

# IMPACT OF HYDROTECHNICAL STRUCTURES ON HYDROLOGICAL REGIME OF THE GWDA AND DRAWA RIVERS

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**ABSTRACT:** The work attempts to determine the impact of hydrotechnical structures on regimes of rivers. The aim of the article is to compare hydrological regimes of the rivers Gwda and Drawa due to the differences of hydrotechnical works located on both rivers. The Gwda River is heavily managed by hydrotechnical infrastructure. Presently, there are twelve hydropower plants located along the entire length of the river. The Drawa River, on the other hand, has little hydrotechnical infrastructure. Only two hydropower plants are located on the Drawa River. The study of the hydrological regime was carried out on the basis of the analysis of changes of water stages and ice phenomena. River profiles selected for the analysis were located downstream of hydrotechnical works, i.e. hydropower plants. The conclusions were based on the comparative analysis. The impacts were identified as the differences in processes described by the analyzed parameters.

**KEY WORDS:** hydrotechnical works, hydrological regime, the Gwda River, the Drawa River

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## Introduction

The hydrological regime, in general, often specified as the river regime describes the state and reactions of river's catchment in relations to the climate system and physiogeographic features of the catchment (Gutry-Korycka 2001). It denotes a certain type of variability of a certain phenomenon in the nature. That variability pertains most frequently to any action related to a river, e.g. ice, water stages or discharge (Dynowska 1972). It is also defined as a kind and time distribution of river discharge during a regular annual course. More specific, it is identified with the runoff regime. There are many different ways of deter-

mining features of runoff regime. Most often, the regime includes variability of water stages and river discharges in the period of multiyear, a year or a season (Dynowska 1972, Rotnicka 1988, Piętka 2009). Specific runoff is a measure of river discharge. Two different approaches are in use to determine the hydrological regime of rivers. Supervised approach, consisting in finding regularities in the multi-year hydrometric data series (Pardé 1957, Dynowska 1972, Lwowicz 1979) and non-supervised approach (Gottschalk 1985, Haines et al. 1988, Rotnicka 1988, Krasovskaia et al. 1994, Wrzesiński 2010a), in which classification procedures are used, most often – grouping (Krasovskaia and Gottschalk 2002, Wrzesiński 2010c).

Studies of multiyear and seasonal specific discharge of rivers in Poland were conducted by Dynowska (1972), Fal and Bogdanowicz (2002) and Michalczyk (2009). Spatial variability of runoff in selected regions in Poland was presented, among others, by Jokiel and Bartnik (2001), Soja (2002), Jokiel (2004, 2010), Bartczak (2007a), Bogdanowicz (2009), Marszelewski and Dąbrowski (2010) and Wrzesiński (2010a, 2014). Main reason for variability of river runoff is sought in the climate variability, specifically in the context of the global warming (Arnell 1999). The influence of North Atlantic Oscillation (NAO) on runoff of rivers has been studied, for the area of Poland by Wrzesiński (2004, 2010b, 2011, 2013a, 2013b, 2014), for the area of Slovakia by Fendekova et al. (2014). Determination of the trend of runoff changes (ascending or descending) in the period of many years is strongly dependent on the period length. Studies of Pekarova et al. (2006) revealed that the analysis of the runoff of the main European rivers during last 150 years did not show any significant ascending or descending trend.

Numerous papers discuss the problem of uneven spread of runoff during a year caused by seasonality of the climate factors. Such studies were conducted by Bower et al. (2004) for British catchments, Renner and Bernhofer (2011) for the area of Saxony/Germany, Gottschalk et al. (2006) in the catchment of Moselle, Krasovskaia et al. (1999) for the Scandinavian rivers, Apsite et al. (2009) in Latvian rivers, Hanel et al. (2012) in Czech Republic. Apart from the climate factors, the influence on runoff from catchment has also various anthropogenic factors (Dynowska 1988, Gutry-Korycka 1993). The river runoff magnitude changes under the influence of, among others, urbanization (Czaja 1986, 2002, Jankowski 1986, 1988, Jokiel 2002) or hydrotechnical structures (Dynowska 1984, Kubiak 1997, 1999, Bartczak 2007b, Kubiak-Wójcicka 2004, 2010, Banach and Jańczak 2011, Kaniecki et al. 2012, Zhang et al. 2012) and others.

The Gwda and Drawa rivers are located in adjoining catchments with similar meteorological conditions, land use and energy potential. The rivers, however differ in the degree of development of hydrotechnical infrastructure. This last element was decisive in selecting both rivers for the comparison of hydrological conditions. According to Choiński (1986), both Gwda and Dra-

wa catchments are the low hydrological activity areas. It means that their discharges in multiyear period are flat and hence more inert. Dynowska (1972) in turn, describes their regime as flat with spring flood and ground-rain-snow type of alim-entation. The aim of the article is to compare hydrological regimes of the rivers Gwda and Drawa in the context of the differences in hydro-technical development of both rivers.

