Eur. Phys. J. Spec. Top. (2023) 232:209–215
https://doi.org/10.1140/epjs/s11734-022-00689-1

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

Dam-induced changes in river flow dynamics revealed by RQA

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Received 27 June 2022 / Accepted 27 September 2022 / Published online 12 October 2022

Abstract The impact of dam construction on the river environment has been widely studied from various perspectives (e.g. biochemical, hydrological, ecological, geomorphological). To obtain new information, recurrence quantification analysis (RQA) is used to analyze the dynamics of mountain river flow and its changes caused by the construction of dam reservoirs with different parameters and functions. The analysis focuses on daily river flow for time periods before and after the construction of selected reservoirs in the Polish Carpathians. RQA shows that the reservoirs in question significantly changed the dynamics of the river flow in terms of the two considered complexity measures, indicating an increase in the regularity, autocorrelation and laminarity of the river flow dynamics for the river section below the reservoirs. Interestingly, the results suggest that the large complex of two reservoirs (Czorsztyn–Sromowce Wyżne) has a weaker impact on the dynamics of the river flow below the dam than the smaller Dobczyce reservoir; this may indicate an important role of the balancing reservoir (Sromowce Wyżne) in mitigating the changes taking place in the affected river system.

1 Introduction

Water runoff in the river bed is the result of many hydrometeorological, geomorphological and biochemical processes taking place in the river catchment. The flow dynamics, non-linear and complex, reflects the direct and indirect interactions between precipitation, surface runoff, infiltration, underground flow, evapotranspiration and other processes, and the conditions in the catchment: its topography, soil type and saturation, land cover, air humidity, etc. The river catchment is therefore a natural non-linear dynamical system [1, 2] in which one of the most important variables of this system is the river flow.

Among the various anthropogenic activities affecting rivers (river channel engineering, e.g. dredging, straightening, diking; water extraction, industrial and domestic effluents), dam construction appears to have a significant impact on the river environment. Dams' reservoirs built on rivers cause the loss of the ecological integrity of rivers, modify a river's flow regime and natural thermal conditions suitable for native aquatic biota, change the sediment load, water quality, energy patterns and water temperature dynamics, and cause the weakening of synchronization between air and water temperatures in the downstream river section. Observed changes may persist for tens of kilometers downstream [3–7].

The aim of the study was to analyze the dynamics of mountain river flow and its changes caused by the construction of dam reservoirs with different parameters and functions to obtain a more complete picture of possible dam-induced impacts. The study area is located in the Polish Carpathians; two medium-sized mountain rivers (132 and 247 km in length, respectively) were selected for analysis: (1) Raba River with the Dobczyce Reservoir (DR), and (2) Dunajec River with a large complex of two reservoirs Czorsztyn–Sromowce Wyżne (CSW). Changes in the daily river flow dynamics were studied using a suitable diagnostic tool–recurrence plots (RP) [8], and recurrence quantification analysis (RQA) [9–12].

This paper is structured as follows: in Sect. 2, a description of the study area and data sets used is given along with a motivation for their selection. This is followed by the description of the employed methods in Sect. 3. The results of the conducted analysis

Trends in Recurrence Analysis of Dynamical Systems. Guest editors: Norbert Marwan, Charles Webber Jr., Andrzej Rysak.

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are reported and discussed in Sect. 4. Finally, the main conclusions are pointed out in Sect. 5.

