CASE STUDY

Current and future variability of water supply to a mountain reservoir (Polish Carpathians)

Witold Bochenek[1] · Łukasz Wiejaczka[2]

Abstract

This study presents the characteristics of the current course of the phenomenon of droughts and floods in the catchment area of a man-made mountainous reservoir and forecasts of water inflow changes to the reservoir over the next three decades. The catchment area of the Klimkówka reservoir on the Ropa River, a tributary of the Wisłoka River, located within the Polish Carpathians was selected for the study. The analysis carried out, using Soil and Water Assessment Tool (SWAT) modelling among other techniques, showed an increase in the importance of low-flow outflow from the upper Ropa catchment and a negative balance of inflow to the reservoir ($Q < 2 \ \mathrm{m^3 \ s^{-1}}$), manifested by a prolonged duration of low flows and an increase in outflow deficit during the year. The duration of flood flows and the runoff excess during these periods show a constant or decreasing tendency, while the length and excess of runoff increase during large floods. Thus, in the upper Ropa catchment, an increase in the intensity of extreme hydrological phenomena is observed. The prepared forecasts indicate an increase in annual runoff from the catchment in the decades 2021–2030 and 2031–2040 and a marked decrease in the decade 2041–2050. In the annual cycle, the projected changes in the coming decades will take different directions. In December only, throughout the entire period 2021–2050, the outflow will increase, whereas in May it will systematically decrease.

Keywords Floods · Droughts · Reservoir · Hydrological forecast · SWAT · Polish Carpathians

1 Introduction

Man-made reservoirs play a key role in the terrestrial water system by influencing surface water flows and storage by regulating water management for various purposes, including irrigation, urban water supply, hydropower generation and flood protection. (Zhou et al. 2016). Reservoir sustainability is a critical issue, however, long-term efforts are hampered by the uncertainties associated with climate change, thus, reservoir managers will need to employ flexible methods to adapt to the challenges of a changing climate (Yasarer and Sturm 2016). Reservoir operating rules developed based on historical information alone will not ensure the optimal use of storage under changing hydrological conditions (Eum et al. 2012). Past climate data can be used as a proxy for possible future droughts and floods, however, these past data may be insufficient for future planning (Wagener et al. 2010). In contrast, simulations using hydrological modelling can inform and develop adaptation strategies—modelling can provide estimates of the extent and likelihood of impacts on local systems, which can form a useful part of risk assessments and reservoir planning and management (Yasarer and Sturm 2016).

Drought represents a natural part of historical climate variability, however, recent drought impacts and climate change projections have increased the need for a structured approach to documenting and understanding drought in a way that can be applied by resource managers (McNeeley

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et al. 2016). The frequent occurrence of drought and the increasing severity of its impacts make traditional approaches to emergencies insufficient, thus necessitating an improved risk management methodology. Strategies such as improved coordination of drought preparedness planning tasks, adaptive operation of water supply systems to prevent severe shortages and wider use of early drought warnings have been proposed (Rossi et al. 2012). Understanding and predicting hydrological drought represents a major challenge due to the complex interactions between climate, hydrology and humans (Yuan et al. 2017). In many parts of the world, there are ongoing heated discussions about the expansion of reservoirs to counter droughts and water shortages because, contrary to common thinking, in some cases the construction of reservoirs increases vulnerability to drought hazards and thus increases the potential damage caused by them (Di Baldassarre et al. 2018).

The impacts of climate change on flood characteristics are highly sensitive to the detailed nature of these changes; at present, only limited confidence can be achieved in the numerical projections of flood magnitude and frequency changes resulting from climate change (Kundzewicz et al. 2014). The hydrological cycle is expected to intensify with global warming, which will likely increase the intensity of extreme precipitation events and flood risks. The intensification of extreme precipitation and flood events can occur in all climate regions, with the severity of this intensification growing with increased water availability from dry to wet regions (Tabari 2020).

Assessing and forecasting the incidence of floods and droughts using various predictive models is the subject of many studies for various physical-geographic regions around the world. (e.g. Chen and Lin 2021; Fischer et al. 2022; Di Nunno and Granata 2023; Elbeltagi et al. 2023). One of the most vulnerable to climate change is mountainous areas (e.g., Rangwala and Miller 2012). Effective management of mountain water resources urgently requires more detailed regional studies and more reliable scenario forecasts; additionally, research in this field must become more inclusive by combining insights from other relevant disciplines (Viviroli et al. 2011). The Carpathian region is one of the areas with the highest risk of floods and droughts in Europe (Spinoni et al. 2013; Mezősi et al. 2016; Bryndal et al. 2017; Didovets et al. 2019; Bokwa et al. 2021). There is an urgent need for information on the projected impacts of climate change on extreme hydrological events to develop a plan to adapt to future floods and droughts (Lane and Kay 2021). Accordingly, forecasting the course of flood and drought phenomena in the context of individual water systems within the Carpathian area is of paramount importance to reservoir management in extreme scenarios.

Within the Polish Carpathians, there are over a dozen large reservoirs with differing hydrotechnical parameters, functions and ages, all of which significantly impact the flow of rivers in the upper Vistula basin. In light of the forecasted changes to rivers' hydrological cycles driven by climate change, there is a need to predict extreme hydrological situations in the context of water resource management in the study area. Thus, the main objective of the analysis undertaken in this work is to (i) characterise the current course of drought and flood phenomena in the catchment area of the Carpathian retention reservoir during the period 1996–2020 and (ii) forecast changes in water inflow to the reservoir over the next three decades (2021–2050). The catchment area of the Klimkówka reservoir on the Ropa River (a tributary of the Wisłoka river) located within the Low Beskids (Fig. 1) was selected for the study. The specific goals of the work are:

– Identifying the spatial and temporal variability of water inflow to the mountain dam reservoir;
– Determining the scale of drought and flood phenomena in the context of water management in the mountain dam reservoir;
– Forecasting the periods of water inflow excess and shortage to the mountain dam reservoir over an annual period.

The basic hypothesis tested in the analysis assumes that in the next few decades, the greatest problem in the context of water management in mountain dam reservoirs will be the observed upward trend in the cases and duration of hydrological droughts, as well as an increase in the frequency of large, flash floods.

2 Study area

The Ropa River (a tributary of the Wisłoka River with an area of 974 km^2) drains the western part of the Low Beskid, which forms the lowest-located mountain unit in the Polish Carpathians, a transitory area between the Western and Eastern Carpathians. Dynowska (1971) interpreted that the hydrological regime of rivers for the area of the Low Beskids is unbalanced, with freshets in spring, summer and winter, as well as contributions from rain–ground–snow supply. The runoff regime in the study area has not changed significantly during the past 60 years (Wrzesiński 2014). The upper Ropa catchment is closed by the Klimkówka reservoir dam, which was launched in 1994. The main aim of this facility is flood control and increasing the Ropa River's low flows. The guaranteed outflow from the reservoir equals 2 m^3 s^{-1}. The Klimkówka reservoir has a maximum capacity of 43.5 million m^3, a surface area of
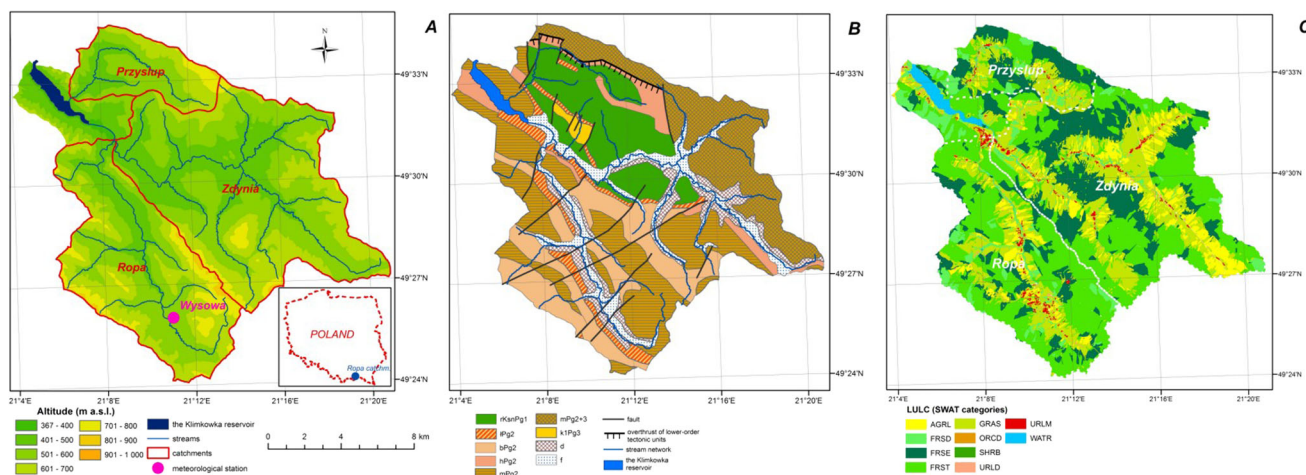
Fig. 1 Research area: hypsometric map (**A**), geological map (**B**), land use and land cover-2018 (**C**) Explanations: for part **B** rKsnPg1—sandstones and shales (the Ropianieckie beds), łPg2—Eocene shales, bPg2—shales and sandstones (the Belowenian beds), hPg2—Shales with thin-bedded sandstones (hieroglyphics beds), mPg2—mica sandstones, mPg2 + 3—glauconitic sandstones with shales, k1Pg3—sanstones and shales (the lower Krosno beds), d—deluvial covers, f—Holocene sediments, for part **C** AGRL -Agricultural Land-Generic, FRSD—Forest-Deciduous, FRSE—Forest-Evergreen, FRST—Forest-Mixed, GRAS—Grassland, ORCD—Orchard, SHRB—Shrubland, URLD—Residential-Low Density, URML—Residential-Med/Low Density, WATR—Water

