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Modelling of long term low water level in the mountain river catchments area

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Abstract: Changing atmospheric conditions, including above all the deepening extreme weather phenomena, are increasing from year to year. This, in consequence, causes an increase in the incidence of low outflows.

The study compares low water levels for two catchments: Biała Woda and Czarna Woda, and phosphorus and nitrogen load using the Nutrient Delivery Ratio (NDR) model in InVEST software. The objective of the NDR is to map nutrient sources from catchment area and transfer to the river bed. The nutrient loads (nitrogen and phosphorus) spread across the landscape are determined based on a land use (LULC) map and associated loading rates described in literature. The studies have shown that low water levels have been more common recently and pose the greatest threat to the biological life in the aquatic ecosystems. The structure of land use is also of great importance, with a significant impact on the runoff and nitrogen and phosphorus load. Phosphorus and runoff from surface sources to the water of Biała Woda and Czarna Woda catchments area has been reduced in forested areas. Only higher run-offs are observed in the residential buildings zone. The nitrogen load was also greater in the lower (estuary) parts of both catchments, where residential buildings dominate.

Keywords: land use changes, low water level, nitrogen load, phosphorus load, small mountain catchments

INTRODUCTION

Mountain regions with harsh environmental conditions, steep, sloping sides, diversified habitats and low human occupation, play an important role a complete range of Ecosystem Services (ES), with freshwater being one of the most important services [Egan, Price (eds.) 2017; Gaglio *et al.* 2019].

Low environmental impact on such regions is paramount to maintain healthy ES in freshwater sources, however human occupation and activities such as agriculture and other land occupation changes ecosystem upstream and create pressures on artificial water reservoirs where nutrients are stored in the sediment bed due to hydrologic lotic to lentic modification of freshwater habitats [Maavara *et al.* 2020; Lehner *et al.* 2011; Muhammed *et al.* 2021].

Climate change, in particular already detected extreme weather phenomena, affect mountain habitats altering hydrologic regimes and biogeochemical cycles. They include, but are not limited to short-lived torrential rains, which are followed by a frequent periods of no-rain. This, in consequence, causes an extensive low runoff periods and an increase in the incidence of low water levels [Kosmowska *et al.* 2016; Kostuch 2003; Yerdelen *et al.* 2021], and leads to the reduction of water in catchment area. Water scarcity impairs ES [Byczkowski 1996]. The combination of land use pattern modification and climate change related torrential rains followed by no rain periods contribute to deterioration of reservoir water quality and ecosystems, mostly associated with P and N accumulation in reservoirs [BOIX-FAYOS *et al.* 2020; KISTNER *et al.* 2013]. Many regions of the world depend on mountains to provide the minimum supply of water. With climate change and population growth, countries which have never experienced severe ES degradation, are now facing serious challenges while attempting to recover from many years of inadequate land management practices.

In the study, use of the new technology contributes to the quick and free of charge analysis providing monitoring tools and solution design strategies. The Millenium Ecosystem Assessment [CARPENTER *et al.* 2009] raised several red flags and from the gathered data an open source software programmes were produced such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) [Stanford University undated]. It offers a suite of models used to map and value the "goods and services" from nature that sustain and fulfil human life. Based on the long-term hydrological and chemical parameters monitoring the model of total phosphorus and nitrogen delivery ratio from surface area in small mountain catchments has been simulated.

The Nutrient Delivery Ratio (NDR) from InVEST fresh-water models will allows to evaluate the delivery of three ecosystem services in the basin: one supply (water), and two regulating (erosion control and water purification). They are essential services. A water scarcity can limit industrial activity, human water consumption and agriculture activities which also contribute to the degradation of water quality [GAGLIO *et al.* 2019; KALICKI *et al.* 2020; SALLUSTIO *et al.* 2017]. Erosion is also a major concern, and is expected to increase due to increasing land-use changes and flood frequency [LLENA *et al.* 2019].

The study aimed to analyse the frequency of low water occurrences in two small mountain catchments and its impact on the ecosystem services. It also helped to determine what parts of the basin are mostly impacted by the observed changes of hydrology and land use. The study creates the basis for mitigation strategies in the future. The assessment of the nitrogen and phosphorus loads introduced from the catchment area to the surface waters forms important part of the study.

