Chapter 9
Flow Regime Patterns and Their Changes

Dariusz Wrzesiński

Abstract Poland is characterized by relatively significantly diversified environmental conditions, reflected in various water supply conditions and seasonality of the river flow, which determines the flow regime. Based on the Pardé coefficient, five types of river regime: three nival (snowy) – poorly, moderately and well-formed, nival-pluvial (snowy-rainy) and pluvial-nival (rainy-snowy), respectively, can be distinguished. While the nival regime is represented mainly by lowland rivers in the central and northern parts of the country, rivers in the southern, upland and mountainous parts have the nival-pluvial and pluvial-nival regimes. Rivers representing the nival poorly formed type are characterized by the most even flows and the highest share of the groundwater flow in the total flow in the annual cycle. In contrast, rivers with the nival well-formed regime are distinguished by the most contrasting types of periods, from deep low-water to very high high-water. Climate changes and the human impact on water relations make the features of the river flow regime change. Rivers with similar changes in flow conditions, except from those with transformation of water relations caused by human activity, also represent similar geographical regions. This indicates the importance of climatic conditions in the modification of the characteristics of the flow regime. Certain evidence of the influence of climatic conditions on changes in the flow regime in the winter-spring period may be a significant decrease in winter flows observed in many rivers, and a delayed increase in the spring thaw in the 1950s and 1960s. In turn, in the 1970s and 1980s in these rivers, there was a disappearance of the winter low-water stages associated with a remarkable increase in the winter flow. These regularities indicate the noticeable impact of changes in the intensity of the North Atlantic Oscillation on the transformation of the characteristics of the flow regime of rivers in Poland. Research confirms that there is a temporarily and spatially differentiated impact of the North Atlantic Oscillation on the level of river flows. This impact is not strong but noticeable. It is observed with varying intensity in rivers in many regions of the country, mainly in winter, spring and summer.

D. Wrzesiński (✉)
Department of Hydrology and Water Management, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Bogumiła Krygowskiego 10, 61-680 Poznań, Poland
e-mail: darwrze@amu.edu.pl

M. Zeleňáková et al. (eds.), *Management of Water Resources in Poland*, Springer Water,
https://doi.org/10.1007/978-3-030-61965-7_9

Keywords River regime · Flow regime typology · River flow regime change · North Atlantic Oscillation · Poland

9.1 Introduction

The country area, even at the regional scale, is characterized by relatively significantly diversified environmental conditions, both climatic, as evidenced by Woś [1], who distinguished 28 climatic regions, and hydrological, reflected in various water supply conditions and seasonality of the river flow, which determines the flow regime. It defines the state and responses of the river system in relation to the climatic system and physical-geographical characteristics of the basin [2]. Therefore, the river regime is the regularity of variability of all phenomena occurring in the river in an average in a multi-year period annual cycle, depending on the properties of the natural environment, mainly climate and the catchment structure. Consequently, the flow regime, the thermal, ice, chemical regime, etc. may be considered. In this chapter, the analysis refers only to the flow regime of rivers in Poland. The analysis of the temporal diversity of hydrological phenomena in the annual cycle may refer to the most characteristic and distinctive periods of the hydrological cycle – the high and low water levels and discharges [3, 4] or it may cover the variability of phenomena in the yearly cycle. In the latter case, the contractual division of the year into monthly periods or seasons is applied, or the variability of phenomena is analysed in hydrological seasons, i.e., periods in the annual cycle, which are characterized by a similar course of climatic and hydrological phenomena and processes.

In order to determine the hydrological regime of rivers, various methods are applied. The recognition of the regularity of the flow variability in the annual cycle is based on both the supervised and unsupervised approaches. In the supervised approach, a few indicators (types of regime) are first defined, and then regularities in the multi-year monthly or seasonal discharges are sought according to the predefined indicators. Such an approach can be exemplified by the typologies of the regime proposed by Pardé [5], Lwowicz [6] or, for rivers in Poland, by Dynowska [7]. In the unsupervised approach, based mainly on the grouping of variables selected for the analysis, there are no such indicators, and determination of the type of regime is made on the basis of data structure so that objects within a single type are as similar as possible. Such an approach was proposed by Gottschalk [8] in the hydrological regionalization of Sweden, and by Rotnicka [9, 10] in Poland. While in the first approach, determining a priori an indicator that decides about the type of regime, exhibits its certain subjectivity, in the second, objectified, unsupervised approach the result of the analysis is affected by the so-called 'stop rule' and the acceptance of a certain degree of compliance within the identified groups.

The earliest, more extensive works on the regime of rivers in Poland were published in the 1970s. Dębski [11] classified our rivers as of a nival-pluvial type in four variants: complex mountain (e.g. the Odra River at gauge Połęck), complex Tatra Mountain (e.g. the Vistula River at gauge Karsy), oceanic (the Słupia River at gauge

Słupsk) and lowland (e.g. the Bug River at gauge Wyszków and the Vistula River at gauge Korzeniewo). However, the most detailed typology of the river regimes in Poland was presented by Dynowska [7]. When determining the type of river regime, she took into account the following factors: the type and share of water supply (groundwater, rain, snow), the nature of the flow variability based on the variability of daily discharges and irregularity of monthly and annual average discharges, and the time of occurrence of the highest discharge. She identified three main types of hydrological regime: balanced, moderate and unbalanced, within which she distinguished 13 subtypes, depending on the number and periods of the occurrence of the largest discharges and the prevailing type of water supply. A cartographic synthesis of the river regime in Poland Dynowska [12] presented in the "Atlas of the Republic of Poland." Based on monthly flow rates, she distinguished five types of river regime: three nival (snowy) – poorly, moderately, and well-formed, nival-pluvial (snowy–rainy) and pluvial-nival (rainy-snowy). An interesting approach to the study on water regime was proposed by Rotnicka [9] on the example of rivers in the Odra drainage basin and the Przymorze catchments. In that approach, different from the previous ones, river regime is understood as the type and time structure of river flows in the normal hydrological cycle. Elements of this structure are the so-called hydrological periods, which are a tool for studying the regime, and the basis for its characteristics. On the basis of the number, types, and sequences of hydrological periods, Rotnicka distinguished six main types of regimes of the studied rivers:

- the five-period regime, contrasting, with deep low-water stage in summer-autumn and pronounced high-water stage in spring (in two variants, e.g. the Odra River at gauge Miedonia, the Warta River at gauge Poznań),
- the four-period regime, with average low-water stage in summer-autumn and pronounced high-water stage in early spring (in two variants, e.g. the Odra River at gauge Gozdowice, the Ner River at gauge Dąbie),
- the three-period lowland regime, with average low-water stage in summer-autumn and low high-water stage in late winter or early spring (e.g. the Gwda River at gauge Piła), the three-period mountain and sub-montane with low low-water stage in summer-autumn and pronounced high-water stage in spring (e.g. the Nysa Kłodzka River at gauge Bystrzyca),
- the two-period regime, with low low-water stage in summer and low high-water stage in winter-spring (e.g. the Parsęta River at gauge Bardy),
- the single-period regime (e.g. the Kłodnica River at gauge Łany Małe).

