ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI ZBORNIK

2019
59
1

ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
59-1 • 2019

Contents

Special issue – Green creative environments

ISSN 1581-6613
9 771581 661010

ACTA GEOGRAPHICA SLOVENICA

59-1
2019

ISSN: 1581-6613
COBISS: 124775936
UDC/UDK: 91

Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/Naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, SI – 1000 Ljubljana, Slovenija

The papers are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si (ISSN: 1581–8314)

Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 € for individuals/za posameznike, 28 € for institutions/za ustanove.
Single issue/cena posamezne številke: 12,50 € for individuals/za posameznike, 16 € for institutions/za ustanove.

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o.
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: Tiskarna Present, d. o. o.
Print run/naklada: 350 copies/izvodov

The journal is subsidized by the Slovenian Research Agency and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/revija izhaja s podporo Javne agencije za raziskovalno dejavnost Republike Slovenije in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/revija je vključena tudi v: SCIE – Science Citation Index Expanded, Scopus, JCR – Journal Citation Report/Science Edition, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Geoscience e-Journals, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google scholar, and CrossRef.

Oblikovanje/Design by: Matjaž Vipotnik.

Front cover photography: Stone bridge over the Rak River on the outskirts of the Rakov Škocjan polje, which is otherwise known for its beautiful natural bridges (photograph: Matej Lipar).
Fotografija na naslovnici: Kamniti most čez reko Rak na obrobju kraškega polja Rakov Škocjan, ki je sicer bolj znano po čudovitih naravnih mostovih (fotografija: Matej Lipar).

Acta geographica Slovenica, 59-1, 2019, 23–36

FLOOD TYPES IN A MOUNTAIN CATCHMENT: THE OCHOTNICA RIVER, POLAND

Małgorzata Kijowska-Strugała, Anna Bucała-Hrabia

The Ochotnica River during the May 2014 flood.

DOI: https://doi.org/10.3986/AGS.2250
UDC: 911.2:556.166(438)
COBISS: 1.01

Flood types in a mountain catchment: The Ochotnica River, Poland

ABSTRACT: This paper presents the results of a study on floods in the Ochotnica River catchment during forty years of hydrological observations (1972–2011). The Ochotnica River is located in the Gorce Mountains, in the Polish Western Carpathians. The characteristics of floods in the Ochotnica River channel were analyzed using limnigraphic records of water levels at the Tylmanowa gauging station and of precipitation based on data from the Polish Institute of Meteorology and the Water Management Station at Ochotnica Górna. Flood types were determined. The predominant type of floods in the Ochotnica River are normal floods with a discharge of 3.80 to 11.94 m^3/s in winter and 4.74 to 16.40 m^3/s in summer. The dominant recent process is incision, at an average speed of 3.2 cm/year. Similar results have been observed in other mountain rivers in Europe.

KEY WORDS: floods, water level, channel bed, Ochotnica River, Carpathians

Vrste poplav v gorskem porečju: reka Ochotnica na Poljskem

POVZETEK: V članku avtorici predstavljata izsledke štiridesetletnih hidroloških opazovanj poplav v porečju reke Ochotnice (1972–2011). Reka Ochotnica teče v pogorju Gorce v poljskem delu Zahodnih Karpatov. Avtorici sta značilnosti poplav v strugi reke analizirali na podlagi limnigrafskih podatkov o vodni gladini, izmerjenih na merilni postaji v kraju Tilmanova, in podatkov o količini padavin, ki sta jih pridobili od Poljskega meteorološkega inštituta in vodomerne postaje v kraju Ochotnica Górna. Na podlagi tega sta določili vrste poplav. Na reki Ochotnica prevladujejo normalne poplave z zimskim pretokom 3,80–11,9 m^3/s in poletnim pretokom 4,74–16,40 m^3/s. Prevladujoči proces v zadnjem času je vrezovanje, in sicer s povprečno hitrostjo 3,2 cm/leto. Podobni rezultati so bili ugotovljeni tudi pri drugih evropskih gorskih rekah.

KLJUČNE BESEDE: poplave, vodna gladina, rečna struga, reka Ochotnica, Karpati

Małgorzata Kijowska-Strugała, Anna Bucała-Hrabia
Polish Academy of Sciences, Institute of Geography and Spatial Organization
mkijowska@zg.pan.krakow.pl, abucala@zg.pan.krakow.pl

This paper was submitted for publication on July 8th, 2015.
Uredništvo je prejelo prispevek 8. julija, 2015

1 Introduction

The Ochotnica catchment is located in the Carpathian Mountains, the second-largest mountain range in central Europe (Pociask-Karteczka 2011). Floods in mountain catchments occur more quickly than in lowland rivers because of steep slopes and narrow valleys (Ruiz-Villanueva et al. 2010). In this article, a flood is understood as an event with a discharge greater than critical values, and not as water spreading over the surface near the river channel (Ozga-Zielińska and Brzezinski 1994). The course of flood events, types, volumes, and durations are important factors for several practical hydrological applications, such as hydropower plant operation (Bezak, Horvat and Šraj 2015).

Flood magnitude depends on precipitation intensity and duration as well as on characteristics of the catchment area, such as the length of the preceding dry period, soil moisture (water retention), vegetation cover, thickness of snow cover, snow water content, and intensity of melting and ground freezing depth (Christen and Christen 2003; Malarz 2005; Ogden and Dawdy 2003; Parajka et al. 2010; Gaal et al. 2012).

The course of floods is also dependent on land-use changes. Urbanization, deforestation (Bork et al. 1998), and agricultural intensification (van der Ploeg and Schweigert 2001) reduce the water-retention capacity of the soil (Mudelsee et al. 2004). These changes cause an increase in flood risk (Yin and Li 2001) and play a key role among the natural factors shaping river channel morphology (Bronstert 2003; Barredo 2007; Frandofer and Lehotský 2011; Kijowska-Strugała 2012; Gorczyca et al. 2014). During the flood in June 1957 in the Guil Valley (Queyras, southern French Alps), the entire valley bottom was affected, and the lower slopes were undermined by lateral cutting, which triggered landslides and transported enormous quantities of material to the valley bottom (Arnaud-Fassetta, Cossart and Fort 2005). During extreme rainfalls in September 2007 in the upper Selška Sora River in Slovenia, a flash flood caused bank erosion, channel-bed widening, and overbank deposition. Several debris flows and shallow landslides were triggered on the slopes, destroying the main road (Marchi et al. 2009). Changing the position of the level of river channel bottoms is one of the more visible morphological processes in mountain areas. In the Carpathians, incision of 1.3 to 3.8 m can be observed in rivers in recent decades (Bucała, Budek and Kozak 2015; Wyżga, Zawiejska and Radecki-Pawlik 2015; Wiejaczka and Kijowska-Strugała 2015). Similar studies have been conducted in other mountain rivers of Europe; for example, between 1928 and 1989/1995 incision (locally up to 5 m) was evident along the 100 km length of the Drôme River (Brookes 1987; Kondolf, Piégay and Landon 2002; Liébault and Piégay 2002; Rinaldi 2003).