STUDY MATERIAL AND METHODS

RESEARCH AREA

The research area is within the Polish Western Carpathians, in particular the two adjacent upland catchments of the Biała Woda and Czarna Woda streams located on the right-bank of the Dunajec River, as part of the Grajcarek hydrographic basin (Fig. 1). The areas of both catchments are similar in size 10.91 km^2 and 11.66 km^2 respectively (Tab. 1).

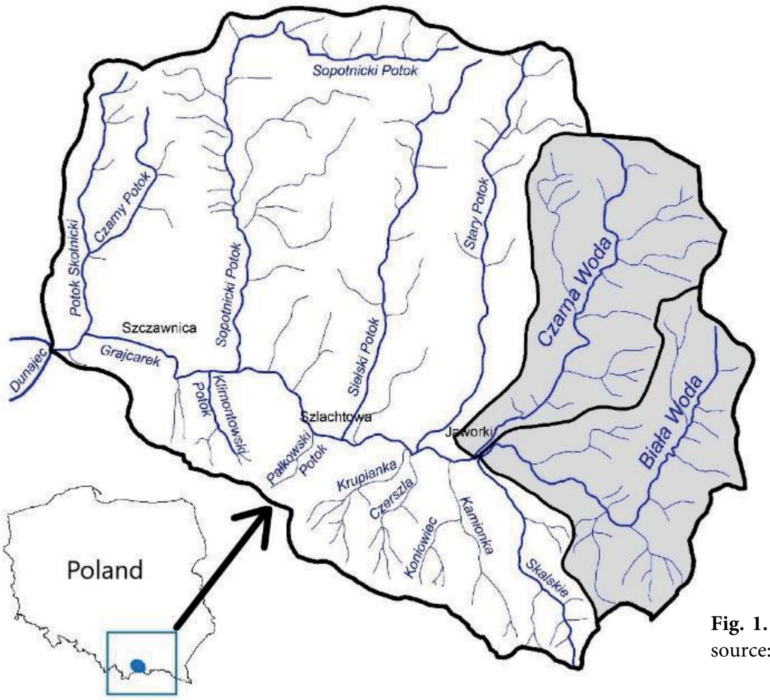

Fig. 1. Catchments of Biała Woda and Czarna Woda – Grajcarek, source: own elaboration

Table 1. Basic morphometric parameters of catchment

No	Catchment stream	Area (km^2)	Average slope inclination (%)	Average elevation[1)] (m a.s.l.)	Average stream slope (%)	Density of river network (km·km^{-2})	Stream lenght (km)
1	Biała Woda	10.91	24	842	4.43	3.15	7.93
2	Czarna Woda	11.66	31	895	7.51	2.38	6.95

1) KUREK, PAWLIK-DOBROWOLSKI [1990].
Source: own study.

Table 1 shows the basic morphometric features of both catchments, sharing similar characteristics, being the major difference the average slope decrease of the watercourse which is 4.43% for the Biała Woda catchment and 7.51% for the Czarna Woda. The average slope of the watercourse parameter is important when analysing the drainage flow depth and velocity.

The landcover of the Biała Woda and Czarna Woda drainage basins is a mostly forest and pastures [TWARDY *et al.* 2002], where both these landuse forms account for over 90% of the total area of both catchments. However, differing significantly in forest cover, where in the Czarna Woda catchment, between 1950 and 1960, it was twice as large as the Biała Woda catchment. Recently this difference has narrowed to around 26%, though still significant. Meadows and pastures predominate in the Biała Woda catchment, where their area is 3.5 times larger than in Czarna Woda catchment. Other forms of land use occupy minor areas (Tab. 2).

Table. 2. Estimated, simplified structure of land use in research catchments

Catchment	Mean from years	Area (km^2)	Land use area (% total area)				
			forest	grasslands	arable land	built-up areas	others
Biała Woda	1950–1960	10.91	29.3	58.0	4.6	0.3	7.8
	1995–2005		56.2	39.8	0.8	0.5	2.6
	2014–2017		62.5	31.6	0.6	1.4	3.9
Czarna Woda	1950–1960	11.66	63.9	34.4	1.1	0.2	0.4
	1995–2005		82.9	15.7	0.5	0.8	0.1
	2014–2017		88.3	8.4	0.3	1.8	1.2

Source: own elaboration.

Analysing the landuse structure of both catchments for the last half-century (Tab. 2), significant changes in the proportion between forest area and grassland are observed, which for its often-non-agricultural role are considered grasslands.