9.2 Types of Regime

A detailed spatial analysis of the typology of features of the river flow regime in Poland in accordance with the criteria proposed by Dynowska [12] in the "Atlas of the Republic of Poland" was presented by Wrzesiński [13], based on the course and amount of monthly discharge rates (Pardé coefficients). In that work, the author used a rich hydrometric material collected at 516 water gauge stations, located on 295 rivers from the period 1971–2010.

Type 1 – the nival poorly formed regime. It is characteristic of rivers whose average flow of the spring month does not exceed 130% of the average annual flow. This refers mainly to the rivers of Przymorze (east of the Parsęta River) and the Pomeranian Lake District (the upper Drawa River, and the Gwda and Brda rivers). This type of regime is also represented by some rivers in the Masurian Lake District, the Lubusz Land, and the Silesian-Kraków Upland (Fig. 9.1). In the annual cycle, these rivers are characterized by the most even flows and the highest share of the groundwater flow in the total flow. In the case of the coastal and lake-district rivers, this is mainly due to a high retention capacity of the catchments (favorable infiltration

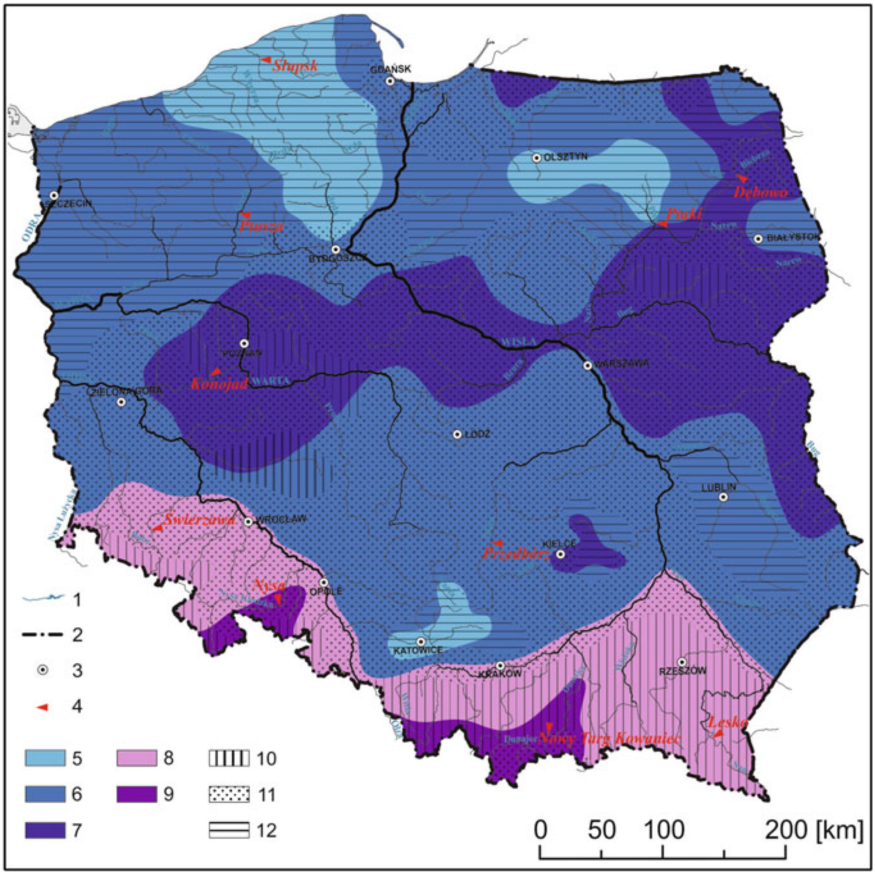

Fig. 9.1 Types of flow regimes of rivers in Poland (after [13]). 1 – Rivers and reservoirs; 2 – state borders; 3 – voivodship cities; 4 – gauges; Types of regime: 5 – nival poorly formed; 6 – nival moderately formed; 7 – nival well-formed; 8 – nival-pluvial; 9 – pluvial-nival; Share of groundwater supply: 10 – below 40%; 11 – 40–60%; 12 – above 60%

conditions), a high lake density and a large number of closed depressions. Upland rivers have balanced flows due to significant retention capabilities of heavily fissured and karstified carbonate rocks, while those in industrial areas due to the human interference in the water cycle. The Przymorze and lake-district rivers are characterized by the smallest variability of flows as well as their extreme irregularity. These rivers are also distinguished by high total flow, over 200 mm, and in the case of the Przymorze rivers even over 300 mm, and the largest share of the groundwater supply in the total flow, which in many rivers is higher than 80% (Table 9.1). The date of occurrence of high water in the rivers of Przymorze and on individual rivers of the Masurian Lake District is relatively stable and occurs in the winter–spring season. In the majority of rivers, the first minimum of monthly flows has a relatively stable or stable date of occurrence, usually in the summer or the summer–autumn period. A strongly stable date of the appearance of a period of low flows is characteristic only of the Brda River (June–July). On the other hand, relatively unstable minima occur in individual rivers, mainly transformed by the human activity, for example in Silesia, and their date falls in the summer–autumn (the Bytomka River) or the autumn–winter (the Brynica River) period. Due to the low variability of flows, these rivers are characterized by the low-contrasting hydrological periods, with the following sequence in the annual cycle: normal period → low high-water → normal period → low low-water (Fig. 9.2). In extreme cases, in rivers with changes in flow conditions caused by human activity, only one normal hydrological period is observed with very even flows (the Brynica River).