3.06 km^2 and a depth of 30 m. The catchment above the reservoir covers an area of 198.2 km^2 and is drained by three main watercourses and their tributaries, namely, the Przysłup (24.3 km^2), Zdynia (104.8 km^2) and Ropa (69.1 km^2) rivers (Fig. 1A). These catchments have diverse relief with crevice-porous type of rock medium. Lithological conditions affect the distribution of rainwater. In areas with a predominance of shales in the bedrock, surface runoff is higher, but in creviced sandstone formations, the role of infiltration and supply of watercourses by throughflow and underground runoff increases (Słupik 1973; Bochenek 2020). Mountain relief (predominantly sandstone bedrock, higher relative heights of mountain ridges and greater terrain slope) occurs in the Przysłup and Ropa catchments, whereas foothills relief (predominantly slate bedrock, lower relative heights of mountain humps and long, gentle slopes) prevails in the Zdynia catchment (Fig. 1B). The highest elevations in the eastern part of the catchment are underlain by glauconite sandstones, which form part of the Palaeogene Magura Nappe. In the western part of the study area, mica sandstones and arches, which form part of the same rock series, have a ridge-forming character. At the base of the valleys, there are shale and sandstone layers that are part of the "Belowes Formation" (Rączkowski et al. 1995). The average height of the Ropa basin above the reservoir is 564 m above sea level (range of 367–901 m above sea level)(Fig. 1A). The area of the upper Ropa catchment is covered by forests (87.4%), most of which are mixed forests (60.1%); a significantly lower share is grassland (8.8%), while 1.6% of the area is covered by complex systems of cultivation and plots and 1.2% by arable land (Fig. 1C). The physiographic parameters of the partial catchments, including the morphometric indicators according to Strahler's method (1957), i.e. bifurcation index (Rb), watercourse length index (Rl) and catchment area index (Ra), are presented in detail in Table 1. Of the studied catchments, the Ropa catchment is characterised by the highest average elevation (598 m above sea level) and the highest average slope (22°), thus representing features typical of the Beskids. The average watercourse network density in the Przysłup and Ropa catchments is similar (0.63–0.64 km^2) and slightly higher in the catchment of the Zdynia River (0.73 km^2). The morphometric parameters of the river network (Rb, Rl and Ra) in each of the studied catchments have values similar to those obtained in other parts of the Western Carpathians (Dobija et al. 1979; Bochenek 2020).

The average annual precipitation sum in 1996–2020 at the precipitation station in Wysowa was 917.4 mm, with the range of changes in annual sums from 637.4 mm (2003) to 1154.2 mm (2010). The range of changes in

Table 1 Basic physiographic parameters of the studied catchments

	Przysłup	Zdynia	Ropa
Ave altitude (m a.s.l.)	569	554	598
Ave Slope (%)	16.9	15.3	22.0
Stream network lenght (km)	15.3	76.2	44.1
Stream network density (km km^{-2})	0.63	0.73	0.64
R_b	2.00	3.50	2.75
R_l	0.30	1.84	1.99
R_a	0.24	2.05	5.70

average monthly precipitation totals ranged from 45.6 mm (December) to 143.5 mm (July). There were no statistically significant trends (p < 0.05) for annual and monthly precipitation totals, except for April, when a downward trend in precipitation was observed (α = -1.29 mm year-1, p = 0.049). In May, the upward direction of change (α = 2.38 mm year-1) was close to reaching the assumed significance threshold (p = 0.072).

3 Material and methods

3.1 Historical database

Calculations of inflow to the Klimkówka reservoir were carried out considering the daily discharges (for the period 1996–2020) from hydrometric gauges closing from the three studied catchments that supply the reservoir with water, obtained from Polish Water Holding "Polish Water". To outline the climatic outflow conditions, rainfall data (for the period 1996–2020) from the Institute of Meteorology and Water Management for the station in Wysowa were used (latitude = 49°26′ 00"; longitude = 21°11′02″).

Long-term measurements allow us to present the average course of atmospheric precipitation throughout the year. To illustrate precipitation changes in the analysed multiannual period, relative deviations of monthly totals, periods of deficiency or excess precipitation and their implications for runoff, classification of monthly rainfall totals (data from Wysowa Zdrój) and inflow to the reservoir were calculated using the approach of Tomaszewska (1994), (Table 2).

3.2 Methods of hydrological data analysis

In this study's analysis, hydrological drought events were defined as occurring each time (i.e. daily) the discharge fell below a threshold value. The threshold discharge for the total hydrological drought was determined using the quantile method (Hisdal et al. 2004), assuming the 70th percentile in the decreasing series of daily discharges. To distinguish severe drought, the 95th percentile was adopted. To distinguish flood days, the quantile method was also used, assuming the 5th percentile for total flood and the 1st percentile for great floods in the decreasing sequence of daily discharge values across the analysed multiannual period.

Threshold values for droughts and floods were calculated based on the daily discharges for each of the three tested watercourses and the total inflow to the reservoir. The natural variability in runoff throughout the year, determined by the snow–rainy hydrological regime, resulted in the adoption of four seasonal thresholds for floods and droughts for the periods November–January (I), February–April (II), May–July (III) and August–October (IV), (Table 3).

The outflow deficit (H_n) from the catchment above the reservoir was calculated as the difference between the recorded water volume and the volume calculated based on the threshold value of the guaranteed discharge (i.e. 2 $m^3 \ s^{-1}$) or the threshold discharge for drought. The excess runoff (H_w) from the catchment above the reservoir was calculated analogously, based on the guaranteed discharge threshold value (2 $m^3 \ s^{-1}$) or the threshold discharge for flooding.

The assessment of the size of hydrological droughts and floods was made using the indicators of insufficient runoff during droughts (d) and excess runoff during floods (f), according to Formula (1):

$$H_{(d,f)} = \frac{V_{(d,f)}}{A} \qquad (1)$$

where H(d, f) is the runoff deficiency index during hydrological droughts (d) or excess runoff during floods (f) [mm], V (d, f) is the runoff deficiency volume below the hydrological drought threshold (d) and excess runoff above the flood threshold (f) [thousand m^3] and A is the catchment area [km^2].

The data were standardised using Formula (2):

$$StV = \frac{xi - \overline{x}}{\sigma} \qquad (2)$$

Table 2 Criteria for precipitation classification of monthly totals according to Tomaszewska (1994)

Class name	Percent of monthly average precipitation total in the multi-year 1996–2020
Extremaly dry	< 25
Very dry	[25–50)
Dry	[50–75)
Normal	[75–125]
Humid	(125–150]
Very humid	(150–200]
Extremaly humid	> 200

Table 3 Seasonal threshold discharge (in m³ s⁻¹) for droughts and floods against the background of average discharge in the catchments of the upper Ropa basin

	I (Nov-Jan)	II (Feb-Apr)	III (May-Jul)	IV (Aug–Oct)
Ave. discharge (m³ s⁻¹)				
Przysłup	0.268	0.611	0.489	0.246
Zdynia	1.000	2.156	1.777	0.937
Ropa	0.797	1.668	1.324	0.671
Droughts (m³ s⁻¹)				
Przysłup				
Total	0.090	0.160	0.080	0.050
Severe	0.040	0.040	0.030	0.020
Zdynia				
Total	0.400	0.700	0.360	0.220
Severe	0.150	0.290	0.140	0.120
Ropa				
Total	0.300	0.610	0.320	0.190
Severe	0.120	0.227	0.140	0.100
Floods (m³ s⁻¹)				
Przysłup				
Total	0.800	2.020	1.527	0.860
Great	1.542	4.563	7.404	2.209
Zdynia				
Total	3.282	7.072	6.050	3.539
Great	6.710	15.700	23.150	10.382
Ropa				
Total	2.436	5.057	4.630	2.500
Great	4.156	9.307	16.476	5.680

where StV is the standardised value, x_i is the value of the ith variable of the monthly average, $\bar{x}$ is the arithmetic mean of monthly averages and σ is the standard deviation of the monthly mean values.

The variability coefficient Cv was calculated using Formula (3):

$$Cv = \frac{\sigma}{\bar{x}} \tag{3}$$

3.3 SWAT input data, model settings and calibration output data

The Soil and Water Assessment Tool (SWAT) model was used to forecast changes in runoff from the three studied catchments. This model is still under development in association with 30 years of research by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) (Gassman et al. 2014). The SWAT model is commonly used to simulate runoff and substance concentrations at different locations around the world, irrespective of lithology, terrain relief, or climatic zone. The data used for the modelling are shown in Table 4.

The hydrological modelling was performed using the ArcGIS/ArcSWAT software and the SWAT 2009 database.

The database contains records comprising local soil parameters (Table 5) and a weather generator.

The simulations were carried out separately for each of the three catchments, divided into watercourse sections and their corresponding subbasins based on the Map of Hydrographic Division of Poland. In the Przysłup catchment, three watercourse sections were distinguished; in the Zdynia catchment area, 19 sections were identified, and 13 sections were identified in the Ropa catchment area.

The creation of hydrological response units was carried out without setting threshold (i.e. upper) values for area elimination in terms of land cover forms, soils or land slopes, all of which constitute a minor share of the studied subbasins. During the simulation process, different roughness coefficients were used in each subbasin for the river bed (Przysłup—0.07, Zdynia—0.035, Ropa—0.05) and land surface (Przysłup—0.104, Zdynia—0.096, Ropa—0.105). The Curve Number (CN) parameter was employed to compute the total surface runoff volume, which requires daily precipitation data. The runoff simulation was carried out for the period 2004–2020 and divided into a calibration period (2004–2011) and validation period (2014–2020); each was preceded by a two-year warm-up period. The simulation was performed with a monthly time step.

