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Directions and Extent of Flows Changes in Warta River Basin (Poland) in the Context of the Efficiency of Run-of-River Hydropower Plants and the Perspectives for Their Future Development

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Abstract: This paper presents changes in the flow of 14 rivers located in the Warta River basin, recorded from 1951 to 2020. The Warta is the third-longest river in Poland. Unfortunately, the Warta River catchment area is one of the most water-scarce regions. It hosts about 150 hydropower plants with a capacity of up to 5 kW. The catchment areas of the 14 smaller rivers selected for the study differ in location, size, land cover structure and geological structure. The paper is the first study of this type with respect to both the number of analyzed catchments, the length of the sampling series and the number of analyzed flow characteristics in this part of Europe. The analysis of changes in the river flows was performed with reference to low minimum, mean and maximum monthly, seasonal and annual flows. Particular attention was paid to 1, 3, 7, 30 and 90-day low flows and durations of the flows between Q50 and Q90%. In addition, the duration of flows between Q50 and Q90% were analysed. Analysis of the direction and extent of particular flow types was performed by multitemporal analysis using the Mann–Kendall (MK) and Sen (S) tests. The analysis of multiannual flow sequences from the years 1951–2020 showed that the changes varied over the time periods and catchments. The most significant changes occurred in the low flows, while the least significant changes occurred in the high flows. From the point of view of the operation of the hydropower sector, these changes may be unfavourable and result in a reduction in the efficiency of run-of-river hydropower plants. It was established that local factors play a dominant role in the shaping of river flows in both positive and negative terms, for the efficiency of the hydropower plants.

Keywords: multitemporal trend analysis; hydropower; climate change; anthropogenic pressure

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1. Introduction

Climate change is considered one of the main factors that will significantly impact the functioning of many sectors of national economies, including the energy sector [1,2]. The hydropower sector, which plays a crucial role in the energy transition of the European energy system [3], is particularly vulnerable to the impacts of climate change [4,5]. One of the probable effects of climate change in Europe is the shift in hydrological regimes [6,7]. Climate change can affect hydropower production by modifying total discharge and their seasonal variability [8]. Unstable hydrological conditions can reduce the energy production of hydropower plants [1,9]. Long-term droughts covering large regions or even continents are particularly dangerous for the hydropower sector [10]. In recent years, the most severe droughts considered the most extreme droughts in Europe occurred in 2003 and 2015 [11]. Looking forward, droughts in many parts of Europe will be more severe and persistent due to climate change [12].

In the future, more extreme droughts could have a significant impact on the availability of water for different sectors of national economies [13]. The study conducted by van Vliet et al. [10] indicates reduced potential for hydropower generation under hydrological drought worldwide. The countries of Southern and Southeastern Europe will be the most vulnerable to drought.

In contrast, in eastern Poland and parts of Portugal, an increase in both flood and drought frequency is expected [14]. Additionally, Trnka et al. [15] point out an increase in drought frequency, duration and severity in Central Europe, which is a direct consequence of climate change. Arnell [16] indicates that the significant changes in the flow regime occur in broad parts of Eastern Europe. Stahl et al. [17] indicate positive trends of annual runoff in western and northern Europe and negative trends in southern and eastern Europe based on the ensemble mean. In the last two decades, Poland has also experienced more extreme droughts and floods as a result of climate change [18].

Studies by Hamududu and Killingtveit [19] show that climate change will not lead to significant changes in global hydropower generation. However, the consequences of climate change in individual countries and regions can be significant, both positive and negative [19]. There will be wide variation in the consequences of climate change in relatively close geographic regions [20]. The studies indicate that hydropower potential is expected to decrease for most European regions except the north [21]. However, Tobin et al. [22] show that the hydropower generation potential can increase in western, northern and eastern Europe while decreasing in Southern Europe. Lehner et al. [23] ascertain that hydropower potential can generally decline in Europe by 7% by 2070. However, on a regional scale, Scandinavia may experience an increase (+30%) and Southern Europe a decrease in hydropower potential (−20 to −50%). This was confirmed by Teotónio et al. [24], who estimate that the hydropower generation in Portugal may decline by 41% in 2050. Chernet et al. [25] suggest that climate change will cause a rise in annual discharges in Norway, resulting in an increase in energy generation of up to 20%. In Switzerland, on the other hand, higher winter run-off has a positive effect on energy production. From an annual perspective, average and wet years increase inflows and thus energy production, while dry years become drier, resulting in the opposite effect [26]. Simulation results show that the most significant shifts in hydrological regimes occur in the regions where snowfall becomes less important due to higher temperatures caused by climate change. As a result, a large part of Eastern Europe will see an increase in winter run-off and a spring flow decrease [16]. At the same time, Rottler et al. [27] show that run-off will increase in winter and spring, while discharge will decrease in summer and at the beginning of autumn. Stahl et al. [28] indicate negative flow trends in the southern and eastern regions and positive trends in other parts of Europe. In most catchment areas, positive trends are observed during the winter months. In contrast, low flows decrease in most regions with the lowest mean monthly flow in summer. Other studies show that low flows in Central and Eastern Europe will not change significantly [29]. In Poland, Adynkiewicz-Piragas and Miszuk [30] show a high regional risk of decreasing water resources and hydropower production. Piniewski et al. [31,32] indicate that due to an increase in precipitation and air temperature in the future, there will be a significant increase in flows during winter. However, Romanowicz et al. [33] point to the absence of such tendencies in the upper Vistula River catchment area (southern Poland).

Schneider et al. [7] show that, besides climate change, other anthropogenic factors may severely alter natural flow patterns on large regional scales. In addition to climate change, Berghuijs et al. [34] indicate that groundwater abstraction has an impact on modifying flow regimes. Especially for Eastern Europe, the increased water consumption for economic development is also a significant factor affecting river regimes [14]. Increases in water consumption may even be of the same magnitude as the projected impact of climate change [35]. Meanwhile, according to Cammalleri et al. [36], the projected increases in water demand may play a more critical role in the future than climate change in continental subregions of Europe. In the dry Mediterranean climate, projections indicate that flows are probably lower in all months of the year. In addition, changes will intensify due to water abstraction for irrigation purposes. However, also in the continental climate, where water is abstracted in large quantities for power generation and irrigation, climate change will probably cause further significant reductions in river flows from spring to autumn [7]. Furthermore, in the subregions of western, central and eastern Europe, predictions of drought reduction may be reversed due to intensive changes in water and land use [12]. In particular, water withdrawal for agriculture impacts the river regime and water availability to other sectors of the national economy [37]. During the last century, river hydrological regimes in the Baltic countries have been subjected to major changes. One of the likely factors responsible for this is climate change. The other factors are changes in land-use patterns, and the development of hydrotechnical buildings could have affected river regimes [38]. Especially in mining–industrial–urban areas, the greatest impact on the hydrological regime of rivers is observed. The consequence of this could even be the complete elimination of the impact of natural hydrometeorological conditions on river discharge [39].

This study aims to analyse the directions and extent of changes in river flow in the context of their impact on the performance of existing run-of-river hydropower plants and further prospects for the development of the hydropower sector in the Warta River catchment area. The main aim of the study is to answer the questions: (1) whether there were significant changes in mean, minimum and maximum flows in the analysed period; (2) whether the duration of low flows increased; (3) whether the duration of available flows decreased. To answer the research questions, daily flows were analysed for 14 rivers located in the Warta catchment area from 1951 to 2020.

2. Materials and Methods

2.1. Study Area

The study covered 14 rivers located in the catchment area of the Warta, the third-longest river in Poland (Figure 1). The catchment area of the Warta River is 54.5×10^3 km^2, which is about 17.5% of the area of Poland. The average annual rainfall in this catchment area ranges from over 650 mm in the southern part to less than 500 mm in the central part. In its northern part, rainfall is up to 600 mm. In about two-thirds of the catchment area, the average annual precipitation is around 550 mm. The mean run-off of the Warta River catchment ranges from 2 to 10 dm^{3}s^{-1}·km^{-2}. The highest run-off occurs in the southern part (about 10 dm^{3}s^{-1}·km^{-2}) near the river headwaters and in the northern part near the headwaters of the Gwda and Drawa rivers (9 dm^{3}s^{-1}·km^{-2}). On the other hand, the lowest run-off occurs in the central part of the catchment (3 dm^{3}s^{-1}·km^{-2}). In some places, the mean run-off is as low as 2 dm^{3}s^{-1}·km^{-2}, the lowest value recorded in Poland.