Both catchments display significant changes in landuse, where secondary succession processes contributed to the increase in forest cover in the Czarna and Biała Woda catchment areas.

STUDY METHODS

This work uses 67 years of landuse (1950–2017) from Corine Landcover and the Polish Institute of technology and Life Sciences data, together with 48 years of hydrologic data (1971–2018), from the Polish Institute of Technology and Life Sciences for 2 watersheds in Poland sharing similar characteristics, though with different historical landuse.

The studies covered the historical period, hydrological years 1971–2018, a full 48 years (data from Research Station in Jaworki – Institute of Technology and Life Sciences, Malopolska Research Centre). In selected analyses, the entire study period was divided into six equal eight-year intervals that corresponded to the hydrological cycles of low water occurrence in both studied catchments. The intervals of hydrological years: 1971–1978 (period 1); 1979–1986 (period 2); 1987–1994 (period 3); 1995–2002 (period 4); 2003–2010 (period 5) and 2011–2018 (period 6). The average unit runoff from the Biała Woda catchment area for many years is 16.98 dm^{-3}·s^{-1}·km^{-2}, while from Czarna Woda is 19.50 dm^{-3}·s^{-1}·km^{-2} (Tab. 3).

The identification of low waters required the setting of equal criteria. The shallow low waters limit value was adopted at the level of the upper limit of low unit outflows for the superior catchment – the Grajcarek stream [BAJKIEWICZ-GRABOWSKA, MIKULSKI 1999]. After conversion – low flows concern all unit outflows smaller than 5.17 dm^{-3}·s^{-1}·km^{-2} from the Biała Woda catchment area and less than 8.35 dm^{-3}·s^{-1}·km^{-2} from the Czarna Woda catchment [KOSTUCH 2003]. In these ranges of unit outflows, they were called shallow low waters. The drain hydrographs were analysed with a minimum duration of 7 days [DYNOWSKA 1971]. The low waters also include the period between neighbouring shallow low waters with an outflow greater than low waters, but smaller than the average unit outflow from many years, if its duration did not exceed two days [OZGA-ZIELIŃSKA 1990; OZGA-ZIELIŃSKA, BRZEZIŃSKI, 1997]. The outflow hydrographs are shown as periods of low flows, which correspond to low water levels. Low waters can be divided into shallow and deep. Shallow low waters occur when the water levels in the river change between the lower limit of medium and medium-low levels for at least several days. Deep low waters are those for which water levels are below medium-low states [BAJKIEWICZ-GRABOWSKA, MIKULSKI 1999].

Table 3. Characteristic discharges in Grajcarek catchment

Characteristic discharges	Specific runoffs (dm^{-3}·s^{-1}·km^{-2})
Low	<8.0
Medium	8.0–29.9
Medium-high	30.0–59.9
High	60.0–79.9
Very high	80.0–149.9
Extremely high	≥150.0

Source: own elaboration based on FIGUŁA [1966].

In turn, the limit values for deep low waters were adopted at the level of the average low unit outflow, which for the Biała Woda stream is 2.57 dm^{-3}·s^{-1}·km^{-2}, and for the Czarna Woda stream 4.85 dm^{-3}·s^{-1}·km^{-2}. The minimum duration of the outflow for deep low waters was 11 days.

Analysis regarding the incidence of low waters conditions were performed using the R program in version 3.5.1 with the RStudio in version 1.1.456. Data organysation and visualysation took place using the tidy-verse package, date conversion, and analysis was done using the CRHMr and hydrostats packages [BOND 2018; R Core Team 2018; SHOOK 2016; WICKHAM 2017].

Changes in the concentration of total phosphorus and nitrogen load were also analysed and a field model of the nutrient delivery ratio for this element was developed for both catchments.

The research used the Nutrient Delivery Ratio (NDR) model in InVEST software, (Freshwater Quality Models) [TALLIS *et al.* 2011].

InVEST mathematical models are spatially-explicit, using maps (GIS) as information sources and producing maps as outputs. The objective of the NDR is to map nutrient sources from catchment area and their transport to the river bed. In this mathematical model applied a simple material balance approach, describing the transport of a mass of nutrient through the defined area (in the analysed watershed/subwatershed). The size of the load in the model is presented in kg of substance per 1 conventional pixel ($kg \cdot px^{-1}$).