Type 2 – the nival moderately formed regime. This is represented by rivers whose average flow of the spring month is from 130 to 180% of the average annual flow. Rivers with this regime are located in:

- the northern part of the country, e.g. in the western part of Przymorze (the Rega and Parsęta rivers), in the Masurian Lake District (the Łyna and Omulew, Czarna Hańcza and Supraśl rivers),
- in the central part – the transit rivers, e.g. the Vistula, Odra and Warta rivers with the Noteć River,
- in the upland belt – rivers located between the Warta and Vistula rivers, the Lublin Upland rivers in the Wieprz catchment.

These rivers are characterized by average flows (100–200 mm), only the riparian and coastal rivers are distinguished by the flow of over 200 mm or even 300 mm. Rivers in the northern part and in the Wieprz catchment are also characterized by a high share of the groundwater supply (60–80%), which in the other rivers of this type of regime is 40–60%. The date of the high-water phase is usually relatively stable and stable and falls in the winter–spring or the spring period. In most rivers, the low-water phase has a relatively stable or a stable date of occurrence, usually in the summer–autumn or the summer period. In comparison with the previous type rivers with the nival moderately formed regime are characterized by greater variability of flows, but the types of hydrological periods and their sequence are similar. The following ones can be distinguished in the yearly cycle: normal period → high-water (from low to high) → normal period → low low-water.

Table 9.1 Types and characteristics of river flow regime in Poland (1971–2010) (after [13])

River	Gauge	Catchment area [km^2]	H [mm]	H_{ground} [%]	Flow variability		High-water phase		Low-water phase		Type of regime
					Daily *Cv*	Extreme irregularity Q_{max}/Q_{min}	SC	Period	SC	Period	
Carpathian mountains											
Soła	Oświęcim	1386	447	22.6	1.963	908	0.316	March–July	0.400	September–November	5
Raba	Proszówki	1470	365	31.8	1.953	2652	0.328	March–April	0.388	September–November	4
Dunajec	Nw. Targ-Kowaniec	681	675	42.8	1.171	239	0.467	April–July	0.513	January–February	5
Wisłoka	Żółków	581	419	21.4	1.978	3300	0.413	March–April	0.412	August–October	4
San	Lesko	1614	581	33.5	1.063	323	0.470	April–May	0.424	September–November	4
Sudety mountains											
Nysa Kłodzka	Nysa	3276	281	39.4	1.089	475	0.372	April–July	0.353	October–December	5
Bystrzyca	Krasków	683	211	30.0	1.714	668	0.324	March–June	0.447	September–November	4
Kaczawa	Świerzawa	134	280	46.2	1.777	927	0.347	March–May	0.486	August–October	4
Kwisa	Nowogrodziec	736	311	48.2	1.217	382	0.318	March–May	0.400	September–November	4
Uplands (built of carbonate rocks)											
Warta	Kręciwilk	66.2	384	68.2	0.610	44.2	0.389	February–April	0.353	July–August	1
Wieprz	Krasnystaw	3001	133	66.9	0.553	36.3	0.504	March–April	0.359	July–September	2
Bystrzyca	Sobianowice	1265	128	65.9	0.624	57.5	0.463	February–April	0.281	July–October	2
Kielce-Sandomierz Upland											
Czarna Nida	Tokarnia	1216	173	50.3	1.193	160	0.486	February –April	0.394	August–October	2
Koprzywianka	Koprzywnica	502	118	44.8	1.815	1072	0.544	February –April	0.463	July–September	3
Lowlands											
Mała Panew	Staniszcze Wlk	1107	203	51.8	1.053	144	0.417	February–April	0.441	August–November	2

(continued)

Table 9.1 (continued)

River	Gauge	Catchment area [km²]	H [mm]	H_{ground} [%]	Flow variability		High-water phase		Low-water phase		Type of regime
					Daily *Cv*	Extreme irregularity Q_{max}/Q_{min}	SC	Period	SC	Period	
Mogilnica	Konojad	663	79	33.1	1.440	1325	0.556	February–April	0.441	July–October	3
Liwiec	Łochów	2466	137	47.1	1.148	240	0.509	February–April	0.544	July–September	3
Wkra	Trzciniec	1928	168	53.0	0.746	94.0	0.525	February–April	0.478	July–September	2
Lake districts											
Drawa	Drawsko Pom	609	226	71.1	0.554	22.2	0.516	January–April	0.422	July–October	2
Rega	Łobez	609	239	72.5	0.462	12.2	0.458	January–March	0.486	July–September	2
Słupia	Słupsk	1450	348	72.1	0.293	8.3	0.382	January–March	0.486	June–August	1
Pisa	Ptaki	3562	186	81.8	0.383	12.7	0.417	February–April	0.366	July–October	1
Łyna	Sępopol	3647	215	62.9	0.630	28.0	0.509	February–April	0.475	June–August	2
Guber	Prosna	1568	170	36.5	1.149	223	0.486	February–April	0.431	August–November	3

Types of regime: 1 – nival poorly formed, 2 – nival moderately formed, 3 – nival well-formed, 4 – nival-pluvial, 5 – pluvial-nival. Regime character (stability coefficient): $SC < 0.20$ – unstable; $0.20 < SC < 0.31$ – relatively unstable; $0.31 < SC < 0.45$ – relatively stable; $0.45 < SC < 0.62$ – stable; $SC > 0.62$ – strongly stable

