those reaches, where banks were protected by gabions covering the entire river bank. The reaches, where rip-rap protected the lower part of a river bank (Fig. 5c), lateral bank erosion undercut higher parts of the bank, and geomorphological changes were significant. This suggests that gabions covering an entire part of a river bank more effectively reduce lateral bank erosion. This type of bank protection infrastructure should be applied in the areas most vulnerable to erosion reaches of a river channel.

Erosional effects after the flood may be related to the constructional solution of grade-control structures. Massive hydraulic drop structures, where flood water fell on a race floor (usually composed of concrete), were able to effectively reduce bed and lateral erosion (Fig. 6e). The grade-controls composed of concrete steps, without erosion-resistant sections, failed to function (Fig. 6d). This suggests that grade-control structures with the race floor effectively prevent erosion and should be applied in practice.

Table 4 Cross-sectional stream power (Ω) and unit stream power (ω) indexes during flash flood in Kasiniczanka. *Source*: this study

Cross section number	A (km^2)	Q_f (m^3 s^{-1})	Ω (W m^{-1})	ω (W m^{-2})
C1	13.1	60.1	1572	11
C2	17.9	72.2	2122	79
C3	22.2	105.5	10,337	56
C4	41.1	163.9	6424	137
C5	48.0	171.5	6721	62

A, catchments area; Q_f, flood peak calculated by slope-area method

4.2.2 Accumulation-type change and its influence on river conditions

River bars are generally expedient in the river channel. They contribute, among others, to the increase in biodiversity and river restoration (Korpak et al. 2008). Before 2014 flood, almost no river bars were in the lower part of the channel, protected by hydrotechnical infrastructure. After the flood, there was an increase in the number of river bars. This result may be interpreted as a positive impact of catastrophic flash floods, for example, in the context of river restoration.

The river bars were usually composed of mineral materials (gravel and boulders up to 150 mm in diameter, mixed with finer material), and they generally developed in the vicinity of cut banks, in the river channel. This may suggest that this material was moved only several tens of meters, in spite of the fact, that high flood magnitude occurred. Tree logs and branches often created wood jams and caused the accumulation of mineral material. These forms reached several tens of m^2 in area and they were generally developed in the wider part of the floodplain and channel, rather than the narrower parts. Similar results were observed in larger Carpathian catchments (Wyżga and Zawiejska 2005). This distribution mainly results from mechanisms of tree wood transportation and its deposition (Korpak et al. 2008). It is worth to note, that wood jams usually create favorable conditions for the accumulation process, but these landforms can also initiate erosional effects. The wood jams created during flood event function as waterfalls, resulting in the development of plunge pools (Fig. 6a). This process, observed in the Kasiniczanka catchment, is rarely reported in other small Carpathian catchments (Izmaiłow et al. 2006).

4.2.3 Geomorphological changes of hillslopes

The geomorphological changes of hillslopes were generally related to the unpaved road network system, where concentrated, rapid overall flow occurred. As a result of this, roads were incised, and massive fans composed of coarse-grained rubble material were accumulated near the incised road outlet (Fig. 6c). Similar processes were reported in other Carpathian catchments after heavy rainstorms (Łajczak et al. 2014; Kroczak et al. 2015). This suggests that unpaved road networks accelerate geomorphological changes of contemporary Carpathian slopes.

4.3 Flood risk management process in small catchments—selected aspects

4.3.1 Flood hazard and exposure—the law regulations and the role of the local governments

Flash floods are among the most dangerous natural hazards in Europe (Barredo 2007). In order to mitigate the negative effects of flooding, the European Union's Flood Directive (Directive 2007/60/EC) obliges all Member States to conduct preliminary flood risk assessment to identify areas where potential significant flood risk exists. Where real risks of flood damage exist, they must develop, flood hazard maps and flood risk maps, for such areas. Finally, flood risk management plans must be drawn up for these zones. They should address all phases of the flood risk management process—particularly: prevention, protection, and preparedness. These European Union regulations are translated into national legislation by the Member States. In the context of such legislation, two issues deserve special emphasis. The first concerns the preliminary flood risk assessment process.