## Methods

The source materials include measurement and observation data collected by water gauge stations operated by the Institute of Meteorology and Water Management – National Research Institute. On the Gwda River, the water gauge station is located in Piła and on the Drawa River it is in Drawiny. Both gauge stations are located downstream of hydrotechnical structures, i.e. hydropower stations. The water gauge station in Piła has been operational since 1888. It is located at the 21.1 km of the Gwda River, 4.6 km downstream of the hydropower plant in Koszyce. Hydrological observations of the Drawa River in Drawiny had started before the observations in Piła, i.e. as early as in 1842. The station is located at the 4.4 km of the Drawa River and the closest hydrotechnical structure, hydropower plant in Kamienna, is located 28.1 km from it.

The study of hydrological research was based on the analysis of changes of water stages, flow values and ice phenomena in the Gwda and Drawa rivers in the period of 1961–2010. The characteristic values (minimum, maximum and mean) of water stages and flow were analyzed as well as their amplitudes and fluctuation trends. Based on the difference between the maximum and the minimum values, the annual amplitudes of water stages were calculated. The quotient of the maximum and the minimum values allowed determining the annual irregularity coefficient. MS Excel spreadsheet exercising linear type of trend line was used to identify ascending or descending trends of particular indicators. Positive or negative trend equation sign determines ascending or descending trend of a given indicator, respectively. Statistical significance of the data was determined with the Student's t-test, at significance level 0.05.

In purpose to determine dry and wet years for both the rivers, two indicators were calculated: coefficient  $k$  and sum of  $(k-1)$ . The coefficient  $k$  is a ratio of mean annual discharge to mean multiyear discharge. It depicts a relative deviation from the multiyear mean value and allows distinguish wet, average and dry years. A dry year has the coefficient  $k < 1.0$ , an average year –  $k = 1.0$  and a wet year –  $k > 1.0$ . A dry and a wet year have been selected, based on the above definition. For those two years daily water stages course has been presented.

In purpose to determine sequences of wet or dry years, a cumulative curve of the coefficient  $k$  (sum of  $(k-1)$ ) has been utilized. If the mean annual discharge is less than the multiyear mean value during a few consecutive years, a descending discharge trend or a dry years sequence takes place. If the opposite condition applies – an ascending trend or a wet years sequence takes place.

In case of ice phenomena, the first and last dates and duration of particular ice forms i.e. frazil ice, fast ice, ice cover, floating ice and ice jam as well as the thickness of ice cover were analyzed.

The conclusions were based on the comparative analysis and the impacts were identified as the differences in processes described by the analyzed parameters. The work attempts to determine the impact of hydrotechnical structures, hydropower plants, on hydrological regimes of rivers.

## Study area

### Physiographic conditions

The catchments of the Gwda and Drawa rivers are located in the North European Plain (31), sub province of the South Baltic Lakeland (314-315),

macroregion of the West Pomeranian Lakeland (314.4) and the South Pomeranian Lakeland (314.6-7) (Kondracki 2002). The Gwda and Drawa rivers are the 4<sup>th</sup> order streams. Catchments of both rivers have similar physiogeographic characteristics. They feature fluvioglacial sands and gravels with multiple drainless depressions and a large number of lakes and forests. The Drawa River is the longest tributary of the Noteć River (185.9 km). Compared to the Gwda River, it is characterized by higher lake density (3.9%) and forest cover (48.1%), greater denivelation (184.2 m) and average longitudinal gradient (3‰). The Gwda River, compared to the Drawa River, is a river with a larger catchment (4944 km<sup>2</sup>), river network density (0.31 km km<sup>-2</sup>) and average altitude (128.1 m a.s.l.) (Table 1).

Both rivers have similar hydrographic net. Their catchments are located in adjoining areas. Both rivers flow from the north to the south. Their largest tributaries are their right bank tributaries in the downstream sections. The largest tributary of the Gwda River is the Piława River, and of the Drawa River – the Mierzęcka Struga River. The largest lakes are located in the northern parts of their catchments and have similar surface areas. In the Gwda River catchment, the largest lake is Wielimie with the area of 1754.6 ha and, in the Drawa River catchment, it is Drawsko Lake with the surface area of 1781.5 ha (Jańczak 1996).

Catchments of both rivers are characterized by similar land use. Based on the Corine Land Cover (EEA 2006), it was established that the dominant land cover in the case of both areas are forests and semi-natural ecosystems. The Drawa River catchment has slightly more forests and semi-natural ecosystems (59.9%) than the Gwda River (51.1%). Both catchments are agricultural-forestry areas.

Table 1. Characteristics of the Gwda and Drawa rivers and their catchments (RZGW 2013)

Characteristics	Gwda River	Drawa River
Stream order	4th	4th
Tributary	right-bank of the Noteć R.	right-bank of the Noteć R.
Length (km)	145.1	185.9
Catchment area (km <sup>2</sup> )	4944	3289
River network density (km km <sup>-2</sup> )	0.31	0.26
Lake density (%)	2.5	3.9
Forest cover (%)	23.0	48.1
Denivelation (m)	160.5	184.2
Average altitude (m a.s.l.)	128.1	120.1
Average longitudinal gradient (‰)	2	3

**Hydrotechnical works**

The Gwda River is heavily managed by hydrotechnical infrastructure. The hydrotechnical works mostly include small hydropower plants the majority of which were built before the World War II. In Western Pomerania, the first hydropower plant, previously known as hydropower plant Żarki, was constructed in Łomczewo in 1905. All other existing today hy-

dropower plants on the Gwda River were built in 1905–1937 (Kubiak 1997). The newest hydropower plant started its operation in the town of Byszki (mouth section of the Gwda River) in 2012.