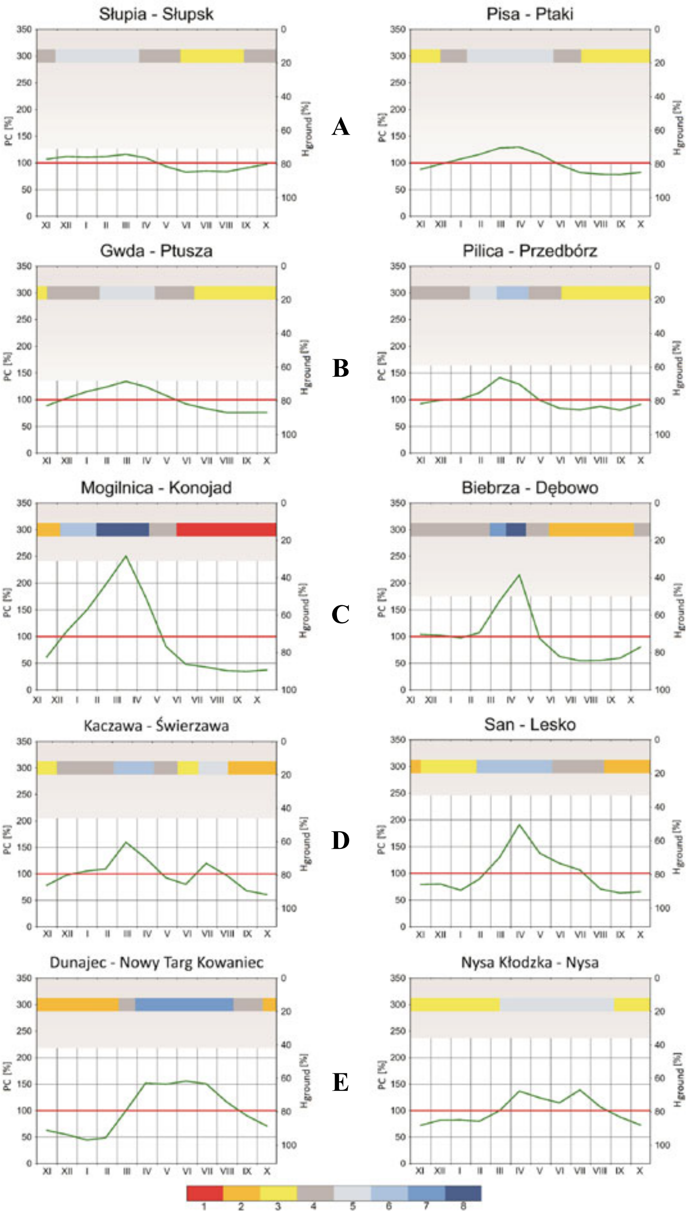

Fig. 9.2 Monthly flow coefficients – Pardé coefficients (PC), share of groundwater supply (H_{ground}) and sequences of hydrological periods of selected rivers of particular types of regime: A – nival poorly formed, B – nival moderately formed, C – nival well-formed, D – nival-pluvial, E – pluvial-nival; Types of periods: 1 – deep low-water, 2 – average low-water, 3 – low low-water, 4 – normal period, 5 – low high-water, 6 – average high-water, 7 – high high-water, 8 – very high high-water (after [13])

Type 3 – the nival well-formed regime. This type of regime is characteristic of rivers with an average flow of the spring month higher than 180% of the average annual flow. These rivers are distinguished by the largest changes in flow in the annual cycle. They are located in the lowland part of the country, from the Greater Poland Lake District and the South-Silesian Lowland through the Central Mazovian Lowland, to the majority of rivers in the eastern part of the country, in the Narew and Bug rivers catchments. Rivers of this type of regime still exist in the Kielce-Sandomierz Upland (in the Kamienna River catchment) and locally in the Myślibórz Lake District (the Myśla River) and on the Szczecinski Coastland (in the Ina River catchment). These rivers lie in the belt characterized by the lowest flows, which usually do not exceed 150 mm. A higher flow, over 200 mm, is observed only in the north-east and in the Kielce Upland. Extremely low flows, below 80 mm, are observed in the Mogilnica and Flinta rivers in the Greater Poland Lake District and on the Tążyna River, the left tributary of the Vistula River in Kujawy (60 mm). The volume of the groundwater supply and the flow variability are also diversified. High variability of daily flows is characteristic of some rivers of the Kielce Upland (the Koprzywianka and Czarna rivers), and on the lowlands the Brok River, which is the right tributary of the Bug River, and the Tążyna River. The latter, like many other rivers of the Great Poland-Kujawy Lake District (the Sama and Mogilnica rivers), is also distinguished by high variability of annual flows ($Cv > 0.600$). At the same time, these rivers usually have a very low groundwater supply (below 40%). There is a short, intense period of meltwater feeding in spring and formation of high-water stage on these rivers. Then, there is a rapid recession of the flood flow and a transition to the low-water stage in the summer-autumn period. A strongly stable period (March–April) of the occurrence of floods is observed in many rivers of north-eastern Poland. In the other rivers, the date of occurrence of the high-water period is stable and earlier (January–March, February–April). Stable, summer–autumn (July–September) is also the date of appearance of the low-water period. Rivers with the nival well-formed regime are distinguished by the most contrasting types of periods with the following sequence: average low-water (or normal period) → low (or average) high-water → very high high-water → normal period → deep (or average) low-water.

Type 4 – the nival-pluvial regime. It is characteristic of rivers whose average flow of the spring month is generally 130–180% of the average annual flow and the flow increase in the summer months is marked, with at least 100% of the average annual flow. This type is represented by rivers of the Sudety Mountains and most of the Carpathian rivers, and by the transit Vistula River up to gauge Puławy, whose regime in this section is shaped by its Carpathian tributaries. These rivers are characterized by a large range of annual flows from 100 mm (the left tributaries of the upper Odra River) to over 800 mm (the upper Vistula River, tributaries of the San River in the Western Bieszczady Mountains). These rivers are characterized by a small share of the groundwater supply in the total flow (20–40%) and a large range of variability of daily flows, from $Cv < 1.0$ in the lower reaches of the mountain rivers to $Cv > 2.0$ in the upper reaches. The date of the high-water phase is usually relatively stable and stable and falls in the spring or the spring–summer period. The least regular date of appearance of the maxima (relatively unstable type) is usually associated with a strong human impact on the water cycle. It is observed, among others, in the Vistula River between gauges Goczałkowice and Nowy Bieruń, in rivers of the Silesian Foothills, in the Skawa River, and in the Odra River catchment in its tributaries – the Bystrzyca River with the Piława River, and the Ślęza River. In most rivers, the low-water phase has a relatively stable or stable date of occurrence, usually falling for the autumn, autumn–winter, and winter periods. A stable low-season period is characteristic of many rivers in the Dunajec River catchment and the tributaries of the Odra – the Kaczawa River and the Bystrzyca River with the Strzegomka River in the Sudety Mountains. Relatively unstable minima occur in individual rivers in the Sudety Mountains and the San River catchment in the summer-autumn period. In the annual cycle, the sequence of hydrological periods is represented by low low-water (or normal period) → average high-water → normal period (or low low-water) → low high-water → average low-water. Sometimes the high-water period in spring is prolonged and connected with the high-water period in summer (the San River).