2 Study area and data

The study was carried out on two Carpathian rivers in the upper Vistula Basin, southern Poland, within the 49° 10′–50° 10′ N and 19° 50′–21° 00′ E coordinates (Fig. 1). A big reservoir (DR) on the Raba River, and a large complex of two reservoirs (CSW) on the Dunajec River were selected for analysis because of their differing parameters (e.g., capacity, depth) and functions (flood control, water supply, electricity production, the maintained minimum outflow). About the same time (between 1986 and 1997), they started operating on rivers with different flow regimes resulting from the climatic and physiographic conditions in individual catchments. The Raba River originates in the Gorce Mountains; its catchment is underlain by sedimentary rocks, mainly sandstone, shale, and marl. The highest peaks in the Gorce Mountains are characterized by a cool climate, with an average annual air temperature below 4 °C and precipitation totals of 1200 mm per year. In the lower lying parts of the Raba catchment the climate is temperate; the average annual temperature is between 6 and 8 °C, while annual precipitation totals reach 800 mm [13]. The Dunajec River originates in the Tatra Mountains. From the springs of the Dunajec to the CSW complex, the drainage basin is underlain by highly permeable carbonate rocks, poorly permeable sandstones and shales, and impermeable crystalline and metamorphic rocks [14], while mean annual air temperature ranges between − 4 and 5 °C, and precipitation totals range between 800 and 1900 mm yr^{-1} [13]. The relatively high runoff coefficient of 0.61 in Czorsztyn [15] is due to the mountainous terrain with steep slopes, which is conductive to rapid runoff. The characteristics of the studied river catchments [16] and reservoirs [17] are outlined in Tables 1 and 2, respectively.

River discharge (flow rate) data at daily resolution for the hydrologic years 1971–2015 (November 1970–October 2015) were made available for research purposes by the Polish Institute of Meteorology and Water Management—the National Research Institute (IMWM–NRI). The data cover time periods before and after the construction of the studied reservoirs; they were divided into three 15-year periods: (1) 1971–1985 (pre-dam period), (2) 1986–2000 (transitional period), and (3) 2001–2015 (post-dam period). For the Raba River, measurements were made: (1) in Mszana Dolna and Stróża, approx. 40 and 19 km upstream of DR, resp.; (2) in Dobczyce, just below the dam; (3) in Gdów and Proszówki, approx. 12 and 40 km downstream of DR, respectively. The data for Dobczyce and Gdów are available for the years 1992–2015 and 1971–1985, respectively, while for Mszana Dolna, Stróża and Proszówki, the data cover the entire time period studied (Table 1). For the Dunajec River, measurements were made: (1) in Nowy Targ-Kowaniec, approx. 25 km upstream of CSW; (2) in Sromowce Wyżne, just below the dam; (3) in Krościenko, approx. 22 km downstream of CSW. For Nowy Targ-Kowaniec and Krościenko, the data cover the entire time period studied, while for Sromowce Wyżne, the data are available for the years 1971–1992 and 1995–2015 (Table 1). As the two missing years (1993–1994) fall into the less important transitional period (1986–2000), they were supplemented on the basis of the water gauge relationship with the Krościenko station to calculate the time-dependent RQA measures.

3 Methods

Changes in the daily river flow dynamics were studied using RPs and RQA, which allow for the study and quantification of a non-linear dynamic system on the basis of its recurrence structure [8–12]. A system's dynamics can be represented by a reconstruction of its phase space trajectory from a given time series $\{x_i\}$, using time delay embedding [18, 19]. RP is a two-dimensional representation of recurrences in a system's dynamics computed on the basis of its reconstructed trajectory, and is defined [8] as

$$R_{i,j} = H(\varepsilon - \|\boldsymbol{x}_i - \boldsymbol{x}_j\|), \boldsymbol{x}_i \in \mathbb{R}^m, i, j = 1 \ldots N, \quad (1)$$

where ε is the predefined threshold or recurrence criterion, $\|\cdot\|$ is the norm, N is the number of reconstructed points $\boldsymbol{x}_i$ of a trajectory, and $H(x)$ is the Heaviside function. In the study, the maximum norm was used together with the recurrence criterion ε = 1% of recurrence points [20] and without embedding. This will enable the comparison of results for different time series. To avoid serial correlation, the Theiler window [21] was set to 365 (= the number of days in the year). Of several RQA measures developed by [9–12], two measures of complexity were taken into account in this study: (1) the measure *determinism* (DET), defined as the fraction of the recurrence points forming diagonal lines of at least length l_{min}; and (2) the measure *laminarity* (LAM), which is the ratio of the recurrence points forming vertical lines of at least length v_{min} [9–12]. As a line structure, $l_{\min} = v_{\min} = 2$ was considered. Moreover, these two employed measures were calculated in a moving window of size w, shifted with a step of size s over the studied time series; yielding so-called time-dependent RQA measures [22]. The statistical significance of changes detected in a system's dynamics is calculated using a bootstrap-based approach providing confidence levels for the most important, line-based RQA measures [22]. As in [22], DET and LAM were used. For the proposed bootstrap approach, test statistics are constructed with B resamplings, and then the confidence intervals are derived on the basis of α-quantiles [22]. The RQA measures were obtained with the use of the CRP Toolbox for MATLAB [23, 24]. DET and LAM are two measures