Presently, there are 12 hydropower plants located along the Gwda River (from its source to the mouth): Spore, Gołębiewo, Lubnica, Węgorzewo, Łomczewo (Żarki), Podgaje, Jastrowie, Ptusza, Tarnówka, Dobrzyca, Koszyce and Byszki (Fig.

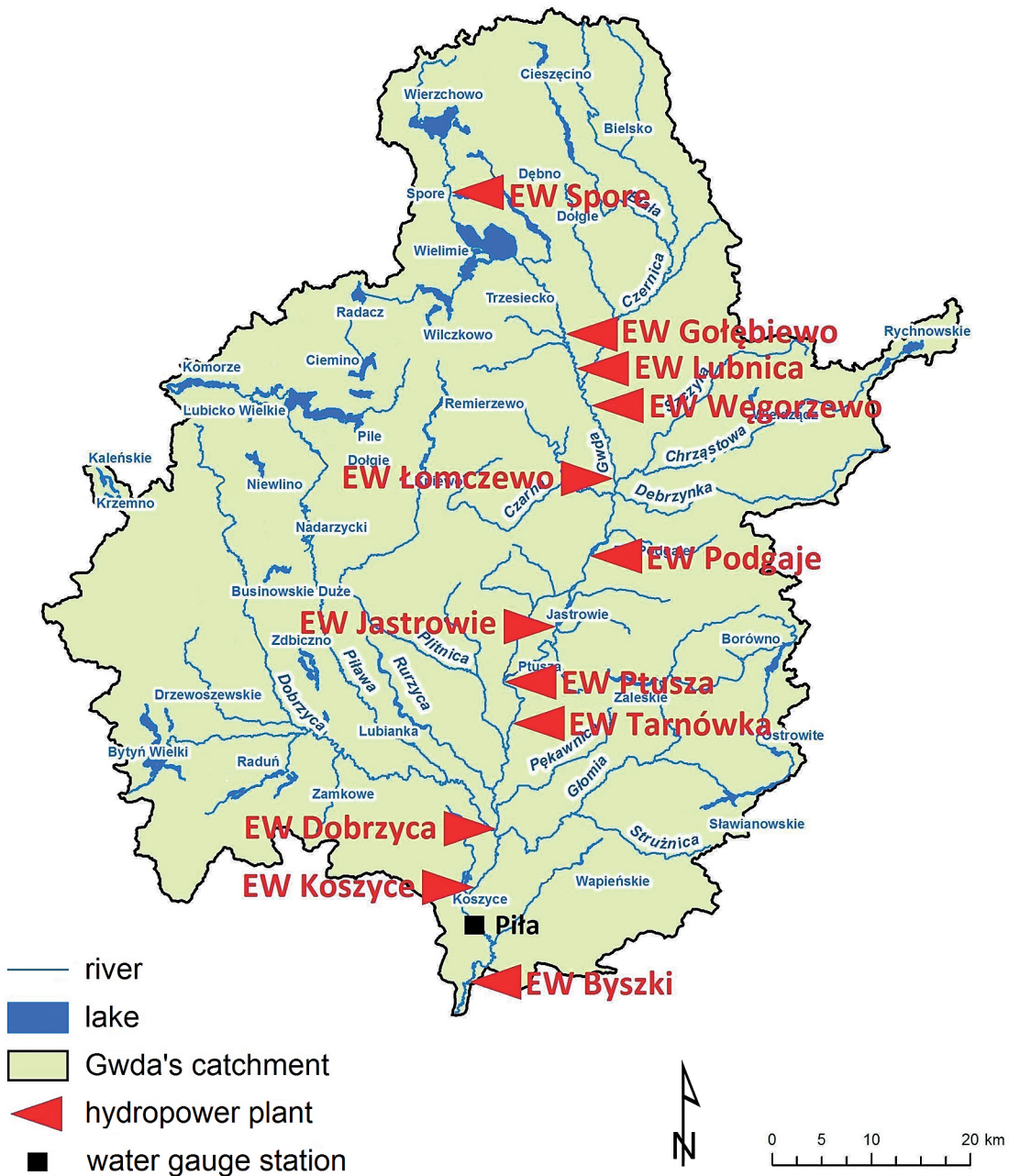


Fig. 1. Locations of hydropower plants on the Gwda River



1). The capacity of hydropower plants located on the Gwda River varies from 15 kW (Hydropower Plant Spore) to 1900 kW (Hydropower Plant Podgaje). Hydropower plants with the largest capacity located on the Gwda River are: Podgaje (1900 kW), Dobrzyca (1800 kW), Jastrowie (1400 kW), Ptusza (1100 kW) and Koszyce (1100 kW). All of them are managed by the Hydropower Plants Ltd. in Samociążek. Accomplishing such a high capacity of hydropower plants was made possible by placing dams and building water reservoirs along the river. The total storage capacity of water reservoirs created for the needs of the hydropower plants is c. 17 M m<sup>3</sup>. In the case

of these hydropower plants, the elevation drop from the top of the reservoir to the river below is the highest: Podgaje (9.3 m), followed by (7.2 m), Ptusza (6.1 m), Dobrzyca (4.8 m) and Koszyce (3.5 m) (Enea 2013).