Table 4 Data used for SWAT modelling

Type of data	Source of data	Spatial or temporal resolution	Data timeliness or time range
Digital elevation model	LiDAR https://mapy.geoportal.gov.pl/imap/Imgp_2.html	10 m	2018
Land use and land cover	Topographic Object Database (BDOT) https://mapy.geoportal.gov.pl/imap/Imgp_2.html	10 m	2016
Soil	Harmonized World Soil Database (soil parameter)	10 m	2010
	https://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/		2010
	European Soil Database v. 2.0 (JRC-ESDAC) (polygons of soil types		
	https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data		
Watercourse network/catchment boundaries	Map of Hydrographic Division of Poland (MPHP)	Vector layer	2016
Weather generator	KLIMADA 2 ($\phi = 49,4992°N; \lambda = 21,1731°E$)	1 month	2011–2020

Table 5 Physical parameters of soils in the upper Ropa catchment

SMU	10151	10133	10146
FAO 90	Dystric Cambisols (CMd)	Eutric Fluvisols (FLe))	Umbric Leptosols (LPu)
HYDGRP	C	C	B
SOL_ZMX (mm)	950	950	700
ANION_EXCL (fraction)	0.5	0.5	0.5
SOL_CRK (m^3/m^3)	0.5	0.5	0.5
SOL_Z (mm)	1000	950	650
SOL_BD (g/m^3)	1.33	1.38	1.36
SOL_AWC (mm/mm)	0.05	0.065	0.025
SOL_K (mm/hr)	24	24	61
SOL_CBN (%)	0.90	0.80	0.44
CLAY (%)	20	21	13
SILT (%)	36	39	22
SAND (%)	44	40	65
ROCK (%)	15	6	10
SOL_ALB (fraction)	0.03	0.03	0.02
USLE_K	0.2046	0.2046	0.1300

The performed *Sensitive Analysis* for the three studied catchments showed the greatest impact of the following parameters on the outflow: the SCS runoff curve number (CN2.mgt), baseflow alpha factor (ALPHA_BF.gw), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN.gw), soil evaporation compensation factor (ESCO.hru), maximum canopy storage (CANMX.hru), available water capacity of the soil layer (SOL_AWC.sol) and threshold depth of water in the

shallow aquifer for "revap" to occur (REVAPMN.gw) (Table 6).

Calibration of the simulation results was performed in the SWAT Calibration and Uncertainty Program (SWAT-CUP) using the Sequential Uncertainty Fitting (SUFI2) algorithm (Abbaspour et al. 2004, 2007). This allowed optimisation of the simulation parameters used in the model (Table 6).

The following measures were used to assess the quality of the observed results following calibration: the

Table 6 Optimised simulation parameters in SWAT

	Przysłup	Zdynia	Ropa
CN2.mgt	0.13	− 0.01	0.02
ALPHA_BF.gw	0.691	0.284	0.410
GWQMN.gw	145.3	5.2	48.0
ESCO.hru	0.476	0.350	0.940
CANMX.hru	28.7	8.1	12.0
SOL_AWC.sol	0.08	0.20	0.18
REVAPMN.gw	320	283	365

coefficient of determination R^2 (Formula 4), for which the evaluation criteria were proposed by Sarma et al. (1973), the Nash–Sutcliff model efficiency coefficient (NSE) (Formula 5) and the per cent deviation coefficient (PBIAS) (Formula 6), for which the evaluation criteria were given by Singh et al. (2004):

$$R^2 = \frac{\left[\sum_{n=1}^{n}\left(Y_i^m - Y_{sr}^m\right)\left(Y_i^s - Y_{sr}^s\right)\right]^2}{\sum_{n=1}^{n}\left(Y_i^m - Y_{sr}^m\right)^2 \sum_{n=1}^{n}\left(Y_i^s - Y_{sr}^s\right)^2} \tag{4}$$

$$NSE = 1 - \frac{\sum_{n=1}^{n}\left(Y_i^m - Y_i^s\right)^2}{\sum_{n=1}^{n}\left(Y_i^m - Y_{sr}^m\right)^2} \tag{5}$$

$$PBIAS = \frac{\sum_{n=1}^{n}\left(Y_i^m - Y_i^s\right)}{\sum_{n=1}^{n} Y_i^m} \cdot 100\% \tag{6}$$

where Y_i^m and Y_i^s are the measured and simulated values, respectively, Y_{sr}^m and Y_{sr}^s are the arithmetic means of the measured values and the simulated values, respectively, and n is the number of values.

3.4 Forecast of inflow to the Klimowka reservoir

For outflow forecasting periods (1) 2021–2030, (2) 2031–2040 and (3) 2041–2050, monthly climatic data (average air temperature, sum of precipitation and sum of solar radiation) were downloaded from the KLIMADA 2.0 online portal (https://klimada2.ios.gov.pl/klimat-scenariusze; administrated by the Institute of Environmental Protection—National Research Institute); these data were downloaded for a grid node of 12.5 × 12.5 km dimensions, with geographic coordinates: λ = 21.1731°E and φ = 49.4992°N, located in the centre of the upper Ropa catchment. The Polish database on climate scenarios (KLIMADA 2.0) is a regional projection of the Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset under the EuroCORDEX initiative (euro-cordex.net). As part of EuroCORDEX, ensembles of regional climate model simulations are created, with external forcings from the general circulation models derived from the CMIP5 set. The methodology for calculating the data for the model is

available on the project's website (https://klimada2.ios.gov.pl/metodyka-opracowania-projekcji-klimatycznych/).

The collected climate data relate to the Representative Concentration Pathways 4.5 (i.e. 4.5 W m^{-2}; RCP4.5) scenario, which assumes an increase in the average temperature on Earth of 2.5 °C by 2100 relative to the pre-industrial era (Climate Model: Temperature Change 2006). The additions to the SWAT2009 database include the differences between the values of air temperature and the sum of solar radiation, as well as the percentage changes in the sums of precipitation in the three forecast periods and the reference period (2011–2020). Outflow calculations in the forecast periods were carried out on the previously used spatial data, considering the climatic data from Wysowa, and were changed by values calculated based on the KLIMADA 2.0 climate data for the reference period 2011–2020 (Table 11).

The complete structure of the research procedure is presented in Fig. 2.

4 Results

4.1 Spatio-temporal characteristics of outflow from the reservoir catchment area in the period 1996–2020

The highest average annual runoff occurred in Przysłup (522.6 mm), the smallest of the studied catchments (Table 7, Fig. 3). In this catchment, the annual runoff sums showed the greatest variability. The catchment area of the Zdynia River, with the lowest average annual runoff (442.4 mm), is characterised by more gentle slopes and a high proportion of grasslands. The average runoff from the Ropa catchment was 509.5 mm. The average annual runoff from the entire upper Ropa catchment area was 464.9 mm. The annual runoff did not show any trends. Only in April there was a downward trend in the monthly runoff in the three studied catchments, ranging from 2.2 to 2.5 mm year-1, caused by a downward trend in monthly precipitation totals in that month.

In the analysed period, no annual outflow trend changes were identified. The high variability of monthly runoff sums from year to year resulted in no statistically significant trends, except in April when a statistically significant negative trend was identified in the studied catchments and the entire upper Ropa basin. A negative outflow trend also occurred in August in the catchment area of the Zdynia River.

Based on the criteria of Tomaszewska (1994), the monthly rainfall sums (Wysowa) and inflow to the Klimkówka reservoir were classified to determine the presence of cause-and-effect relationships between the studied
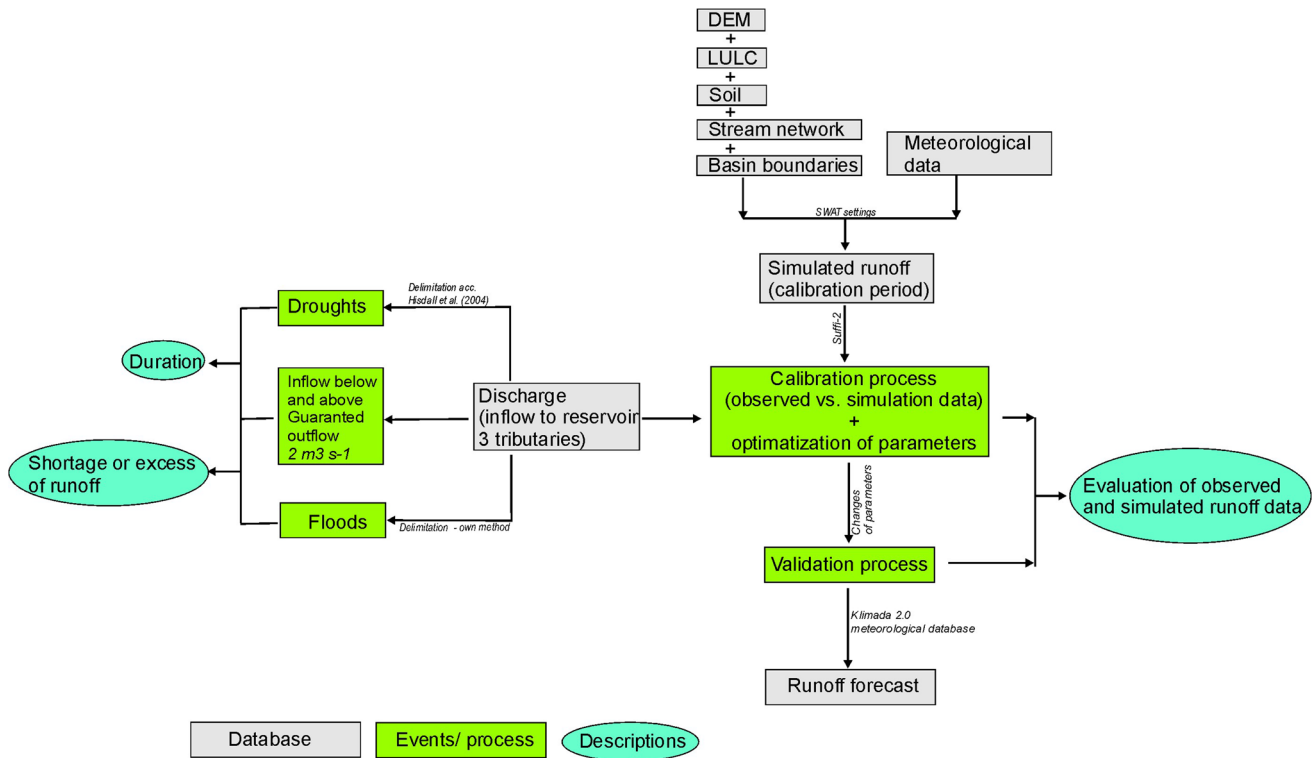
Fig. 2 The course of the research procedure