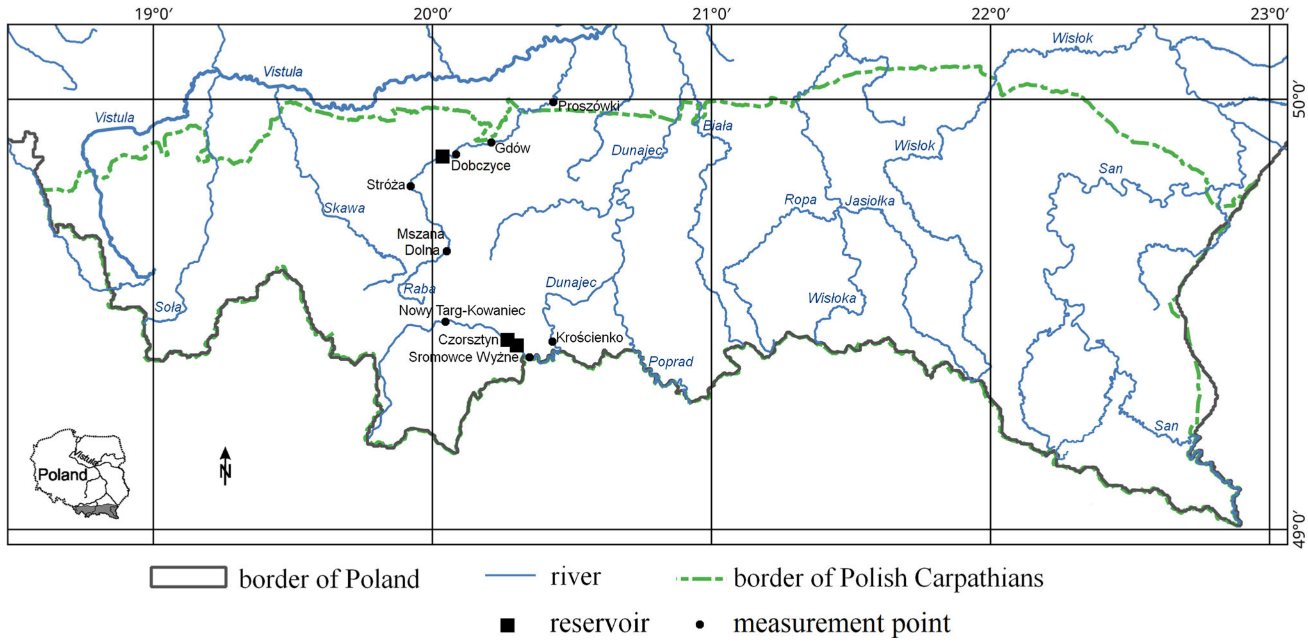

Fig. 1 Study area–the Polish Carpathians with dam reservoirs: Dobczyce on the Raba River and Czorsztyn–Sromowce Wyżne on the Dunajec River

Table 1 Physical and hydrologic characteristics of the river catchments studied [16]. The last column shows the time span of the studied data

River	Gauging station	River kilometer	Catchment area (km^2)	Median elevation (m a.s.l.)	Mean catchment slope (–)	Mean annual discharge (m^3s^{-1})	Time span of data studied
Raba	Mszana Dolna	102.1	158	598	0.028	2.5	1971–2015
Raba	Stróża	80.6	644	581	0.030	9.9	1971–2015
Raba	Dobczyce	61.9	768	Nd	Nd	9.8	1992–2015
Raba	Gdów	50.2	929	523	0.021	11.7	1971–1985
Raba	Proszówki	21.5	1470	423	0.016	19.0	1971–2015
Dunajec	Nowy Targ-Kowaniec	198.6	681	836	0.046	16.4	1971–2015
Dunajec	Sromowce Wyżne	171.4	1265	475	0.043	25.0	1971–1992, 1995–2015
Dunajec	Krościenko	149.2	1580	413	0.040	32.0	1971–2015