The Drawa River does not have such developed hydrotechnical infrastructure. There are only two hydropower plants: Kamienna, built before the World War I (1898) and Borowo (1916–1918) (Fig. 2). In the 1940's, there existed plans to build a cascade of hydroelectric plants on the Drawa River (Barnimie, Zatom, Moczele, Mostniki and the existing Kamienna) but they have never been realized. Hydropower plant Kamienna-

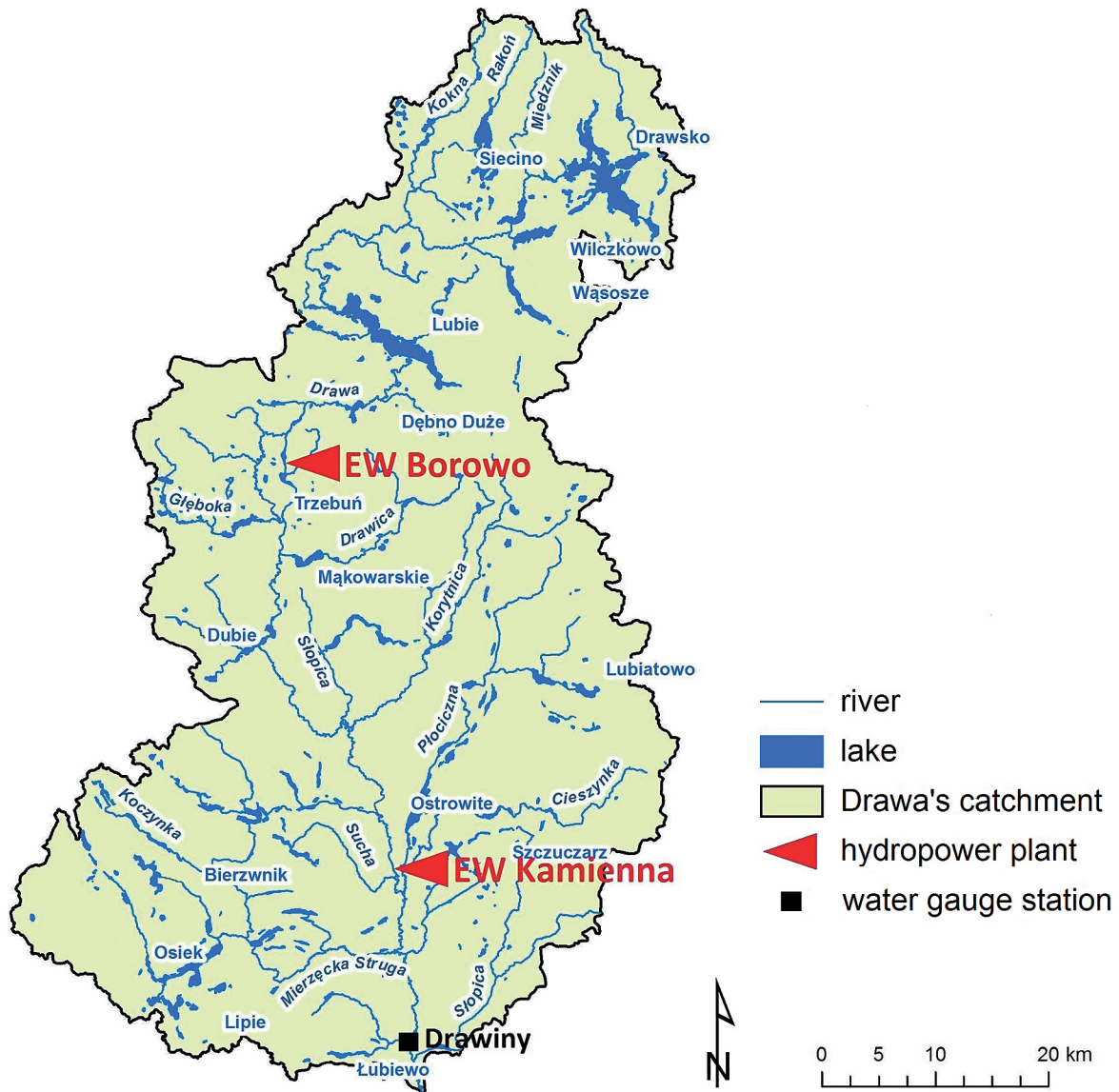


Fig. 2. Locations of hydropower plants on the Drawa River

na with the capacity of 960 kW and the water elevation drop of 7.6 m is managed by Hydropower Plants Ltd. in Samociążek. It is one of the oldest operating hydropower plants in Poland. Hydropower Plant Borowo is located in the upper catchment and is managed by the Energia-Hydro Ltd. Its capacity is 450 kW and the water elevation drop – 8.6 m (Energia 2013). The Plant takes advantage of retention capacity of lakes Mielno and Zły Łęg.

