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The water outflow from neighbouring mountain catchments in the Polish Carpathians: A comparative analysis

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Abstract: The study covered water resources of two mountain streams in the Polish Carpathians. These were the Biała Woda and Czarna Woda streams, the catchments of which are adjacent to each other. Water flows in both streams were measured during the hydrological years from 2006 to 2020. Next, water outflows from the catchments were calculated. The study aimed to determine differences in the water resources of those catchments in a very small mountainous area.

The study showed quantitative similarity in water resources in the entire multi-annual period but at the same time large differences in shorter periods. Instantaneous and daily outflows showed the largest differences, but differences in annual outflows of up to 20% were also recorded. Therefore, hydrological data from operational cross-sections to assess water resources of neighbouring uncontrolled watercourses should cover multi-annual mean values. It was found that during periods of increased runoff (from melting snow or precipitation), the outflow from the Biała Woda catchment was much larger, while during rain-free periods, the outflow from the Czarna Woda catchment prevailed. All short-term flood like outflows were at least several tens of per cent higher in the Biała Woda catchment. The higher retention capacity of the Czarna Woda catchment can be attributed to the land use (mainly forest areas). The results can be used for modelling catchments of similar parameters and determining their retention capacity.

Keywords: hydrological data, mountain catchment, water outflow, water resources, water runoff

INTRODUCTION

Mountain areas are very important for the supply of water to people and industries (Viviroli and Weingartner, 2004; Hill *et al.*, 2014). For example, in Poland, mountain areas, which cover 9% of the country's area, provide about 30% of water (Kostuch, 1976). Good water management in mountain areas requires detailed mapping of the resource (Fleming and Sauchyn, 2013; Quincey *et al.*, 2018). This is often problematic due to limited measurement data and, at the same time, wide variation in topography, meteorology, soils and vegetation affecting water resources (Becker and McDonnell, 1998; Sun *et al.*, 2013).

Water resources in a given area are usually equal to the amount of water flowing in watercourses. Measurements of flows and then the determination of outflows over a desired time period (e.g. day, month, year) allow for a variety of hydrological analyses (Nadal-Romero *et al.*, 2009; Ciupak and Michalec, 2022), including the calculation of water volumes available for human activity (Madzia, 2014; Wurbs, 2017). However, in mountainous areas, the density of permanent points measuring the flow of water is very low, making it difficult to determine water resources. Other difficulties include spatial variation of water cycle components. A particularly frequent problem related to the parameterisation of water resources in the mountains is to determine the amount of precipitation (Weingartner, Viviroli and Schadler, 2007). Precipitation largely depends on the topography of the terrain, including its position relative to incoming air masses. Kozak *et al.* (2019) showed that in mountainous areas, the annual precipitation at measuring stations located only a few kilometres away can differ by up to 30%. As the number of measuring stations in mountains is usually low, various mathematical models are used to determine the volume of water supplied to the area by precipitation (Daly, Neilson and Phillips, 1994; Goovaerts, 2000; Gultepe, 2015). Modelling can provide valuable data. However, small errors associated with supra-regional atmospheric circulation may translate into significant deviations in the calculation of local precipitation (Minder *et al.*, 2008). Such issues can be important for the assessment of water resources.

The research questions discussed in the article include the retention capacity of small mountain catchments and limit outflows in such catchments.

The study aims to determine whether variation in water resources (outflows) could be expected in a very small mountainous area. It was assumed that in a very small mountainous area (with uniform climate conditions), water resources of individual streams depend on human activity, i.e. human transformation of catchment areas. Therefore, an area of only 22.6 km^2, consisting of two adjacent catchments with different land use, was selected for the study. For this purpose, multi-annual measurements of the amount of water flowing through the two streams from their catchments were used. The article also discusses the possibility of using hydrological data from operational measurement points to calculate water resources in unmonitored watercourses.

STUDY AREA AND METHODS

STREAMS SELECTED FOR THE STUDY

The study area is located in southern Poland, in the Carpathian Mountains (49°24'N, 20°34'E). The study covered two adjacent catchments of Biała Woda and Czarna Woda, about 11 km^2 each (Fig. 1). The Biała Woda and Czarna Woda streams converge in Jaworki and continue as the Grajcarek stream. The cross-sections used for measurement are located in Jaworki, upstream from the convergence point. In the two locations, measurement devices were fitted at small dams.

The source of the Biała Woda stream is located at 935 m a.s.l. and the stream begins as the Obidza stream. The length of Biała Woda (from Obidza to its confluence with Czarna Woda) is 7.29 km and the average gradient of the stream bed is equal to 51‰. The catchment up to the measurement cross-section (dam) covers 10.91 km^2. The width of the catchment varies between 1.5 and 3.0 km with the average of 2.0 km and its length in the main thalweg is about 7.9 km. The length of the watershed is 17.36 km.

The source of Czarna Woda is located at 1,085 m a.s.l. in the peak part of the Radziejowa Mountain. The length of Czarna Woda (from its source to confluence with Biała Woda) is 6.95 km and the average gradient of the stream bed is equal to 75‰. The catchment up to the measurement cross-section (dam) covers 11.66 km^2. The length of the catchment is 7.0 km and the width varies from 0.5 to 3.2 km (average 2.0 km). The length of the watershed is 16.94 km.

