Impact of the North Atlantic Oscillation on river runoff in Poland

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INTRODUCTION

Deviations of climatic elements from average levels, like those caused by changes in the atmospheric circulation, modify the conditions in which the river runoff forms. The river regime is controlled by both, precipitation and air temperature, whose magnitudes show a significant dependence on the intensity of zonal circulation. A simple indicator characterising the atmospheric circulation over the north Atlantic is the North Atlantic Oscillation Index (henceforth, NAO). The North Atlantic Oscillation is considered a very important climate-forming factor in Poland (Marsz and Żmudzka, 1999; Marsz, 2001). It has been found to be greatly responsible for temperature rise in the cold season of the year (Kożuchowski and Degirmendžić, 2002; Marsz and Styszyńska, 2001; Niedźwiedź, 2002; Przybylak et al., 2003), and to have a great impact on the radiation and humidity conditions (Bryś and Bryś, 2002), precipitation (Styszyńska, 2001; Wibig, 2001), and the persistence and thickness of snow cover (Falarz, 2007). The issue that has not generated much interest on the part of researchers has been the effect of NAO on the runoff of Polish rivers. Kaczmarek (2002, 2003) has shown NAO to affect the volume of meltwater floods on rivers of Central Europe: in a positive NAO stage the spring floods are generally lower than in a negative stage. Investigations have also corroborated the influence of NAO on the Warta discharges (Styszyńska and Tamulewicz, 2004) and the existence of asynchronous relationships between winter NAO indices and the discharges of some Carpathian rivers and the Vistula, on which low-water stages develop in the later months of the year, at the close of summer and in autumn (Limanówka et al., 2002; Pociask-Karteczka et al., 2002). An analysis of changes in the hydrological seasons and runoff regime characteristics of rivers in different NAO stages has been made by Wrzesiński (2004, 2005, 2007) and Danilovich et al. (2007). On the rivers of Central Europe the sequence of hydrological seasons usually does not change; what changes is the starting date, duration and intensity of a hydrological event occurring in the given period. Spring floods in a negative NAO stage are clearly of greater magnitude, delayed and shorter, while in a positive NAO stage one can observe an earlier start of the low-water season and a higher low-flow runoff, with the duration of low-flow seasons remaining basically unchanged.

The aim of the present research was to examine the extent to which the North Atlantic Oscillation affects the runoff of Polish rivers: its seasonal structure and spatial variability.

METHODS

The analysis embraced monthly, seasonal and annual runoff of 148 Polish rivers taking into consideration Hurrell's winter NAO index as well as Rogers' monthly and seasonal NAO indices from the years 1951-2000. The selected rivers are distributed evenly throughout Poland and represent a diversity of environmental conditions (Fig. 1).

Fig. 1. Location of profiles on the rivers under study.

Linear correlation analysis was employed to establish relations between the streamflow and the North Atlantic Oscillation. A study was made of the correlations between the winter NAO index and monthly, seasonal and annual runoff as well as correlations between annual runoff and seasonal NAO indices. Next, differences were calculated between the monthly and seasonal runoff observed in the years with exceptionally high ($NAO_{DJFM}>2$) and low ($NAO_{DJFM}<-2$) values of the winter NAO index and their statistical significance was determined. Also calculated were monthly and seasonal deviations of runoff in the years with high NAO_{DJFM} indices from that in the years with their low values (assuming the runoff in the years with low NAO_{DJFM} indices to be 100%), and runoff deviations in the years with high and low NAO_{DJFM} indices from average runoff figures (assuming the mean runoff in the years 1951-2000 to be 100%). Finally, a classification of the rivers was made in terms of the similarity of deviations of their seasonal runoff between the different NAO_{DJFM} stages. In the classification procedure use was made of Ward's method of hierarchical grouping.

RESULTS

Correlations of monthly flows with NAO_{DJFM}

It follows from the analysis of the coefficients of correlation between the winter NAO index and monthly flows that the correlations are positive on most of the rivers in January and February (Fig. 2). Statistically significant positive correlations are observed in January on mountain rivers ($p<0.5$) and in January and February on the rivers in the north (Pomeranian Lakeland, $p<0.05$) and north-east of Poland ($p<0.001$). In March positive correlations keep dominating on the rivers of northern Poland, although they are less significant statistically; it is only on the rivers in the extreme north-east that they reach $p<0.001$. In turn, in central Poland negative correlations, locally statistically significant, start to predominate. In April the relations change. Throughout the country negative correlations can be observed, the strongest holding in the east, in the Bug, Narew and Biebrza river basins ($p<0.01$), on the rivers of the middle basins of the Oder, Warta and

Vistula, and in the western part of the Mazurian Lakeland ($p<0.05$).