Type 5 – the pluvial-nival regime. This regime is represented by rivers whose average flow of the summer month is higher or almost equal to the average flow of the spring month, and in both cases, the flow is generally 130–180% of the average annual flow. Such regularity in the Sudety Mountains is exhibited by the Nysa Kłodzka River, and in the Carpathian Mountains by the upper Vistula River, the Soła and Uszwica rivers, and rivers in the Dunajec catchment. At the country level these rivers are distinguished by the highest flows, which on average are about 500 mm, and in the case of mountain streams are higher than 1000 mm, or even 1500 mm (the Potok Kościeliski River, the Białka River at gauge Łysa Polana). That flow consists mainly of surface flow, while the share of the groundwater supply is usually lower than 40%. As a rule, rivers with that regime are also distinguished by high variability of daily flows (Cv > 1.5). The date of flooding in these rivers is relatively stable and stable. Such a feature of the flow regime is characteristic of rivers in the Nysa Kłodzka, Soła and Dunajec catchments, in which the stable date of monthly maxima falls in the spring or the spring–summer period. In turn, strongly stable maxima are recorded only in the Białka and Potok Kościeliski rivers (May–July). In most rivers, the minimum monthly flows have a relatively stable date of occurrence, usually falling in the autumn, autumn and winter periods, and in the Tatra Mountains rivers in the winter period. Many rivers in the Dunajec River catchment are characterized by the stable low-water period. The most stable date of the appearance of monthly minima is characteristic only of the Tatra Mountains streams: the Białka and Potok Kościeliski. In the sequence of hydrological periods, the regime of these rivers is characterized by the occurrence of the average (low) low-water → normal period → long, high high-water in spring–summer → normal period → average low-water.

9.3 Changes of Flow Regime Patterns

Contemporary climate changes and the human impact on water relations make the features of the river flow regime change. Studies on the regularity of their variability in the multi-year period (1951–2010) and the hydrological cycle allow identifying groups of rivers having different scales and causes of modification of the hydrological regime [14]. Rivers with the largest changes in the flow regime caused by human activity are found in different regions of the country. These include: the Kłodnica, Brynica and Czarna Przemsza rivers in the Silesian region, the Oława River in Lower Silesia, the Ner River flowing through the Łódź agglomeration, rivers in the hydrographic system of the Drwęca, Ina and Drawa river catchments in the Pomeranian Lake District, and rivers of Przymorze – the Wieprz and the Łupawa. These rivers are distinguished by a decrease in flow in the years 1951–1970 and an increase in 1971–1990. Observed changes usually occur in the winter period (from mid-December to mid-February) and in the summer-autumn season (from mid-June to the end of the hydrological year). In the summer and autumn seasons, a higher flow was also observed in 1981–2000 (from mid-June to the end of the hydrological year). The different nature of changes in the flow regime is presented by other rivers transformed by the human activity in Silesia: the Brynica and Biała Przemsza, but also the lower Nysa Kłodzka River, the upper Warta with the Oleśnica, Barycz, Pilica, Łasica, Rawka rivers, the upper Noteć River with the Gąsawka and Wierzyca rivers, the Wda and Brda rivers in the lower Vistula basin. Until 1985, higher, and after that year, lower flows than the average were observed. The biggest changes usually occur at the beginning of the hydrological cycle, that is in November and December. In the years 1961–1980, these rivers were characterized by an increase, and in the years 1983–2002 a decrease in flow. In 1961–1980 a higher flow was also observed from mid-April to early July, and in some rivers even up to the end of the hydrological year. The more stable flow regime is represented by rivers located in the north-eastern part of the country – in the Narew River catchment (except for the Bug River), some rivers of Przymorze (the Rega, Parsęta and Słupia rivers) and the lake-district Gwda River. However, in 1951–1970 usually lower than average flows were observed in these rivers, especially in the winter season (in the Narew River from January to March). In turn, in the years 1970–1989 higher flows occurred in the summer-autumn period, and in the years 1975–2000 also in winter. Other regularity can be observed in the case of the majority of rivers in the middle and lower Warta River catchment, in the middle and lower reaches of the Odra basin and in rivers in the Pilica catchment. In the years 1961–1990, these rivers were characterized by a clear increase in flows from December to the beginning of February, as well as from May to July. At the scale of the whole country, the most stable features of the flow regime are represented by rivers of the upper and middle Vistula basin together with the Bug River and the Sudety Mountains tributaries of the Odra River. Exceptions include the Dunajec River at gauge Czorsztyn, the Nysa Kłodzka River, and the Wieprz River at gauge Zwierzyniec.

Rivers with similar changes in flow conditions, except from those with transformation of water relations caused by the human activity, also represent similar physical and geographical regions. This indicates the importance of climatic conditions in the modification of the characteristics of the flow regime, and the spatial diversity of these changes results from the local variability of the flow caused by the environmental conditions of the catchment. Certain evidence of the influence of climatic conditions on changes in the flow regime in the winter-spring period may be a significant decrease in winter flows observed in many rivers, and a delayed increase in the spring thaw in the 1950s and 1960s. In turn, in the 1970s and 1980s in these rivers there was a disappearance of the winter low-water stages associated with a remarkable increase in the winter flow, sometimes prolonging the less pronounced spring high-water period. These regularities indicate the noticeable impact of changes in the macroscale intensity of the air circulation type, which is the North Atlantic Oscillation, on the transformation of the characteristics of the flow regime of rivers in Poland.