The study area (the Ochotnica catchment) of 107.6 km^2 is located in the Gorce Mountains in the Western Carpathians (Figures 1, 2) characterized by deep valleys (Starkel 1972). The Ochotnica River is 22.7 km long and it is a left tributary of the Dunajec River. The average slope for the entire watercourse is 36.1‰ (ranging from 56.8‰ in the upper course to 15.5‰ in the lower course). The Ochotnica River channel is carved into solid rock with numerous shelves and rock outcrops upstream, and it is cut into sediments

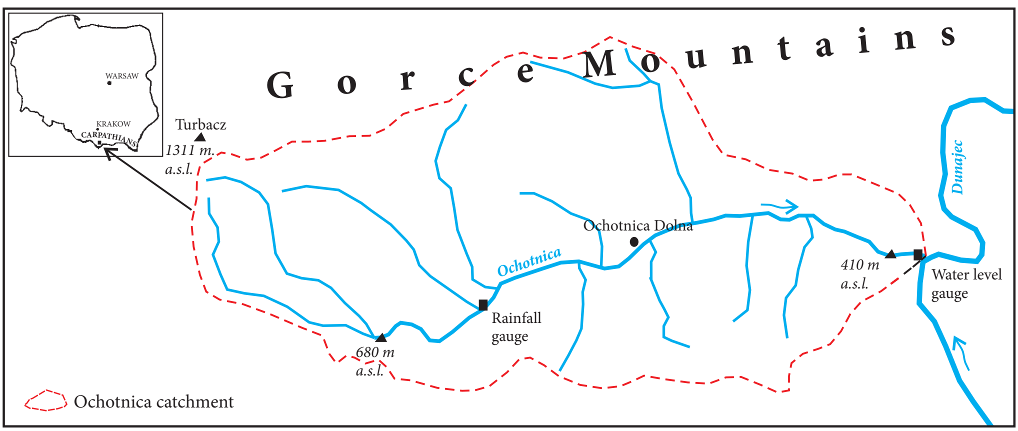

Figure 1: Location of the study area in the Polish Carpathians (Gorce Mountains).

in the middle and lower parts, where it is also braided (Krzemień 1984). Along the entire course, the Ochotnica River is fed by twelve left tributaries of and twenty-three right tributaries. The tributaries play an important role during flooding because they distort the natural wave of the flood, leading to delays or accelerations in the culmination of the main river below the mouth (Kijowska-Strugała 2015).

River floods in the Gorce Mountains frequently occur in spring and summer. Snowmelt floods are the result of thawing snow, and summer floods are the result of torrential and extreme rainfall, whereby the amount in three to five days can exceed 100 to 250 mm (Starkel 1976). Such high rainfall leads to catastrophic floods, as exemplified by the catchments of Konina, Jaszcze, Jamne, and Kamienica stream (Niemirowski 1974; Krzemień 1984). During the flood in July 1970, maximum daily precipitation was 154.9 mm, and discharges reached 15.5 m^3/s and 16.5 m^3/s in Jaszcze and Jamne streams, respectively. Bank erosion dominated in both streams, cutting the banks from 1.2 to 7 m. Mean incision of the bed reached 32 cm, and the maximum was 1.2 m (Niemirowski 1974).

This paper determines the types, duration, temporal variability, and magnitude of the Ochotnica River floods between 1972 and 2011. To properly identify the floods, the characteristics of the basic meteorological and hydrological parameters are presented below; these include precipitation, runoff coefficient, discharge regime, and maximum discharges. To show changes in the river channel morphology caused by floods, the dynamics of the position of river channel bottoms were also analyzed, based on long-term observation series of minimum water levels.

2 Methods

Data from the Institute of Meteorology and the Water Management Station were used to analyze floods. Discharges were analyzed based on limnigraphic records of water levels at the Tylmanowa gauging station closing the catchment (Figure 1) and precipitation data from the rain gauge in Ochotnica Górna. A forty-year period (1972–2011) of hydrometeorological observations was selected for detailed analysis.

It is assumed that a flood is an event in which discharges (Q) equal or exceed the discharge threshold (Q_t). The selection of the criterion of flood threshold that is part of the definition of the event has a decisive influence on the results (e.g. Ramos, Bartholmes and Thielen-del Pozo 2007). The discharge threshold of the flood (Q_t) was calculated using the following equation (Ozga-Zielińska and Brzezinski 1994):

$$Q_t = ½ (NWQ + WSQ),$$

where NWQ is the minimal maximum discharge during the multiyear period and WSQ is the maximum mean discharge of the multiyear averages.

In order to show the variability of flooding in a small mountain catchment, floods were divided into three types: low, normal, and high. WSQ is the threshold value of low floods, NWQ is the critical value of normal floods, and the average maximum discharge of the multiyear period (SWQ) is used for high floods. Selecting the criteria for flood threshold as part of the definition of the event has a decisive influence on the results.

Floods usually depend on the season, and the seasonality approach opens the way to studying mixed flood frequency distributions (Sivapalan et al. 2005; Ouarda et al. 2006). This article presents floods from the summer (May–October) and winter (November–April) half of the hydrological year.

The probability of the maximum discharges (Qmax) during floods was also calculated based on the decile method found in Dębski (1954).

A statistical analysis was conducted to determine the months with the highest frequency of floods. For each month of the hydrological year, the coefficient of variation (C_v) of average monthly discharge was calculated. Based on the discharge coefficient (k), the river regime was calculated using the following equation (Pardé 1957):

$$k = SQ_M / SQ_R,$$

where SQ_M is the average monthly discharge and SQ_R is the average annual discharge. The minimum water level was used to identify the dynamics of the Ochotnica channel (aggradation and erosion processes) after floods.

3 Driving force: precipitation

The average annual precipitation in the Upper Ochotnica from 1972 to 2011 was 838.7 mm, showing a variability of 629.2 mm (1984) to 1,109.9 mm (2007). Based on the forty-year study period, an increasing trend of annual precipitation was observed in the study area, averaging 4.3 mm per year (Figure 2). During the twentieth century in Europe, the mean annual precipitation has increased in northern Europe and has decreased in southern Europe (New, Hulme and Jones 1999).

According to the precipitation classification by Kaczorowska (1962), nineteen years (Figure 2) were within the normal range, similar to the average of the multiyear period. In the forty-year period analyzed, as many as thirteen years had above-average rainfall (i.e., 917 mm; Figure 2). On average, 64% of the precipitation occurs in the summer half of the hydrological year (May–October). During the period analyzed, there were 170 days with precipitation on average; during the summer half-year, the average number of days with precipitation was ninety, and in the winter half-year seventy-five days. The maximum number of days with precipitation in the summer half-year was 120 days in 1974 and the minimum sixty-two days in 1982, whereas in the winter half-year these were 105 days (1993) and fifty days (1987), respectively.