Table 7 Annual statistical characteristics of runoff in catchments of three tributaries of the Klimkówka reservoir during 1996–2020

	Przysłup	Zdynia	Ropa	Whole upper Ropa
Average	522.6	442.4	509.5	464.9
σ	177.8	117.6	125.9	99.0
Cv [%]	34.0	26.6	24.7	21.3

variables (Table 8a, b). In the analysed period, the number of 'dry' months (< 75% of the average) in terms of runoff (144 months) exceeded the number identified from rainfall (107 months) (Fig. 4). In both cases, there was a statistically insignificant upward trend. For the 'wet' months (> 125% of the mean), no marked directions of changes were found, with a similar frequency of cases (54 months for rainfall and 53 months).

The guaranteed outflow from the reservoir to the Ropa River channel below the dam is 2 m³ s⁻¹. Maintaining the

**Fig. 3** Annual runoff totals in the catchments of the three tributaries to the Klimkówka reservoir in 1996–2020
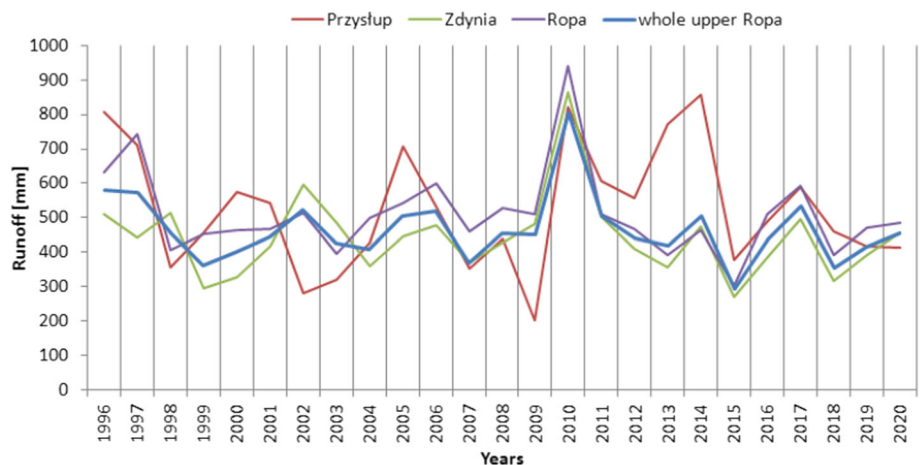
Table 8 Classification of (a) monthly precipitation totals and (b) monthly totals of inflow to the reservoir

a.

Years	11	12	1	2	3	4	5	6	7	8	9	10
1996	49.3	26.6	22.0	20.6	30.4	55.5	99.9	56.9	137.6	113.7	159.4	55.7
1997	27.7	27.0	20.2	32.7	28.9	76.9	102.0	105.1	157.2	62.1	60.9	65.8
1998	51.9	58.4	55.9	73.8	35.4	111.3	113.7	139.9	151.9	39.9	73.3	95.8
1999	58.2	54.0	26.4	105.0	32.8	86.0	61.9	105.5	129.0	76.9	37.3	80.2
2000	64.2	46.8	96.0	95.7	115.6	67.1	127.7	62.6	230.1	79.6	32.8	2.7
2001	25.2	29.2	61.9	39.1	56.7	116.2	62.8	185.7	220.3	89.1	95.1	31.0
2002	57.6	46.9	48.1	47.4	27.2	43.6	120.3	112.5	230.8	152.1	111.7	111.9
2003	26.5	30.4	39.3	37.2	28.6	58.2	76.3	89.1	78.1	26.5	78.6	69.6
2004	18.2	37.7	44.0	95.6	47.1	52.3	95.1	119.0	298.6	99.6	29.7	56.0
2005	81.7	11.1	88.8	46.1	47.4	59.4	116.1	142.9	126.8	191.8	54.6	31.3
2006	22.4	104.0	24.9	36.2	76.1	69.6	131.3	213.6	30.9	151.3	13.8	26.8
2007	91.8	27.8	96.1	52.9	53.2	27.0	36.9	152.7	54.4	118.2	184.7	83.1
2008	76.4	29.7	34.5	23.7	57.7	41.3	75.6	96.8	197.5	95.7	96.3	81.7
2009	21.3	53.3	30.8	32.3	74.3	24.2	125.9	223.3	58.4	150.6	36.6	115.8
2010	78.8	38.7	37.8	39.7	23.3	80.2	237.6	198.2	136.6	118.8	143.0	22.5
2011	45.0	71.5	38.6	18.2	13.0	44.0	71.1	123.5	250.6	27.8	17.4	60.9
2012	2.0	39.7	72.1	48.3	40.9	42.3	99.1	168.1	121.7	31.7	49.1	59.3
2013	39.9	40.0	78.3	52.5	52.7	36.7	129.8	138.1	49.9	12.9	96.7	30.7
2014	112.3	21.4	33.6	33.6	79.9	45.7	203.4	65.6	155.5	141.9	85.6	98.8
2015	13.2	25.1	86.2	33.8	59.0	39.9	129.3	53.4	68.8	78.0	73.9	55.3
2016	89.0	26.1	37.6	104.3	32.0	84.7	77.7	68.1	230.3	113.5	54.7	170.7
2017	59.1	77.9	28.7	44.5	38.4	75.5	119.0	117.7	151.0	88.0	134.6	102.1
2018	57.3	77.2	19.5	52.9	50.1	29.0	98.1	127.5	136.7	60.4	47.7	56.8
2019	36.3	68.6	71.0	28.1	32.2	68.2	208.1	25.3	44.1	101.5	51.7	50.3
2020	17.3	31.6	12.8	79.6	24.8	34.8	119.6	95.8	64.3	79.5	35.4	126.8

b.

Years	11	12	1	2	3	4	5	6	7	8	9	10
1996	35.5	15.9	28.4	17.1	49.9	98.9	66.7	52.6	26.1	27.4	106.1	55.4
1997	29.6	28.9	32.4	72.8	50.7	75.1	50.3	62.7	94.5	50.7	10.6	14.2
1998	30.8	45.9	49.9	79.6	23.8	88.0	24.8	29.4	29.5	10.9	10.8	30.4
1999	25.3	24.8	15.7	23.1	100.9	43.4	17.9	39.4	24.2	14.9	7.9	25.0
2000	14.3	32.3	12.0	52.6	95.7	89.0	14.7	6.2	44.5	24.6	8.5	6.1
2001	7.0	6.5	14.4	27.5	70.0	48.4	6.3	62.4	142.1	24.0	22.9	11.8
2002	15.8	12.1	38.1	85.6	33.9	35.8	26.0	77.8	21.8	50.6	23.5	103.3
2003	39.8	17.4	16.8	10.5	102.8	136.1	53.5	16.9	11.9	4.0	7.3	7.7
2004	8.8	10.0	4.8	29.8	57.7	52.6	34.7	28.2	123.5	27.7	16.9	13.1
2005	31.6	34.2	39.5	36.9	87.5	76.7	67.8	50.8	8.3	54.9	8.0	8.6
2006	8.1	20.5	30.8	22.7	98.8	97.1	26.9	157.2	25.3	10.4	14.9	5.6
2007	18.2	5.7	47.1	57.2	58.1	14.0	7.8	28.4	5.0	8.6	86.2	31.4
2008	56.8	50.2	29.3	50.8	46.5	27.7	22.5	9.3	57.2	22.1	46.9	35.4
2009	14.1	28.9	31.3	42.1	91.0	36.6	16.3	103.7	13.7	22.5	8.2	43.2
2010	45.9	25.8	28.6	29.7	85.1	54.2	133.2	224.7	63.9	27.8	70.2	15.9
2011	15.3	53.1	50.9	25.2	38.7	34.8	24.0	54.1	161.8	31.5	9.5	7.1
2012	4.6	9.1	15.9	28.8	166.8	54.8	58.2	65.0	18.3	6.5	4.8	6.7
2013	10.9	12.6	21.6	36.1	73.8	136.7	25.7	64.0	18.0	6.0	7.1	4.6
2014	49.2	27.8	27.2	40.0	56.7	26.9	63.0	15.3	93.2	42.4	25.1	38.2
2015	9.9	14.2	36.8	50.8	63.3	26.0	58.7	10.5	5.4	4.7	4.0	7.3
2016	24.5	30.5	21.3	100.7	37.9	41.3	32.3	7.5	25.1	27.5	14.0	72.6
2017	54.4	36.9	24.7	57.9	99.8	40.1	72.0	15.2	27.0	17.7	50.1	37.5
2018	51.0	71.5	32.9	17.5	66.8	35.2	12.5	15.6	33.1	6.9	5.8	5.3
2019	5.4	15.8	32.2	65.6	53.0	28.3	171.4	12.0	6.3	12.7	6.3	6.5
2020	17.3	31.6	12.5	79.8	40.7	8.3	25.2	105.6	23.4	12.0	9.0	89.5