## Results

### Water stages

The analysis of the impact of hydrotechnical works on the rivers first included changes of water stages of the Gwda and Drawa rivers in the period of 1961–2010. The mean annual water stages of the Gwda River show small decreasing trend (trend line  $y = -0,038x + 141,8$ ,  $R^2 = 0,001$ ) while, in the case of the Drawa River, it shows strong increasing trend (trend line  $y = 0,288x + 65,6$ ,  $R^2 = 0,186$ ). The variability of characteristic values of water stage in the period of 1961–2010 is different for each river. The differences are reflected in the amplitude of annual water stages. The highest amplitude of water stages in the Gwda River was 204 cm in 1970 and the Drawa River it was 141 cm in 1963. The lowest amplitude, on the other hand, was 57 cm in 1993 in the Gwda River while in the Drawa River 36 cm, twice, in 1973 and 1996.

Another analyzed element was the irregularity coefficient of water stages which is the ratio of the maximum and the minimum values in a given year. The Drawa River shows bigger irregularity of water stages than the Gwda River. The irregularity coefficient of water stages in the Drawa River ranges varied from 1.7 in 1996 to 5.1 in 1963. The irregularity coefficient of the Gwda River ranged from 1.6 in 2009 to 3.1 in 1982 (Fig. 3).

Both rivers differ in variability of daily water stage values. The analysis of daily water stages of both rivers in wet and dry years in the period of 1961–2010 showed that the Gwda River was characterized by considerable fluctuations of water in 24-hr periods. For the purpose of comparison, The courses of daily water stages of the Gwda and the Drawa in 1981 and in 2006 have been presented. 1981 is a year with high amplitude of water stages and the coefficient of water stage irregularity. It is also a year, in which the coefficient of discharge ( $k$ ) reached its highest values of the whole analyzed multiyear period. It meant that it was a wet year (Fig. 4). 2006, in turn, was a year with low amplitude of water stages, low coefficient of water stage irregularity and the lowest value of the coefficient  $k$  in the whole analysed multiyear period. It was named a dry year (Fig. 5). The sudden day to day changes of water stages in both, 1981 and 2006, in the Gwda River resulted from the operation of hydropower plants. Regulation of water stages by hydrotechnical works located along the Gwda River makes it possible to manage the quantity of inflowing water in such a way as to prevent the develop-

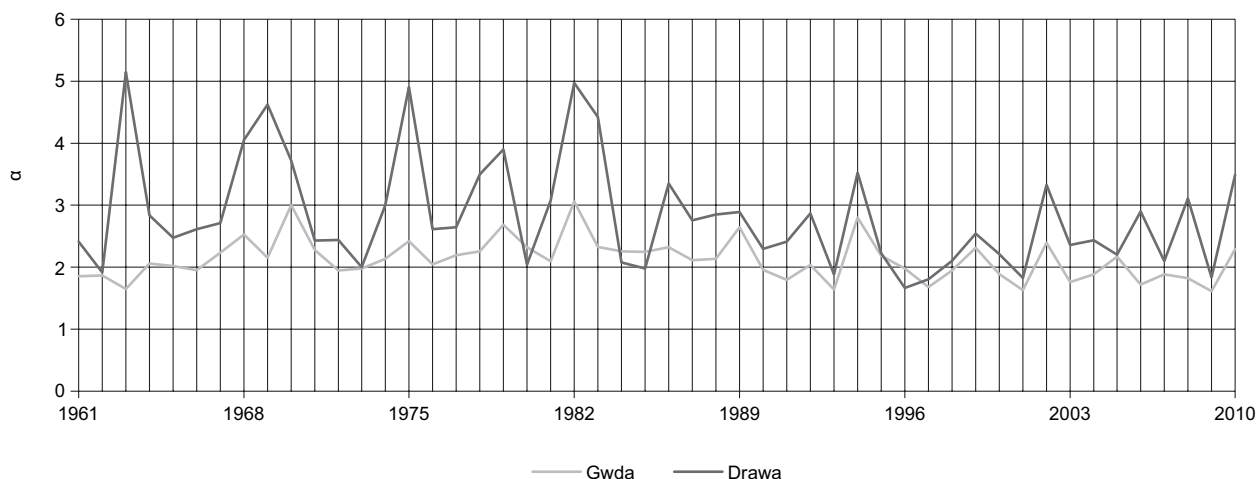


Fig. 3. Irregularity coefficient of water stages of the Gwda River in Piła and the Drawa River in Drawiny in hydrological years 1961–2010