The highest monthly total precipitation was recorded in July and June, at 123 and 109 mm, respectively (Figure 3). In the Carpathians and the northern part of the Alps, the annual precipitation maxima typically occur in July and August (Parajka et al. 2010).

In small catchments in central Europe, under moderate climate conditions, floods are caused by local convective precipitation events with high intensity (Bryndal 2014). The highest daily rainfall occurred in the Ochotnica catchment on the following days: June 30th, 1973 (94.9 mm), May 17th, 1985 (92.3 mm), July 8th, 1997 (70.0 mm), July 23rd, 2008 (76.3 mm), and September 1st, 2010 (94.6 mm). A number of studies have documented increases in intense precipitation based on records (Alpert et al. 2002; Klein Tank and Können 2003). According to Parajka et al. (2010), lower variability in the mean date of occurrence of annual maximum daily precipitation is observed over the Alps than over the Carpathians. They also found that the greatest daily precipitation is consistently produced by similar atmospheric regimes, whereas a broader variety of processes are responsible for smaller events.

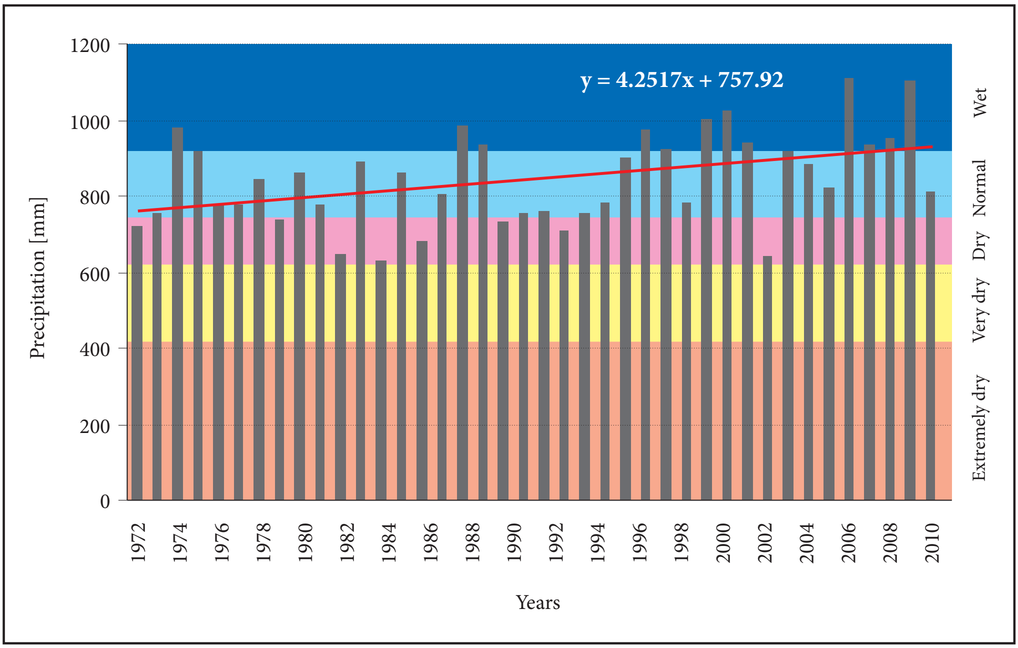

Figure 2: Annual precipitation from 1972 to 2011 at the Ochotnica Górna station based on the classification of precipitation ranges proposed by Kaczorowska (1962).

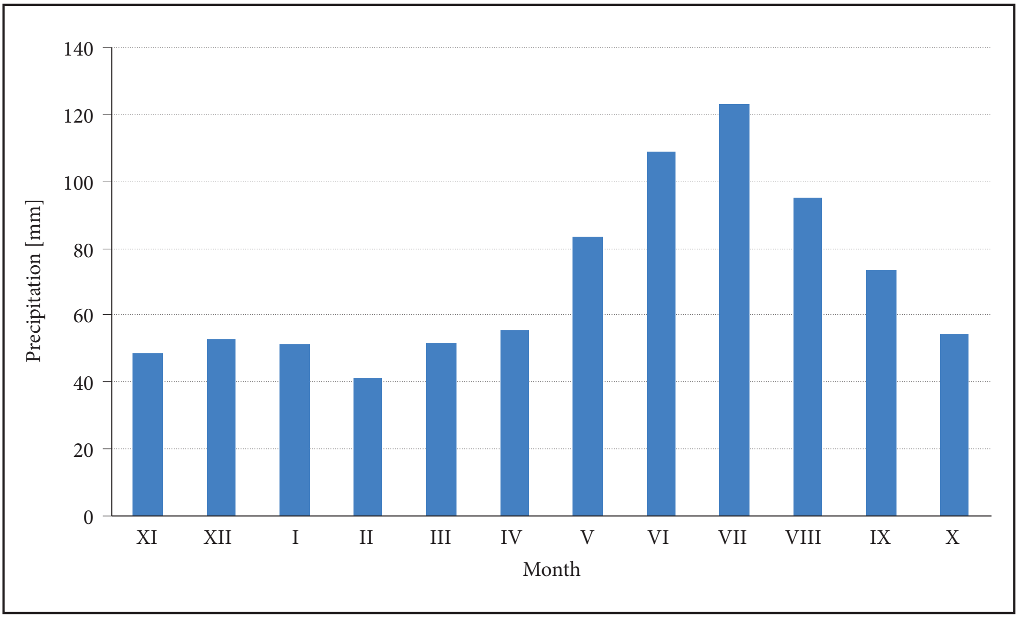

Figure 3: Average monthly precipitation from 1972 to 2011 at the Ochotnica Górna station (Institute . . . 2015).

4 Results

4.1 Runoff coefficient and the probability of maximum discharges

The runoff coefficient is a key concept in hydrology and floods, and is an important diagnostic variable for catchment response. Examination of runoff coefficients is useful for catchment comparison to understand how different landscapes filter rainfall into a flood event (Holko, Herrmann and Kulasova 2006; Marchi et al. 2010). According to Schaake (1990), it is possible to determine the size of floods based on runoff and precipitation.

The average runoff coefficient from 1972 to 2011 was 62.8%. The highest runoff coefficient (91.8%) was recorded in 1980 (Figure 4).

The greater variation of runoff in western Europe, compared to eastern Europe, reflects the greater variability in topography, and hence rainfall. Across most of lowland Europe, runoff is between 25 and 45%, whereas it exceeds 70% in high precipitation areas such as the Alps (Arnell 1999; Magnuszewski 2000; Marchi et al. 2010).

The runoff coefficients in the Ochotnica catchment do not show any significant trends. Similar results were obtained by Pekarova, Miklanek, and Peka (2006) for European rivers over the last 150 years.

The runoff irregularity coefficient (the ratio of the annual maximum to minimum runoff) in the Ochotnica River ranged from 3.4 mm in 1978 to 17.9 mm in 2000, and it shows an increasing trend (Figure 4). High recent values of the coefficient are due to the great diversity of total monthly precipitation. Compared to other Carpathian rivers, this coefficient is not high, and it is determined by a continuous water supply during the summer and the autumn lows.