To present a complete situation of changes in flow in the Warta River catchment, 14 catchments located within the catchment area were selected for detailed analysis. The surface areas of the analysed catchments range from 243 km^2 (NK) to 4725.67 km^2 (GP) (Table 1). The southernmost catchments are GG, ON, WR and NK. The DD and GP catchments are located in the north, and the FR, WP, MK and MG are in the middle part of the Warta catchment area. Essential characteristics of the study catchments in terms of landform, river network density and lake density index are presented in Table S1. In the whole catchment of the Warta River, there are about 150 hydropower plants, among which run-of-river plants with power below 5 MW are predominant. Due to hydrometeorological conditions in the Warta catchment area, the highest number of hydropower plants is located in its northern and southern parts and the lowest in the central one (Figure 1).

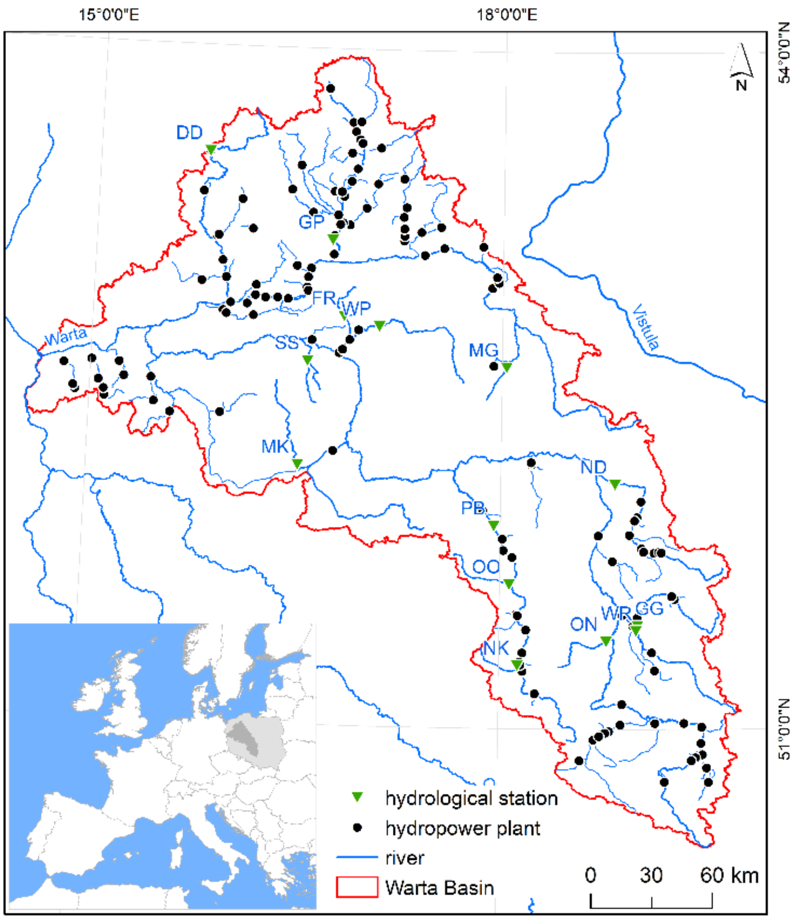

Figure 1. Study site location.

Table 1. Hydrological description.

No	River	Station	Abbreviation	Catchment Area	Location	
					Altitude	Longitude
1	Ner	Dąbie	ND	1727.21	52°05′05″ N	18°49′26″ E
2	Mała Noteć	Gębice	MG	217.75	52°36′02″ N	18°02′01″ E
3	Grabia	Grabno	GG	807.98	51°27′30″ N	18°59′07″ E
4	Widawka	Rogóźno	WR	1271.25	51°26′08″ N	18°58′27″ E
5	Niesób	Kuźnica Skakawska	NK	243.00	51°16′47″ N	18°07′54″ E
6	Prosna	Bogusław	PB	4282.38	51°53′54″ N	17°57′13″ E
7	Mogilnica	Konojad	MK	719.39	52°09′04″ N	16°31′56″ E
8	Sama	Szamotuły	SS	397.34	52°36′44″ N	16°34′53″ E
9	Drawa	Drawsko Pomorskie	DD	592.49	53°31′37″ N	15°48′39″ E
10	Oleśnica	Niechmirów	ON	595.77	51°23′17″ N	18°45′44″ E
11	Wełna	Pruśce	WP	1139.74	52°46′23″ N	17°05′54″ E
12	Gwda	Piła	GP	4725.67	53°09′05″ N	16°44′25″ E
13	Flinta	Ryczywół	FR	283.07	52°48′59″ N	16°50′22″ E
14	Ołobok	Ołobok	OO	444.68	51°38′22″ N	18°04′08″ E

2.2. Materials

The research material consisted of daily flows of 14 rivers located in the Warta River catchment area from 1951 to 2020 (Table 1, Figure 1). The data were provided by the Institute of Meteorology and Water Management—National Research Institute (IMGW-

PIB). All analyses were conducted for hydrological years, beginning on 1st November of the preceding year and lasting until 31 October of a given year. In the first preliminary step, the data completeness was checked. In two cases, FR and OO, data were incomplete in single years. For FR, data gaps concerned 2015 (no data for the entire year) and 2016, while for OO, the gaps concerned 2012. In both cases, the missing data were supplemented before proceeding to the next stage of analysis. For this purpose, data from nearby stream gauges were used; for FR, the data were supplied from the WP and for OO from the NK. Calculations were performed using artificial neural network (ANN) tools available in Statistica 13.1 package. A standard procedure was used in which a series of corresponding data was divided into a training sample (70%), a test sample (15%) and a validation sample (15%).

2.3. Methods

To provide a general representation of flow changes in the rivers selected for analysis, low, mean and high flow values were calculated for months, half-years and years. Low flows were then analysed in detail [40]. These characteristics are crucial from the point of view of the operating time of run-of-river hydropower plants and the quantity of energy produced. For this purpose, 1, 3, 7, 30 and 90 day minimum flows were determined according to the methodology applied [41,42]. Flow duration curves were developed for each river, from which flow values of 50 (Q50%), 70 (Q70%) and 90% (Q90%) were obtained (Figure 2). For example, low river flow (Q90%) is described as the percentile of daily streamflow that is exceeded 90% of the time. Searcy [43] indicated the flow available at 50 and 90% of the time (Q50 and Q90%) as flow standards for waterpower statistics. The Q90% measures the prime power, and the Q50% is an index of the power potential with storage, whereas Rugumayo and Ojeo [44] indicate that the 90% exceedance flow value can be used as one of the measures of groundwater contribution to stream flow. The ratio Q90/Q50 can be used to represent the proportion of stream flow from groundwater sources. Then, for each year, the number of days with flows below Q50 and Q90% and the duration of flows between Q50 and Q90%, respectively, were calculated.

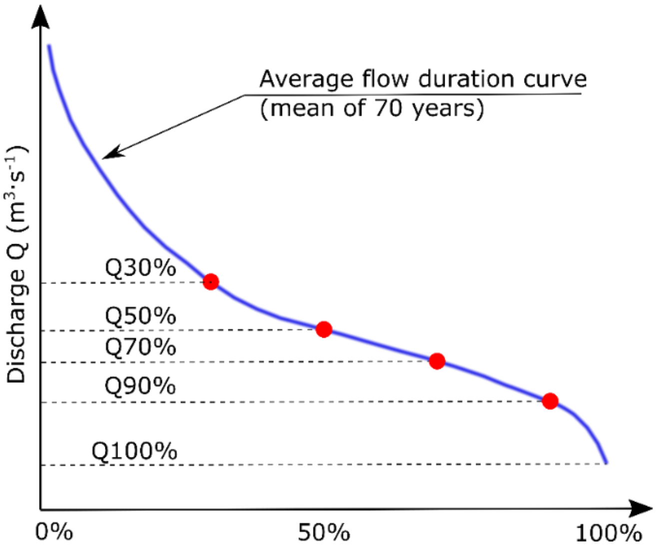

Figure 2. Flow duration curve.