It can be seen from the above description that the catchments are similar in size. Their land use is described in the discussion section of this article and hydroclimate data are provided in Table 1. The land use structure of both catchments is presented on the basis of field observations, information from literature and cartographic materials available at the spatial information portal of the Geodesy and Cartography Head Office (Pol. Główny Urząd Geodezji i Kartografii) – https://www.geoportal.gov.pl/ (BDOT10k).

METHODS FOR DETERMINATION OF WATER OUTFLOW

The flow measurements were carried out in 2006–2020, i.e. from 1 November 2005 to 31 October 2020. In order to carry out the measurements, the beds of both streams, just before their confluence in Jaworki, were walled and separated with dams (Fig. 2). A cutout was made in the middle of each dam, in which a metal overflow was installed. It supported a free water flow. Water level gauges were fitted at the dams, allowing the full water layer to flow through the overflow. Thus, the well-known method of measuring the flow by means of an overflow was used. In case of water surge, water overflowed the entire dam (fitted with metal edge) which became an overflow within bank walls. It should be added that similar dams had been in operation at the same

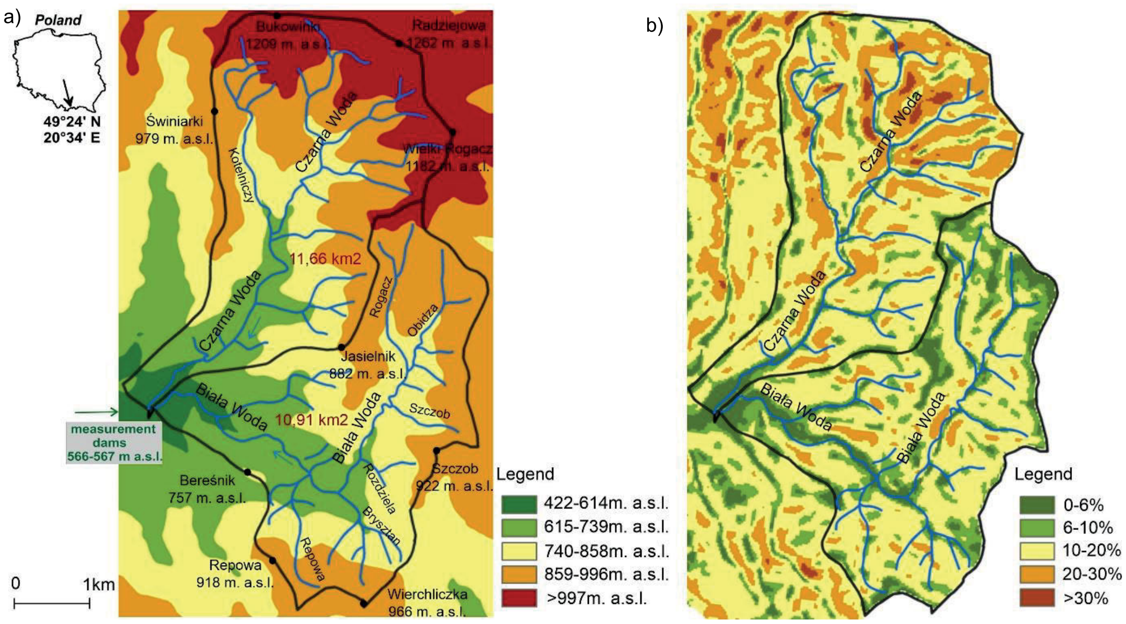

Fig. 1. The catchments of the Biała Woda and Czarna Woda streams: a) elevation map, b) slope map; source: own elaboration based on Digital Elevation Model (DEM) (Copernicus, no date)

Table 1. Geographical parameters of the Biała Woda and Czarna Woda catchments

Parameter	Value for	
	Biała Woda	Czarna Woda
Average elevation (m a.s.l.)[1]	842.07	895.44
Average annual precipitation (mm)[2]	904	975
Average main stream slope (‰)	51	75
Average tributaries slope (‰)[1]	91–151	108–210
Average terrain slope (%)[1]	24	31
Area (ha) in the class of terrain slope[1]		
– 3–6%	18.5	0.0
– 6–10%	65.8	19.5
– 10–20%	292.0	231.6
– 20–30%	292.4	269.7
– >30%	348.5	644.7
– undetermined e.g. rocks, ravines	73.8	0.0
Density of stream network ($km \cdot km^{-2}$)[1]	3.15	2.38
Length of all permanent streams (km)[1]	34.34	27.66
Number of natural wellspring[1]	99	54
Granulometry of the soil cover[1]		
– loamy sand (%)	0.0	12.0
– sandy loam (%)	50.9	63.0
– sandy clay loam (%)	22.7	13.9
– clay loam (%)	10.9	5.7
– clay (%)	0.9	0.0
– others, including rocks (%)	14.6	5.4

Source: own elaborations based on data [1] Prochal (1962), [2] Figuła (1966).

Fig. 2. The measuring cross-section with a dam on the Biała Woda stream; source: own elaboration (photo: *A. Jaguś*)

locations in earlier years, but these were destroyed by water in June 2005 during a particularly violent water surge. Later in the same year, the dams were built anew as reinforced concrete structures and new measurements could be carried out from 1 November 2005. The measurements were carried out as part of research by the Institute of Technology and Life Sciences – National Research Institute (Pol. Instytut Technologiczno-Przyrodniczy – Państwowy Instytut Badawczy, ITP – PIB).