The average discharge in the Ochotnica River in the multiyear period analyzed was 1.81 m^3/s. Ziemońska (1973) proposed eight river classes with different average discharges in the Polish Carpathians. The Ochotnica River is in the second class, with discharges ranging from 1 to 3 m^3/s. On average, for approximately 234 days annually, the Ochotnica River had a discharge of 0.5 to 2 m^3/s, and the discharge was 2 to 5 m^3/s for seventy-seven days (Figure 5). A discharge greater than 10 m^3/s was recorded for an average of four days. There are no differences in average discharges during the summer and winter hydrological half-year during the period analyzed.

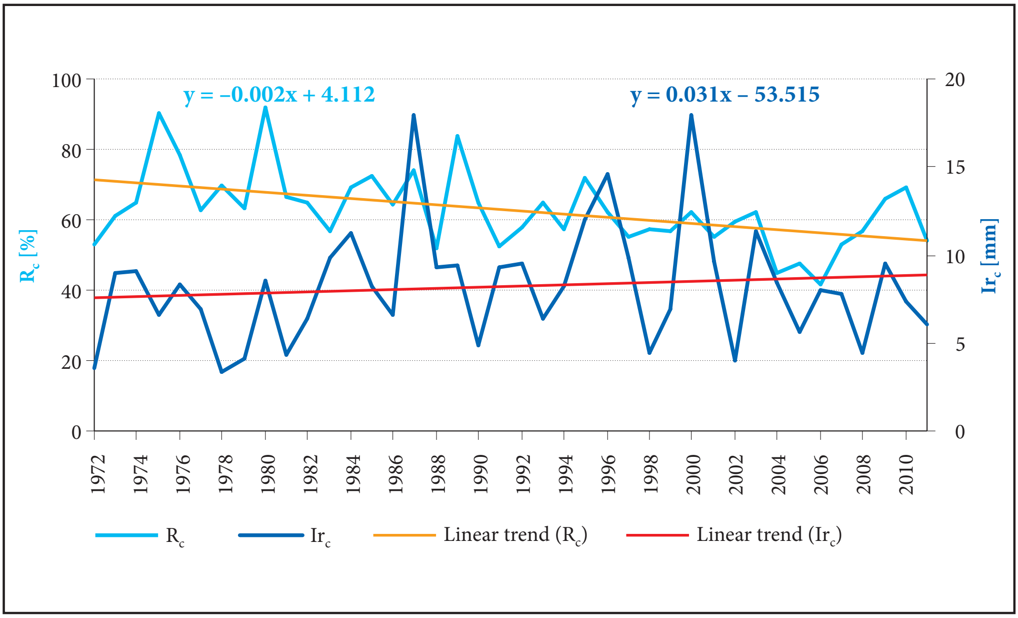

Figure 4: Runoff coefficient (R_c) and irregular runoff coefficient (I_{rc}) in the Ochotnica River from 1972 to 2011.

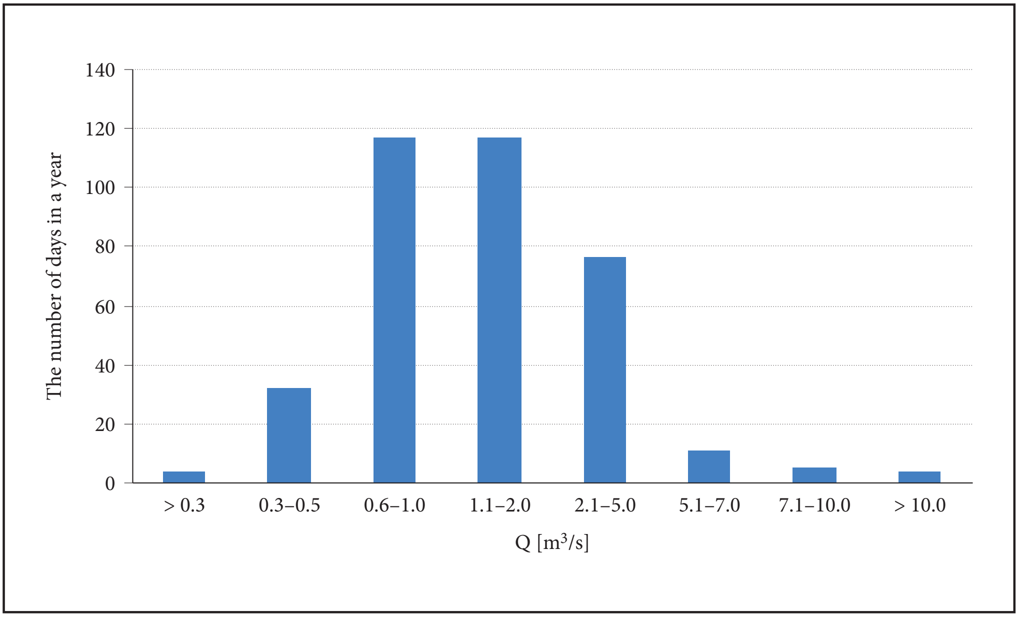

Figure 5: Frequency of average daily discharge in the Ochotnica River from 1972 to 2011.

On the basis of forty years of observations of water discharge in the Ochotnica River, a theoretical probability curve was plotted for the maximum discharge using a Pearson distribution (Type III), starting from a value of 1% (Table 1). Maximum discharges are directly related to floods (Patton and Baker Konrad 1976).

Table 1: Probability (%) of maximum discharges (m^3/s) and recurrence period (*T*) in the Ochotnica River based on the Pearson distribution (Type III).

Probability (%)	Discharge (m^3/s)	*T* (Year)
1	92	100
2	80	50
5	70	20
10	38	10
20	25	5
50	15	2
100	4	1

4.2 Discharge regime

A discharge regime describes the average seasonal behavior of a river, as determined by its genetic sources and its ambient climate. The discharge regime is a useful tool for identifying spatial and temporal variations in the magnitude and seasonality of discharge, and for determining the periods more susceptible to floods (Wrzesiński 2012). The Ochotnica River is an example of a river with a complex, primary, snow-rain regime with its peak discharge in the second half of winter and in the summer (Figure 6). The first, higher discharge peak occurs in April, and the second, lower one in July. Low discharges in the autumn and winter are the consequence of reduced precipitation (especially in the autumn) and snow retention. Discharge coefficient values in the Ochotnica River were close to $k = 1.5$ in the spring, which is characteristic of the Carpathian rivers west of the Dunajec River (Chełmicki, Skąpski and Soja 1998–1999).

In the Ochotnica River, the spring months (March, April, $C_v = 0.4$) are characterized by the lowest variability in discharge. This relationship is due to a high degree of reproducibility in the water supplied by snowmelt (Chełmicki, Skąpski and Soja 1998–1999). The greatest discharge variability ($C_v > 0.7$) is in May, September, and December. High values of the coefficient of variation in May and September are associated with limited recurrence of floods in individual years. In December, winter thawing may be a destabilizing factor. The average value of the coefficient of variation from 1972 to 2011 is 0.63, indicating high stability of the rhythm of discharge in the river analyzed.