The North Atlantic Oscillation (NAO) is attributed to a very important, climactic role in Poland [15–18]. There are also more and more papers documenting the impact of the North Atlantic Oscillation on the flow of rivers in Poland. Kaczmarek [19] pointed to the impact of the NAO on the magnitude of high-water stages caused by thaw in the Central European rivers. In the positive phase of the NAO, lower spring high-water stages are usually observed than in the negative phase. Other studies also confirmed the impact of the NAO on the Warta River flows [20] and the existence of asynchronous relationships between the winter NAO indices and flows of some Carpathian rivers and the Vistula River [21, 22]. Analyses of changes in hydrological periods and features of the river flow regime in various phases of the NAO_{DJFM} were made by Wrzesiński [23–26], and Wrzesiński and Paluszkiewicz [27]. The height of the flow in various NAO_{DJFM} phases is temporally and spatially differentiated. In the positive NAO_{DJFM} phase in the winter months (January–February), higher flows are observed in rivers in the north-eastern part of the country and the mountains. In the spring months, higher flows in rivers almost all over the country are in the negative phase of the NAO_{DJFM}. Significantly lower than the average flows in the positive phase of the NAO are observed in the summer months. As a consequence, at this stage of the NAO_{DJFM} the annual flows in most rivers are lower than average, and in rivers between the Odra and Vistula by as much as 20–40%. This is also confirmed on the maps of average flows in rivers in both NAO_{DJFM} phases (see Figs. 9.3 and 9.4).

Wrzesiński [28] presented the directions of the transformation of the types of the flow regime of rivers in Poland in the years 1971–2010 in various phases of the NAO_{DJFM}. In that paper, values of the NAO_{DJFM} winter index were used. That index is the normalized mean difference in the atmospheric pressure from December to March, between Lisbon and Stykkisholmur and Reykjavik in Iceland [29]. The type of regime was established in accordance with the criteria proposed by Dynowska [12] for the entire period 1971–2010 and for 10 years with high ($NAO_{DJFM} > 2.20$) and 10 years with low ($NAO_{DJFM} < -0.23$) values of the NAO_{DJFM} winter index. These numbers correspond to the first and third quartiles from the entire NAO_{DJFM} index set from the years 1971–2010. In the examined variants, the rivers in the distinguished types of the regime are characterized by a similar distribution and range of changes in monthly flows in the average annual cycle. The distinguished groups of rivers represent the same types of regime. However, they differ in numbers, which has consequences in a different picture of their spatial distribution (Fig. 9.3). The analysis shows that in the studied NAO_{DJFM} phases,, there is a frequent transformation of the flow regime of many rivers. Compared to the average conditions (1971–2010), in

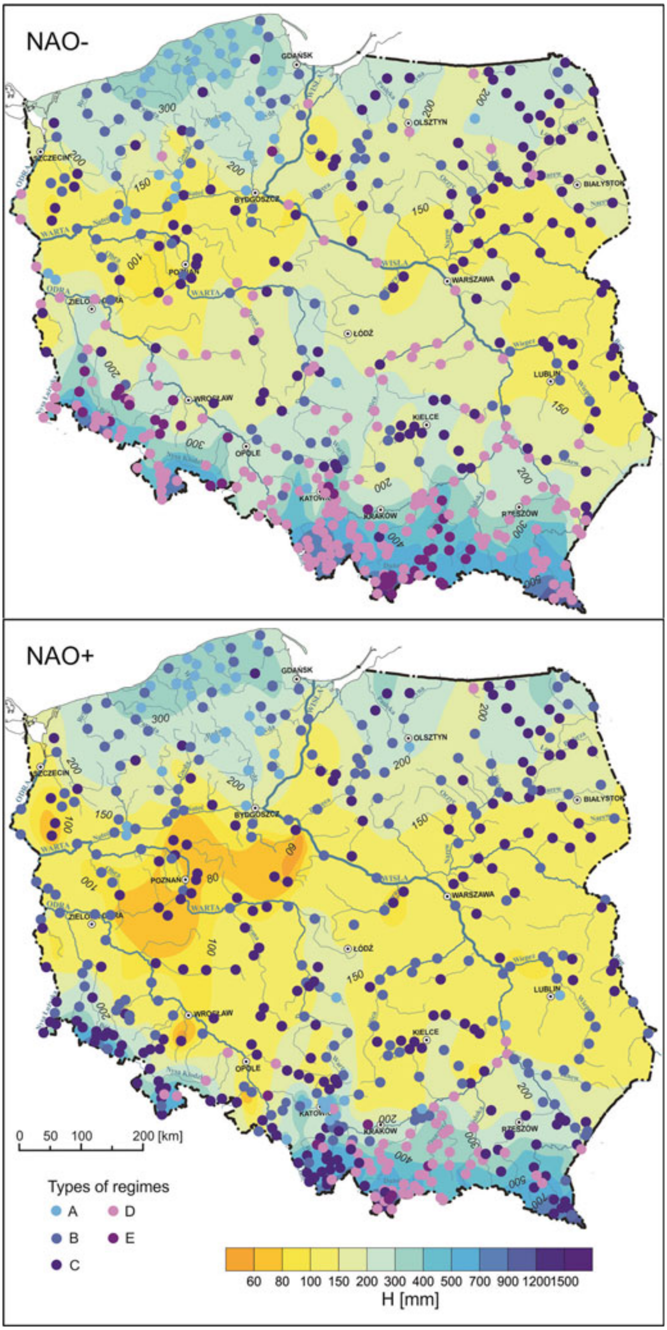

Fig. 9.3 Spatial distribution of types of regime against the average annual flow in the negative (NAO–) and positive (NAO+) phases of the North Atlantic Oscillation. Types of regime: A – nival poorly formed; B – nival moderately formed; C – nival well-formed; D – nival-pluvial; E – pluvial-nival