Flash floods occur locally; therefore, there is lack of information/databases regarding these phenomena (Bryndal 2014a). As a result, many small catchments are not identified at the preliminary flood risk assessment stage, and finally, there is a lack of flood hazard, flood risk maps, and flood management plans, to support flood risk management process in small catchments. Such documents are usually developed for larger catchments (several tens of km^2 in area). The second aspect is related to the definition of low probability flood, which in practice, usually denotes 0.5 and 0.2% floods. The flood in the Kasiniczanka catchment revealed that flood peak in small catchment can exceed 0.1% flood.

The abovementioned aspects lead to the conclusion, that flood risk management process related to flash floods in small catchments is very complicated. The question is: how to deal with local flash floods in small Carpathian catchments? Taking into account that flash floods are characterized by a short time to peak and high magnitude of the flood wave, the way to mitigate the negative impacts of flooding is, in authors' opinion, the reduction of an exposure. The exposure generally describes who and what may be harmed by the flooding. In authors' opinion, local governments, which are responsible for the preparation of local development plans, can effectively reduce the exposure to flooding (e.g., restriction in types of buildings and its parameters, etc.). In this context, the key information is the flood extent (it characterizes the flood hazard), which should be included to the development plans. Since flood magnitude can extend 0.1% flood, an inundated area for the Maximum Probable Flood (MPF) should be delineated in small catchments. The extend of the MPF and its elevation may allow decision-makers to prepare local development plans, which contribute to flood mitigation effectively. In authors' opinion, delineation of the MPF extent and the law regulations owing to the reduction in exposure (e.g., the local planistic documents) are fundamental steps to mitigate negative effects of flash floods in small Carpathian catchments. These are the base for other actions (e.g., preparedness, increase in awareness, etc.) for citizens and institutions that are involved in mitigating and reducing the effects of flooding.

4.3.2 Designing and functioning of bridges and culverts

Another issue which deserves special attention, in the context of flood risk management process, is the design of culverts and bridges. These elements are usually designed for 1% flood. Many studies (Bryndal et al. 2010a, b, c) reveal that the 0.1% flow is exceeded during flash floods in small catchments. Under such conditions, many culverts and dams can be destroyed, as was the case in the Kasiniczanka catchment. Two factors contributed to the destruction of this infrastructure. The first is related to downward and site bank erosion by flood water, which overflowed a bridge deck (Fig. 6f, g). The second is associated with the movement of organic material such as tree logs, which clogged the culverts and bridges and contributed to their destruction (Fig. 6f). In this context, the following conclusion can be drawn: bridge design, especially in small catchments, where flash floods are expected more frequently, should take into account flows, which may occur during lower probable floods. Moreover, bridge construction should not limit the movement of floodwater (e.g., arch-type bridges).

5 Conclusion

The main conclusions of this study are as follows:

(A) Hydrometeorological aspects

1. The rainfall occurred in a cold front zone, separated the polar maritime air flowing from the Atlantic Ocean and continental tropical air. Because many local flash flood events have been recorded under similar synoptic conditions, they can be considered as likely to trigger local flash flood events in this geographical region.

2. The rainfall event lasted for 3 h, with the mean hourly rainfall intensity ranging from 19 to 31 mm h^{-1}, resulting in an amount exceeding 90 mm. In small Carpathian catchments, such precipitation usually generates enormous flash floods, as was confirmed by this study and investigations carried out in other Carpathian catchments.

3. A hydrological post-flooding investigation, complemented using hydrological modeling, enabled the reconstruction of the hydrological parameters of the flash flood. Hydrological modeling process and the models used in this study have limitations and the results are burdened with uncertainty, what have been discussed in hydrological literature many times (e.g., Feldman 2000; Mistra and Singh 2003; Gaume and Borga 2008). However, this study confirms that comprehensive hydrological investigation (in spite of methodological limits) may be a good approach for collecting hydrological data about flash floods in small ungauged catchments.