During the study period, water levels in the overflows were recorded continuously by limnigraphs located in wells dug next to the reservoirs (system of communicating vessels). Once a day, the operation of the limnigraphs was checked and water levels at level gauges recorded. The limnigraphs plotted water level changes on strips of paper, covering a period of one week. The recording made by a limnigraph makes it possible to determine water levels at any time of day or night (Fig. 3).

By analysing the limnigraph plots, water levels were determined at 30-minute intervals with an accuracy of 0.1 cm. For each water level, the flow ($dm^3 \cdot s^{-1}$) was calculated on the

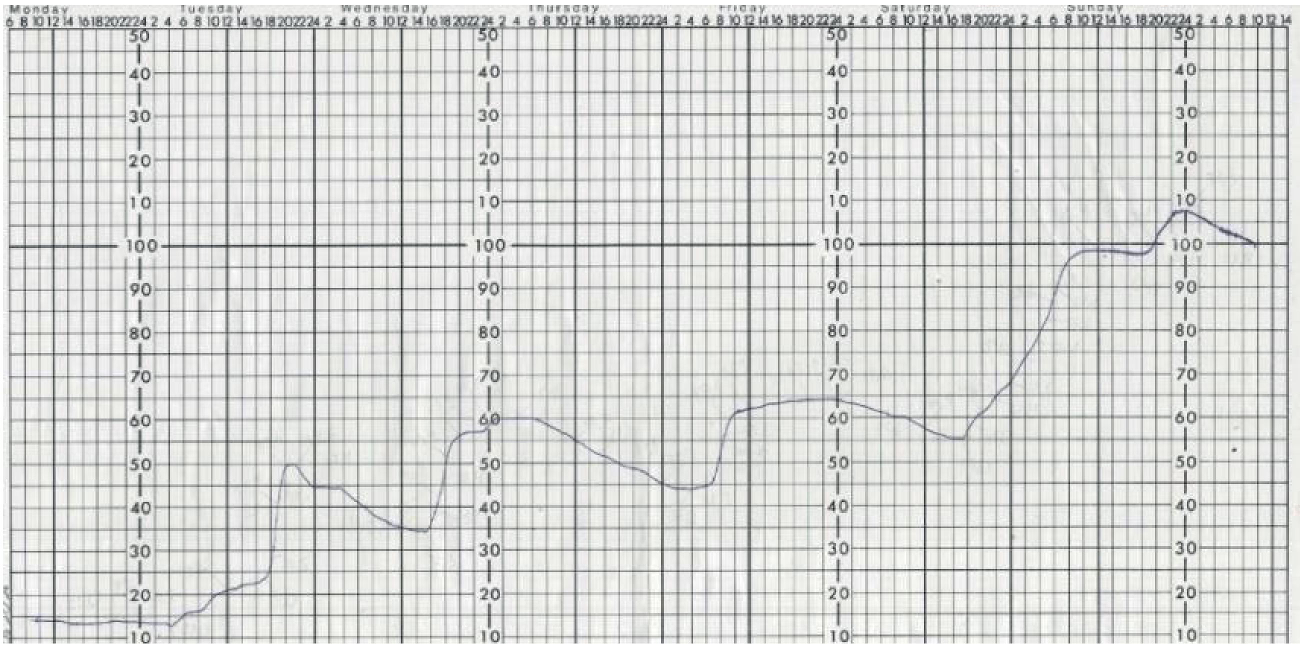

Fig. 3. A limnigraph plot in the cross-section on the Czarna Woda stream, from 25 May to 1 June 2020; source: documentation of the ITP – PIB, Branch in Kraków

basis of overflow parameters. Therefore, flow values were available every 30 min. This supported accurate calculation of water flow during each day ($m^3 \cdot day^{-1}$) and longer periods. Annual, monthly, daily and instantaneous outflows are presented in this article. To compare the two catchments, all outflow data are converted to outflows from a unit area of 1 km^2.

RESULTS

ANNUAL OUTFLOWS

The outflows from the catchments varied in individual years (Fig. 4). In 2010, when a large area of Poland experienced flooding (Nachlik and Kundzewicz, 2016), the outflows exceeded 1 mln $m^3 \cdot km^{-2}$. In contrast, in 2012, they were less than 0.3 mln $m^3 \cdot km^{-2}$. The comparison of annual outflows from the Biała Woda and the Czarna Woda catchments showed that in certain years they were almost the same (e.g. 2012, 2013). However, in certain years, large differences could be found. The largest differences in outflows from the two catchments were around 20% and occurred in 2008 (larger outflow from Czarna Woda catchment) and in 2014 (larger outflow from Biała Woda catchment).

In the multi-annual period of 2006 to 2020, the mean annual outflow in both catchments was similar. It was 540 thous. $m^3 \cdot km^{-2}$ in the Biała Woda catchment and 531 thous. $m^3 \cdot km^{-2}$ in the Czarna Woda catchment. The mean annual outflow from the Biała Woda catchment was 1.7% higher than the outflow from the neighbouring catchment. A correlation was found between the annual outflows from the Biała Woda and Czarna Woda catchments throughout the study period ($r = 0.96$). No significant trend in the annual outflows was found.

MONTHLY OUTFLOWS

The monthly outflows from both catchments varied throughout the year. They were the lowest in winter (from December to February) and the highest at the beginning of spring (in May and June). Significantly higher variations of monthly outflows were found for the Biała Woda catchment (Fig. 5). The monthly outflows from the Biała Woda catchment ranged between 2.5 and 417.3 thous. $m^3 \cdot km^{-2}$ and from the Czarna Woda catchment between 4.4 and 261.3 thous. $m^3 \cdot km^{-2}$. The mean monthly outflow from the Biała Woda catchment was 45 thous. $m^3 \cdot km^{-2}$ and 44.2 thous. $m^3 \cdot km^{-2}$ from the Czarna Woda catchment.