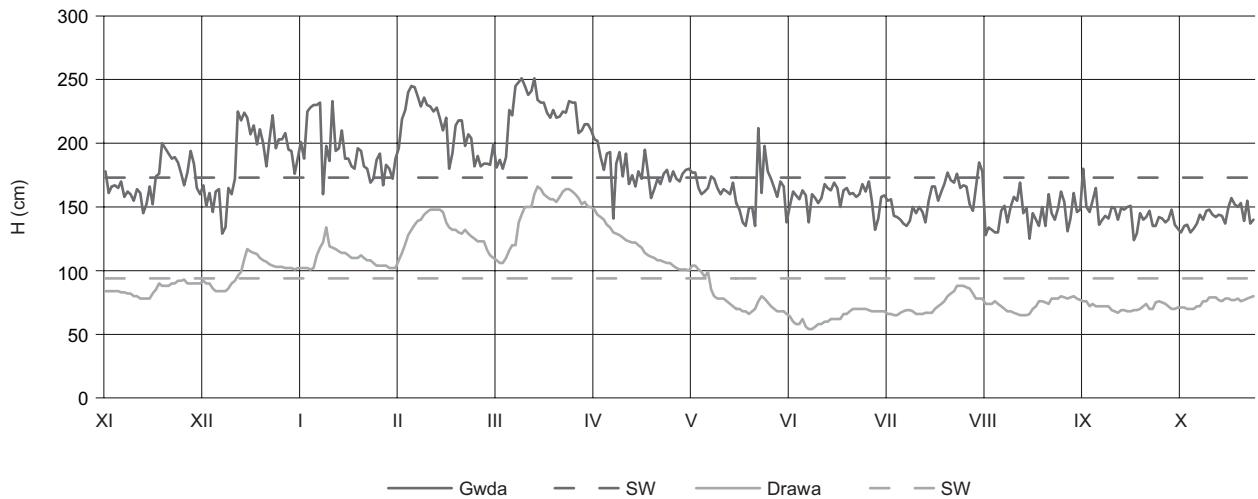


Fig. 4. Daily water stages of the Gwda River in Pila and the Drawa River in Drawiny in hydrological year 1981 (wet year)

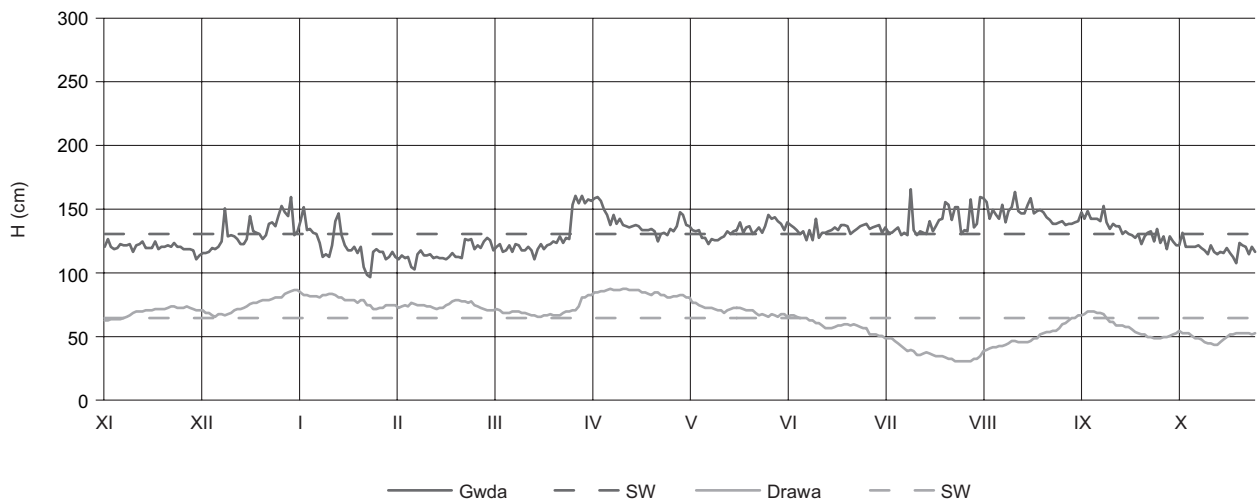


Fig. 5. Daily water stages of the Gwda River in Pila and the Drawa River in Drawiny in hydrological year 2006 (dry year)

ment of low flow. This possibility depends on the storage capacity of retention reservoirs located in the vicinity of hydropower stations. The course of the chart that presents water stages of the Drawa River, contrary to the Gwda River, is smooth, with no sudden change. In the wet year (1981), maximum daily water stage increase reached 15 cm, while for the Gwda River it was 70 cm. In the dry year (2006), maximum daily increase of water stage was significantly lower and reached 5 cm for the Drawa River and 32 cm for the Gwda River.

## Discharges

The analysis of characteristic values of discharges in the Gwda and Drawa rivers indicated that both rivers had more similar patterns

than patterns of water stage. The maximum value of mean annual discharge in the Gwda and Drawa rivers in the analyzed multi-year period

Table 2. Hydrological characteristics of the Gwda and Drawa River in 1961–2010

Characteristics	Gwda River	Drawa River
Characteristic values of water stages (cm)		
NNW	80	26
SSW	141	73
WWW	306	175
Characteristic values of water discharge ( $\text{m}^3 \text{s}^{-1}$ )		
NNQ	9.7	7.3
SSQ	27.3	21.4
WWQ	114.0	51.0
Characteristic values of specific runoff ( $\text{dm}^3 \text{s}^{-1} \text{km}^{-2}$ )		
NNq	2.1	2.2
SSq	5.8	6.5
WWq	24.2	15.5