4. Taking into account the maximum flow, the maximum specific flow (3.6–4.6 m^3 s^{-1} km^{-2}) and the K flood index (3.9–4.1), this flood event is one of the worst recorded in catchments ranging from 13 to 48 km^2 in area, in the Carpathians as a whole.

(B) Geomorphological changes

5. Flow magnitude exceeding 0.1% flood resulted in the geomorphological changes of a river channel and floodplain terrace. Detailed analysis of these changes allows conclude that:

   (a) there was an increase in the number and dimension of cut banks and river bars after the 2014 flood.

   - in the river channel, bars were usually composed of gravel (up to 150 mm in diameter). The bars usually occurred in the vicinity of cut banks, suggesting that the transport of rubble material was restricted to several dozens of meters, in spite of high flood peak.
   - on the floodplain terrace, bars were composed of coarse-grained material. Many bars were composed of organic substances (including tree logs) and mineral material. These bars, reached several tens of m^2 in area, and they were generally developed in the wider part of the floodplain and channel, rather than the narrower parts.

   (b) greater geomorphological changes occurred in unmanaged channel reaches (the upper and middle parts of the catchment), contrary to lower parts, where river channel is partially protected by a hydrotechnical infrastructure. The geomorphological changes correspond to higher values of unit stream power index.

   (c) bank protection infrastructure, grade-control and hydrological drop infrastructures, slightly reduced, but did not fully eliminated lateral and bed erosion. The intensity of the erosion process was related to constructional solutions in the design of this

infrastructure. Grade-control structures with the race floor effectively prevent erosion and should be applied in practice.

(d)   the intensity of geomorphological processes on the hillslopes was mainly related to the unpaved roads system. The conclusion is that that road networks play important role in geomorphological changes the of contemporary Carpathian slopes.

      (C) Flood risk management aspects

6.   The flood risk management process in small catchments is complicated and hampered by: a lack of flood risk maps, and the fact, that the maximum flow recorded during flash flood events exceeds even the 0.1% flood. The authors' hold that the extent of the Maximum Probable Flood in small catchments should be developed and included in local development plans.

7.   Bridge design, especially in small catchments, where flash floods are expected more frequently, should take into account lower than 1% probable flow. Moreover, bridge construction should allow for the free movement of flood water.

References

Barredo JI (2007) Major flood disasters in Europe: 1950–2005. Nat Hazards 42:125–148

Bartnik A, Jokiel P (2015) Geografia wezbrań i powodzi rzecznych. Wyd. UŁ., Łódź

Biernat B, Bogdanowicz E, Czarnecka H, Dobrzyńska I, Fal B, Karwowski S, Skorupska B, Stachy J (1991) Zasady obliczania maksymalnych rocznych przepływów rzek polskich o określonym prawdopodobieństwie pojawienia się. IMGW, Warszawa

Borga M, Stoffel M, Marchi L, Marra F, Matthias J (2014) Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. J Hydrol 518:194–205

Bryndal T (2010) Parametry hydrologiczne wezbrań spowodowanych krótkotrwałymi intensywnymi opadami deszczu w Polsce. Ann UMCS Sect B Geogr Geol Mineral Petrogr 65:43–71

Bryndal T (2014a) 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. Carpath J Earth Environ Sci 9(3):109–122

Bryndal T (2014b) Parametry hydrologiczne wezbrań opadowo-nawalnych w polskiej, słowackiej i rumuńskiej części Karpat. Prz Geogr 86(1):5–21. doi:10.7163/PrzG.2014.1.1

Bryndal T (2015) Local flash floods in Central Europe: a case study of Poland. Nor Geogr Tidsskr Nor J Geogr 69(5):288–298. doi:10.1080/00291951.2015.1072242

Bryndal T, Cabaj W, Suligowski R (2010a) Hydrometeorologiczna interpretacja gwałtownych wezbrań małych cieków w źródłowej części Wielopolki w dniu 25 czerwca 2009 roku. In: Magnuszewski A (ed) Monografie Komitetu Inżynierii Środowiska PAN 69. Komitet Inżynierii Środowiska, Polskiej Akademii Nauk, Warszawa, pp 81–91