Nd not determined

Table 2 Physical characteristics of the studied reservoirs [17]

River	Reservoir	Capacity (million m^3)	Depth (m)	Area (km^2)	Year of construction	Functions[a]
Raba	Dobczyce	125.0	28	10.7	1986	F, S, E, M(5.3)
Dunajec	Czorsztyn	244.7	50	11.0	1997	F, S, E, M(9.0)
Dunajec	Sromowce Wyżne	7.5	8.5	0.9	1994	B, E

[a] *F* flood control, *S* water supply, *E* electricity production, *M(q)* the maintained minimum outflow q (m^3s^{-1}), *B* balancing reservoir

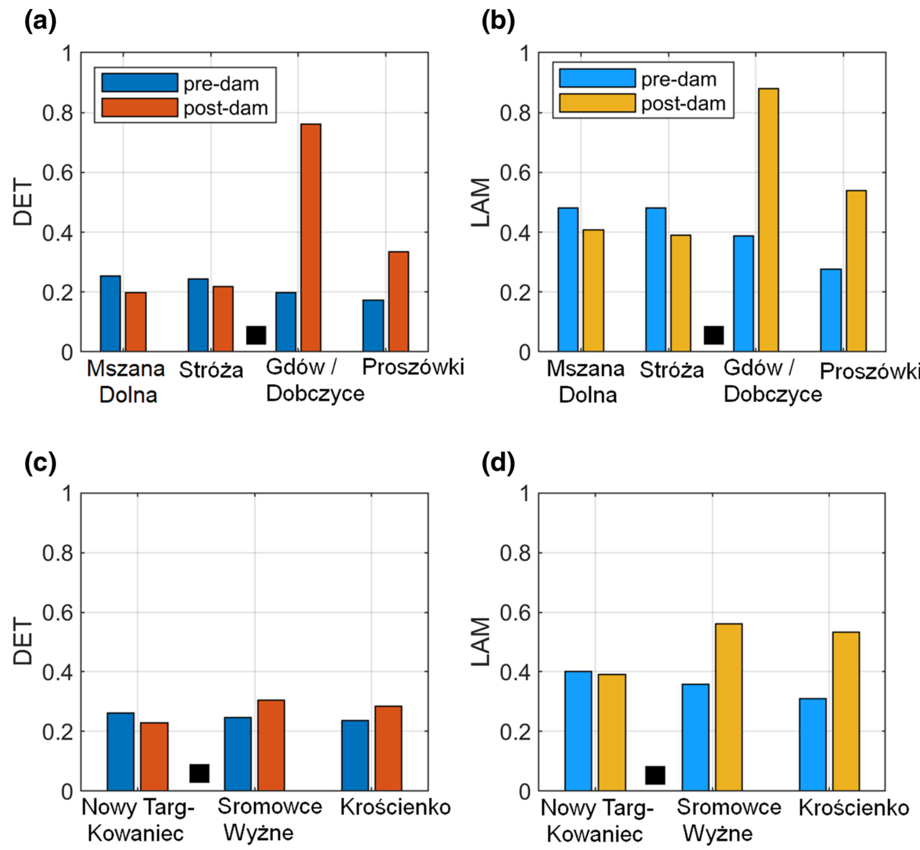

Fig. 2 Two complexity measures (DET, LAM) calculated for the river flow measured in the pre-dam and post-dam periods (1971–1985 and 2001–2015, resp.) above and below dam reservoirs (black square) on: (**a**, **b**) the Raba River; (**c**, **d**) the Dunajec River