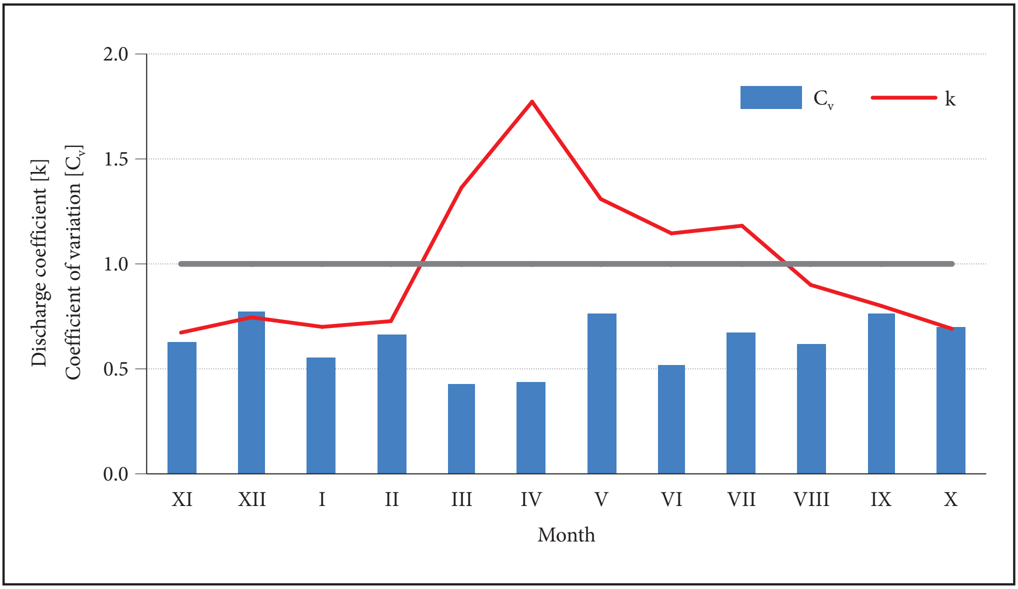

Figure 6: Differences in the monthly annual course of the discharge coefficient (*k*) and coefficient of multiyear variability of monthly discharge (C_v) for hydrological years from 1972 to 2011 in the Ochotnica River.

5 Discussion

5.1 Characteristics of floods

Low, normal, and high floods occurring in the hydrological winter and summer half-years were analyzed. Using the criteria for defining floods given in the Methods section, it was assumed that low floods occur when the culminating discharge is greater than 3.26 m^3/s during winter and 4.22 m^3/s in summer (Table 2).

Table 2: Quantitative character of floods in the Ochotnica channel from 1972 to 2011.

Measure	Value
Mean discharge	1.8 m^3/s
Mean specific discharge	0.017 $m^3/s/km^2$
Maximum daily discharge	79.8 m^3/s
Winter hydrological half-year	
Low flood	3.26–3.80 m^3/s
Normal flood	3.80–11.94 m^3/s
High flood	> 11.94 m^3/s
Summer hydrological half-year	
Low flood	4.22–4.74 m^3/s
Normal flood	4.74–16.40 m^3/s
High flood	>16.40 m^3/s
Maximum duration of flood	55 days
Mean duration of flood in winter/summer hydrological half-year	24 days 7 h / 12 days 17 h

In the forty years of observations (1972–2011), 295 floods were calculated. The average for each hydrological year was seven floods. There is a decreasing trend of the flood numbers in the hydrological winter half-year and an increasing trend in the summer half-year. The trends are not statistically significant.

Low floods accounted for approximately 17% and 15% of all floods in the winter and summer hydrological half-years. High floods in the entire multiyear period accounted for only 14% of the total number of floods (12% in the winter hydrological half-year and 15% in the summer half-year; Figure 7).

Floods are closely linked to the type of water source flowing into the river channel. The magnitude and course of floods in winter are related to the amount of water from melting snow in a time unit. Rapid snowmelt often causes major spring floods. In mountainous regions, spring floods are usually not as high as the summer rainfall floods, but they have an increased frequency of single snowmelt floods (January–March) and floods from mixed water supply (April). Snowmelt flood formation (especially thaw) is influenced by a southern catchment exposure. In the winter half-year during the period analyzed, 146 floods were recorded. The average flood duration was 24.29 days (7% of the year), longer than summer floods. This is connected with the water supply from various parts of the asymmetric catchment. Over the forty years, April was characterized by the highest number of floods (forty-nine).

Summer floods are more dynamic than winter floods. In the multiyear period analyzed, a total of 149 floods were recorded in the hydrological summer half-year. During this time, floods are caused by torrential and extreme rainfall. Summer floods occurred in the channel of the Ochotnica River irregularly and lasted shorter than the floods during the winter months (an average of 12.71 days). High floods accounted for 15% of these, or 2 percentage points more than in the hydrological winter half-year. The average value of the maximum daily discharge during all of the floods in summer half-year amounted to 16.4 m^3/s, and the absolute maximum discharge of 79.8 m^3/s was recorded on May 2nd, 1989. This was 144 times greater than the average discharge.

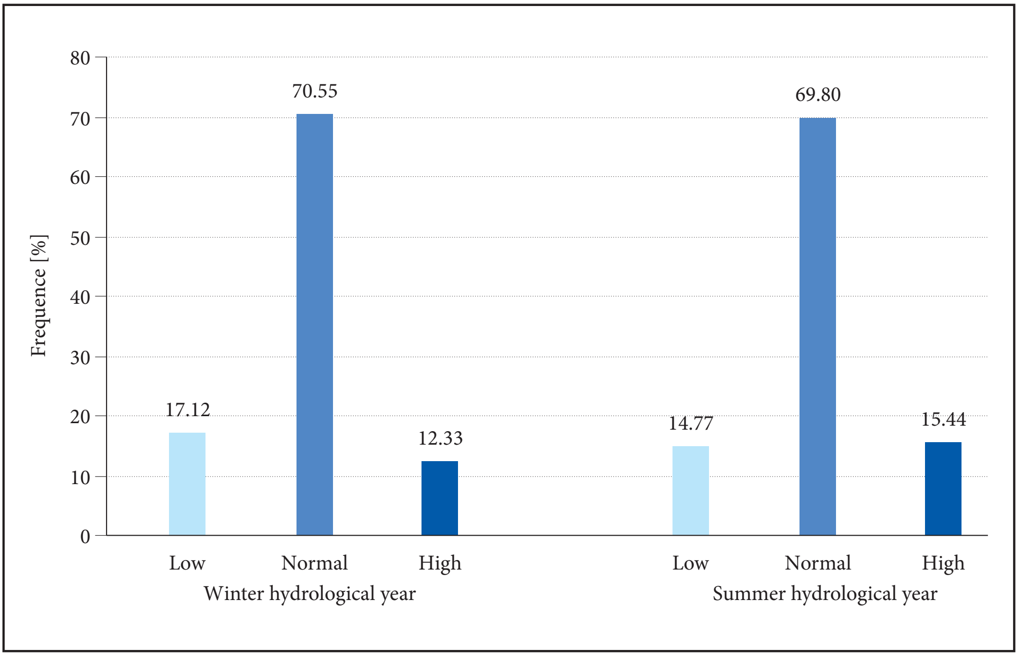

Figure 7: Frequency of flood types in the Ochotnica River in the winter (November–April) and summer (May–October) hydrological half-years from 1972 to 2011.