The nutrient loads across the landscape, are determined based on a land use (LULC) map and associated loading rates described in literature [BREUER *et al.* 2008; ENDRENY, WOOD 2003; HAMEL *et al.* 2015; HAMEL, GUSWA 2015; HAN *et al.* 2021; HARMEL *et al.* 2006; ZHANG *et al.* 2021].

RESULTS

The study analyses changes in the frequency of shallow low waters in both studied catchments. Their seasonal distribution is similar, low water conditions occurred in the months from September to March. An upward trend in low waters is also noted in the summer (July, August) since the 1990s. A clear periodicity of low water occurrence in hydrological years was also observed Figure 2.

There is a permanent increase in the number of days during which shallow low water conditions occurred (Fig. 3). In the first period (1971–1978) in the Biała Woda stream, the shallow low waters lasted a total of 442 days (15% of the 8 years). In the Czarna Woda stream, 337 days with shallow low waters were registered during this period (11.5% of the period duration). Over the years, these values increased accordingly – reaching in the sixth-period values for Biała Woda – 857 days (29.3%) and Czarna Woda – up to 1023 days (35% of the entire period). The shape of summary curves shows a significant increase in days with shallow low waters but also characterises their seasonal distribution. In the 70s of the 20th centuries, long, non-discontinuous periods of several years were recorded (horizontal sum curves, e.g., for time intervals 1 and 2, i.e. for the years 1971–1986), while the last years were often low waters periods separated by much shorter non-discontinuous periods (short horizontal sum curves – Fig. 3).

Deep low waters in the scale of the analysed period occurred much less frequently than shallow low waters (Fig. 4). They mainly concerned autumn and winter months (from September to January) and during the 48 years; they occurred sporadically. Deep low waters were recorded in the months from November to March only in the hydrological years 1985 and 1987. However, it is worrying that deep low waters were recorded mainly in recent years (e.g. 2004, 2012, 2013), both in the winter and summer-autumn months, which, given the increasing number of shallow low waters, gives a quite pessimistic picture of future hydrological changes in both catchments.

After analysing the deep low waters in the set of time intervals, this unfavourable phenomenon is even more noticeable. A clear increase in the number of days with deep low waters in both analysed streams occurred only recently in the hydrological years 2011–2018 (Fig. 5). For these eight years, there were more days with deep low waters than during the previous five periods, i. e. up to 40 years. Both shallow (Fig. 3) and deep (Fig. 5) occur more frequently in the Czarna Woda stream.

Phosphorus and runoff from surface sources to the water of Biała Woda and Czarna Woda catchments area has been reduced in forested areas. Only higher run-offs are observed in the