A summary of all the indices used during the analysis is given in Table 2.

Table 2. Indicators of flow changes.

Parameter	Number of Parameters	Description
Monthly low, mean and high flows	36	NovL, DecL, JanL, FebL, MarL, AprL, MayL, JunL, JulL, AugL, SepL, OctL NovM, DecM, JanM, FebM, MarM, AprM, MayM, JunM, JulM, AugM, SepM, OctM NovH, DecH, JanH, FebH, MarH, AprH, MayH, JunH, JulH, AugH, SepH, OctH
Half-year minimum, mean and maximum flows	6	WHL, WHM, WHH SHL, SHM, SHH
Annual minimum, mean and maximum flows	3	YL, YM, YH
Annual 3 day, 7 day, 30 day and 90 day minima (low flow)	4	DL3, DL7, DL30, DL90
Q50, Q70 and Q90% exceedance flow value	4	TBQ30%, TBQ50%; TBQ70%, TBQ90%
Flow duration between Q50 and Q90%	1	TQ5090%
Total	54	

The table is a compilation of the analysis period and flow characteristics (periods: Y—year; WH—winter half-year; SH—summer half-year; months—Jan., Feb., Mar., Apr., May, Jun., Jul., Aug., Sep., Oct., Nov., Dec.; D—day) (flow characteristics: L—low flow (minimum), M—mean flow, H—high flow (maximum).

The Mann–Kendall (MK) test [45], was used to determine the direction of change in the flow characteristics shown in Table 2. In contrast, the extent of flow changes was determined using the non-parametric Sen test (S) [46]. In order to remove the autocorrelation from the series of data, the trend-free pre-whitening (TFPW) procedure was used [47]. The adopted procedure is the most frequently used when analysing hydrological data. This is because the method based on MK and S test is less sensitive to extreme values compared to the methods based on linear regression and Student's t-test. The wild binary segmentation (WBS) method developed by Fryzlewicz [48] was used to detect breakpoints in the series of analysed flow characteristics. In WBS, the exploration of change point was performed at random intervals as WBS allows several change points to be determined. Because the calculations with the WBS methods showed the occurrence of numerous breakpoints in the analysed indicators of flow changes within individual rivers and corresponding indicators within all rivers, multitemporal trend analysis was applied. Following McCabe and Wolock [49] and Tomas-Burguera et al. [50], the Mann–Kendall and Sen test statistics were calculated for every possible combination of start and end years in 1951–2020 for DL7, YM, TBQ50, TBQ90 and TQ5090%. This involved performing 1327 calculations for each flow indicator. A total of 92,890 calculations were performed for the five indicators and 14 rivers. Statistical analyses using MK, S, and WBS tests were performed at a significance level of 0.05. The critical value of Z statistic in MK test is -1.96 and 1.96. The *modifiedmk* package developed by Patakamuri and O'Brien [51] was used to analyse the direction and extent of changes using MK and S tests. For change-points calculations, the *wbs* package developed by Baranowski and Fryzlewicz [52] was used.

In the next step, cluster analysis (CA) was conducted to group rivers based on the extent and direction of flow changes. The cluster analysis was performed following Ward's method, and the square Euclidean distance was used as a distance measure. The division of rivers into groups and subgroups was achieved by taking the cut-off values of 66 and 25% from $D_{Link}{\cdot}D_{Link{\cdot}max}{\cdot}$,100% distance, respectively [53]. Finally, a principal component analysis was employed to identify land cover and landform factors related to changes in individual flow characteristics. Among the natural factors, the following parameters were considered: catchment area (A); drainage density (DD); mean slope (MS); mean elevation (ME); maximum elevation difference (MED); latitude (Lat); longitude (Lon); land use characteristics—urban fabric (UF); industrial, commercial and transport units (ICT); mine, dump and construction sites (MDC); artificial, non-agricultural vegetated areas (AnA); arable land (AL); permanent crops (PC); pastures (P); heterogeneous agricultural areas (HA); forests (F); scrub and/or herbaceous vegetation associations areas (AHV); open spaces with little or no vegetation (OS); wetlands (WE) and waters (WA). In addition, the location of the catchment area defined by longitude (Lon) and latitude (Lat) was considered. The landform parameters were determined based on a digital terrain model (DTM) with a resolution of 100 m. The DTM was developed based on airborne laser scanning (LIDAR) measurement data made available by the Head Office of Geodesy and Cartography in Poland. The land cover structure was determined based on the Corine Land Cover 2018 database provided by the Chief Inspectorate for Environmental Protection in Poland. Land cover categories distinguished at the second level of detail were used.

3. Results

A summary of characteristic flows of the analysed rivers is presented in Table 3. The highest mean flow was observed in the Gwda River in the Pila section (GP), about 26.85 $m^3 \cdot s^{-1}$. On the other hand, in the Mała Noteć, Niesób and Flinta, the mean flows between 1951 and 2020 were lower than 1.0 $m^3 \cdot s^{-1}$.

Table 3. Characteristic flows of the analysed rivers.

No	River (Abbr.)	MALF	MAMF	MAHF	Q30%	Q50%	Q70%	Q90%	MAMLF
1	Ner (ND)	0.410	9.86	86.0	10.50	7.55	5.56	3.40	2.46
2	Mała Noteć (MG)	0.003	0.59	7.47	0.70	0.45	0.29	0.13	0.15
3	Grabia (GG)	0.380	4.12	86.0	4.14	2.74	1.80	1.11	1.09
4	Widawka (WR)	0.670	8.22	104	9.04	7.28	5.81	3.80	4.13
5	Niesób (NK)	0.040	0.97	33.6	1.02	0.72	0.48	0.25	0.23
6	Prosna (PB)	0.960	15.59	230	16.50	11.10	7.36	4.52	3.88
7	Mogilnica (MK)	0.004	1.62	31.8	1.55	0.79	0.39	0.18	0.17
8	Sama (SS)	0.014	1.04	20.5	1.07	0.63	0.32	0.14	0.16
9	Drawa (DD)	0.378	4.04	18.8	4.70	3.47	2.54	1.59	1.59
10	Oleśnica (ON)	0.190	2.38	70	2.33	1.49	0.97	0.58	0.56
11	Wełna (WP)	0.028	3.31	36.9	3.60	2.25	1.34	0.66	0.77
12	Gwda (GP)	8.200	26.85	111	29.90	25.10	21.20	16.60	14.47
13	Flinta (FR)	0.001	0.65	7.28	0.70	0.41	0.23	0.09	0.10
14	Ołobok (OO)	0.006	1.57	33	1.56	0.92	0.54	0.28	0.25

MALF—multiannual low flow; MAMF—multiannual mean flow; MAHF—multiannual high flow; MAMLF—multiannual mean low flow.

Dividing the mean flow for the 1951–2020 period by the catchment surface area yielded the run-off rate for the study rivers. The highest run-off value was found for the Drawa River catchment at 6.8 $dm^3 \cdot s^{-1} \cdot km^{-2}$, while the lowest for the Flinta and Mogielnica catchments, i.e., 2.3 and 2.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$, respectively. Generally, the highest run-off occurred in the south and north parts of the Warta catchment area. Most often, the run-off value exceeded 5 $dm^3 \cdot s^{-1} \cdot km^{-2}$. In the catchments located in the middle part of the Warta River, the run-off values were up to 3 $dm^3 \cdot s^{-1} \cdot km^{-2}$. It should be noted that the northern and southern parts of the Warta River catchment area have the largest number of small hydropower plants.