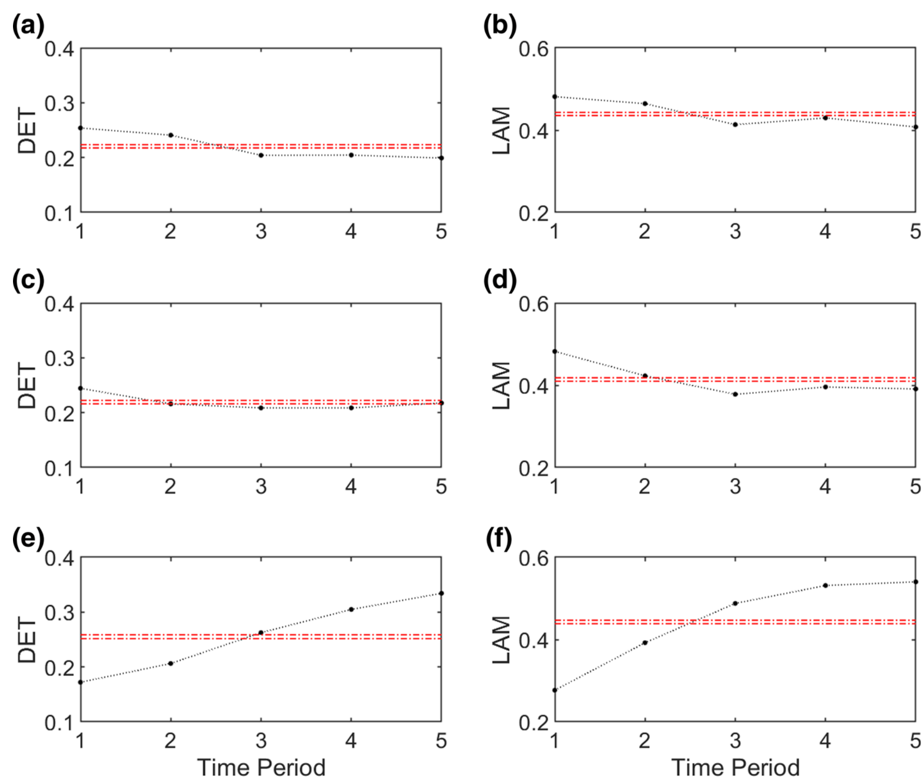

Fig. 3 Time-dependent RQA measures (DET, LAM) for the Raba River flow in: (**a**, **b**) Mszana Dolna; (**c**, **d**) Stróża (above the Dobczyce Reservoir); (**e**, **f**) Proszówki (below the Dobczyce Reservoir) over the period 1971–2015. Time periods: 1: 1971–1985 (pre-dam), 3: 1986–2000 (transitional), 5: 2001–2015 (post-dam). Parameters: *no embedding*, ε = 1% of recurrence points, Theiler window = 365, $l_{\min} = v_{\min} = 2$, moving window $w = 5478$, and $s = 2739$; 99% confidence levels are shown as dash-dotted lines