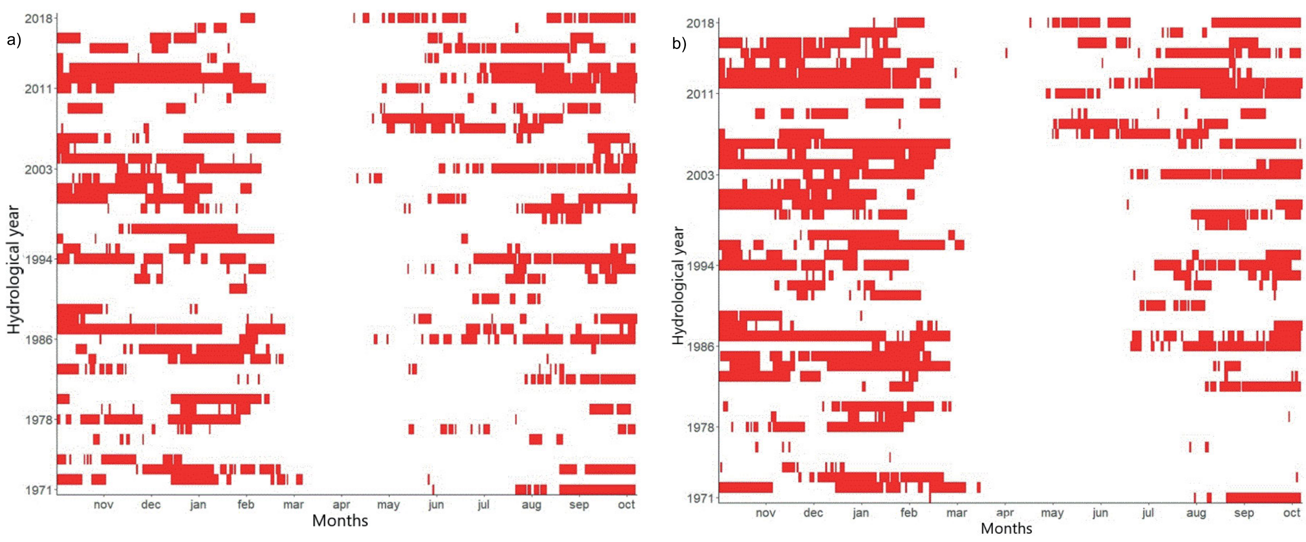

Fig. 2. Occurrence periods of shallow low water level in studied catchments in years 1971–2018: a) Biała Woda stream, b) Czarna Woda stream; source: own study

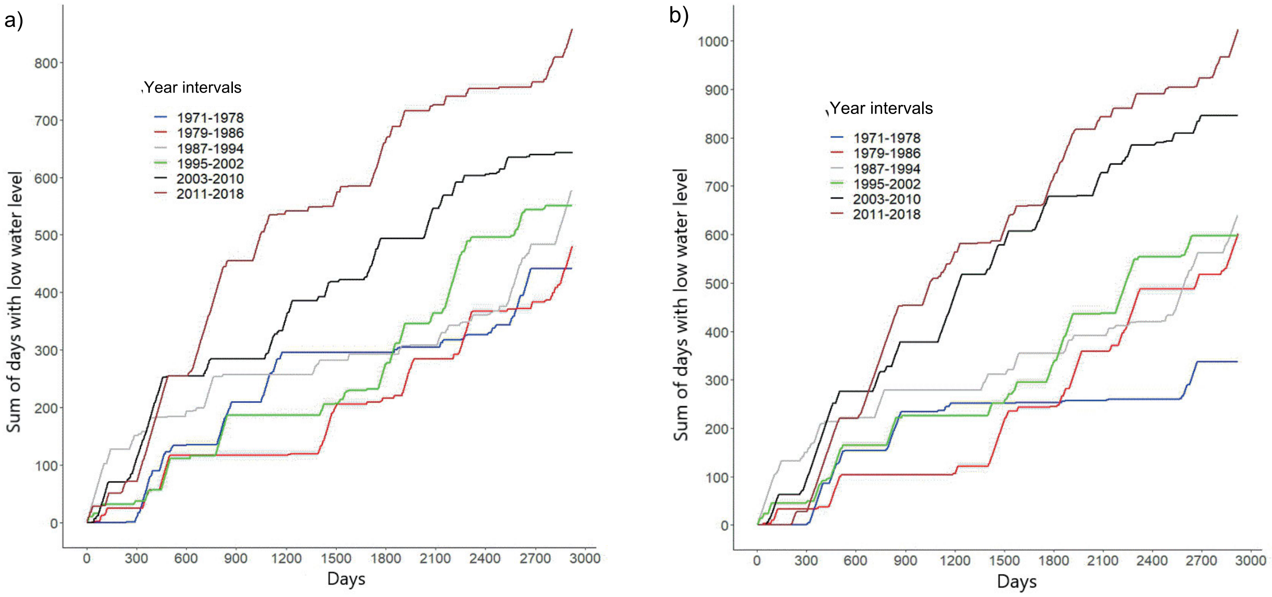

Fig. 3. Summary of shallow low water level days for studied catchments: a) Biała Woda, b) Czarna Woda; source: own study