5.2 The dynamics of the Ochotnica channel

Analysis of changes in the position of river channel bottoms can be performed based on the minimum conditions of the river (e.g. Wiejaczka and Kijowska-Strugała 2015; Tamang and Mandal 2015). The use of data on water levels in the river provides reliable information about the direction of change (incision or raising) and its intensity. Incision is a common response of alluvial channels that have been disturbed such that they contain excess amounts of flow energy or stream power relative to the sediment load (Simon and Rinaldi 2006). If the river capacity is less than the load, deposition would be expected.

On the basis of an analysis of the minimum water levels from 1972 to 2011, two periods can be identified with different tendencies in changing the position of the Ochotnica channel bottom. The first covers the period from 1972 to 1996, when aggradation was the predominant process, whereas from 1997 to 2011 incision dominated (Figures 8, 9).

A clear decrease, by 70 cm, during the lowest minimum water level in 1997, as compared to 1996, was due to extreme floods. In July, the maximum water level was 344 cm, corresponding to a discharge of 17.6 m^3/s. Such a high discharge was caused by daily rainfall exceeding 70 mm. In July, the rainfall total was 291 mm and was 2.5 times higher than the average value from 1972 to 2011 (Froehlich 1998; Bucała 2012).

Between 1972 and 1996, the minimum water levels ranged from 186 cm (1973) to 286 cm (1993), whereas between 1997 and 2011 they ranged from 158 cm (2011) to 216 cm (2003). In 1983, at the level of 276 cm, the discharge recorded was 3.16 m^3/s, whereas it was only 0.45 m^3/s in 1996. This proves that the bed of the Ochotnica rose between 1972 and 1996. The course of the lowest monthly water levels during this period also shows a tendency to raise the channel bottom, amounting to 3.9 cm/year (Figure 8). In 1997, the lowest water level was 206 cm, with a discharge of 0.81 m^3/s, and in 2010 at the same water level the discharge recorded was 2.24 m^3/s. The examples show that the same water level in the multiyear period corresponds to increasingly higher discharges, which is clear evidence of the river channel deepening. The average rate of the annual lowest water level decreasing from 1997 to 2011 is 3.2 cm/year (Figure 9).

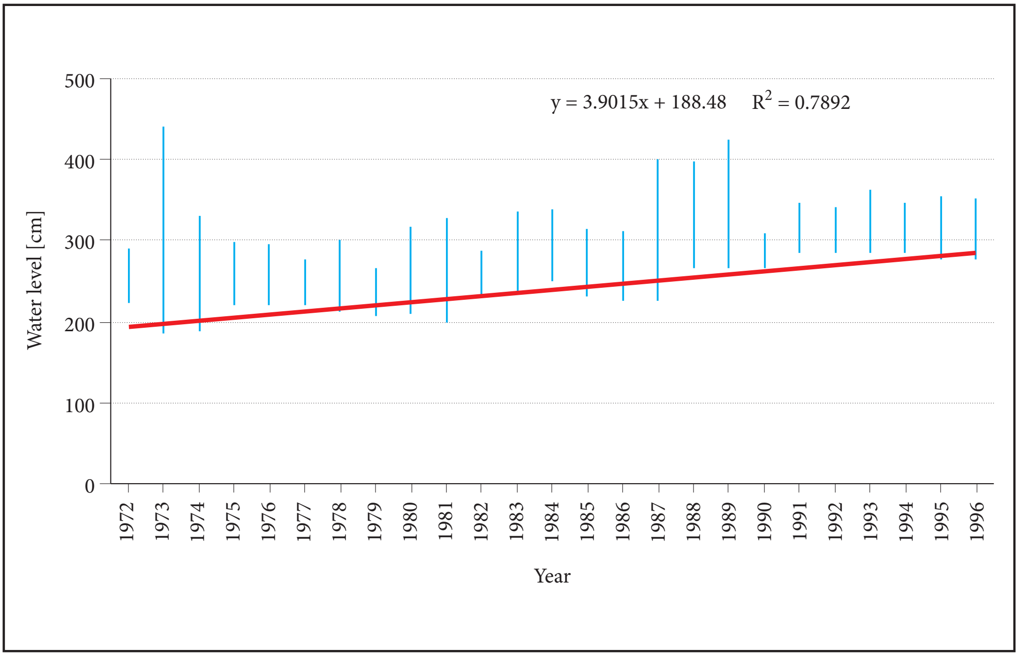

Figure 8: Minimum and maximum annual water level in the Ochotnica River from 1972 to 1996.

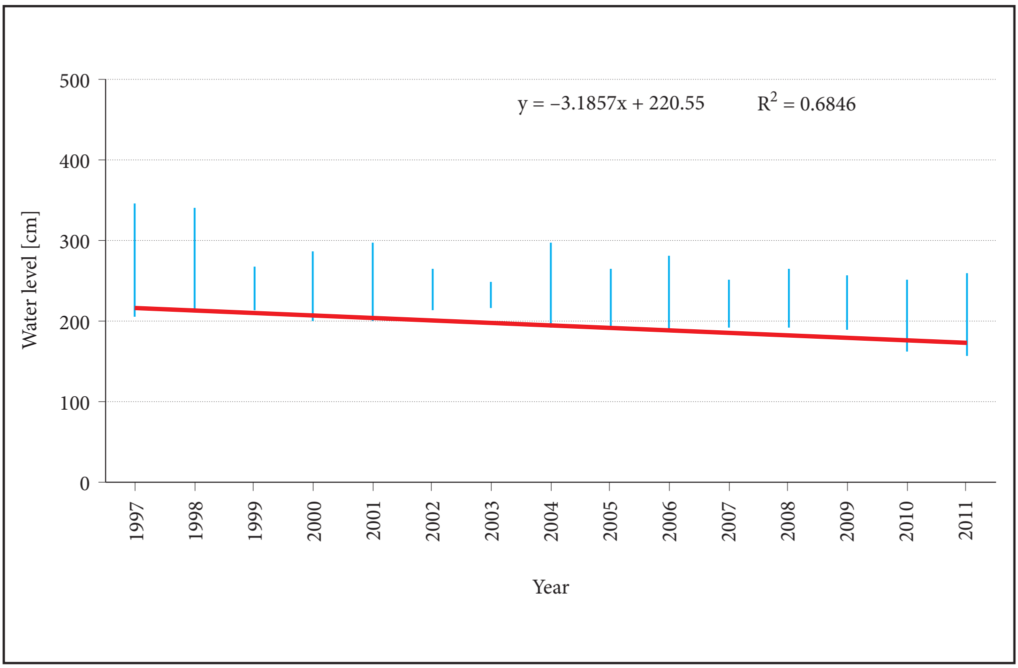

Figure 9: Minimum and maximum annual water level in the Ochotnica River from 1997 to 2011.