A comparison of the results showed that the monthly outflows from the Czarna Woda catchment were more often higher than the outflows from the Biała Woda catchment. The outflows from the Czarna Woda catchment prevailed in August (14 out of 15 outflows analysed), June (11), July (11), April (10), September (10) and October (10). The outflow from the Biała Woda catchment was significantly larger in March (14). This predominance also occurred to January (8) and February (8). In certain months, measurements showed very large differences between outflows from the two catchments, sometimes exceeding 100%. For example, clearly larger outflow (in thous. $m^3 \cdot km^{-2}$) from the Biała Woda catchment (BW) than the Czarna Woda catchment (CW) occurred in:
- November 2006: BW – 70.4, CW – 25.8;
- May 2014: BW – 209.6, CW –124.1;
- September 2017: BW – 90.8, CW – 31.6.

In contrast, significantly larger outflow (in thous. $m^3 \cdot km^{-2}$) from the Czarna Woda catchment than the Biała Woda catchment was recorded in:
- February 2011: CW – 34, BW – 16.9;
- October 2013: CW – 29.8, BW – 10.8;
- August 2017: CW – 72.4, BW – 40.8.

For the entire study period, a correlation was found between the monthly outflows from the Biała Woda and Czarna Woda catchments, with a coefficient of $r = 0.92$, which was lower than the correlation between the annual outflows. There was no significant trend in the monthly outflows (Biała Woda $R^2 = 0.0051$; Czarna Woda $R^2 = 0.0165$).

DAILY OUTFLOWS

The daily outflows from the Biała Woda catchment varied from 37 $m^3 \cdot km^{-2}$ to 168.2 thous. $m^3 \cdot km^{-2}$. The mean was 1,478 $m^3 \cdot km^{-2}$. The minimum outflow occurred in February 2012 and the maximum in June 2010. In the Czarna Woda catchment, the daily minimum outflow was 87 $m^3 \cdot km^{-2}$ and it occurred in November 2006. The maximum outflow was recorded in June 2010 at 51.7 thous. $m^3 \cdot km^{-2}$. The mean daily outflow from the Czarna Woda

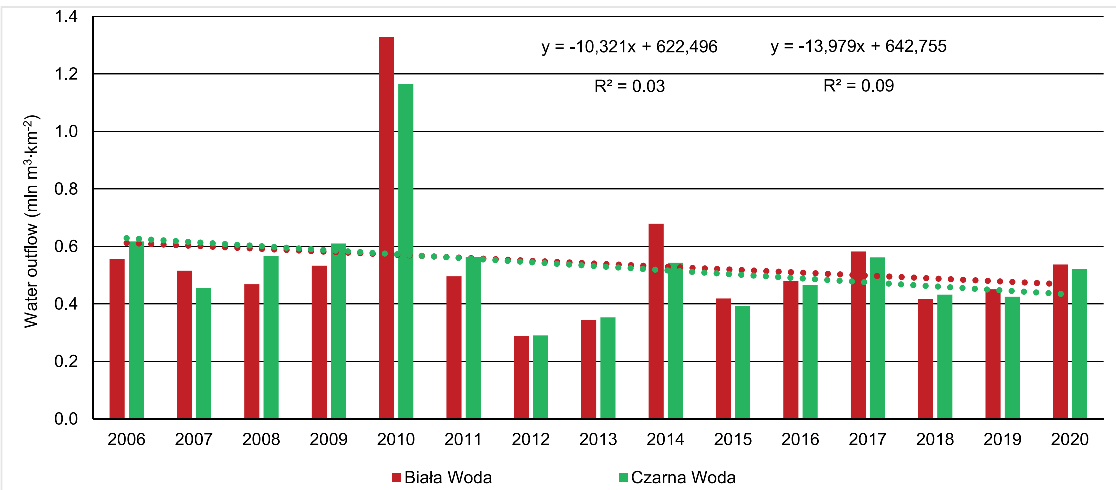

Fig. 4. Annual unit outflows from the Biała Woda and Czarna Woda catchments; R^2 = determination of coefficient; source: own study