Bryndal T, Cabaj W, Gębica P, Kroczak R, Suligowski R (2010b) Gwałtowne wezbrania spowodowane nawalnymi opadami deszczu w zlewni potoku Wątok (Pogórze Ciężkowickie). In: Ciupa T, Suligowski R (eds) Woda w badaniach geograficznych. Uniwersytet Jana Kochanowskiego w Kielcach, Kielce, pp 307–319

Bryndal T, Cabaj W, Suligowski R (2010c) Gwałtowne wezbrania potoków Kisielina i Niedźwiedź w czerwcu 2009 r. (Pogórze Wiśnickie). In: Barwiński M (ed) Obszary metropolitalne we współczesnym

środowisku geograficznym. Wydział Nauk Geograficznych Uniwersytetu Łódzkiego, Łódź, pp 337–348

Bryndal T, Kroczak R, Soja R (2015) Hydrological response of a small catchment located in extremely humid monsoonal climate—the Maw-Ki-Syiem case study (Cherrapunji, Meghalaya Plateau, India). Episodes 38(1):31–38

Chow VT (1959) Open-channel hydraulics. Mc-Graw-Hill, New York

Creutin JD, Borga M (2003) Radar hydrology modifies the monitoring of flash-flood hazard. Hydrol Process 17:1453–1456

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 On the assessment and management of flood risks. Off J Eur Union L 288:27–34

Flood risk maps (2014) Sheet Mszana Dolna M-34-77-C-c-4. KZGW, Warszawa

Françou J, Rodier JA (1969) Essai de classification des crues maximales: floods and their computation. In: Proceedings of the leningrad symposium, August 1967. IAHS-UNESCO-WMO, Louvain, pp 518–527

Gaume E, Borga M (2008) Post-food field investigations in upland catchments after major flash foods: proposal of a methodology and illustrations. J Flood Risk Manag 1:175–189

Gaume E, Bain V, Bernardara P, Newinger O et al (2009) A compilation of data on European flash floods. J Hydrol 367(1–2):70–78

Gorczyca E, Krzemień K, Wrońska-Wałach D, Sobucki M (2013) Channel changes due to extreme rainfalls in the Polish Carpathians. In: Lóczy D (ed) Geomorphological impacts of extreme weather, case Studies from Central and Eastern Europe. Springer, Dordrecht, pp 23–35

Hydrologic Modeling System HEC-HMS (2015) US Army Corps of Engineers, Hydrologic Engineering Center. http://www.hec.usace.army.mil/software/hec-hms/. Accessed 30 May 2015

Izmaiłow B, Kamykowska M, Krzemień K (2006) The geomorphological effects of flash floods in mountain river channels. The cases study of the river Wilsznia (Western Carpathian Mountains). Prace Geogr IGiPZ UJ 116:89–103

Kamykowska M, Kaszowski L, Krzemień K (1999) River channel mapping instruction. Key to river bad description. In: Krzemień K (ed) River channel, pattern, structure and dynamic, vol 104. Prace Geograficzne IGiPZ UJ, Kraków, pp 9–23

Korpak J, Krzemień K, Radecki-Pawlik A (2008) Influence of anthropogenic factors on changes of Carpathian stream channels. Infrastructure and ecology of rural areas 4. Polish Academy of Sciences, Commission of technical infrastructure, Kraków

Kowalczuk I, Mykhnowych A, Pylypovych O, Rud'ko G (2013) Extreme exgenus processes in Ukrainian Carpathians. In: Lóczy D (ed) Geomorphological impacts of extreme weather, case studies from Central and Eastern Europe. Springer, Dordrecht, pp 53–66

Kroczak R, Bryndal T, Bucała A, Fidelus J (2015) The development, temporal evolution and environmental influence of an unpaved road network on mountain terrain: an example from the Carpathian Mts. (Poland). Environ Earth Sci 75(3):1–14. doi:10.1007/s12665-015-5055-6

Łajczak A, Margielewski W, Rączkowska Z, Święchowicz J (2014) Contemporary geomorphic processes in the Polish Carpathians under changing human impact. Episodes 37(1):21–32