Processes occurring in recent times in the Carpathian environment (e.g., incision of channel bottoms) are related to an increase in the sum and intensity of precipitation and are probably caused by changes in land use (Klimek 1987; Kijowska-Strugała and Demczuk 2015). Land-use changes leading to forest expansion at the expense of agricultural land and, related to this, conversion of braided rivers to incised, single-thread channels have also been noted in other European mountains (Wohl 2006).

6 Conclusion

In terms of the types, duration, variability, and magnitude of floods, the forty-year period analyzed (1972–2011) shows the basic regularities observed in small mountain catchments in Europe. The analysis of measured floods does not indicate an increasing frequency. The runoff coefficient and number of floods in the last two decades do not show significant differences with regard to values that occurred in the previous two decades. Similar results have been observed in other mountain rivers in Europe. However, in the Ochotnica River in the last two decades a greater number of high floods has been noted. This can be related to an increased sum and intensity of precipitation over the last forty years, which is also documented in other European catchments.

Floods on the Ochotnica River usually occur in April and June, which is connected with its snow-rain river regime. Winter floods last longer than summer floods. This is related to the way the river channel is supplied with water from snowmelt in various parts of its asymmetric catchment.

The analysis of the minimum water levels showed significant changes in the dynamics of the position of the Ochotnica River channel bottom over time. Since 1997, the predominant process in the channel, as in the case of other Carpathians rivers, has been incision. The deep erosion observed in Carpathian rivers in the last decade is probably associated with changes in land use (a decrease in arable land and increase in forest area), which have intensified due to the economic transformation of the country and, in recent years, Poland's accession to the EU.

7 References

Alpert, P., Ben-Gai, T., Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., Manes, A. 2002: The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophysical research letters 29-11. DOI: https://doi.org/10.1029/2001GL013554

Arnaud-Fassetta, G., Cossart, E., Fort, M. 2005: Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, Southern French Alps). Geomorphology 66, 1-4. DOI: https://doi.org/10.1016/j.geomorph.2004.03.014

Arnell, N. W. 1999: The effect of climate change on hydrological regimes in Europe: a continental perspective. Global environmental change 9-1. DOI: https://doi.org/10.1016/S0959-3780(98)00015-6

Barredo, J. I. 2007: Major flood disasters in Europe 1950–2005. Natural Hazards 42-1. DOI: https://doi.org/10.1007/s11069-006-9065-2

Bezak, N., Horvat, A., Šraj, M. 2015: Analysis of flood events in Slovenian streams. Journal of Hydrology and Hydromechanics 63-2. DOI: https://doi.org/10.1515/johh-2015-0014

Bork, H. R., Bork, H., Dalchow, C., Faust, B., Piorr, H. P., Schatz, T. 1998: Landschaftsent-wicklung in Mitteleuropa, Wirkungen des Menschen auf Landschaften. Stuttgart.

Bronstert, A. 2003: Floods and climatic change: interactions and impacts. Risk Analysis 23-3. DOI: https://doi.org/10.1111/1539-6924.00335

Brookes, A. 1987: River channel adjustment downstream from channelization works in England and Wales. Earth Surface Processes and Landforms 12-4. DOI: https://doi.org/10.1002/esp.3290120402

Bryndal, T. 2014: 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. Carpathian Journal of Earth and Environmental Sciences 9-3.

Bucała, A. 2012: Contemporary environmental changes of Jaszcze and Jamne stream valleys in the Gorce Mountains. Geographical Studies 231.

Bucała, A., Budek, A., Kozak, M. 2015: The impact of land use and land cover changes on soil properties and plant communities in the Gorce Mountains (Western Polish Carpathians), during the past 50 years. Zeitschrift fur Geomorphologie 59-2. DOI: https://doi.org/10.1127/zfg_suppl/2015/S-59204

Chełmicki, W., Skąpski, R., Soja, R. 1998–1999: Hydrological regime of Carpathian rivers in Poland. Folia Geographica, series Geographia-Physica 29-30.

Christensen, J. H., Christensen, O. B. 2003: Climate modelling: Severe summertime flooding in Europe. Nature 421. DOI: https://doi.org/10.1038/421805a

Dębski, K. 1954: Prawdopodobieństwo zjawisk hydrologicznych i meteorologicznych. Warszawa.

Frandofer, M., Lehotský, M. 2011: Channel adjustment of a mixed bedrock-alluvial river in response to recent extreme flood events (the upper Topľa river). Geomorphologia Slovaca et Bohemica 11-2.

Froehlich, W. 1998: Transport rumowiska i erozji koryta potoków beskidzkich podczas powodzi w lipcu 1997 roku. Powódź w dorzeczu górnej Wisły w lipcu 1997 roku. Kraków.

Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., Blöschl, G. 2012: Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology. Water Resources Research 48-4. DOI: https://doi.org/10.1029/2011WR011509

Gorczyca, E., Krzemień, K., Wrońska-Wałach, D., Boniecki, M. 2014: Significance of extreme hydro-geomorphological events in the transformation of mountain valleys (Northern Slopes of the Western Tatra Range, Carpathian Mountains, Poland). Catena 121. DOI: https://doi.org/10.1016/j.catena.2014.05.004

Holko, L., Herrmann, A., Kulasova, A. 2006: Changes in runoff regimes in small catchments in Central Europe: Are there any? *International Association of Hydrological Sciences* 308.

Institute of Meteorology and Water Management, 2015. Rainfall data 1972–2011. Warszaw.

Kaczorowska, Z. 1962: Opady w Polsce w przekroju wieloletnim. Geographical Studies 33.

Kijowska-Strugała, M. 2012: Impact of downpours on fluvial processes in the Polish Carpathians as exemplified by the Bystrzanka stream. Studia Geomorphologica Carpatho-Balcanica 46-1. DOI: https://doi.org/10.2478/v10302-012-0002-2

Kijowska-Strugała M. 2015: Transport of suspended sediment in the Bystrzanka stream (Polish Flysch Carpathians) under changing antropopressure. Geographical Studies 247.

Kijowska-Strugała, M., Demczuk, P. 2015: Impact of land use changes on soil erosion and deposition in a small polish carpathians catchment in last 40 years. Carpathian Journal of Earth and Environmental Sciences 10-2.