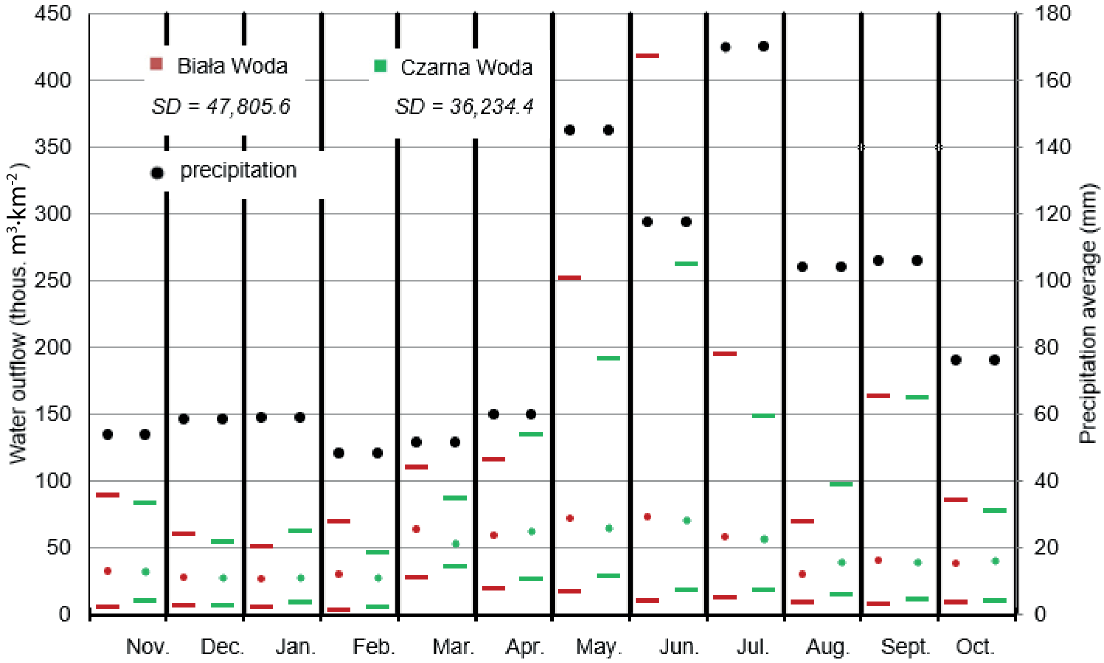

Fig. 5. Monthly unit outflows (minimum, average, maximum) from the Biała Woda and Czarna Woda catchments and the precipitation at the meteorological station in Jaworki in the hydrological years of 2006–2020; *SD* = standard deviation; source: own study

catchment was 1,457 $m^3 \cdot km^{-2}$. The variability of daily outflows from the studied catchments is expressed by *SD* values equal to 4,048 $m^3 \cdot km^{-2}$ for the Biała Woda catchment and 2,124 $m^3 \cdot km^{-2}$ for the Czarna Woda catchment.

A summary of the frequency of specific outflows provides interesting information (Fig. 6). The study period covered 5,479 days. In the Biała Woda catchment, outflows up to 750 $m^3 \cdot km^{-2}$ occurred during 50% of days and outflows over 3,000 $m^3 \cdot km^{-2}$ during 9.5% of days. In the Czarna Woda catchment, the frequency of the same outflows was 35% and 6.3% respectively. Outflows of 750–3,000 $m^3 \cdot km^{-2}$ were recorded far more frequently in the Czarna Woda catchment.

A comparison of daily outflows from the two catchments showed that they differed on average by 557 $m^3 \cdot km^{-2}$ (median difference 359.5 $m^3 \cdot km^{-2}$). There were days when the differences were very small, only 0.2 $m^3 \cdot km^{-2}$. Differences of less than 10 $m^3 \cdot km^{-2}$ were recorded for 101 days. The largest difference of 116.4 thous. $m^3 \cdot km^{-2}$ occurred on 4 June 2010. On that day, the outflows from the catchments of Biała Woda and Czarna Woda

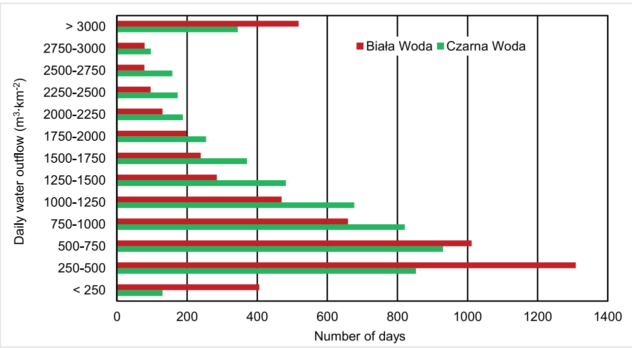

Fig. 6. Histogram of daily outflows from the Biała Woda and Czarna Woda catchments in the hydrological years 2006–2020; source: own study

were 168.1 thous. $m^3 \cdot km^{-2}$ and 51.7 thous. $m^3 \cdot km^{-2}$ respectively. Differences exceeding 1,000 $m^3 \cdot km^{-2}$ occurred on 474 days.

Larger daily outflows from the Biała Woda catchment were recorded for 1,537 days – they were larger on average by 1,030 $m^3 \cdot km^{-2}$ than these from the Czarna Woda catchment. Larger daily outflows from the Czarna Woda catchment were recorded for 3,942 days. They were larger on average by 372 $m^3 \cdot km^{-2}$.

For the entire study period, a correlation was found between the daily outflows from the Biała Woda and the Czarna Woda catchments, but it was weaker (r = 0.87) than for the monthly outflows. There was no significant trend in the daily outflows (Biała Woda R^2 = 0.0008 and Czarna Woda R^2 = 0.0054).

INSTANTANEOUS OUTFLOWS

An instantaneous outflow (expressed in $dm^3 \cdot s^{-1} \cdot km^{-2}$) is in Poland the basic measure of water resources in a given area (Dynowska, 1991). The mean outflow in the Polish Carpathians exceeds 10 $dm^3 \cdot s^{-1} \cdot km^{-2}$. In the Tatra Mountains, the highest mountain range, it reaches over 50 $dm^3 \cdot s^{-1} \cdot km^{-2}$, whereas in highland regions it is up to several $dm^3 \cdot s^{-1} \cdot km^{-2}$, and in lowland regions, it often does not reach 2 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The maximum, mean and minimum instantaneous outflows from the studied catchments were determined for each month over the study period (180 months). Calculations showed that the mean outflows were similar in both catchments, i.e. in the Biała Woda catchment 16.90 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and in the Czarna Woda catchment 16.99 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (0.6% difference). The tabulation of instantaneous outflows shows that the minimum outflows were larger in the Czarna Woda catchment and the maximum outflows were larger in the Biała Woda catchment (Tab. 2).