| extrematy dry	very dry	dry	normal	humid	very humid	wet
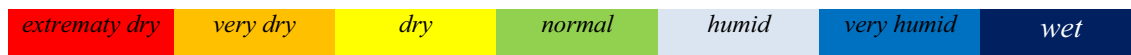
Fig. 4 Number of 'dry' (< 75% of the average) and 'wet' (> 125% of the average) months in terms of rainfall and runoff in the multi-year period 1996–2020
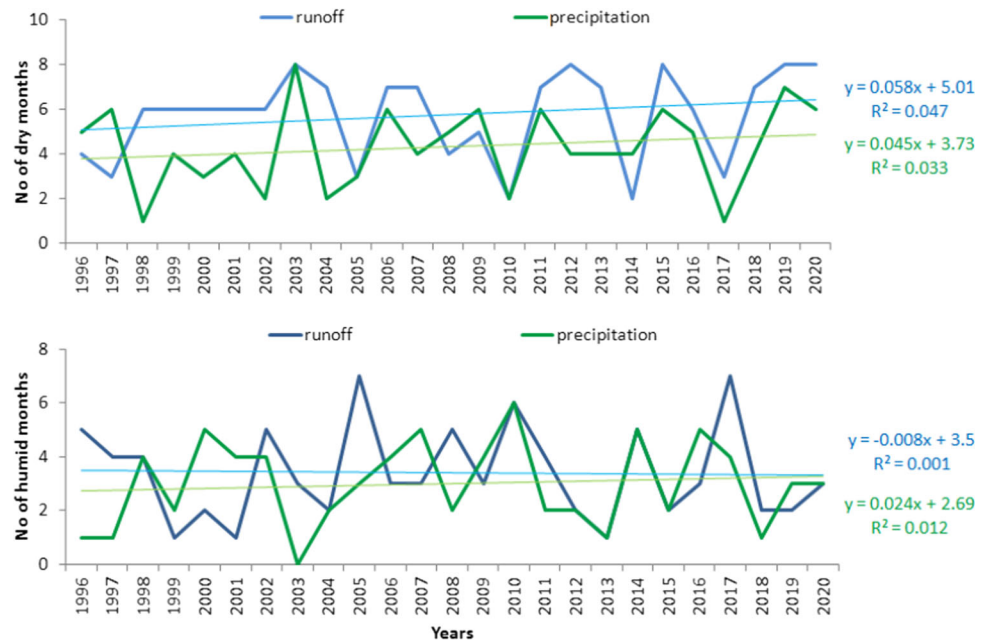

same level of reservoir filling requires the water supply to be equal to the outflow. The study identified the number of days in a year where the average inflow to the reservoir was less than 2 $m^{3\ s-1}$, less than 1 $m^{3\ s-1}$ and less than 0.5 $m^{3\ s-1}$ (Fig. 5); the average annual number of days meeting these criteria were 233, 156 and 54 days, respectively. No statistically significant trends were identified during the 25 years of the reservoir's operation, however, in each case, the direction of changes indicates an increase in the number of days with low inflow to the reservoir and a decrease in water volume. Furthermore, the lower the inflow threshold value, the higher the trend coefficient, thus indicating an increase in the duration of lower inflows to the reservoir.

Thus, the deficit of water supply to the reservoir increased at the time when the volume of the guaranteed outflow was not reached (Fig. 6). The average annual sum of the outflow deficit totalled 233.1 mm over the studied period, with annual sums ranging from 38.5 mm (1997) to 162.4 mm (2015). The high variability of the annual values did not allow the identification of a statistically significant trend, however, the monthly volumes of outflow deficiency below 2 $m^{3\ s-1}$ in April and August exhibited upward trends in the analysed period.

The study covered the number of days with inflow to the reservoir (i.e. total flows from the three watercourses) exceeding 2 $m^{3\ s-1}$ (guaranteed outflow), 5 $m^{3\ s-1}$ and 10 $m^{3\ s-1}$ (Fig. 7). The average numbers of days in a year
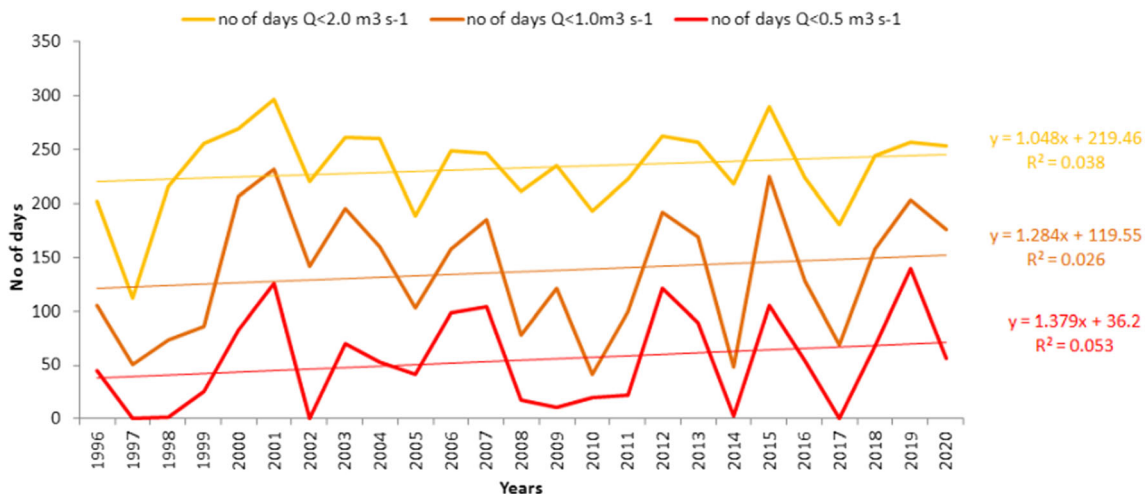
Fig. 5 Number of days with average inflow to the Klimkówka reservoir below 2.0, 1.0 and 0.5 $m^{3\ s-1}$ with linear trends of their changes over the years
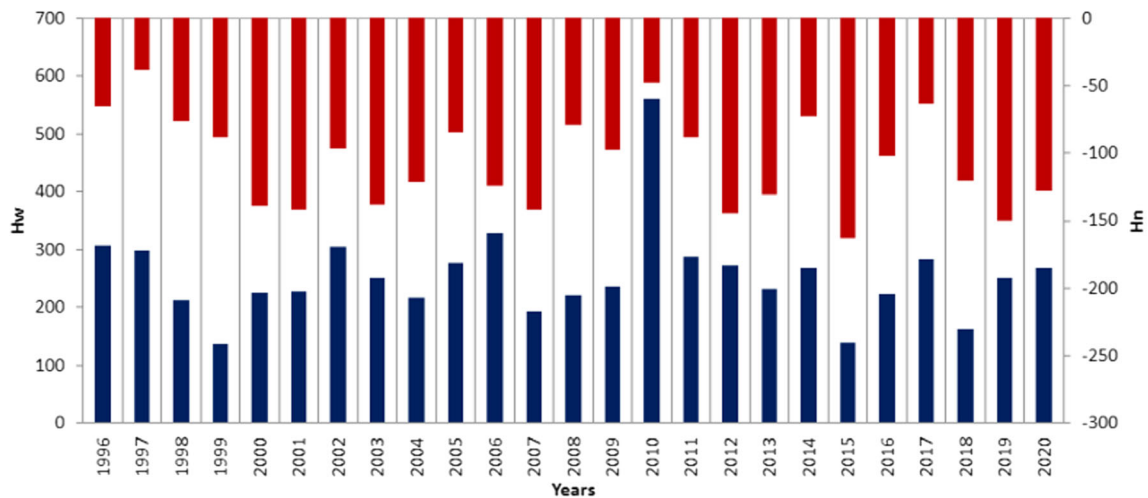
Fig. 6 Deficit (H_n) and excess (H_w) of inflow to the Klimkówka reservoir below or above 2 m$^{3\ s-1}$
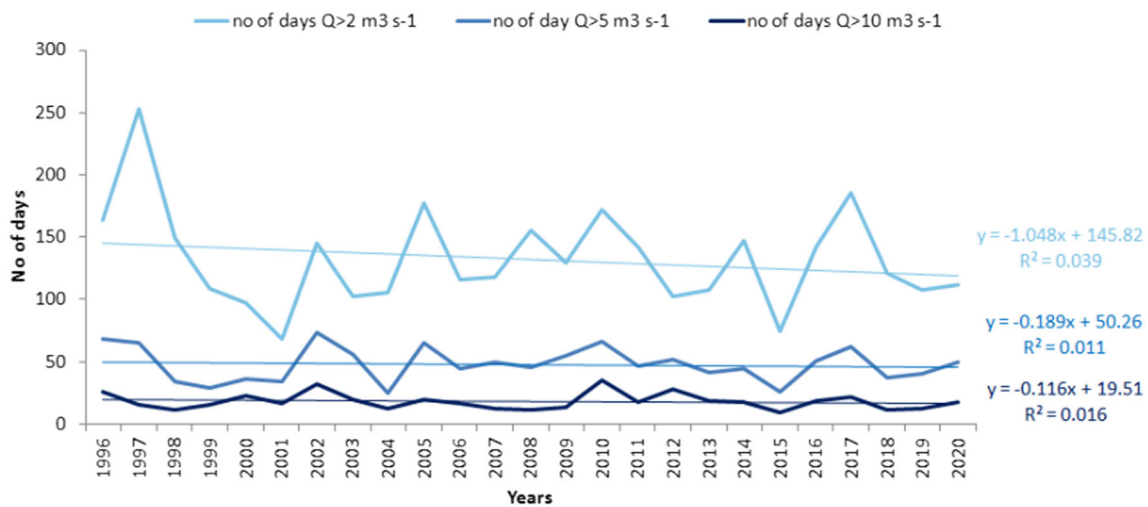
Fig. 7 Number of days with average inflow to the Klimkówka reservoir above 2.0, 5.0 and 10.0 m^3.s^{-1} with linear trends of their changes over the years

meeting the above criteria were 132, 48 and 18 days, respectively. In each case, a decreasing (statistically insignificant) trend in event frequency in the multiannual period was identified, indicating an increase in the number of days annually with flow values that do not compensate for the water loss associated with maintaining the guaranteed outflow. The excess runoff, i.e., exceeding the guaranteed value, was 255.8 mm on average, with the annual sums ranging from 138.5 mm (1999) to 562.0 mm (2010) (Fig. 6).