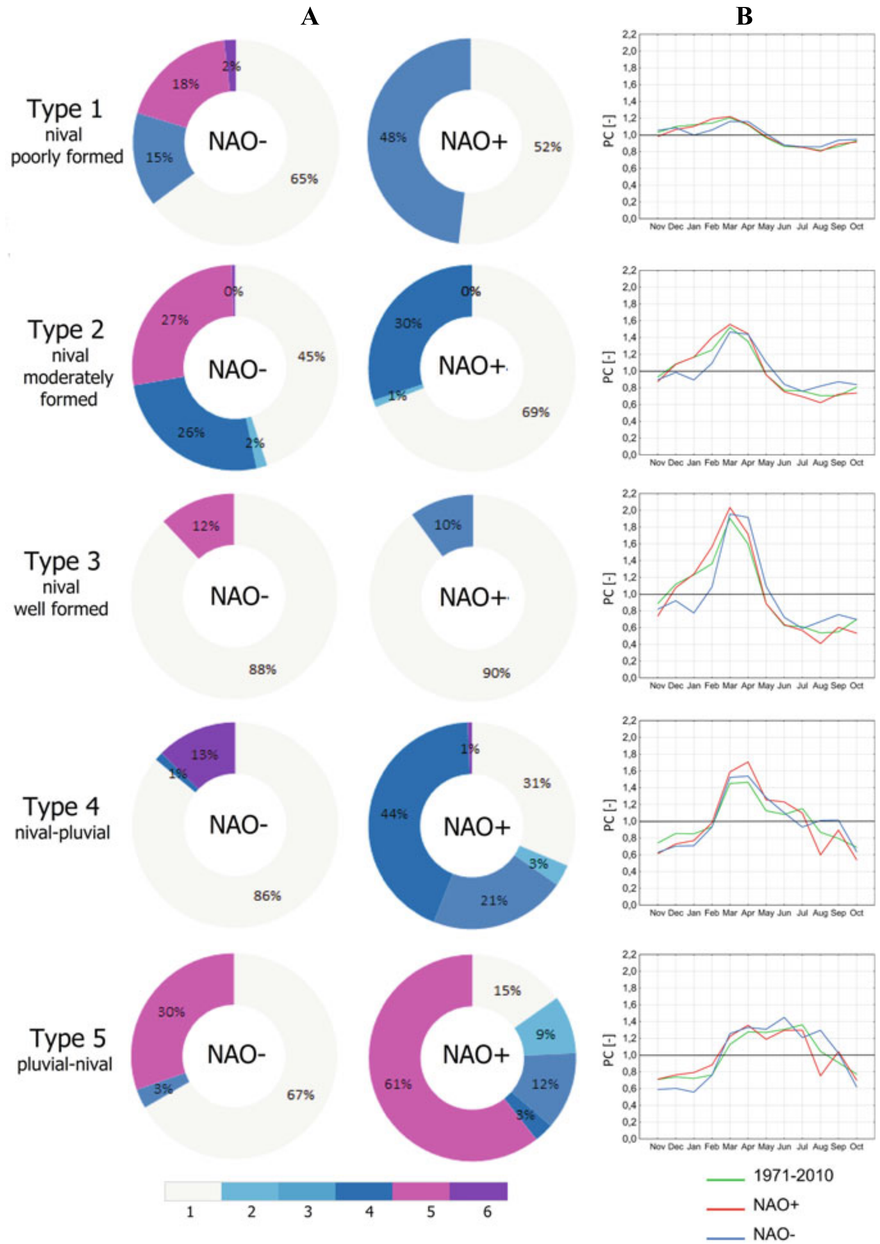

Fig. 9.4 Directions of transformation of regime types (A) and the monthly flow coefficients – Pardé coefficients (PC) (B) in different NAO phases. 1 – no change; 2 – change into type 1; 3 – change into type 2; 4 – change into type 3; 5 – change into type 4; 6 – change into type 5

the negative phase of the NAO_{DJFM} the most stable types of regime are type 3 (the nival well-formed regime) and type 4 (the nival-pluvial regime), which in 85% of river profiles have not changed. Few changes of the regime consist of transformation from type 3 into type 4, and from type 4 into type 5, which proves an increase in flows in the summer months. In this phase, a less stable type of regime is type 1 – the nival poorly formed regime, and type 5 – the pluvial-nival regime. In both cases, in approximately 35% of river profiles representing these types of regime a transformation of type occurs. In the case of type 1 of regime, there is a change into the nival moderately formed regime or the nival-pluvial regime, while the pluvial-nival regime is transformed into the nival-pluvial one. Most often, in more than 55% of cases, the nival moderately formed regime is transformed. This regime is changed into the nival well-formed or the nival-pluvial regime. The observed direction of transformation indicates that in the negative phase of the NAO_{DJFM} in many rivers, there is an increase of the spring and summer flows. In the positive phase of the NAO_{DJFM}, type 3 remains the most stable type of regime – the nival well-formed regime. It represents 90% of all profiles, at which it was identified for the average conditions. On a small number of lake-district rivers, this type of regime is changed into the nival moderately formed one. Compared with the average conditions in the positive phase of the NAO_{DJFM}, more frequent transformations are subject to type 2 – the nival moderately formed regime (mainly changed into the nival well-formed one – in some lake-district and upland rivers, and in the Prosna River catchment) and type 1 – the nival poorly formed regime, which in rivers, mainly of the eastern part of the Pomeranian Lake District, is transformed into the nival moderately formed regime. Compared to the average conditions, in the positive NAODJFM phase, types 4 and 5 are of the least stability. The nival-pluvial regime is transformed at almost 70% of profiles into the nival moderately formed type (the middle and lower reaches of some rivers in the Sudety Mountains and the San River), but mostly into the nival well-formed type (most of the upper reaches of the Sudety Mountains rivers, the Vistula and San rivers). The most frequent transformations are observed in the case of rivers, which in average conditions represent type 5 – the pluvial-nival regime. In the positive phase of the NAO_{DJFM} they account for only 15% of cases, in the other cases the regime is changed, mainly into type 4 – the nival-pluvial regime. This direction of transformation is observed in most rivers in the Dunajec catchment. Research confirms that there is a temporarily and spatially differentiated impact of changes in the intensity of the North Atlantic Oscillation on the level of river flows in Poland. This impact is not strong but noticeable. It is observed with varying intensity in rivers in many regions of the country, mainly in winter, spring and summer. In the negative phase of the NAO_{DJFM}, it was observed in 31% of the examined rivers, and in the positive one – in 43%. In particular, changes in flows of the spring and summer seasons are crucial due to the adopted typology criteria of the river regime. Thus, the observed transformations of the regime type in the two NAO_{DJFM} phases against the background of average conditions are understandable and indicate the possible destabilization of the characteristics of the flow regime of many rivers in Poland in the changing climatic conditions caused by the varying intensity of the macroscale type of circulation, which is the North Atlantic Oscillation.