The river flow changes from 1951 to 2020 expressed in terms of all indicators are shown in Table S2. On the other hand, to fully represent the changes in all rivers from 1951 to 2020, the results of the Z statistics are presented in Figure 3.

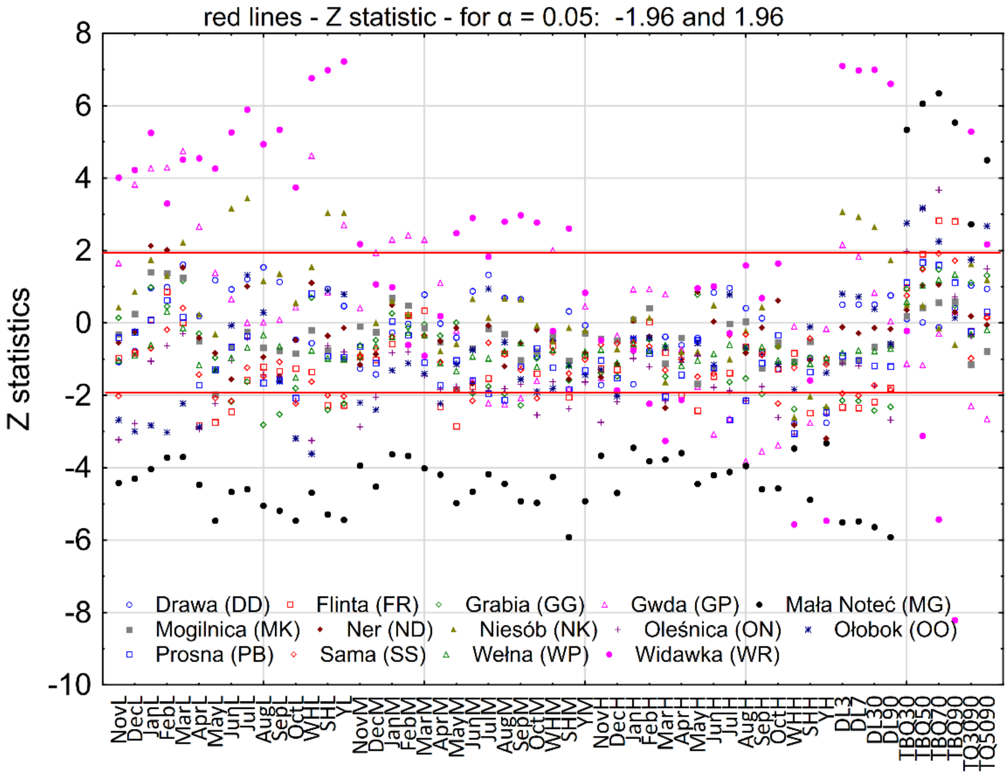

Figure 3. Z-statistic values for the analysed flow indices from 1951 to 2020.

Generally, significant differences were found for two of the analysed rivers. For the Widawka River (pink circle), there was an increase in low flows in all months and mean flows in the summer months. No change was observed for high flows. On the other hand, in the case of the Mała Noteć River, there was a decrease in low, mean and high flows. In general, the Z-statistic values for most flow change indices ranged within ±1.96, indicating that the changes are statistically insignificant at the 0.05 level.

The results indicate an increase in low flows between December and April for the Gwda River. Similar changes were also found in single months for the Ner and Niesób. For the rivers: Oleśnica, Ołobok, Flinta, Sama and Grabia, the low flow decreases were recorded in individual months. Considering the 3, 7 and 30 day minimum flows, their decreases were observed for the Mała Noteć, Grabia, Sama and Flinta, whereas their increases were noted for the Niesób and Widawka. No significant changes were observed in the yearly mean (YM) flows except for the Mała Noteć River. On the other hand, the decreases in the maximum flows from 1951 to 2020 were reported for the Widawka, Mała Noteć, Ner, Drawa, Prosna, Niesób and Oleśnica. Analysing the number of days with flows below Q90%, an increase in this number was found for the Flinta and Mała Noteć and a decrease for the Widawka River. For the number of days with flows below Q50%, there was an increase for the Mała Noteć, Ołobok and Oleśnica and a decrease for the Widawka River. Taking into account changes in the time of flow occurrence from Q90 to Q50%, it was observed that for the Gwda and Mała Noteć, there was a decrease, and for the Ołobok and Widawka there was an increase.

Considering all 55 flow indicators, the most changes occurred in the Mała Noteć (55 cases) and Widawka (36 cases). In contrast, the least changes occurred in the Wełna (zero cases), Mogilnica (one case), Drawa (two cases), Ner (five cases), Prosna (seven cases). The scattering of points on the graph indicates that the most significant changes occurred in the low flows and the least significant in the high flows. However, an apparent trend was noted towards a decrease in maximum flows. In the case of the Widawka River, the increase in flows is caused by water discharges from the dewatering of lignite opencast mines in Bełchatów [54]. In the case of the Mała Noteć River, the situation is more complicated. It may be connected partly with lowering of the groundwater level in connection with the dewatering of lignite opencast mines, as for other water bodies located within the range of the Konin lignite mine [55]. In the other catchments, the impact of climate change is modified by catchment properties and the overlapping impact of anthropogenic factors (flow regulation, reservoirs water management, water abstraction for irrigation). The changes described above are well illustrated by cluster analysis (Figure 4).

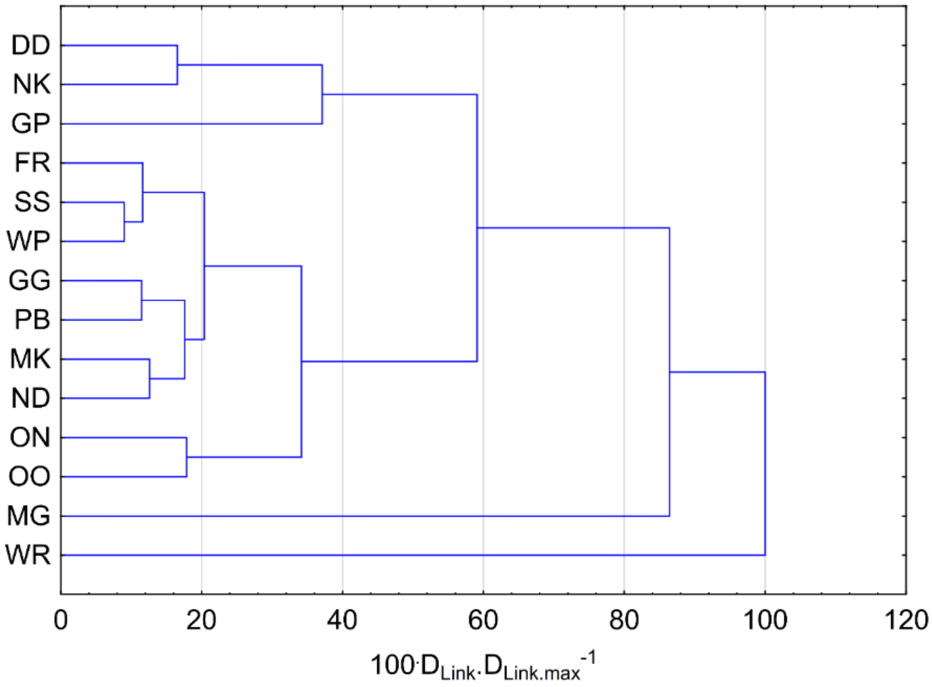

Figure 4. CA results based on indicators of flow changes for 1951–2020.

The Mała Noteć and Widawka evidently stand out in the whole cluster analysis. However, in relation to the remaining rivers, the analysis differentiates their regional division which is: (1) Drawa and Gwda; (2) Sama, Wełna and Flinta; (3) Grabia, Prosna, Ner, Oleśnica and Ołobok. Furthermore, local factors linked to anthropogenic pressures may further influence the flow changes in some catchments.