4.2 The scale of droughts and floods phenomena in the reservoir catchment

Based on the adopted criteria, seasonal threshold values of the discharge for hydrological droughts and floods were calculated (Table 3). The annual average number of days with hydrological droughts (both for total and severe drought) in the Ropa catchment above the reservoir is lower than that in each of the separately examined catchments (Table 9). The highest number of days with total and severe droughts was recorded in the Przysłup catchment, while the lowest was recorded in the Zdynia catchment. In terms of seasonal trends, droughts most often occurred in the August–October period, except for the Przysłup catchment, where severe droughts occurred most often in the May–July period. In the period 1996–2020, the number of days with a low discharge did not show a trend in any of the distinguished catchments, however, several years showed periods of increases and decreases in drought duration during the year. The study of outflow from the entire upper Ropa catchment showed an increase in the number of days with a low flow; this trend was statistically insignificant (p = 0.08), however, this value is nonetheless

Table 9 Annual average duration of hydrological droughts (in days)

Period	Total drought				Severe drought		
	Przysłup	Zdynia	Ropa	Upper Ropa	Przysłup	Zdynia	Ropa
Nov–Jan	28.2	27.4	27.6	26.9	5.0	4.7	4.6
Feb–Apr	27.0	26.4	26.3	26.0	5.2	4.6	4.4
May–Jul	28.5	27.4	29.2	26.6	6.6	4.9	6.0
Aug–Oct	31.6	29.0	29.8	27.0	4.8	5.9	5.0
Year	115.3	110.4	112.9	106.5	21.7	20.1	19.9

Fig. 8 Number of days in the year with simultaneous low flow in the studied catchments
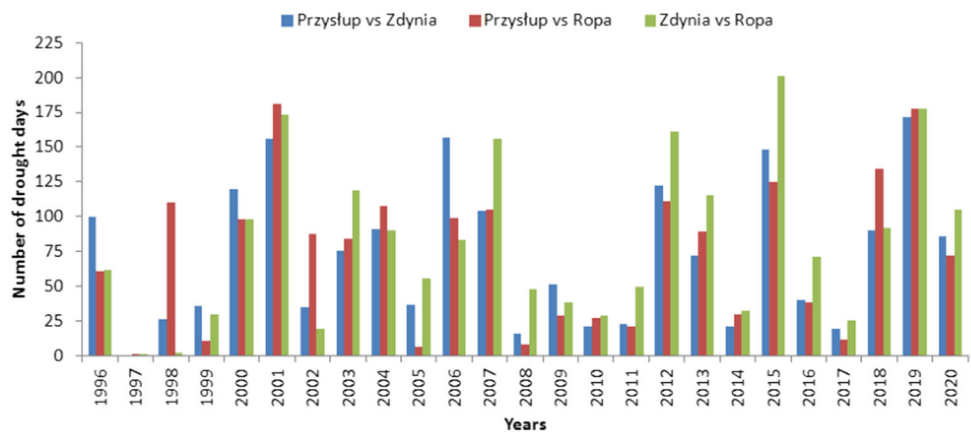
close to the threshold of a statistically significant trend (i.e. $p < 0.05$).

The simultaneous occurrence of droughts in the studied catchments was also examined in this study (Fig. 8). In the analysed multi-year period, the highest number of days with simultaneous occurrence of low-flow values was recorded in the Zdynia and Ropa channels (2013 days), the most of which occurred in 2015 (201 days) (Fig. 8). The number of days with 'common' occurrence of low flow in Przysłup and Zdynia, as well as the Przysłup and Ropa channels, was lower, amounting to 1816 and 1,805 days, respectively. The probable cause of the longest 'common' occurrence of low flows in the catchment areas of the Zdynia and Ropa basins is a similar share of forest in the land cover of both areas (84.1% of the Zdynia catchment area and 87.5% of the Ropa basin), while in the Przysłup catchment, the share of this form of land cover increases to 93.2%. Geological diversity can also have an impact, affecting aquifer flow and surface water recharge because water flows faster through cracked sandstone than through shale massifs and with much less water absorption. The average annual deficit in the runoff from the studied catchments during droughts was as follows: 15.3 mm in the Przysłup catchment, 13.6 mm in the Zdynia catchment, 17.8 mm in the Ropa catchment and 16.6 mm in the whole catchment area above the reservoir. The largest runoff deficit occurred in each of the analysed catchments in the February–April period, accounting for 41 to 47% of the annual deficit, while the smallest occurred in the August–October period (10%). This quarter also showed an increase in the runoff deficit in the Zdynia and Ropa catchments. Thus, the magnitude of the drought is not related to the frequency of low flows.

Using the quantile method, the duration of flood inflow to the reservoir was identified, which was around 18 days year^{-1}. This is comparable to the results of Bochenek (2020), who conducted a multivariate analysis of flooding in the Bystrzanka riverbed (the Ropa tributary downstream of the Klimkówka reservoir). However, variability of flood duration in each catchment area in a year and the differences between the catchments in a given year were large (Fig. 8).

The Cv values for the number of days with flooding in a year were as follows: 57% in the Przysłup riverbed, 47% in Zdynia, 39% in Ropa and 38% in the whole basin above the reservoir. The obtained results indicate that the response to water supply (rainfall or thaw), or lack thereof, in the Przysłup riverbed is fastest compared to other rivers. Additionally, the number of days with flooding in the Przysłup river in some years (2000, 2013 and 2014) is more than twice the duration of flooding in the other two rivers for the equivalent years (Fig. 9). The duration of high floods in the Przysłup riverbed increases even more in these years relative to the other rivers.

High floods, the average duration of which was about 4 days year^{-1} in each of the studied catchments, were
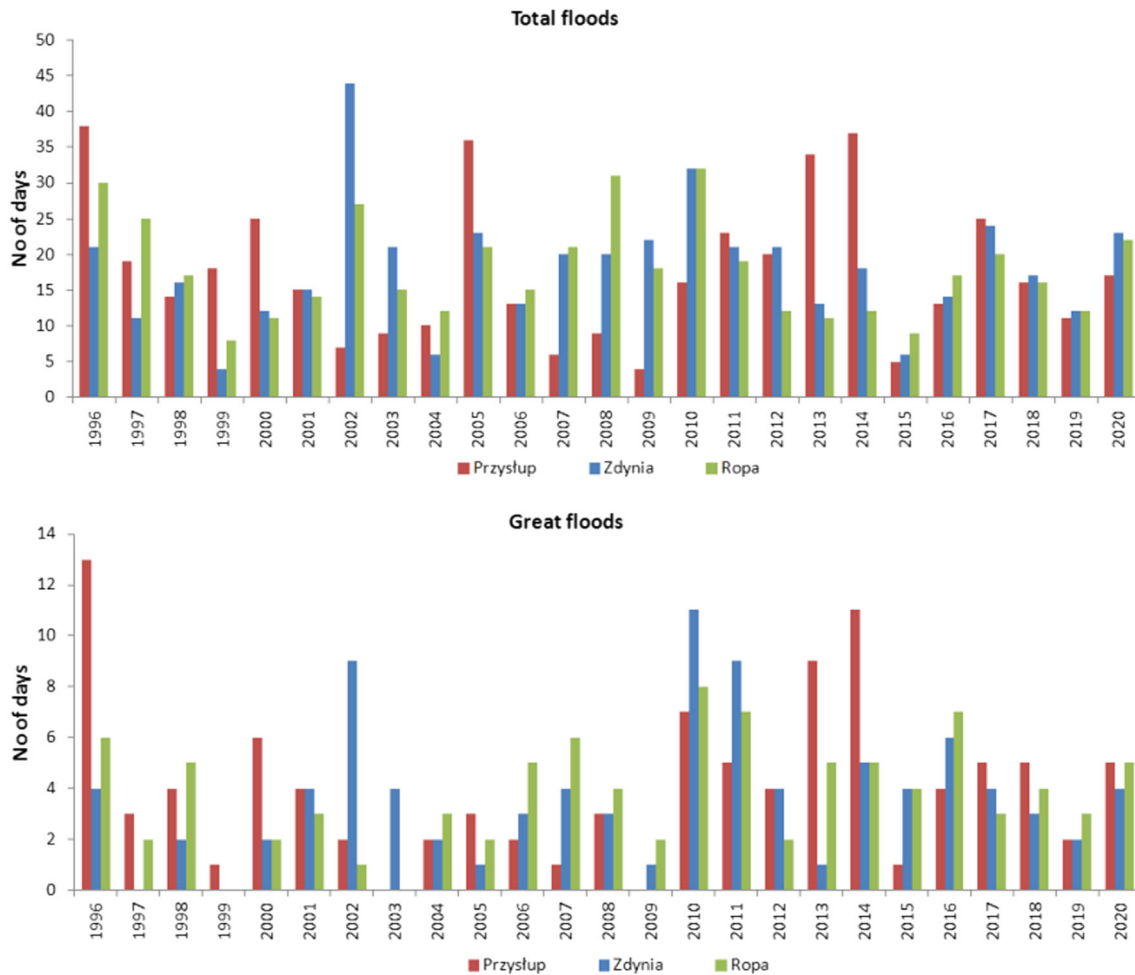
Fig. 9 Number of days with floods in the channels of the three streams

characterised by higher Cv values than the floods when treated as a whole, with values of 79% in Przysłupa, 47% in Zdynia, 57% in Ropa and 56% in the entire basin above the reservoir. The Cv differentiation between the watercourses, in this case, corresponds to the Cv of the duration of the flood flows.