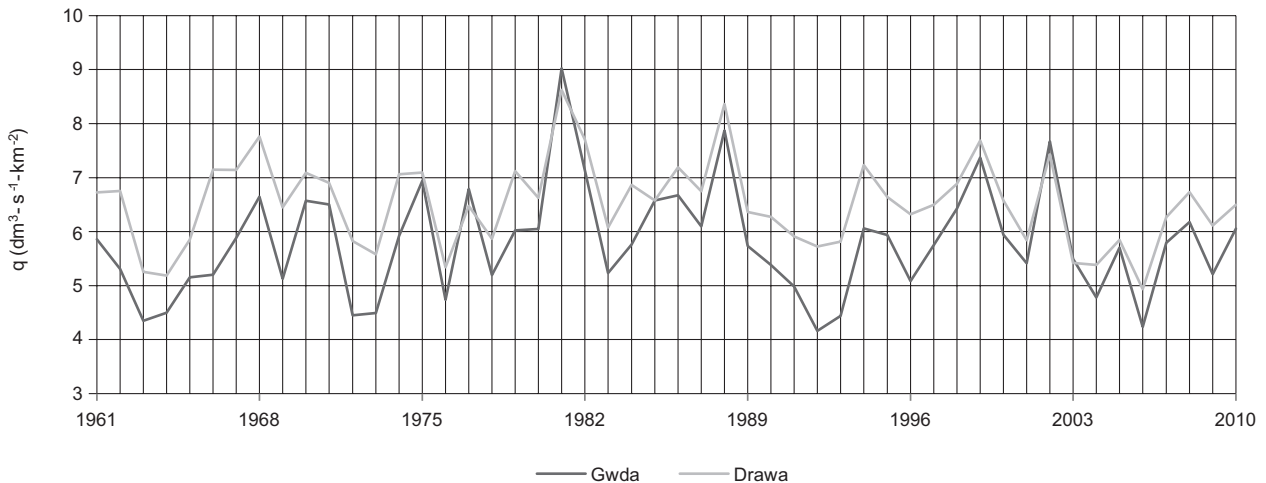


Fig. 6. Mean annual specific runoff of the Gwda River in Piła and the Drawa River in Drawiny in hydrological years 1961–2010

occurred in the same year – 1981. In the Gwda River in Piła it was  $42.4 \text{ m}^3 \text{ s}^{-1}$  and in the Drawa River in Drawiny –  $28.3 \text{ m}^3 \text{ s}^{-1}$ . All the values of characteristic discharges are higher in the Gwda River than in the Drawa River. The largest difference ( $63 \text{ m}^3 \text{ s}^{-1}$ ) was noted between the maximum values in a multiyear period in each river (Table 2).

The variation of annual specific runoff values of the Gwda and Drawa rivers showed even bigger similarities. The variations had repeatedly similar patterns. The extreme values of specific runoff in 1961–2010 are characterized by nearly similar values in the same years. The maximum specific runoff in both rivers was noted in 1981, and the minimal value occurred in 2006 (twice

in the Gwda River – also in 1992). The values of specific runoff in the Gwda River varied from 4.2 to  $9.0 \text{ dm}^3 \text{ s}^{-1} \text{ km}^{-2}$ , and 4.9 to  $8.6 \text{ dm}^3 \text{ s}^{-1} \text{ km}^{-2}$  in the Drawa River (Fig. 6). Significant differences were noted in case of the maximum specific runoff values. The values in the Gwda River were almost twice as big the values in the Drawa River (Table 2).

In order to determine increasing and decreasing discharge trends of the Gwda and Drawa rivers, the coefficient  $k$  and the sum  $(k-1)$  were calculated. Coefficient  $k$  is the ratio of mean annual flow value to a multiyear mean value. The value of  $k < 1.0$  coefficient allows to qualify given year as dry,  $k > 1.0$  as wet and  $k = 1.0$  as average. The highest (1.6 and 1.3) and the lowest (0.7 and

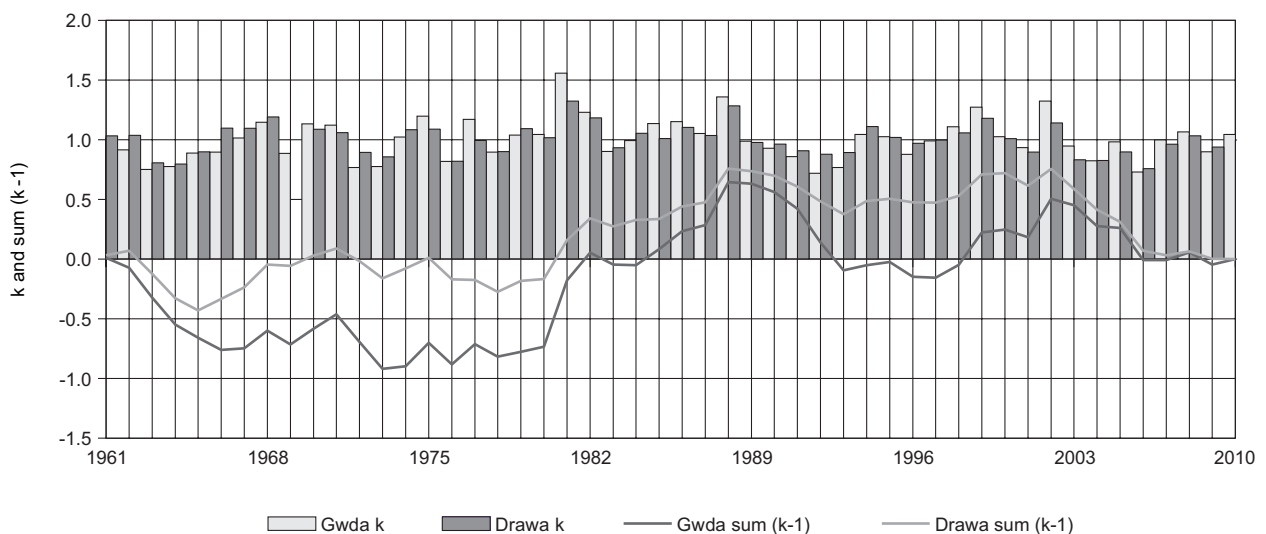


Fig. 7. Coefficient  $k$  and sum  $(k-1)$  for the Gwda River in Piła and the Drawa River in Drawiny in hydrological years 1961–2010