9.4 Conclusions

Due to different environmental conditions, rivers in Poland are characterized by a relatively large diversity of water supply conditions and seasonality of the river flow, enhanced by its variability. This results in the distinction of five types of flow regime. The lowland areas are dominated by three simple nival regimes: poorly, moderately and well-formed, while in the highlands and in the mountain areas two complex regimes, namely nival-pluvial and pluvial-nival can be distinguished. Determination of the features of the river flow regime based on different approaches: supervised and unsupervised, allowed a better recognition of the regularity of the river flow variability in the annual cycle. Key elements determining water resources, such as duration, time of appearance and stability of the high and low water periods were included. The paper also describes how contemporary changes in climatic conditions and human impact on water conditions affect the characteristics of the river flow regime. Multiannual and seasonal flow changes were found, which are of particular importance in the spring and summer seasons due to the adopted criteria of the typology of the river regime. Studies confirmed that the destabilization of the flow regime characteristics of many rivers in Poland may be triggered by the changing climatic conditions. These are caused by the varied intensity of macro-scale air circulation types, such as the North Atlantic Oscillation, whose impact is not strong but noticeable and statistically significant in the winter season. Recent research revealed that the climatic conditions and flow regime of rivers in Poland may also be influenced by the North Atlantic Thermohaline Circulation (NA THC) [30].

9.5 Recommendations

The obtained results of this study indicate that further research is needed to detect changes in the water cycle, the amount of the river flow, and its regime at various spatial scales in order to identify the hydrological consequences of contemporary climate change and human impact.

Acknowledgements The author is grateful to the Institute of Meteorology and Water Management in Warsaw for providing the data used in this paper.

References

1. Woś A (2010) Climate of Poland in the second half of the 20th century. Wyd. Naukowe UAM, Poznań, 489 p (In Polish)
2. Gutry-Korycka M (2001) Geographical conditions of river regimes. WGSR UW, Warszawa, 192 p (In Polish)
3. Dębski K (1961) Hydrological characteristics of Poland. PWN, Łódź-Warszawa (in Polish)

4. Mikulski Z (1963) Outline of hydrography of Poland. PWN, Warszawa ((In Polish))
5. Pardé M (1957) Rivers. Warszawa, PWN, 234 p (in Polish)
6. Lvovich MI (1938) Experience from classification of the USSR's rivers. Trudy GGI, 6, Leningrad (in Russian)
7. Dynowska I (1971) Types of river regimes in Poland. Zeszyty Naukowe UJ, CCLXVIII, Prace Geogr, vol 28, 150 p (in Polish)
8. Gottschalk L (1985) Hydrological regionalisation of Sweden. Hydrol Sci J 30:65–83
9. Rotnicka J (1988) Taxonomic foundations of the classification of river regime; the example of the catchments of the Odra and Polish coastal rivers. Wyd. UAM, Seria Geografia, vol 40, 130 p (in Polish)
10. Rotnicka J (1993) A typology of hydrological periods for use in river regime studies. Quaestiones Geographicae 15(16):77–95
11. Dębski K (1970) Hydrology. Arkady, Warszawa ((In Polish))
12. Dynowska I (1997) The river flow regime. In: Atlas of the Republic of Poland, Główny Geodeta Kraju, Warszawa
13. Wrzesiński D (2017) River regimes. In: Jokiel P, Marszelewski W, Pociask-Karteczka J (eds) Hydrology of Poland, PWN, Warszawa, pp 215–221 (in Polish)
14. Wrzesiński D, Sobkowiak L (2018) Detection of changes in flow regime of rivers in Poland. J Hydrol Hydromech 66(1):55–64
15. Marsz A, Żmudzka E (1999) The North Atlantic oscillation and the lenght of a vegetative period in Poland. Przegl Geofiz 44(4):199–210 ((In Polish))
16. Marsz A (1999) The North Atlantic oscillation and the thermal regime in the area of north-west Poland and the Polish coast of the Baltic Sea. Przegl Geogr 71(3):225–245 ((In Polish))
17. Marsz A, Styszyńska A (2001) North Atlantic oscillation and air temperature in Poland. Wyższa Szkoła Morska, Gdynia, 107 pp (in Polish)
18. Styszyńska A (2001) North Atlantic oscillation and precipitation on the territory of Poland. Prace Stud Geogr 29:232–241 ((in Polish))
19. Kaczmarek Z (2003) The impact climate variability on flood risk in Poland. Risk Anal 23:559–566
20. Styszyńska A, Tamulewicz J (2004) Warta river discharges in Poznań and atmospheric circulation in the North Atlantic region. Quaestiones Geogr 23:63–81
21. Limanówka D, Nieckarz Z, Pociask-Karteczka J (2002) The North Atlantic Oscillation impact on hydrological regime in Polish Carpathians, interdisciplinary approaches in small catchment hydrology: monitoring and research FRIEND international conference, Demanovska Dolina, 132–213
22. Pociask-Karteczka J, Limanówka D, Nieckarz Z (2002–2003) The North Atlantic Oscillation impact on hydrological regime in Polish Carpathians (1951–2000). Folia Geographica, series GeographicaPhysica, 33–34, 89–104 (in Polish)
23. Wrzesiński D (2005) Changes of the hydrological regime of rivers of Northern and Central Europe in various circulation periods of the North Atlantic Oscillation. Quaestiones Geogr 24:97–109
24. Wrzesiński D (2008) Typology of spatial patterns seasonality in European rivers flow regime. Quaestiones Geogr 27A(1):87–98
25. Wrzesiński D (2011) Regional differences in the influence of the North Atlantic Oscillation on seasonal river runoff in Poland. Quaestiones Geogr 30(3):127–136
26. Wrzesiński D (2013) Entropy of river flows in Poland. Studia i Prace z Geografii i Geologii 33. Bogucki Wydawnictwo Naukowe, Poznań, 204 p (in Polish)
27. Wrzesiński D, Paluszkiewicz R (2011) Spatial differences in the impact of the North Atlantic Oscillation on the flow of rivers in Europe. Hydrol Res 42(1):30–39
28. Wrzesiński D (2018) Typology of the river flow regime in Poland in different phases of the North Atlantic Oscillation. Badania Fizjograficzne R. IX, Seria A—Geografia Fizyczna (A69):265–278

29. Hurrell J (1995) The climate data guide: Hurrell North Atlantic Oscillation (NAO) Index, National Center for Atmospheric Research, Boulder, USA. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlanticoscillation-nao-index-station-based. Last modified 20 Oct 2015
30. Wrzesiński D, Marsz AA, Styszyńska A, Sobkowiak L (2019) Effect of the North Atlantic Thermohaline circulation on changes in climatic conditions and river flow in Poland. Water 11(8):1622