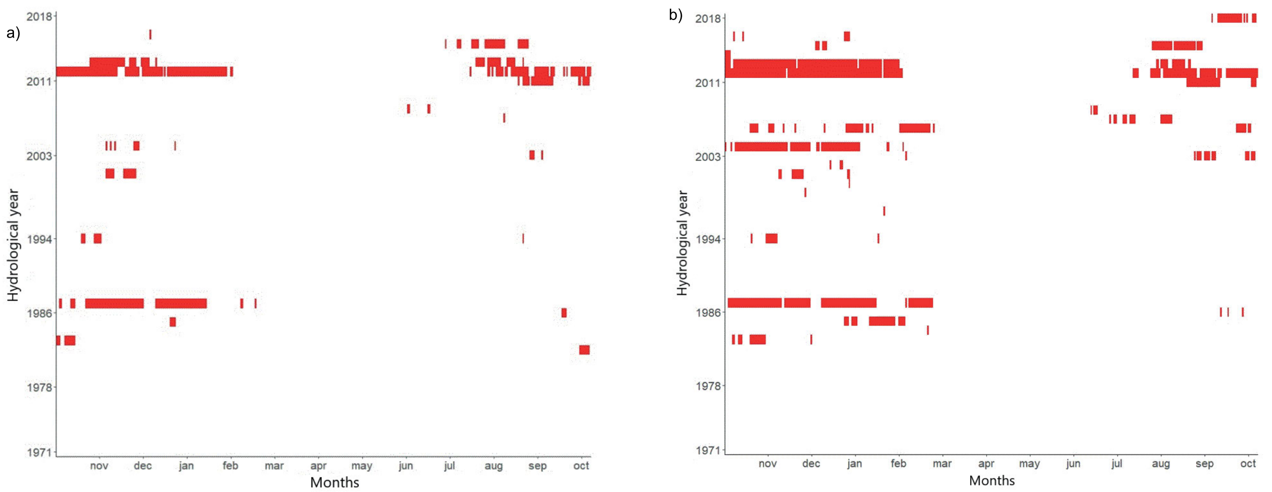

Fig. 4. Occurrence periods of deep low water level in studied streams in years 1971–2018: a) Biała Woda stream, b) Czarna Woda stream; source: own study

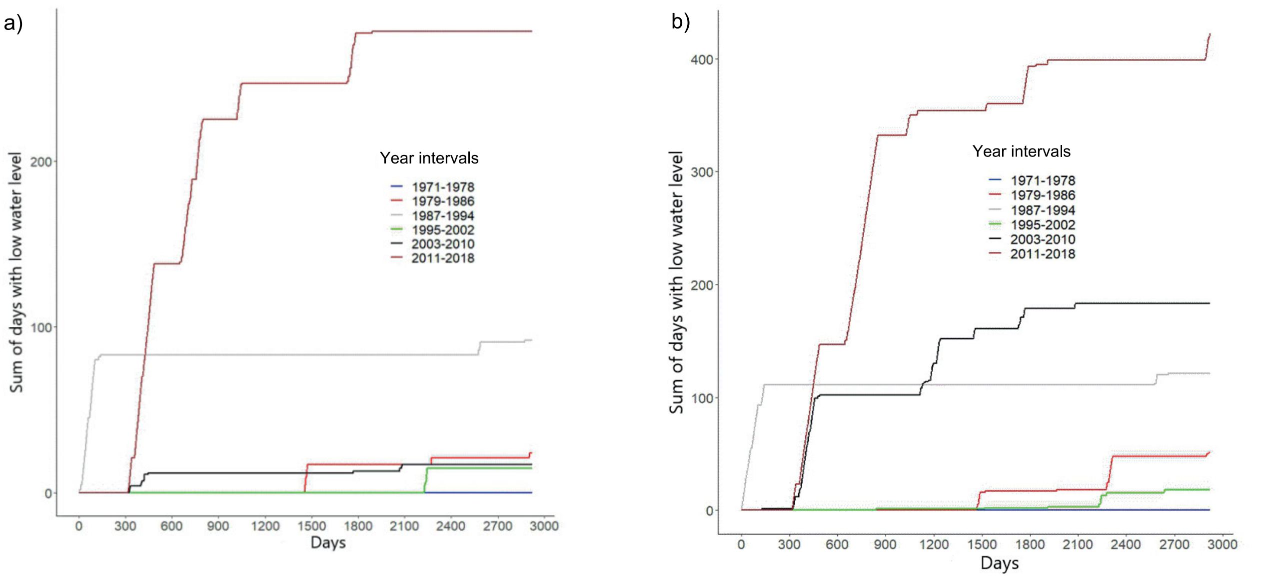

Fig. 5. Summary of deep low water level days for studied streams: a) Biała Woda, b) Czarna Woda; source: own study

residential buildings zone (Fig. 6). The higher concentrations of phosphorus can be observed in the Biała Woda catchment, in its central and estuary parts, where urbanised areas dominate.

The nitrogen load was also greater in the lower (estuary) parts of both catchments, where residential buildings dominate. In the remaining part of the Biała Woda catchment (green areas, rocks, extensively used pastures) the nitrogen load did not exceed 0.006 kg·px^{-1} (kilogram per conventional pixel). While the minimum increase in the nitrogen load is observed in the completely forestry central part of the Czarna Woda catchment (Fig. 7).