A series of minimum outflows (the lowest minimum) can be described by the following equations:

Table 2. Instantaneous outflows from the Biała Woda and Czarna Woda catchments in the hydrological years of 2006–2020 (based on monthly outflows)

Outflow	Value for	
	Biała Woda	Czarna Woda
	$dm^3 \cdot s^{-1} \cdot km^{-2}$	
The lowest minimum	0.18	0.82
Mean minimum	5.11	7.94
The highest minimum	20.27	30.41
The lowest mean	1.00	1.74
Mean long-term	16.90	16.99
The highest mean	156.09	99.70
The lowest maximum	3.26	2.92
Mean maximum	174.13	83.16
The highest maximum	1,946.2	598.9

Source: own study.

– for Biała Woda: $y = 0.0128x + 54.567$ ($R^2 = 0.0004$);
– for Czarna Woda: $y = -0.0764x + 99.496$ ($R^2 = 0.0049$).

There were no clear trends in these outflows in the two catchments, but they were correlated ($r = 0.85$).

A series of maximum outflows (the highest maximum) can be described by the following equations:
– for Biała Woda: $y = -2.4746x + 2{,}123.7$ ($R^2 = 0.0012$);
– for Czarna Woda: $y = -2.2356x + 1{,}171.9$ ($R^2 = 0.0062$).

There were no clear trends in these outflows in the two catchments, but they were correlated ($r = 0.91$).

DISCUSSION

CATCHMENT RETENTION CAPACITY

Many factors influence the outflows from catchments in the Polish Carpathians. These include especially precipitation, land morphology, soil cover, vegetation, human activity and retention structures. The outflow is obviously related to the variability between seasons (Kędra, 2017; Baran-Gurgul, 2022). In general, spring (March–May) is a period of melting snow cover and prolonged runoff. Summer (June–August) is characterised by a dynamic meteorological situation with intense precipitation causing flooding, but also hot periods without rain (especially in August). In autumn (September–November), outflow from catchments gradually decreases as rainfall is not very heavy and more prolonged than in summer. In winter (December–February), the hydrological situation is relatively stable with water accumulated in the form of snow, partially melting thaw periods. All these regularities were observed in the studied catchments, although they were repeatedly disturbed.

In the Polish Carpathians, the rock-soil substrate features and the slope of the terrain are generally not conducive to rainwater infiltration. This potentially generates a large share of runoff in water outflow from catchments (Dynowska, 1991). In order to reduce runoff and increase the catchment retention capacity, various measures are promoted in forested, agricultural and built-up areas (Jaguś, 2021; Suchanek-Gabzdyl, 2022). Their aim is to reduce the intensity of runoff and flood and water shortage in stream beds during rain-free periods through appropriate land use (Wyżga *et al.*, 2018; Jaguś, 2019; Kopacz *et al.*, 2021).

The study clearly shows that the catchments have different retention capacity. This is shown, among other things, by the amplitudes of outflows, histogram of outflows, and the differences in outflows. All figures demonstrate that the retention capacity of the Czarna Woda catchment (lower runoff) is higher. This is best reflected in the analysis of daily outflows in each and every period. The analysis shows that during periods of intensive water supply (rains, melting snow), the outflow from the Biała Woda catchment is clearly larger, while during rain-free periods, the outflow from the Czarna Woda catchment becomes larger. In addition, all short-term outflows, i.e. floods, are at least several dozens per cent larger in the Biała Woda catchment. An example of daily outflows is shown in Figure 7. Reasons for the situation lie in environmental differences between the two catchments.

The environmental characteristics of the catchments have been described by many authors since the 1960s (Prochal, 1962; Figuła, 1966; Kurek and Pawlik-Dobrowolski, 1990). The basic

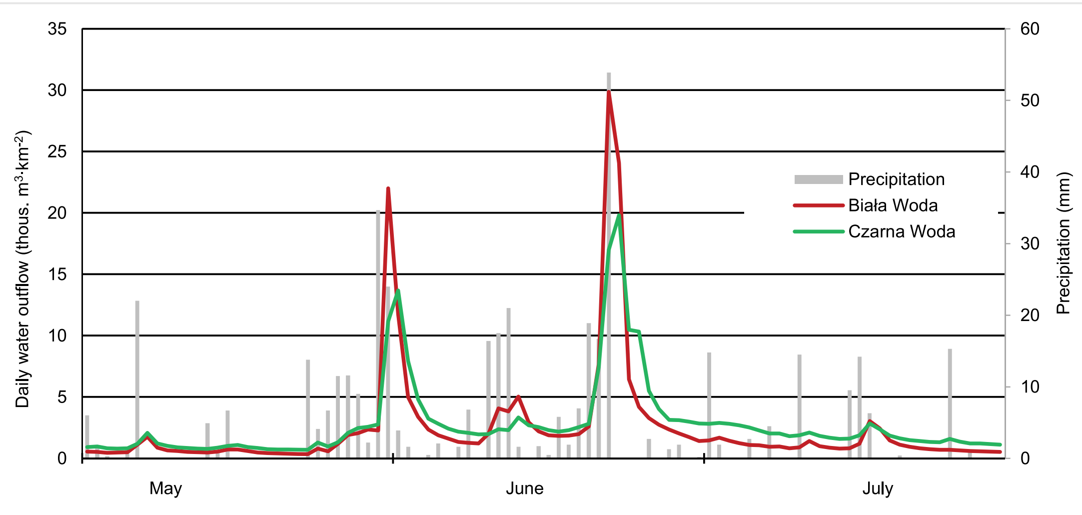

Fig. 7. Daily unit outflows from the Biała Woda and Czarna Woda catchments and precipitation at the meteorological station in Jaworki in May–July 2020; source: own study