PCA allowed distinction of two principal components that explain, respectively, 52.8 and 26.3% of the internal structure of the data (Figure 5). The analysis shows that the increases in low flows occur in the catchments with higher mean slopes (MS), while the increases in high and mean flow values of semi-annual and annual flows from the second half of the year and from the whole year are related to the catchment location (Lat) and catchment area (A), as well as a greater proportion of scrub and/or herbaceous vegetation associations areas (AHV), open spaces with little or no vegetation (OS) and wetlands (WE). In contrast, an increase in the number of days with flows in the range from Q90 to Q50% occurred in the catchments with higher river network density.

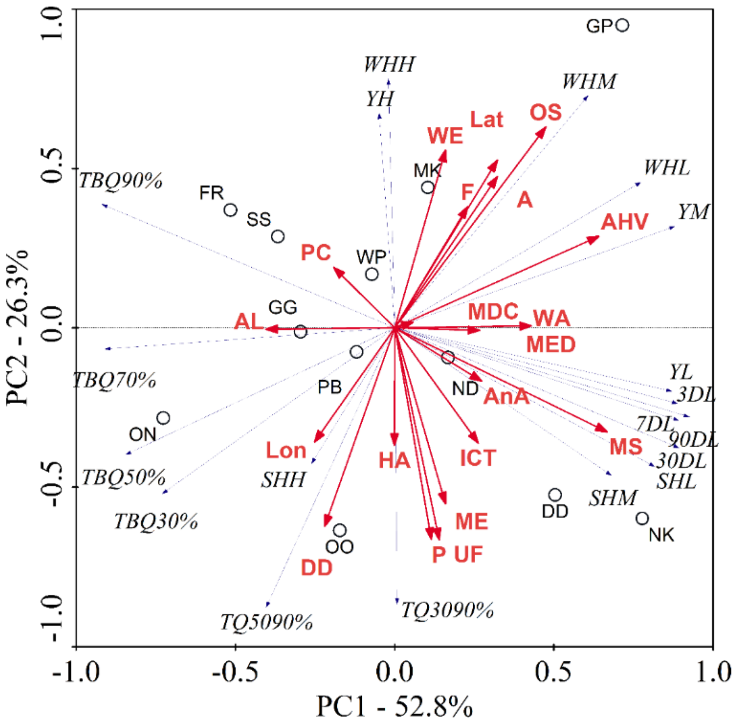

Figure 5. Results of principal component analysis. Catchment area (A); drainage density (DD); mean slope (MS); mean elevation (ME); maximum elevation difference (MED); longitude (Lon); latitude (Lat); land use characteristics—urban fabric (UF), industrial, commercial and transport units (ICT); mine, dump and construction sites (MDC); artificial, non-agricultural vegetated areas (AnA); arable land (AL); permanent crops (PC); pastures (P); heterogeneous agricultural areas (HA), forests (F); scrub and/or herbaceous vegetation associations areas (AHV); open spaces with little or no vegetation (OS); wetlands (WE) and waters (WA).

The analysis of the dataset across all parameters using the WBS method revealed the occurrence of 1 to 11 breakpoints. In addition, it should be noted that the occurrence of breakpoints differed between individual indicators of flow changes. This indicates the impact of local factors on the changes in individual features of the analysed catchment areas. Thus, it is difficult to make a uniform analysis of flow changes for all rivers and indicators for the same periods. Therefore, that multitemporal trend analysis was carried out for every possible combination of start and end years in the 1951–2020 period for DL7, YM, TBQ50, TBQ90 and TQ50–90% for characteristic flows of key importance for hydropower plants. For example, two rivers were selected to present the results: one located in the lowest run-off zone—Flinta—and the other located in the higher run-off zone—Gwda. The results for the other rivers are described in the Supplementary Materials (Figures S1–S5). The figures allowed a comprehensive analysis of the extent of changes that have taken place over the period examined both in terms of the directions and extent of changes in the flows of individual rivers. Multitemporal trend analysis of yearly mean (YM) flows showed great differentiation in both the direction and extent of changes in this parameter over the 1951–2020 period (Figures 6 and S1). In general, however, these values were not statistically significant. For the rivers Gwda and Flinta, in the period from 1970 to 2020, a tendency for the YM to decrease was observed (Figure 6a,b). The most significant changes in mean flows were noted for the Mała Noteć (downward tendency) and the Widawka (upward tendency). For all rivers except the Widawka, a downward trend was dominant (red). The most extensive changes in the mean flows occurred over the past 25 years (lower right corner of Figures 6 and S1).

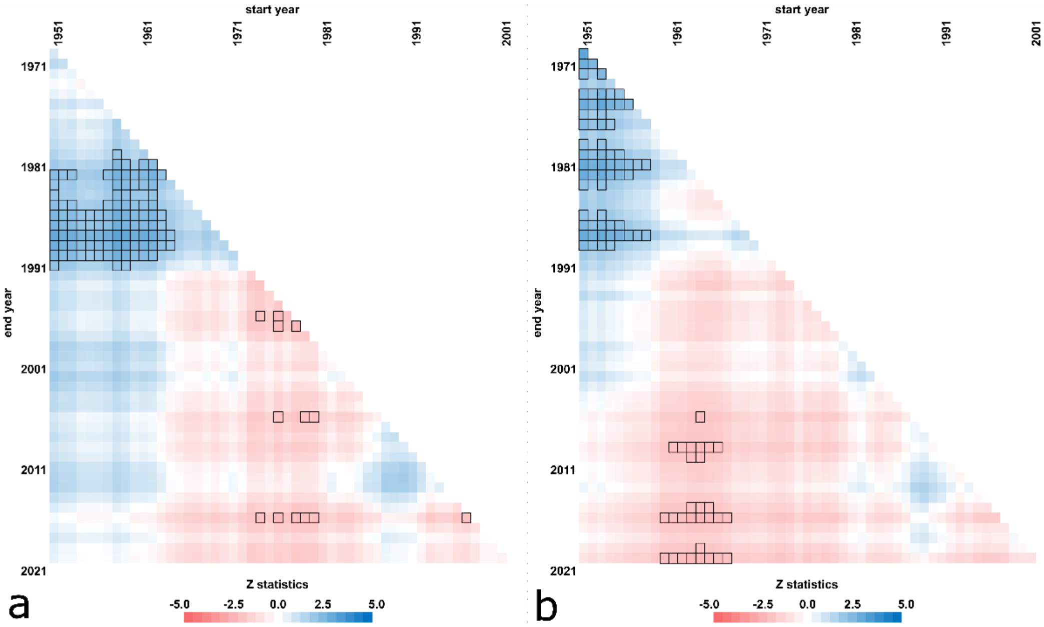

Figure 6. Multitemporal trend analysis of yearly mean flows (YM) for the Gwda (**a**) and Flinta (**b**) rivers (marked fields indicate statistically significant changes at the level 0.05).

Additionally, analysis of measurement sequences with the baseline from 1961 to 1986 for most rivers indicates a decrease in the mean flows, as of the rivers: Ner, Grabia, Prosna, Drawa, Wełna or even Widawka. The analysis revealed the regional character of changes in the mean flows. However, significant differences do not coincide in time for all rivers; their pattern and direction are similar for the rivers: Gwda (GP) and Drawa (DD); Mogilnica (MK), Sama (SS), Flinta (FR) and Wełna (WP) and Oleśnica (ON), Ołobok (OO), Prosna (PB), Grabia (GG) and Niesób (NK). This conclusion is confirmed by the cluster analysis performed on the basis of the results obtained from the multitemporal trend analysis (Figure 7).