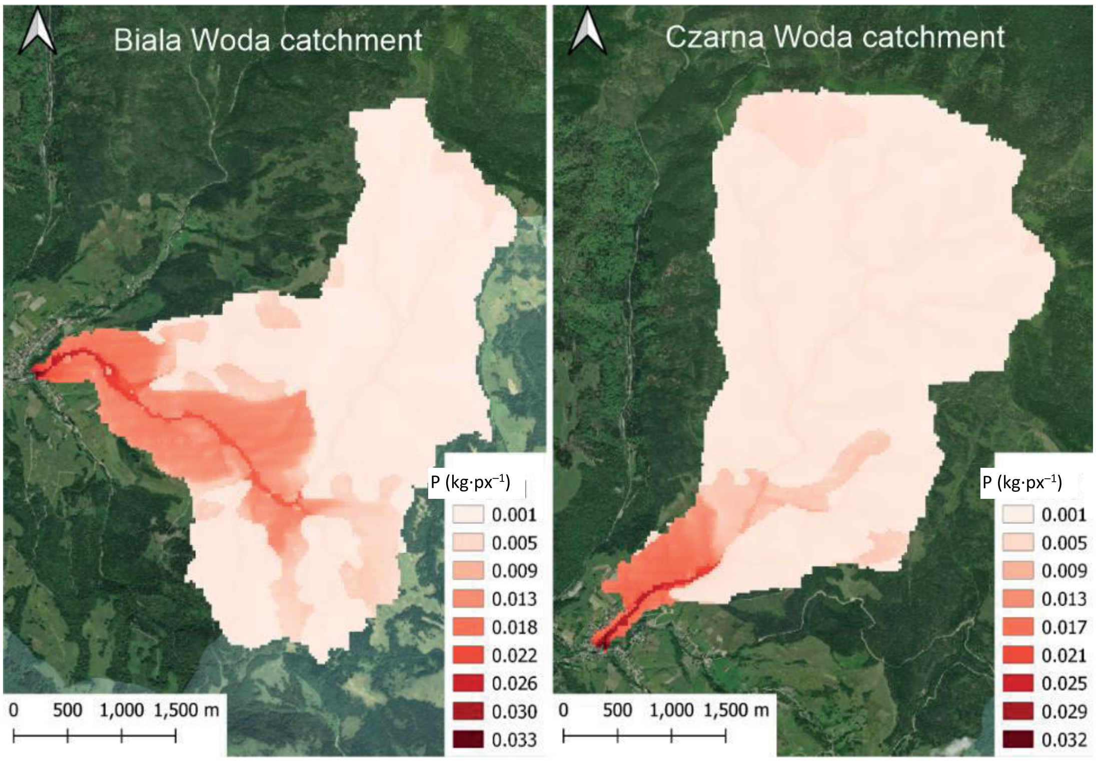

Fig. 6. Model of total phosphorus delivery ratio from surface area in basin of Biała Woda and Czarna Woda; source: own study