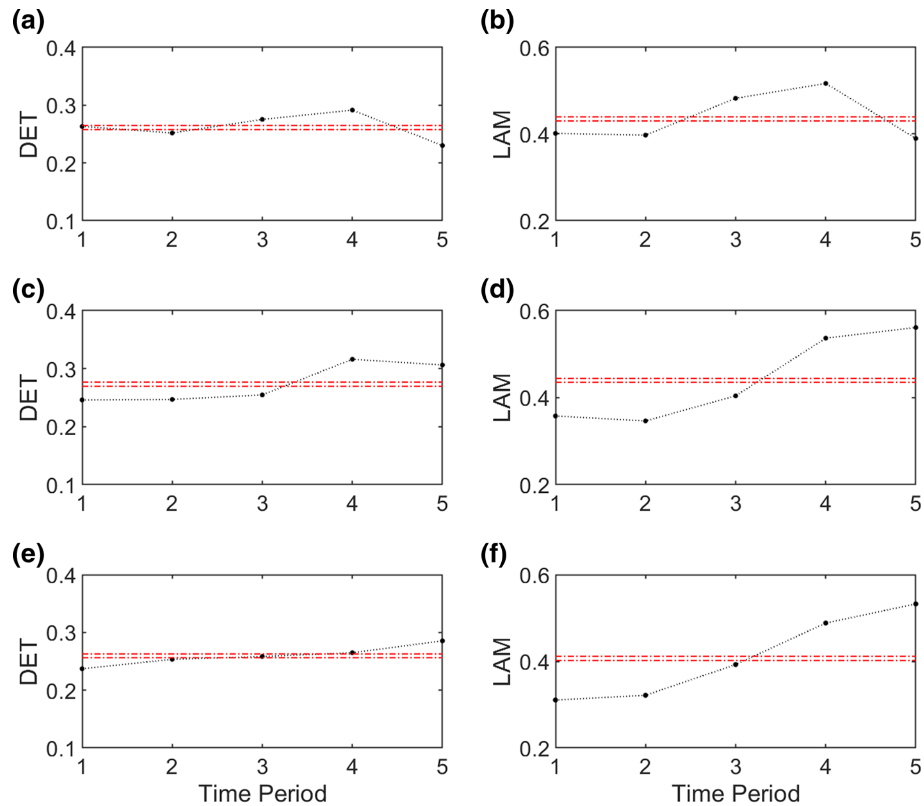

Fig. 4 Time-dependent RQA measures (DET, LAM) for the Dunajec River flow in: (**a**, **b**) Nowy Targ-Kowaniec (above the Czorsztyn–Sromowce Wyżne reservoir complex); (**c**, **d**) Sromowce Wyżne; (**e**, **f**) Krościenko (below the Czorsztyn–Sromowce Wyżne reservoir complex) over the period 1971–2015. Time periods: 1: 1971–1985 (pre-dam), 3: 1986–2000 (transitional), 5: 2001–2015 (post-dam). Parameters: *no embedding*, $\varepsilon = 1\%$ of recurrence points, Theiler window = 365, $l_{\min} = v_{\min} = 2$, moving window $w = 5478$, and $s = 2739$; 99% confidence levels are shown as dash-dotted lines

that provide insight into different aspects of river flow dynamics. The DET can be related to the predictability of the local river flow, while the LAM reports the probability that the river flow values for the next time instant (next day for daily flow) will not change or will change very slowly; this, in turn, may be partly related to the persistence of river flows.

4 Results and discussion

Figure 2 shows two measures of complexity, DET and LAM, calculated for the daily discharge of the Raba and Dunajec rivers in the pre-dam and post-dam periods. In the pre-dam period, DET and LAM tend to decrease along the river length in the studied river sections (approx. 80 km of the Raba and 50 km of the Dunajec). In the post-dam period, this tendency is not visible: DET and LAM are slightly smaller upstream from DR (in Mszana Dolna and Stróża) for the post-dam period compared to the pre-dam period; a significant increase in DET and LAM below DR (in Gdów/Dobczyce and Proszówki) can be observed in the post-dam period compared to the pre-dam period (Fig. 2a, b). Also for the Dunajec River (Fig. 2c, d) below the dam (in Sromowce Wyżne and Krościenko), a clear increase in LAM and a slight increase in DET can be observed in the post-dam period compared to the pre-dam period, while a slight decrease in DET and LAM is observed above the dam (in Nowy Targ-Kowaniec).

Interestingly, in the post-dam period, DET and LAM in Dobczyce (just below the dam) are exceptionally high (0.770 and 0.886, resp.), while in Sromowce Wyżne (just below the CSW complex), they are clearly lower (0.307 and 0.546, resp.). This may suggest that the CSW complex has a weaker impact on the dynamics of the river flow below the dam than the smaller Dobczyce Reservoir; this may also indicate an important role of the balancing reservoir (Sromowce Wyżne) in mitigating dam-induced changes in the Dunajec river.

To study the time-dependent behavior of the time series in question, the time-dependent RQA measures DET and LAM were computed. A moving window was applied to each data series of length N ($N = 16{,}434 = 45$ yr) independently, with size $w = 5478$ (15 yr) and step $s = 2739$ (7.5 yr). A bootstrap approach was employed [22] using $B = 1000$ resamplings, and the 99% confidence level computed (taking into account both the upper and lower confidence level). In Gdów/Dobczyce, the data (Table 1) do not cover the entire period (45 years) considered for time-dependent RQA measures, so these data are not used in further analysis.