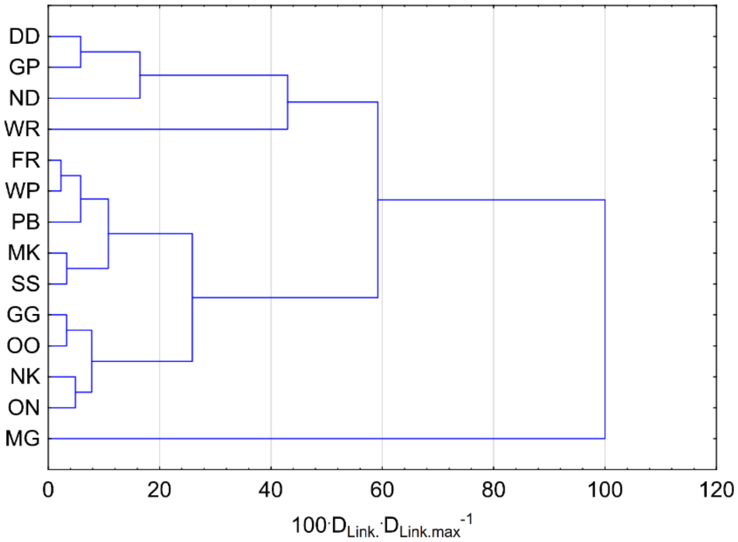

Figure 7. Results of CA based on the results of multitemporal trend analysis of yearly mean flows (YM) over the period 1951–2020.

Greater changes were noted for the parameter of 7 day minimum flows (DL7) (Figures 8 and S2). In particular, these flows were reduced in the rivers: Flinta, Ner, Mała Noteć, Grabia, Prosna, Drawa, Wełna and Ołobok. Similarly, a tendency for a decrease in the 7 day minimum flows dominated the overall picture of changes. For the Flinta River, a DL7 decrease occurred almost throughout the whole analysed period (Figure 8b). For the Gwda River, on the other hand, there was a tendency for a DL7 decrease since the early 1970s, but for different periods, these changes were statistically insignificant (Figure 8a). For the Mała Noteć River, which is located within the range of impact of lignite mines operating in central Poland, a tendency for a DL7 decrease dominated throughout the whole period of study. For the Widawka River, the situation was changing, there were periods of increased and decreased DL7. This observation may be related to the volume of water discharge from the dewatering of the Belchatow lignite opencast mine. For these two rivers, the impact of anthropogenic activity completely changes the effect of climatic factors. In general, the downward trend in both YM and DL7 may result in decreased performance and increased downtime in hydropower plants due to water shortages. The similarities of the analysed catchments in terms of changes in DL7 are presented in Figure 9.

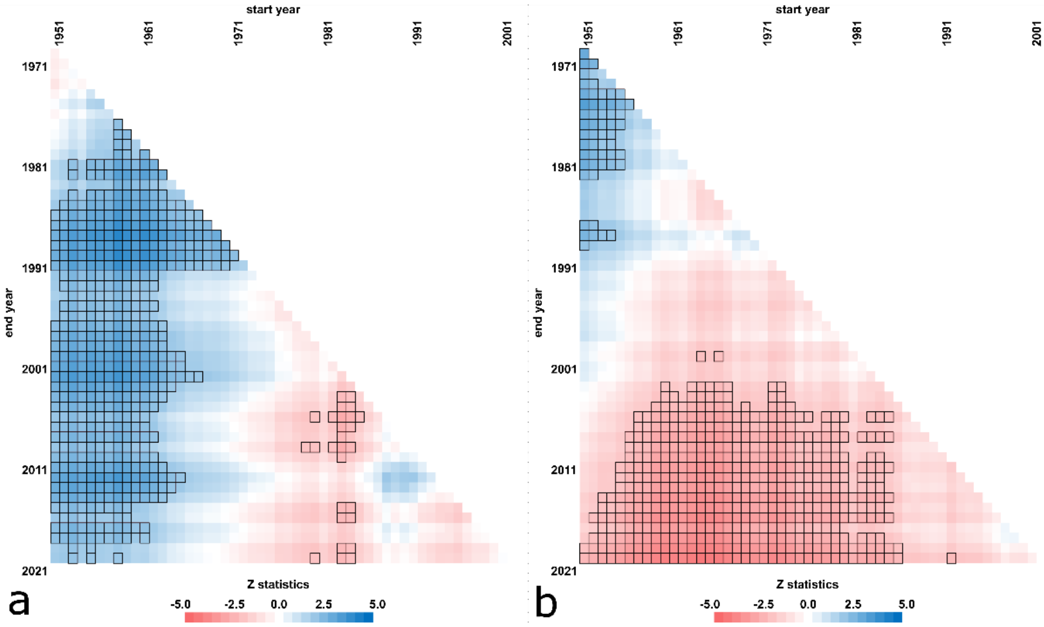

Figure 8. Multitemporal trend analysis of 7 day minimum flows (DL7) for the Gwda (**a**) and Flinta (**b**) rivers (marked fields indicate statistically significant changes at the level 0.05).

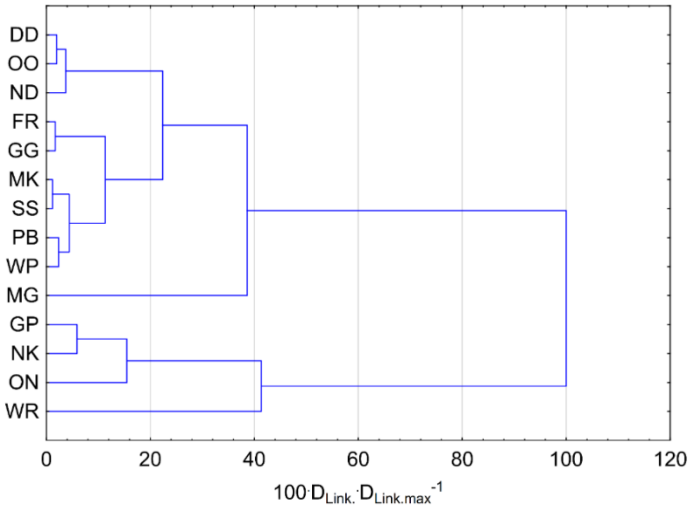

Figure 9. Results of CA based on the results of multitemporal trend analysis of 7 day minimum flows (DL7) over the period 1951–2020.

However, number of days with flows below Q50 and Q90% were analysed. The analysis of the number of days with flows below Q50%, from the multiannual period 1951–2020, shows that there is an upward trend for the majority the rivers (Figures 10 and S3). For each of the rivers studied, the nature of the changes in this respect is somewhat different. For the Flinta River (Figure 10b), since the early 1960s, the number of days with flows below Q50% showed an upward trend, indicating that the flows below the mean value were more frequent. A slightly different situation emerges for the Gwda River (Figure 10a). On the whole, the changes are not statistically significant; moreover, the tendency for increasing number of days with flows below Q50% was observed since the 1970s. Similarly as for YM and DL7, the changes in TBQ50% were clearly distinct for the Widawka and Mała Noteć rivers. For the remaining rivers, the regional nature of changes was noted. The analysis showed similarities between the rivers located in the south, in the central part of the catchment and in the north (Figure S3). It should be noted that the similarities were greater in the central and southern catchments in the studied area.