Klein Tank, A. M. G., Koennen, G. P. 2003: Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. Journal of Climate 16-22. DOI: https://doi.org/10.1175/1520-0442(2003)016<3665:TIIODT>2.0.CO;2

Klimek, K. 1987: Man's impact on fluvial processes in the Polish Western Carpathians. Geografiska Annaler 69-1. DOI: https://doi.org/10.2307/521379

Kondolf, G. M., Piégay, H., Landon, N. 2002: Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. Geomorphology 45, 1-2. DOI: https://doi.org/10.1016/S0169-555X(01)00188-X

Krzemień, K. 1984: Współczesne zmiany modelowania koryt potoków w Gorcach. Geographical Studies 59.

Liébault, F., Piégay, H. 2002: Causes of 20th century channel narrowing on mountain and piedmont rivers of southeastern France. Earth Surface Processes and Landforms 27-4. DOI: https://doi.org/10.1002/esp.328

Magnuszewski, A. 2000: Hydrology and water quality of European rivers. The Waterscape. Uppsala.

Malarz, R. 2005: Effects of flood abrasion of Carpathian alluvial gravels. Catena 64-1. DOI: https://doi.org/10.1016/j.catena.2005.07.002

Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., Pogačnik, N. 2009: Comprehensive post-event survey of a flash flood in Western Slovenia: observation strategy and lessons learned. Hydrological processes 23-26. DOI: https://doi.org/10.1002/hyp.7542

Marchi, L., Borga, M., Preciso, E., Gaume, E. 2010: Characterisation of selected extreme flash floods in Europe and implications for flood risk management. Journal of Hydrology 394, 1-2. DOI: https://doi.org/10.1016/j.jhydrol.2010.07.017

Mudelsee, M., Börngen, M., Tetzlaff, G., Grünewald, U. 2004: Extreme floods in central Europe over the past 500 years: Role of cyclone pathway »Zugstrasse Vb". Journal of Geophysical Research: Atmospheres 109-23. DOI: https://doi.org/10.1029/2004JD005034

New, M., Hulme, M., Jones, P. 1999: Representing twentieth century space-time climate variability. Part I: development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate 12-3. DOI: https://doi.org/10.1175/1520-0442(1999)012<0829:RTCSTC>2.0.CO;2

Niemirowski, M. 1974: Dynamika współczesnych koryt potoków górskich. Geographical Studies 34.
Ogden, F. L., Dawdy, D. R. 2003: Peak discharge scaling in small Hortonian watershed. Journal of Hydrologic Engineering 8-2. DOI: https://doi.org/10.1061/(ASCE)1084-0699(2003)8:2(64)
Ouarda, T. B. M. J., Cunderlik, J. M., St-Hilaire, A., Barbet, M., Bruneau, P., Bobée, B. 2006: Data-based comparison of seasonality-based regional flood frequency methods. Journal of Hydrology 330, 1-2. DOI: https://doi.org/10.1016/j.jhydrol.2006.03.023
Ozga-Zielińska, M., Brzeziński, J. 1994: Hydrologia stosowana. Warszawa.
Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, M., Cheval, S., Dumitrescu, A., Gaume, E., Hlavčová, K., Merz, R., Pfaundler, M., Stancalie, G., Szolgay, J. Blöschl, G. 2010: Seasonal characteristics of flood regime across the Alpine-Carpathian range. Journal of Hydrology 349, 1-2. DOI: https://doi.org/10.1016/j.jhydrol.2010.05.015
Pardé, M. 1957: Rzeki. Warszawa.
Patton, P. C., Baker, V. R. 1976: Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resources Research 12-5. DOI: https://doi.org/10.1029/WR012i005p00941
Pekarova, P., Miklanek, P., Pekar, J. 2006: Long-term trends and runoff fluctuations of European rivers. International Association of Hydrological Sciences 308.
Pociask-Karteczka, J. 2011: River runoff response to climate changes in Poland (East-Central Europe). International Association of Hydrological Sciences 344.
Ramos, M. H., Bartholmes, J., Thielen-del Pozo, J. 2007: Development of decision support products based on ensemble forecasts in the European flood alert system. Atmospheric Science Letters 8-4. DOI: https://doi.org/10.1002/asl.161
Rinaldi, M. 2003: Recent channel adjustments in alluvial rivers of Tuscany, central Italy. Earth Surface Processes and Landforms 28-6. DOI: https://doi.org/10.1002/esp.464
Ruiz-Villanueva, V., Díez-Herrero, A., Stoffel, M., Bollschweiler, M., Bodoque, J. M., Ballesteros, J. A. 2010: Dendrogeomorphic analysis of flash floods in a small ungauged mountain catchment (Central Spain). Geomorphology 118, 3-4. DOI: https://doi.org/10.1016/j.geomorph.2010.02.006
Schaake, J. C. 1990: From climate to flow. New York.
Simon, A., Rinaldi, M. 2006: Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79, 3-4. DOI: https://doi.org/10.1016/j.geomorph.2006.06.037
Sivapalan, M., Blöschl, G., Merz, R., Gutknecht, D. 2005: Linking flood frequency to long-term water balance: Incorporating effects of seasonality. Water Resources Research 41-6. DOI: https://doi.org/10.1016/10.1029/2004WR003439
Starkel, L. 1972: Karpaty zewnętrzne. Geomorfologia Polski. Warszawa.
Starkel, L. 1976: The role extreme (catastrophic) meteorological events in contemporary evolution of slopes. Geomorphology and Climate. Chichester.
Tamang, L., Mandal, D. K. 2015: Bed material extraction and its effects on the forms and processes of the lower Balason River in the Darjeeling Himalayas, India. Geographia Polonica 88-3. https://doi.org/10.7163/GPol.2015.3
Wiejaczka, Ł., Kijowska-Strugała, M. 2015: Dynamics of the channel beds level in mountain rivers in the light of the minimum water stages analysis. Carpathian Journal of Earth and Environmental Sciences 10-4.
Wohl, E. 2006: Human impacts to mountain streams. Geomorphology 79, 3-4. DOI: https://doi.org/10.1016/j.geomorph.2006.06.020
Wrzesiński, D. 2013: Uncertainty of Flow Regime Characteristics of Rivers in Europe. Quaestiones Geographicae 32-1. DOI: https://doi.org/10.2478/quageo-2013-0006
Wyżga, B., Zawiejska, J., Radecki-Pawlik, A. 2015: Impact of channel incision on the hydraulics of flood flows: Examples from Polish Carpathian rivers. Geomorphology 272-1. DOI: https://doi.org/10.1016/j.geomorph.2015.05.017
Van der Ploeg, R., Schweigert, P. 2001: Elbe river flood peaks and postwar agricultural land use in East Germany. Naturwissenschaften 88-12. DOI: https://doi.org/10.1007/s00114-001-0271-1
Yin, H., Li, C. 2001: Human impact on floods and flood disasters on the Yangtze River. Geomorphology 41, 2-3. DOI: https://doi.org/10.1016/S0169-555X(01)00108-8
Ziemońska, Z. 1973: Stosunki wodne w Polskich Karpatach Zachodnich. Geographical Studies 103.