parameters are summarised in Table 1 in the chapter of "Study area and methods". The values of certain parameters may indicate that larger and more dynamic outflows should occur in the Czarna Woda catchment (higher elevation, more precipitation, higher slope of the terrain). On the other hand, the values of hydrographic and soil parameters may indicate faster outflows in the Biała Woda catchment (higher number and density of watercourses, lower soil filtration capacity). Therefore, it is worth discussing the influence of land use on the outflow rate. In general, forms of land use in the studied catchments are shown in Figure 8 and Table 3.

The high retention capacity of mountain catchments is mainly associated with a large acreage of forested areas. However, retention parameters of a forest (interception, infiltration, water use, etc.) depend on many factors, including species composition and tree stand condition, as well as forest management techniques. The flood control provided by a forest is debatable especially under conditions of heavy and prolonged precipitation. Nevertheless, to a greater or lesser extent a forest has a retention function. This is confirmed by numerous studies in various regions of the world (Guojing *et al*., 2005; He *et al*., 2012; Švihla, Černohous and Šach, 2014; Reinhardt-Imjela *et al*., 2018). Interesting results were obtained by Dubicki and Woźniak (1993) who studied outflows from mountain catchments subjected to large-scale deforestation in the 1980s. They found that the removal of tree stands almost immediately caused an increase in outflows from streams, reaching up to 35%. In the case of the Biała Woda and Czarna Woda catchments, during the study period, forested and wooded areas occupied 56–63% and 83–88% of the area, respectively (Kopacz *et al*., 2021). Therefore, in terms of retention potential, it is clearly in favour of the Czarna Woda catchment.

Grasslands are also important in terms of retention in mountainous areas (Deng and Wang, 2010). Studies on runoff in the Polish Carpathians showed that the average annual runoff volume within grasslands used as meadows was only 2.2 to 2.4% of total precipitation (Kopeć, 1990). Although grasslands in the Biała Woda catchment covered 32–40% of the area during the study period (Kopacz *et al*., 2021), they were mainly used as pasture for sheep. As seen in the field, animals often gnaw

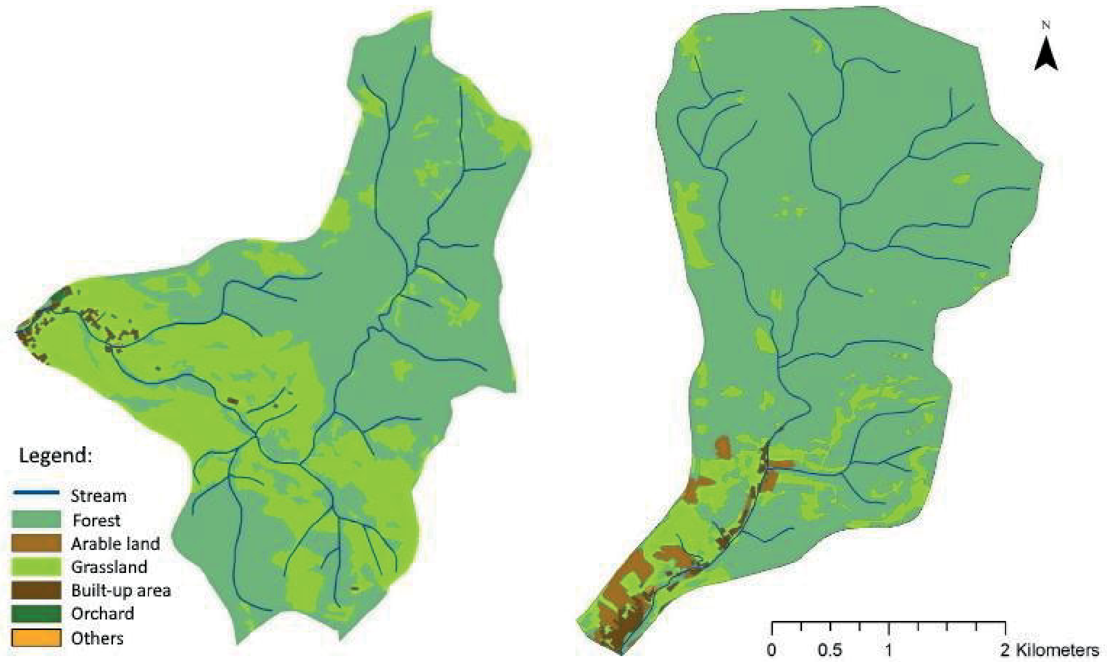

Fig. 8. Land use in the Biała Woda and Czarna Woda catchments based on BDOT10k cartographic materials; source: own study

Table 3. Land use classes in % of the Biała Woda and Czarna Woda catchments on BDOT10k cartographic materials

Land use	Biała Woda	Czarna Woda
	%	
Arable land	0.02	2.17
Built-up area	0.90	1.17
Forest	65.19	85.35
Grassland	33.74	11.21
Orchard	0.10	0.02
Others	0.05	0.08

Source: own study.

vegetation almost to the soil surface and damage the surface with their hooves. This results in increased runoff. In contrast, the grasslands in the Czarna Woda catchment, which cover 8–16% of the area (Kopacz *et al*., 2021), were used as meadows or were not used at all.