The average annual excess runoff caused by the floods amounted to 120 mm in the Przysłup catchment, 87 mm in the Zdynia catchment area and 81 mm in the Ropa catchment area. The greatest excess runoff occurred in the May–July period, during which it accounted for 48 to 51% of the annual sum of excess runoff. The lowest share in the annual total of excess runoff (8–9%) was recorded in all catchments in the November–January period.

Due to the different variability ranges of the number of days with high and low water, the number of days in a year when these hydrological phenomena occurred was standardised (Fig. 10). Comparing the examined catchments, no regularities or similarities were identified over many years of standardised frequency values for the analysed events. As a rule, these values take opposite signs and the

number modulus values are similar. However, in some years, the same sign was recorded in both standardised values. Where both values are negative (e.g. 2007 and 2008 in Przysłup and 1999 and 2014 in Ropa), the role of average flows increases. When both are positive (e.g. in 2000 and 2012 in Przysłup and 2007 in Ropa), the role of average flows decreases. Despite the proximity of their locations, variability in the landscape features, geological structure and thus different infiltration and retention conditions as well as anthropopressure intensity lead to different conditions and functioning of the runoff channels supplying water to the Klimkówka reservoir.

4.3 Spatio-temporal prediction of the outflow from the reservoir catchment area

Based on the daily discharge values of the main tributaries to the reservoir, the 'historical' patterns of changes in hydrological processes and events were determined. A forecast of changes in the runoff from the three analysed catchments was then prepared for the decade periods
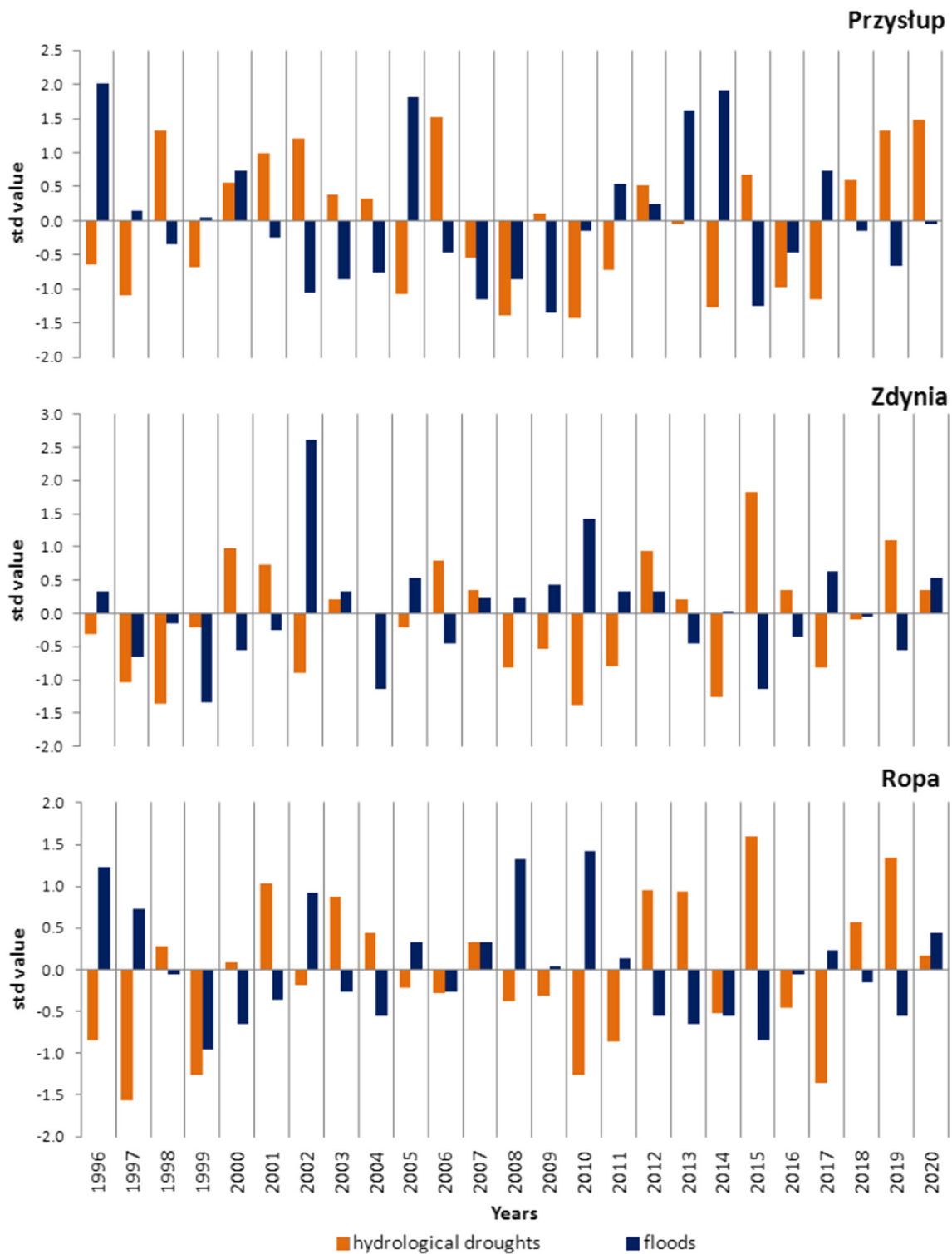
Fig. 10 Standardised values of the number of days with the occurrence of floods and hydrological droughts in the three streams

2021–2030 (1), 2031–2040 (2) and 2041–2050 (3), relative to changes during the reference decade 2011–2020 (0). The 30-year forecasting period is relatively short due to anticipated land cover changes, which have been particularly intense in the Western Carpathians over the past 30 years.

In the first stage of modelling, the simulation parameters were optimised in order to best match the observed (calculated based on measurements) and simulated average monthly flows. This fit was described using the assessment measures (see Table 10).

Table 10 Assessment of comparisons between the observed and simulated flows during the calibration (cal.) period (2004–2011) and validation (val.) period (2014–2020)

Catchment	R^2		NSE		PBIAS	
	cal	val	cal	val	cal	val
Przysłup	0.57***	0.38**	0.56**	0.32*	3.2****	5.6****
Zdynia	0.66****	0.61***	0.65**	0.59**	1.7****	10.9***
Ropa	0.67****	0.54***	0.66***	0.55**	8.3****	2.3****

*Not acceptable

**Acceptable

***Good

****Very good

The optimised parameters were introduced into the SWAT model to perform reliable simulations in the forecast periods. The conducted simulation showed the average monthly discharges in the forecasted decades, converted to a runoff layer.

The forecast changes in the runoff layer in the Zdynia, Ropa and whole upper Ropa catchments are similar (Fig. 11). The largest average increase in runoff layer during 2021–2030 will occur in July (approx. 4.5 mm), while the greatest decrease will occur in March (4–6 mm). The greatest runoff layer increases during 2031–2040 will occur in January and December (approx. 6 mm), whereas the largest decreases also occur in March and in May (4–7 mm). The highest runoff layer increase in 2041–2050 will also occur in January (4–4.5 mm), whereas the greatest decrease will occur in August and September (approx. 5–6 mm). Broadly, in the spring (March–May), during the entire research period (2021–2050), the outflow from the entire catchment area and all sub-catchments will be reduced. In addition, there will be a further reduction in the runoff due to thaw floods, observed based on historical flow data (Bochenek 2020). In the decade 2041–2050, runoff reduction will occur for most months (except for the winter season), and the greatest runoff reduction will occur in August and September.

In the decades 2021–2030 and 2031–2040, the annual runoff will increase in all the surveyed catchments (Table 11). However, in the decade 2041–2050, there will be a clear reduction in outflow compared to the 2011–2020 period. Compared to the previous decade (2031–2040), the reduction in annual runoff in this period across the entire catchment area will exceed 32 mm.

From the perspective of the functioning of an artificial reservoir during droughts, the drought presence (i.e. month) and the size of the negative hydrological balance of the reservoir (i.e. the difference between the inflow and guaranteed outflow) both play a decisive role. According to the forecast of the inflow to the reservoir prepared for a three-decade period (2021–2050) using the SWAT model, a negative balance will occur in April (1.107 million m³ on average) and in September (0.573 million m³ on average). In annual average terms, the sum of the 'shortage of outflow' in the next decades will be as follows: 2021–2030—1.096 million m³, 2031–2040—1.272 million m³ and 2041–2050—2.674 million m³. Thus, the volume of the inflow that does not compensate for the guaranteed outflow will increase.

5 Discussion

The hydrological cycle of rivers is expected to intensify as a result of climate change, which may lead to an increased risk of extreme hydrological events (floods and droughts) in the future (e.g. Kundzewicz 2019; Lane and Kay 2021). Mountainous areas are highly sensitive to the effects of climate change, including extreme short- and long-term weather phenomena (e.g., Bokwa et al. 2021; IPCC 2021). The amplified relative importance of extreme hydrological phenomena is also observed in the Carpathian Mountains (e.g. Spinoni et al. 2013; Bryndal et al. 2017; Didovets et al. 2019; Bokwa et al. 2021). Our analysis, which was carried out in relation to one of the Carpathian rivers in the upper Vistula basin, confirms the research hypothesis of intensifying above-average hydrological phenomena in the distribution of water flows in future decades. The investigation showed a greater increase in the duration and scarcity of water during hydrological droughts and, to a lesser extent, an increase in short but rapid (high-peak flow) high floods. According to Naz et al. (2018), the increased frequency of both high and low flows has the potential to make man-made reservoirs operating along rivers more vulnerable to future climatic conditions.