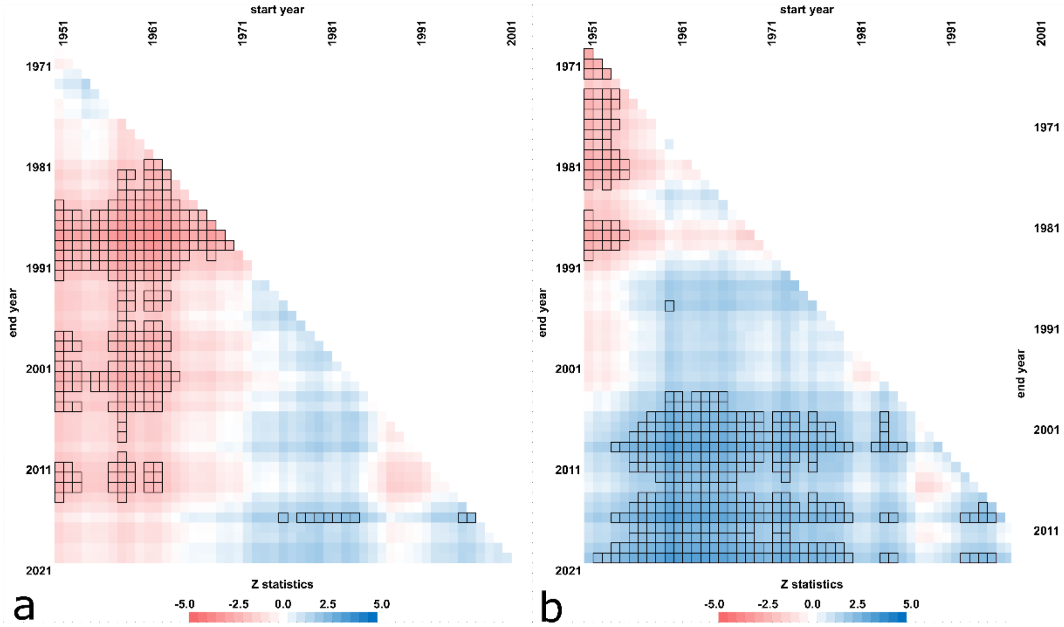

Figure 10. Multitemporal trend analysis of the time of flows below Q50% (TBQ50%) for the Gwda (**a**) and Flinta (**b**) rivers (marked fields indicate statistically significant changes at the level 0.05).

From the perspective of hydropower plant operation, low flows—particularly their duration—are especially important. The analysis of the duration of flows below Q90% showed that in the case of the Flinta, Ner and Mała Noteć rivers, there was an increase in the number of days with flows below Q90% (Figures 11 and S4). For the other rivers, the changes are less significant, generally statistically insignificant. It should be noted that over the past 25 years, for the majority of the rivers studied there was a tendency for an increase in the number of days with flows below Q90% (Figure S4).

However, when it comes to the duration of flows in the range from Q90 to Q50%, the situation varies greatly between the studied rivers (Figures 12 and S5).

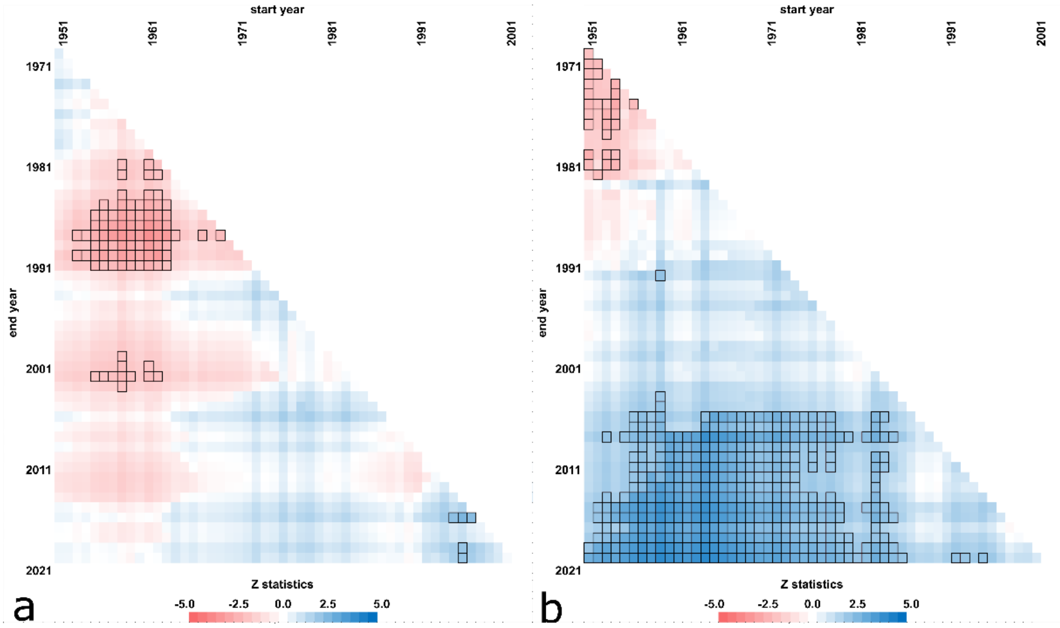

Figure 11. Multitemporal trend analysis of the time of flows below Q90% (TBQ90%) for the Gwda (**a**) and Flint (**b**) rivers (marked fields indicate statistically significant changes at the level 0.05).

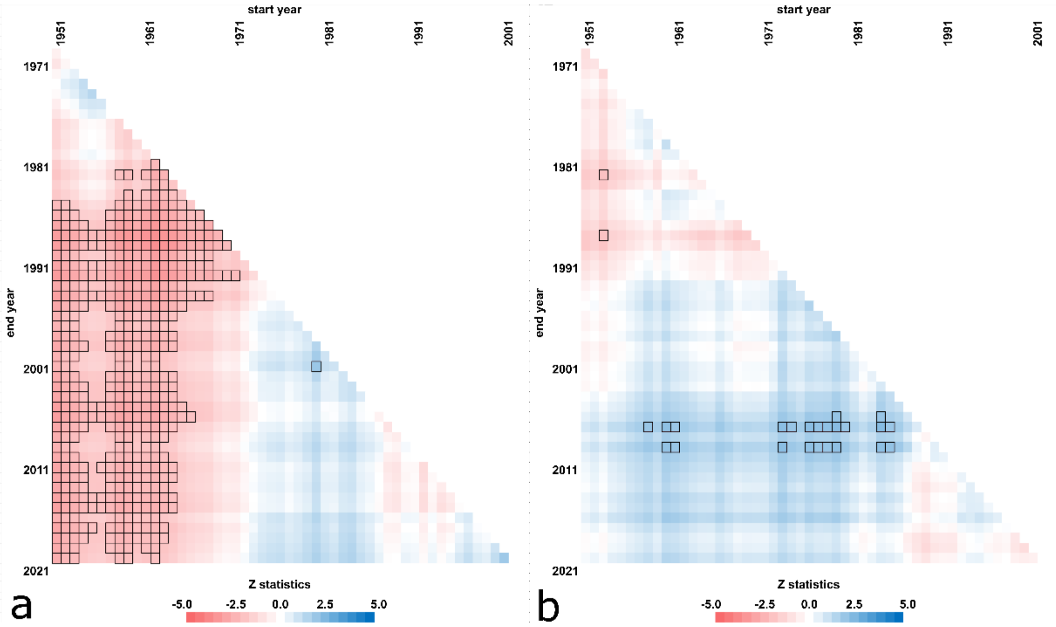

Figure 12. Multitemporal trend analysis of the time of flows between Q50 and Q90% (TQ5090%) for the Gwda (**a**) and Flinta (**b**) rivers (marked fields indicate statistically significant changes at the level 0.05).

For the Flinta River (Figure 12b), the changes are statistically insignificant throughout the whole period. Meanwhile, for the Gwda River, an analysis of measurement series from the years 1951 to 1971 shows that there was a tendency for the duration of these flows to become shorter (Figure 12a). This was usually due to an increase in the duration of flows of above Q50%. An increase in the duration of flows between Q90 and Q50% was the most pronounced for the Mała Noteć River (Figure S5b). However, these changes are not beneficial from the perspective of hydroelectric power production. For the majority of the rivers, the changes of TQ5090% were generally statistically insignificant (Figure S5).

The exceptions were the Ner, Widawka and Ołobok rivers, in which the changes were multidirectional and varied throughout the analysed period.

4. Discussion

This paper presents analysis of the changes in river flows in the central region of Poland, CE Europe, on the example of 14 catchments located in the Warta Basin. This part of CE Europe belongs to the most water scarce region. Moreover, it should be emphasized that Poland is in a phase of transformation of its energy system, which is presently mainly based on hard and brown coal. There is an interest in investing in energy systems based on renewable energy sources in Poland, including the hydropower sector, which is currently based on small run-of-river hydropower plants. The functioning of the hydropower sector depends, among other things, on the stability of river flows over the years. Moreover, long-term data series are used at the stage of investment planning, designing and operation. Stability of flows is also one of the key elements that affect the economic efficiency of an investment.