The low retention capacity of the Biała Woda catchment is also influenced by the presence of limestone rocks on the land surface, which cover 1.8% of the catchment. This catchment is also characterised by a large number of gullies (Prochal, 1962) which become water runoff pathways during rainy weather. Rocks and gullies can hardly be found in the Czarna Woda catchment. Although arable land is present in the Czarna Woda catchment, it has not been observed to cause an acceleration of water outflow as it was separated from the stream bed by grassland and a development zone.

TRANSFER OF DATA

Various calculation methods are used to determine the amount of water flowing in a given watercourse cross-section where measurements are not taken (Ozga-Zielińska and Brzeziński, 1997; Radecki-Pawlik *et al.*, 2020; Woodson *et al.*, 2021; Zhang *et al.*, 2022). These include the following: 1) interpolation, 2) extrapolation, 3) flow transformation, 4) hydrological similarity, 5) analysis of water balance, 6) analysis of regional dependencies and 7) mathematical modelling. These methods often use flow values from operational measurement points located on the same or on a different watercourse. Data from the monitored (measurement) cross-section are transferred to unmonitored cross-sections.

The results of measurements from the cross-sections on the Biała Woda and the Czarna Woda helped to check conditions for data transfer from one cross-section to another. Data from the monitored cross-section (M) were extrapolated to the unmonitored cross-section (UM) in line with the following formula:

$$Q_{\mathrm{UM}} = Q_{\mathrm{M}} \frac{A_{\mathrm{UM}}}{A_{\mathrm{M}}} \tag{1}$$

where: Q_{UM} = outflow in an unmonitored cross-section (m^3), Q_{M} = outflow in a monitored cross-section (m^3), A_{UM} = catchment area of the unmonitored cross-section (km^2), A_{M} = catchment area of the monitored cross-section (km^2).

The Czarna Woda cross-section was selected as the monitored one. The outflows measured in Czarna Woda in different periods were converted to the cross-section of Biała Woda and then compared with the measured outflows from Biała Woda (Tab. 4).

Calculations show that a period of one year should not be used for data transfer, as the difference between predicted and actual values can be large. It is advantageous to use an annual or monthly or daily mean values over a period of at least several years. The analyses cover a mean values over 5 years and over the entire study period of 15 years. As the calculations have shown, mean values over several years can give objective results. In the case of extreme outflows, it is necessary to take into account the mean value over the entire period available; the longer the period, the better. The transfer single extreme values is unacceptable, as differences between predicted and actual outflows can reach several hundred per cent.

Table 4. Transfer of outflow values from Czarna Woda to Biała Woda

Outflow	Czarna Woda (measured value)	Biała Woda		
		calculated value	measured value	difference (%)
Annual (e.g. 2011) (mln $m^3 \cdot y^{-1}$)	6.57	6.15	5.41	13.6
Annual average from 2006–2010 (mln $m^3 \cdot y^{-1}$)	7.96	7.45	7.42	0.4
Annual average from 2006–2020 (mln $m^3 \cdot y^{-1}$)	6.19	5.79	5.89	1.7
Average monthly from 2006–2010 (thous. $m^3 \cdot month^{-1}$)	663.7	621.1	618.6	0.4
Average monthly from 2006–2020 (thous. $m^3 \cdot month^{-1}$)	515.9	482.7	490.9	1.7
Daily average from 2006–2010 (thous. $m^3 \cdot d^{-1}$)	21.9	20.5	20.3	0.9
Daily average from 2006–2020 (thous. $m^3 \cdot d^{-1}$)	17.0	15.9	16.1	1.4
Temporary minimum ($dm^3 \cdot s^{-1}$)	9.6	9.1	2.0	357
Temporary average from 2006–2010 ($dm^3 \cdot s^{-1}$)	252.2	236.0	232.7	1.4
Temporary average from 2006–2020 ($dm^3 \cdot s^{-1}$)	198.1	185.4	184.4	0.5
Temporary maximum ($dm^3 \cdot s^{-1}$)	6,982	6,533	21,233	225

Source: own study.

CONCLUSIONS

A comparison of outflows from the Biała Woda and Czarna Woda catchments showed that water resources in small, neighbouring mountain catchments are similar on a multi-annual scale. However, they can be very different in the short term. This was confirmed by the decreasing correlation coefficients of outflow from both catchments on a year–month–day basis.

The Czarna Woda catchment had a higher retention capacity than Biała Woda. This was particularly evidenced by the differences in outflows during the passage of flood waves. Retention processes in the Czarna Woda catchment also led to minimum outflows several times higher than in the Biała Woda catchment. The slower outflow from the Czarna Woda catchment can be linked to the impact of forested areas and unused grassland.

During the study period of 2006–2020, no permanent trends in the outflows were found. The large variation in water resources from year to year seems to reflect changes in climate conditions observed worldwide.

The lack of a dense network of permanent outflow measurement points in mountainous areas can make it difficult to determine water resources. An objective transfer of hydrological data to unmonitored watercourses can be based on measurements over a period of several years.

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