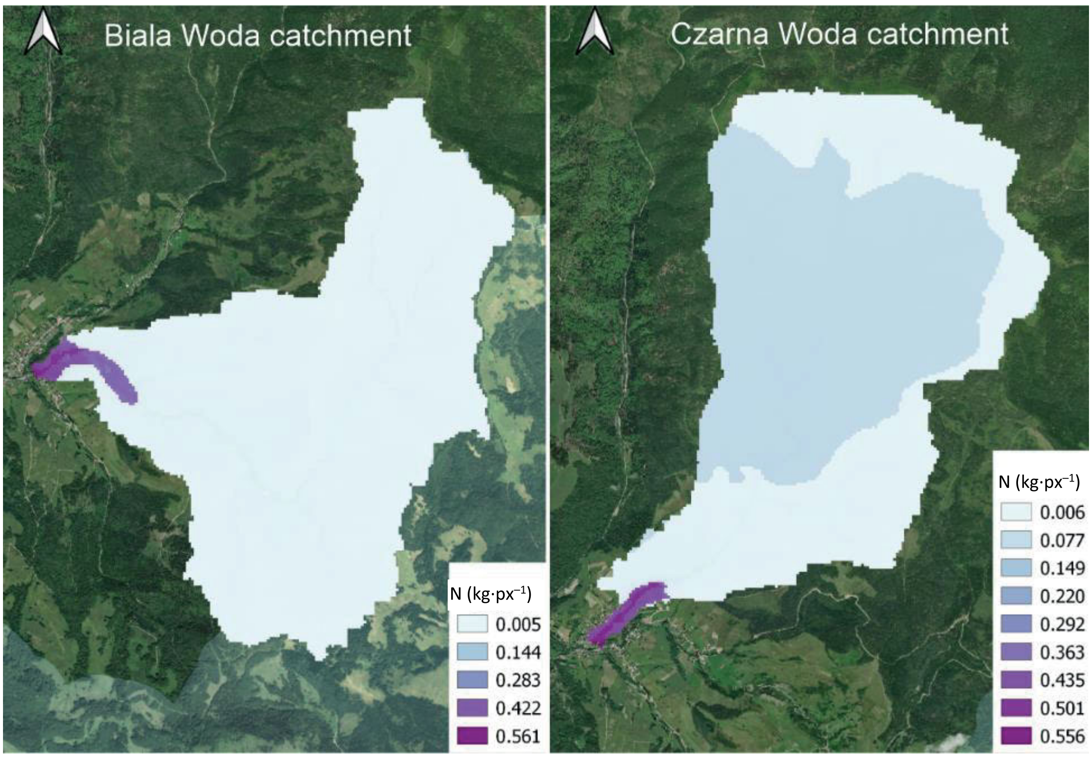

Fig. 7. Model of total nitrogen delivery ratio from surface area in basin of Biała Woda and Czarna Woda; source: own study

DISCUSSION

Small mountain catchments (Carpathian) have specific hydrological characteristics. Hydrograms in mountain streams differ in shape and dynamics compared to lowland rivers [BAILEY *et al.* 2003]. To a much greater extent, the size and nature of the surface runoff from the catchment area are determined by indirect factors, such as the terrain and the way it is developed [BAJKIEWICZ-GRABOWSKA 2008]. It is obvious that in mountain basins we register extreme phenomena more often, both floods and low waters conditions. This variability is shaped both in the spatial arrangement, which was analysed on the example of two catchments with different land-use structures, in particular in the proportion of afforestation. Their size and distribution were typical for mountain conditions. The lowest values were recorded in the winter months (from January to March), while the highest was in June and July. The seasonal distribution of low waters in both research catchments was similar, they occurred mainly in the winter, more often in the more forested Czarna Woda catchment. However, since the 1990s, there has been an upward trend in low waters emergence, which is also more common in summer (July, August). Over the years, the temporal nature of low waters also changed – in the 1970s low waters were separated by long, even several years non-discount periods, while recently low waters periods appear more often and are separated by much shorter non-discount periods. The influence of forest cover on the proportions in the occurrence of low waters is also noted. Even in the 1970s, the barely forested Biała Woda catchment area recorded more low waters than the heavily forested Czarna Woda catchment area.

These changes have a positive effect on the stabilysation of the biogeochemical cycles of nutrient elements [POWERS, MARÍN-SPIOTTA 2017; WINBOURNE *et al.* 2018; SZALIŃSKA, DOMINIK 2006]. The reduction of arable and pasture land is associated with a reduction in the export of macro and microelements to the water of both rivers. Evidences from literature, such as the catchment area of Hubbard Brook (USA), proved the role of plant cover in the cycle of elements in nature. Along with controlled logging, the exports of selected elements from the area to the Hubbard Brook River increased significantly [BAILEY *et al.* 2003; BORMANN, LIKENS 2012; BURTON, LIKENS 1975].

CONCLUSIONS

1. In the last 48 years, there have been slow but consistent hydrological changes in the Carpathian drainage basins. Low water levels occur more and more often and in the last eight years the occurrence of so-called deep low waters, which poses the greatest threat to the biological life of aquatic ecosystems.
2. The increase in the number of days with low water levels in both catchments probably be caused by irregular rainfall, which was not analysed in this study.
3. The impact of afforestation on the incidence of low waters, compared to other factors, is getting smaller, and this phenomenon is noticeable in the entire Western Carpathian region. This is indicated by the studies conducted by the Institute of Technology and Life Sciences in Jaworki.
4. The land use structure in the last several dozen years has a significant influence on the runoff, as well as nitrogen and phosphorus loads.

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