In this study, an in-depth analysis of flow conditions was carried out. The analysis revealed great diversity of changes in the character of flow within the analysed catchments. As this study shows, the potential impact of climate change on river flows, indicated in recent years, is of secondary importance. The impact of climate change on river flows is modified by natural factors, i.e., the physiographic conditions of the catchment, geological structure and, to a greater extent, by anthropogenic factors related to flow regulation, water management in retention reservoirs, water abstraction for irrigation and changes in land use. This study shows that in the period from December to March the climate factors have the dominant role. In the remaining period, the influence of climatic condition changes is modified by the catchment properties and the overlapping anthropogenic factors. The impact of climatic and anthropogenic factors may be multidirectional, which affects the flow characteristics in the analyzed catchments. In the context of the operation of the hydropower sector, some changes are positive and some negative. The same is indicated by Hamududu and Killingtveit [19] who noted large variation in the changes in the river flows (increases/decreases) within regions. Similar character of changes in the analysed flows within the region studied, together with the influence of local factors, suggests that climatic factors do not play a dominant role. This is consistent with the findings of Kundzewicz ed. [56] and Madsen et al. [57] according to which there is no strong evidence that river flows in recent years have been directly influenced by climate change. Piniewski et al. [58] have suggested that there is a strong random component in the river flow process, changes are weak and their spatial pattern is complex. Changes in the rivers' flows may be influenced by other local factors [59], primarily those related to human activity [37,60,61]. The analysis has shown that the changes are most pronounced in the catchment areas of the rivers Widawka and Mała Noteć rivers. This is mainly due to the dominant role of anthropogenic factors. The same conclusion has been drawn by Wrzesiński and Sobkowiak [62], who claim that the largest changes in the flow regime in Polish rivers have taken place in the catchments under the strongest human impact. Results obtained in this study concerning the potential impact of opencast lignite mines should be considered, especially in other European countries such as Germany and the Czech Republic. Based on the analysis of Alves Dias et al. [63] the largest lignite mines are located in Poland, Germany, Bulgaria and Romania. The results show that the greatest variation in changes occurs within low flows and the smallest within high flows. However, it is important to highlight the large difference between individual catchments, especially with respect to changes in minimum flows. The strong spatial variability of low flows is, according to Tramblay et al. [64], controlled by local catchment characteristics. Moreover, Piniewski et al. [58] have suggested that the decreases in the low flows are essentially observed in the rivers with the low mean flow. However, these results were not confirmed in this study. In general, it should be emphasised that in the majority of the catchments studied by us there was a prevailing tendency towards decreasing flows. With regard to the periods in which the biggest changes occurred, it should be noted that low flow changes occur mainly during winter months but in a small proportion of the catchments analysed. Klavins et al. [65], as well as Klavnis and Rodinov [37], based on studies of rivers in the Baltic countries and Belarus, have identified a significant upward trend in winter, while in other seasons no trend has been detected. Kędra [66], in a case study of the Soła River located in southern Poland, also notes increasing trends in its mean flows during the winter and spring seasons. Different results were obtained by Hannaford and Buys [66], who studied the UK rivers and found that increased runoff and high flows occur in winter and autumn, and decreased flows in spring. Moreover, Hannaford and Buys [67] have indicated that in summer, there was no compelling evidence for a decrease in overall runoff or low flows. In general, the analysis of the multitemporal trends of the mean (YM) and minimum (DL7) flows showed that in most of the catchments there was a tendency for these parameters to decrease over time, but in most cases these changes were statistically insignificant. The dominant downward trends in river flow indicators for Polish rivers have been also presented by Banasik et al. [68] and Somorowska [69]. Furthermore, Piniewski et al. [58] have indicated that the extent of increases in river flows is generally smaller than that of decreases.

If only the results of an analysis for the period 1951–2020 are considered, the statistical values of the Mann–Kendall and Sen tests do not indicate any substantial changes in flow values for most rivers. Similar results have been obtained by Zeleňáková et al. [70] who adopted a similar approach in their study. A wider perspective of changes in flow characteristics and climatic conditions over the years is provided by the multitemporal analysis of [59,71], so the latter should be preferred when analysing long-term changes in hydrometeorological characteristics [72]. The multitemporal trend analysis gives a complex description of the ongoing changes in flows. Furthermore, the analysis shows that the length of the data series and time range may have a significant impact on the obtained results.

The results of the study show that the greatest changes over 70 years concern the low and mean flows, which may directly affect the efficiency of existing hydropower plants and the profitability of investments in new hydropower plants. Especially over the last 30 years, changes in flows that are relevant to the hydropower sector have been most significant. Majone et al. [73] have also indicated that changes in water availability have an impact on the technical hydropower potential of a river. However, it should be noted that the small amount of electricity produced by hydropower plants may be caused not only by hydrological conditions but also by outdated installations that are incapable of economic use of the existing river energy potential [9]. To develop suitable adaptation strategies, it is important to know how hydrologic conditions change on a regional scale [12]. Moreover, development in the hydropower sector should each time be preceded by a detailed analysis of long-term hydrological data [74]. The data from multi-year flow series also allow environmental flow calculations [73,75], which are important for the functioning of aquatic river ecosystems. The starting point for analysing future changes in the river regime is an analysis of its past status. It allows answering the question of how flows have changed and identification of the factors responsible for the changes. Moreover, it is necessary to continue hydrological monitoring in Poland to document how the future transformation and adaptation of agriculture and other sectors of the national economy to climate change will translate into changes in river flows, and thus, the functioning of the hydropower sector and the potential for investment in new facilities.

This paper is a starting point for further research, in order to answer the question of how future climate change will affect the hydrological regime of rivers and what consequences this will have on the operation of the hydropower sector. The collected data will be used for identifying model parameters then calibrating and validating the model for further application to climate change impact assessment. It should be noted that analyses related to climate change impact assessment require a number of assumptions to be made in the context of emission rate and, in addition, assumptions regarding the transformation of various sectors of the national economy that directly or indirectly affect river flows.

5. Conclusions

The presented analysis of river flows located in the Warta River catchment area allows for the formulation of the following conclusions.

- The analysis of multiannual flow sequences from the years 1951–2020 showed that the changes varied over the time periods and catchments.
- It was established that local factors, mainly of an anthropogenic nature, play a dominant role in the shaping of river flows in both positive and negative terms for the efficiency of the hydropower sector.
- The most significant changes occurred in the low flows and the least significant in the high flows. From the point of view of the operation of the hydropower sector, these changes may be unfavorable and result in a reduction in the efficiency of run-of-river hydropower plants.
- The multitemporal trend analysis indicates a dominant downward trend in low and mean flows. It is also important to note that the trend was particularly pronounced over the last 30 years.
- The results show that the number of days with flows below Q90% tended to increase over the years. While these changes are usually not statistically significant, they can result in increased downtime of run-of-river hydropower plants.
- The analysis of changes in the flow indicators against the background of the catchment's landform, hydrographic network and land cover did not find them to be dominant. In general, changes in flows are caused by the influence of a number of factors, predominantly by those of anthropogenic nature, together with changes in climatic conditions and the variability of natural factors.
- The multitemporal trend analysis gives a more comprehensive understanding of the influence of the length of the data series and the data span on the obtained results.
- The analysis of long-term historical data series is important for the planning, design, operation and economic efficiency of investments related to run-of-river hydropower plants.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en15020439/s1: Figure S1: Multitemporal trend analysis of mean yearly discharges (YM); Figure S2: Multitemporal trend analysis of 7 days minimum discharges (DL7); Figure S3: Multitemporal trend analysis of flows time below Q50% (TBQ50%); Figure S4: Multitemporal trend analysis of flows time below Q90% (TBQ90%); Figure S5: Multitemporal trend analysis of flows time below Q90% (TBQ90%); Table S1: Catchment characteristics; Table S2: The results of trend analysis for the period 1950–2020.

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