The resultant plots for the Raba and Dunajec rivers are shown in Figs. 3 and 4, respectively. As can be seen in Fig. 3, DET and LAM show approximately the same change direction (a slight decrease) in the studied period (1971–2015) in Mszana Dolna and Stróża (that is, above DR), while the opposite direction of change (a significant, gradual increase) in DET and LAM is visible in Proszówki (below DR). In Proszówki (Fig. 3e, f), the first two values of DET and LAM are significantly low (1st and 2nd point on each graph) and the next three values are significantly high (3rd, 4th, and 5th point), so the change from low to high values is first observed in the 1986–2000 transitional period, coinciding with the construction of DR (in 1986). For the Dunajec (Fig. 4), DET and LAM in Nowy Targ-Kowaniec (i.e. above CSW) are approximately at the same level in the pre-dam and post-dam period (1st and 5th point), while a significant increase in LAM is observed in Sromowce Wyżne and Krościenko (below CSW) after the construction of the CSW complex (in 1997; 4th and 5th point on each graph relates to the years 1986–2000 + 7.5-yr shift and 2001–2015, resp.). In the post-dam period, the increase in DET is also significant in Sromowce Wyżne, but less visible in Krościenko. For the Dunajec during the transitional period (3rd point on each graph) covering 15 years, no significant changes in DET and LAM below the dam are visible, as this period covers only the first three years after the CSW complex was built. In other words, while the data can be expected to provide information on changes in DET and LAM since 1998, changes in 3 years are likely to be less pronounced when combined with 12 years.

An increase in DET for the river discharge most likely indicates an increase in the regularity and autocorrelation [22] of the flow dynamics of the Raba and Dunajec rivers. This is largely in line with the fact that the operation of the retention reservoir is driven by deterministic (repetitive) control instructions, hence each reservoir can be considered a highly deterministic element in the river system. In the light of the obtained results, it would be worth considering how to modify the existing instructions controlling the operation of retention reservoirs so that the natural regularity and autocorrelation of the river flow dynamics would not undergo significant changes.

Moreover, the obtained results suggest that in general, independent of the dams, the regularity and autocorrelation of the natural river flow dynamics tend to decrease along the river length, i.e. with the increase of the catchment area, at least in the studied sections of the mountain rivers. It would be worth checking if this trend continues along the entire length of the mountain river, but the most common problem is the availability of good quality data from multiple gauges simultaneously from a sufficiently long period before the construction of dams.

As flow regulations by dams may reduce native species abundance and favor nonnative species that may displace native species adapted to more variable flows and heterogeneous habitat conditions [25], dam management would also take into account the dynamic aspects of the water released to minimize human interference with the natural flow of the river.

5 Conclusions

On the basis of RPs and RQA, the conducted analyses indicate that:

(1) The flow dynamics in the Raba River downstream from the Dobczyce Reservoir has significantly changed in the post-dam period (2001–2015) compared to the pre-dam period (1971–1985). An increase in the two considered complexity measures (DET, LAM) was observed for the flow dynamics at least 40 km below the Dobczyce Reservoir, which was not accompanied by similar changes in the river flow dynamics at a similar distance above the Dobczyce Reservoir.

(2) The observed changes in the flow dynamics in the Dunajec River after the construction of the Czorsztyn–Sromowce Wyżne reservoir complex are less visible, especially for DET. However, a significant increase in LAM was identified in the river flow dynamics at least 22 km below the CSW complex.

(3) Interestingly, the results suggest that the large complex of the two reservoirs (Czorsztyn–Sromowce Wyżne) has a weaker impact on the dynamics of the river flow below the dam than the smaller Dobczyce Reservoir; this may indicate an important role of the balancing reservoir (Sromowce Wyżne) in mitigating the changes taking place in the affected river system.

(4) The increase in the RQA measures (DET, LAM) points to an increase in regularity, predictability, and laminarity of the river flow dynamics for the river section below the studied reservoirs.

Acknowledgements This work was supported by the Polish Ministry of Education and Science (R&D funding). The author has no relevant financial or non-financial interests to disclose.

Data availability statement The data that support the findings of this study are available from the Polish Institute of Meteorology and Water Management—the National

Research Institute (IMWM–NRI). Restrictions apply to the availability of these data, which were used under license for this study. Data are available at https://danepubliczne.imgw.pl/ with the permission of IMWM–NRI.

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