0.8) values of the coefficient  $k$  in the Gwda and Drawa rivers occurred in the same years of the analyzed period (1981 and 2006). The period with the strongest increasing trend (1.4 and 1.0) for the Gwda and Drawa rivers occurred in the same years from 1978 to 1990. The strongest decreasing trend ( $-0.8$ ) in the Gwda River took place in 1961–1966 and in the Drawa River in 2002–2007. This leads to conclusion that the Drawa River reacts sooner to changes in alimentation conditions than the Gwda River which first stores its water in retention reservoirs (Fig. 7).

### Ice phenomena

Freezing of rivers impacts their water stages and flow values, ratio of runoff from river basins, conditions of the entire river ecosystem, operations of hydrotechnical works, causes damages of water structures and makes navigation impossible. Freezing of rivers very often creates flood hazard (Kornaś 2014). The variability of ice phenomena in the Gwda River in Piła and the Drawa River in Drawiny in the period of 1961–2010 showed significant differences. The maximum duration of ice phenomena occurrences in the Gwda River was 97 days in 1970 while in the Drawa River it was shorter almost by a half, i.e. 58 days in 1987. Of all the ice forms, the longest lasting was fast ice in both rivers (Gwda River – 97 days, Drawa River – 51 days) (Table 3). In the analyzed period, there were no occurrences of ice cover or ice jam in the Gwda River. The absence of ice cover at the Piła station resulted from the higher velocity downstream of hydropower plant and the pollutants discharged to the river from the city. Whereas in the Drawa River, all forms of ice phenomena were noted: frazil ice, fast ice, ice cover, floating ice and ice jam. The Drawa River, therefore, was characterized by higher variability of each ice

phenomenon than the Gwda River in the studied multiyear period.

Ice cover occurred in the Drawa River three times: in 1963, 1970 and 1987. Its maximum duration was 32 days in 1963. The maximum thickness of ice cover was 11 cm in 1987. The ice jam in the Drawa River in Drawiny was noted in only one day – January 31, 2010. Smaller variability was noted in the case of the first and last dates of occurrences of particular ice forms in a year. Ice phenomena in the Gwda River in Piła and in the Drawa River in Drawiny were first noted in the second half of November (Gwda River – November 17, Drawa River – November 16) and their latest thaw date was registered in the second half of March (Gwda River – March 22, Drawa River – March 18) (Table 3). The first and the last ice form to appear was fast ice in both rivers. The earliest date of ice cover in the Drawa River was December 24, 1970, and the latest date of ice cover occurrence was February 3, 1963.

### Conclusions

The catchments of both the Gwda and the Drawa have similar physiogeographic characteristics, which include location, catchment size, geological structure, drainage density, land denivelations or land use. Significant factor of difference is a degree of hydrotechnical structure. There are 12 hydropower plants on the Gwda River, while on the Drawa River there are only 2. Furthermore, the plants on the Drawa River are located far from the water gauge.

The study included the analysis of mean annual, monthly and daily values of water stages, discharge and ice phenomena collected at the water gage Piła on the Gwda River and at the water gauge Drawiny on the Drawa River for the period of 1961–2010. The conclusions are as follows:

Table 3. Ice phenomena in the Gwda River in Piła and the Drawa River in Drawiny in 1961–2010

Characteristics	Gwda River			Drawa River		
	Duration (days)	First date	Last date	Duration (days)	First date	Last date
Fast ice	97	17.11	22.03	51	16.11	18.03
Frazil ice	29	29.11	14.03	38	24.11	09.03
Floating ice	14	28.12	09.03	7	13.12	17.02
Ice cover	0	-	-	32	24.12	03.02
Ice jam	0	-	-	1	31.01	31.01
Ice phenomena	97	17.11	22.03	58	16.11	18.03

- Mean annual water stages have slight negative trend on the Gwda River and a positive trend on the Drawa River,
- Annual water stage irregularity coefficient on the Gwda River is smaller than on the Drawa River,
- Day to day water stage changes are more sudden on the Gwda River than on the Drawa River,
- Mean annual runoff amplitude is higher on the Gwda River than on the Drawa River,
- Descending trend of mean annual runoff coefficient ( $k$ ) is always longer on the Gwda River than on the Drawa River,
- Ascending trend of mean annual runoff coefficient is always shorter in the Gwda River than on the Drawa River,
- Duration of ice phenomena in a year is longer on the Gwda River and shorter on the Drawa River, but in the latter case, the range of the phenomena is larger.

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