In studies of trends in changes in mountain river flows, a key issue is demonstrating that identified patterns are statistically significant to the commonly accepted level of p = 0.05. This fact was emphasised in other studies of Carpathian rivers (e.g. Stachy 1972; Soja 2002; Bochenek 2020). Soja (2002) claims that, in the case of long series of measurements, achieving a statistically significant runoff

Fig. 11 Changes in the average monthly runoff layer in the forecast decades (1— 2021–2030, 2—2031–2040, 3— 2041–2050) in relation to the reference period 0—2011–2020 (in mm)
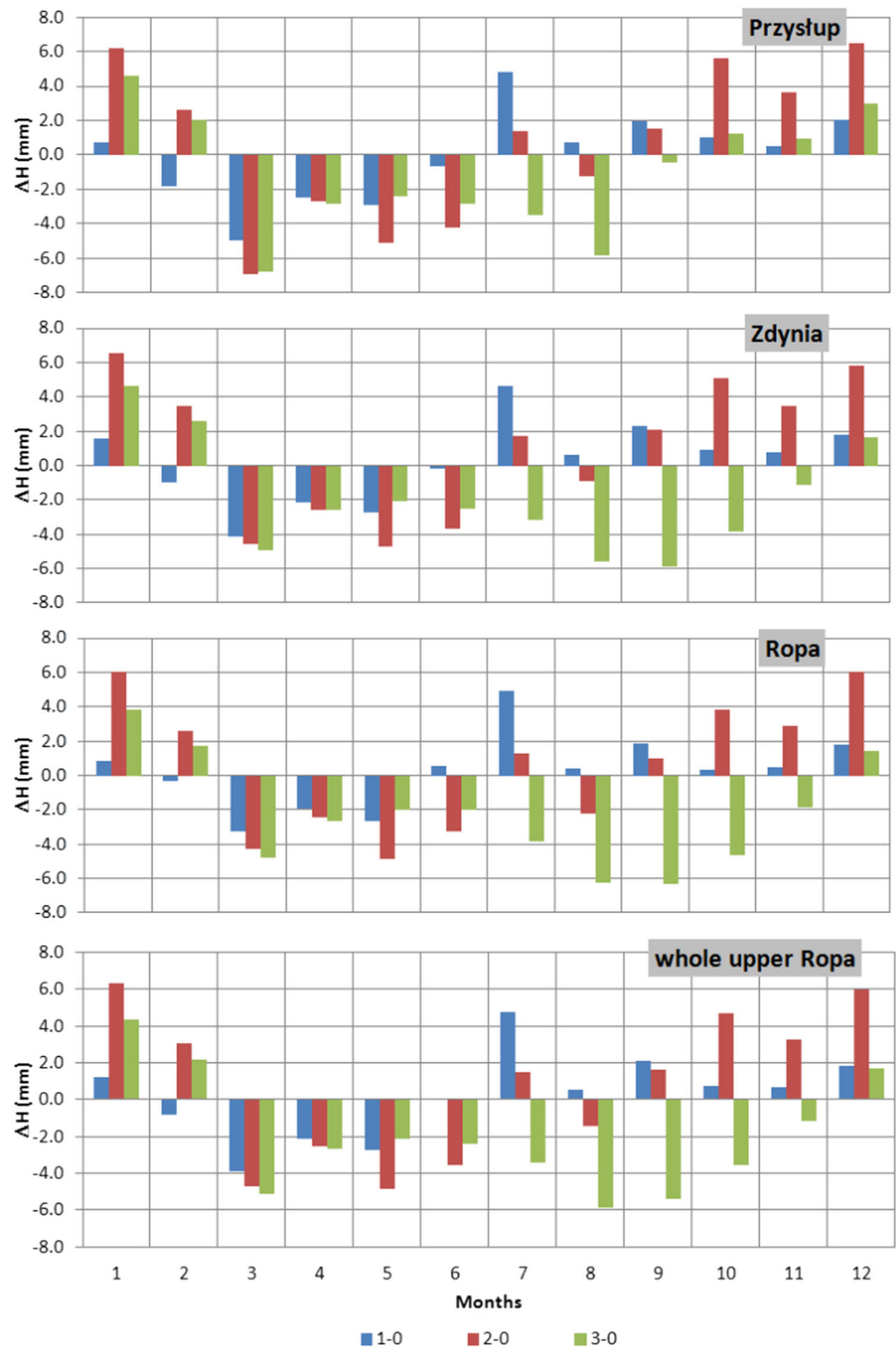
trend is extremely difficult due to the 'overlap' of the effects of human activities (e.g., changes in land cover and land use, buildings, water exploitation) on climatic factors (rainfall, evaporation). The assumption of a significance level of $p = 0.10$ would increase the number of statistically significant relationships and trends for several decades-old

data sequences identified in hydrological analyses of the Carpathian rivers.

The smaller Carpathian catchments are particularly susceptible to extreme hydrological events (Bryndal et al. 2017); thus, careful management of water resources in mountain catchments is of considerable importance. For

Table 11 Changes in the average annual runoff in the forecast decades in relation to the reference period 2011–2020 (in mm)

Catchment	2021–2030	2031–2040	2041–2050
Przysłup	− 0.9	7.2	− 12.7
Zdynia	2.5	11.7	− 22.9
Ropa	3.0	6.6	− 27.4
upper Ropa	2.3	9.4	− 23.2

this reason, for many rivers or river systems, simulations are carried out to predict the temporal and spatial distribution of river flows, creating a so-called decision support system (DSS), which is particularly important in the context of improving the quality of management of retention reservoirs operating in river courses (Alemu et al. 2011). In DSS, SWAT modelling is often used to quantify some of the indicators that make up the multicriteria analysis matrix (e.g. Sulis et al. 2009). In the case of the Klimkówka reservoir on the Ropa River, a particularly severe shortage of inflow to the reservoir caused by hydrological low flows is forecast to occur in March and April, i.e. during the period of typically intense outflow of meltwater from the Carpathian catchment area. The reason for this change is the already observed decrease in snowfall and decreasing length of the snow cover deposition period, caused by a sharp increase in air temperature and field evaporation at the transition from winter to spring (Bochenek 2020). This decreasing outflow of meltwater is observed not only in the Western Carpathians but also throughout Poland (Piętka 2009).

The conclusions regarding the forecast changes in the sum of runoff observed in the Ropa catchment above the Klimkówka reservoir are confirmed by studies using the SWAT model in other locations. Long-term studies show a reduction in runoff due to climate change. In the Ugam River basin (southern Kazakhstan), an average flow decrease of 0.5 $m^3 s^{-1} year^{-1}$ in the period 2019–2048 was identified (Uzbekov et al. 2021). An even greater reduction in runoff by 2099 is forecast in the Andas river catchment area (a tributary of the Blue Nile), ranging from 48.8 to 95.6% (depending on the climate scenario) (Tarekegn et al. 2022). Similarly, in the Sulcis River catchment area (Sardinia, Italy), a 52% runoff reduction is projected between 2006 and 2021 (Pulighe et al. 2021). The runoff forecasts from the upper Ropa catchment for 2041–2050 show the greatest decline in the summer, unlike the Mediterranean Aspio catchment (southern Italy), where an outflow increase is forecast in the summer (Busico et al. 2020). This is confirmed by the diversification of the directions and sizes of seasonal outflow changes on a global scale. In this study, climate scenarios and the SWAT

model were also used to indicate periods of excess and shortage of inflow to the retention reservoirs. Using a similar approach, Momiyama et al. (2020) compared two 20-year periods of water inflow to the Sagami reservoir (Japan), indicating the months of key drought (February and April) and flood risk (June and July). The presented outflow forecasts for the upper Ropa basin do not indicate such a drastic reduction in outflow in the next 30 years; however, the presented forecasts in this work are based on the less restrictive RCP 4.5 scenario. The RCP 4.5 scenario is a stabilisation scenario, which means the radiative forcing level stabilises at 4.5 $W{\cdot}m^{-2}$ before 2100 by employing a range of technologies and strategies to reduce greenhouse gas emissions (Climate Model: Temperature Change (RCP 4.5)–2006–2100). Given the activities undertaken within the European Commission, aimed at the use of renewable energy sources and the reduction of pollutants emitted into the atmosphere, it is more likely that the assumptions of this climate scenario will be met.

6 Conclusions

1. During the functioning of the Klimkówka artificial dam reservoir, an increase in the significance of low-flow outflow was identified, manifested by an increase in the duration of low flows and outflow deficits throughout the year in the Ropa basin, situated above the reservoir. The number of dry months ($< 75\%$ of the average total) in terms of rainfall and runoff is increasing, while the number of wet months ($> 125\%$ of the average total) in terms of runoff is not changing.

2. The three main tributaries feeding the reservoir (Przysłup, Zdynia and Ropa) are characterised by different low flow and flood trajectories in the following years, despite their proximity. This situation is influenced by the diversity of the environmental characteristics of each of these catchments: surface, relief and land cover.

3. Comparing the examined catchments, no similarities were found in the long-term course of the standardised values of low flow and flood frequency.

4. The prepared forecasts indicate an increase in the annual runoff from the analysed catchments in the decades 2021–2030 and 2031–2040, with a marked decrease in the decade 2041–2050.

5. For most months, changes in upcoming decades will exhibit different signs and magnitudes. Only in December, for the entire period 2021–2050, will outflow increase, whereas in May it will systematically decrease.

6. The SWAT model makes it possible to determine the average outflow changes for months, without

indicating the size and course of changes in individual years of the analysed decade. Nonetheless, the information obtained is valuable for predictive purposes, allowing the services responsible for water management to have improved awareness of the possibility of shortages or excess water supply to dam reservoirs.

Declarations

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