Lambor J (1971) Engineering hydrology. Arkady, Warszawa

Lenart W (1993) Opad atmosferyczny. In: Soczyńska U (ed) Podstawy hydrologii Dynamicznej. Wyd, UW, Warszawa, pp 101–116

Lumbroso D, Gaume E (2012) Reducing the uncertainty in indirect estimates of extreme flashflood discharges. J Hydrol 414–415:16–30

Marchi L, Borga M, Preciso E, Gaume E (2010) Characterization of selected extreme flash floods in Europe and implications for flood risk management. J Hydrol 394:118–133

Marchi L, Cavalli M, Amponsah W, Borga M, Crema S (2015) Upper limits of flash flood stream power in Europe. Geomorphology 272(1):68–77

Mistra SK, Singh VP (2003) Soil conservation service curve number (SCS-CN) Methodology. Kluwer, Dordrecht

National Engineering Handbook (2010) Part 630, hydrology, chapter 15 time of concentration. United States Department of Agriculture, Natural Resources Conservation Service

Ostrowski J, Czarnecka H, Glowacka B et al (2012) Nagłe powodzie lokalne (flash flood) w Polsce i skala ich zagrożeń. In: Lorenc H (ed) Wpływ zmian klimatu na środowisko, gospodarkę i społeczeństwo. Tom 3., Klęski żywiołowe a bezpieczeństwo wewnętrzne kraju. Wydawnictwo IMGW-PIB, Warszawa, pp 123–149

Parczewski J (1960) Warunki występowania gwałtownych wezbrań na małych ciekach. Wiad Służ Hydrol Meteorol 8:1–159

Pekarova P, Bacova Mitkova V, Miklanek P (2015) Flash flood on July 21, 2014 in the Vratna Valley. In: Mastorakis NE, Buluceva A (eds) New developments in environmental science and geoscience.

Proceedings of the international conference on environmental science and geoscience (ESG 2015). INASE, Vienna, pp 34–38

Rinaldi M, Amponsah W, Benvenuti M, Borga M, Comiti F, Lucía A, Marchi L, Nardi L, Righini M, Surian N (2016) An integrated approach for investigating geomorphic response to extreme events: methodological framework and application to the October 2011 flood in the Magra River catchment, Italy. Earth Surf Process Landf 41(6):835–846

Siwek JP, Żelazny M, Chełmicki W (2011) Influence of catchment characteristics and flood type on relationship between streamwater chemistry and streamflow: case study from Carpathian Foothills in Poland. Water Air Soil Pollut 214:547–563

Surian N, Righini M, Lucìa A, Nardi L, Amponsah W, Benvenuti M, Borga M, Cavalli M, Comiti F, Marchi L, Rinaldi M, Viero A (2016) Channel response to extreme floods: insights on controlling factors from six mountain rivers in northern Apennines, Italy. Geomorphology 272:78–91

Tomczuk T, Dąbrowska M (2014) Commentary to synoptic situation of Poland. IMGW-PIB. http://pogodynka.pl/polska/komentarz. Accessed 06 Aug 2014

Verez M, Nemeth I, Schlaffer R (2013) The effects of flash floods on gully erosion and alluvial fan accumulation in the Kőszeg Mountains. In: Lóczy D (ed) Geomorphological impacts of extreme weather, case studies from Central and Eastern Europe. Springer, Dordrecht, pp 301–3011

Wyżga B, Zawiejska J (2005) Wood storage in a wide mountain river: case study of the Czarny Dunajec, Polish Carpathians. Earth Surf Process Landf 30:1475–1494

Feldman AD (ed) (2000) Hydrologic modeling system HEC-HMS. Technical reference manual. US Army Corps of Engineers, Hydrologic Engineering Center. Davis, CA

Zoccatelli D, Borga M, Zanon F, Antonescu B, Stancalie G (2010) Which rainfall spatial information for flash flood response modelling? A numerical investigation based on data from the Carpathian range, Romania. J Hydrol 394(1–2):148–161