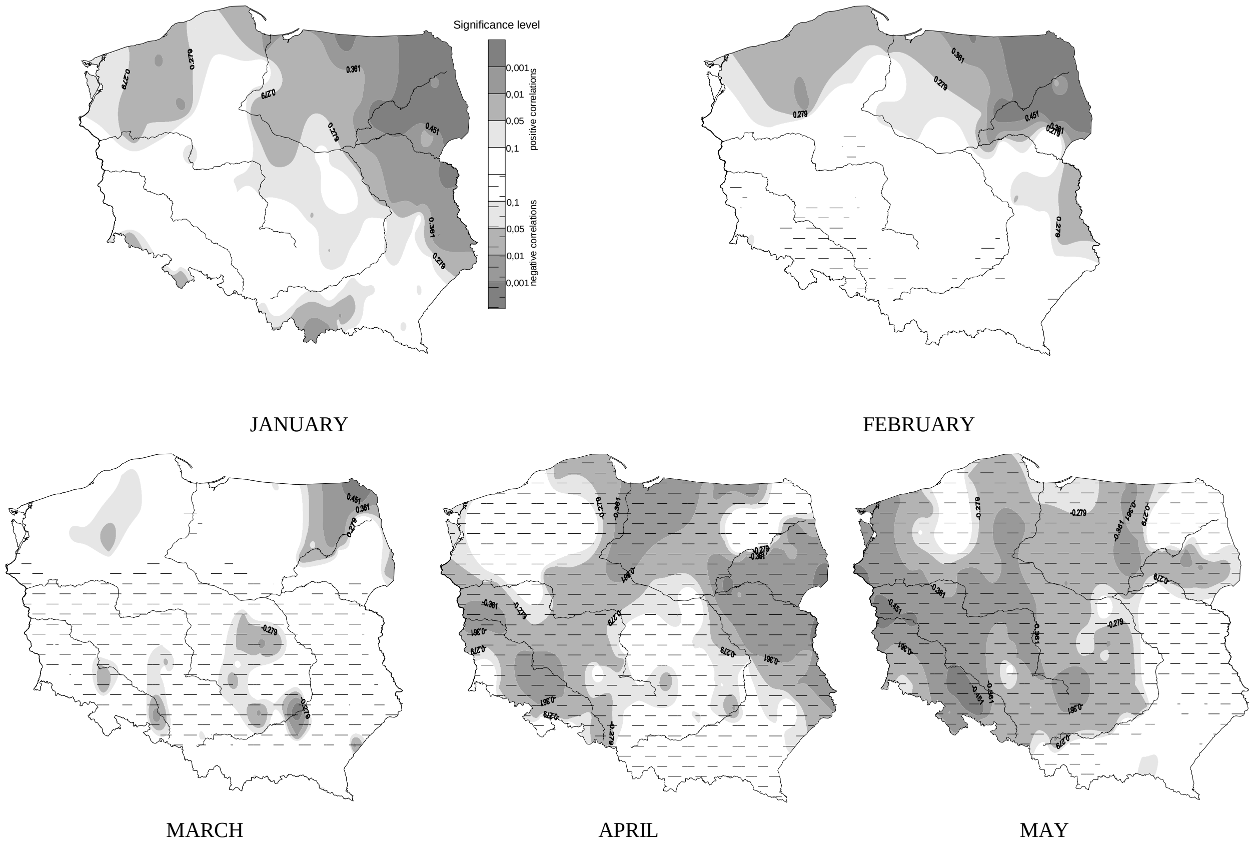


Fig. 2. Correlations of monthly flows with the winter NAO index and level of significance of the correlation coefficient.

The situation is similar in May, with the significance of the negative correlation coefficients ($p<0.01$) increasing in western and central Poland and markedly decreasing in the east. The rivers of the East Carpathians even show positive correlations, but they are not statistically significant. In the remaining months, no statistically significant relations can be observed on the majority of the rivers under study, but negative correlations clearly predominate. Sporadically, statistically significant negative correlations can appear in June in the upper parts of the Noteć and Warta river basins ($p<0.05$), in August in the Carpathian catchments east of the Dunajec ($p<0.05$), and in September in the upper Warta and Pilica basins ($p<0.05$). Positive correlations are recorded in June on some rivers of the Pomeranian and Mazurian Lakelands, and from July to December mostly in the eastern and north-eastern parts of the country.

Correlations of seasonal flows with NAO_{DJFM}

The runoff in the winter season (XII-II) on most of the rivers shows positive correlations with NAO_{DJFM} (Fig. 3). Statistically significant correlations can be observed on the rivers of the Pomeranian and Mazurian Lakelands and single streams of the Sudeten (the Nysa Kłodzka, Kamienica, Czarny Potok, $p<0.05$), with the rivers in the north-easternmost part of the country (upper parts of the Narew, Biebrza, Gołdapa, Łyna, Guber and Krzna basins) displaying positive correlations at the $p<0.001$ significance level. Spring runoff (III-V) on most Polish rivers shows negative correlations with the winter NAO index. They are the strongest ($p<0.05$) on rivers of the upper Oder, upper and middle Warta, and middle Vistula river basins. They are the weakest, locally even positive, on lakeland and Carpathian rivers. In summer (VI-VIII) and autumn (IX-XI) the runoff of most rivers displays negative, insignificant correlations with NAO_{DJFM}. In autumn the area of positive correlations tends to grow in the north-eastern part of the country, but they are not statistically significant.

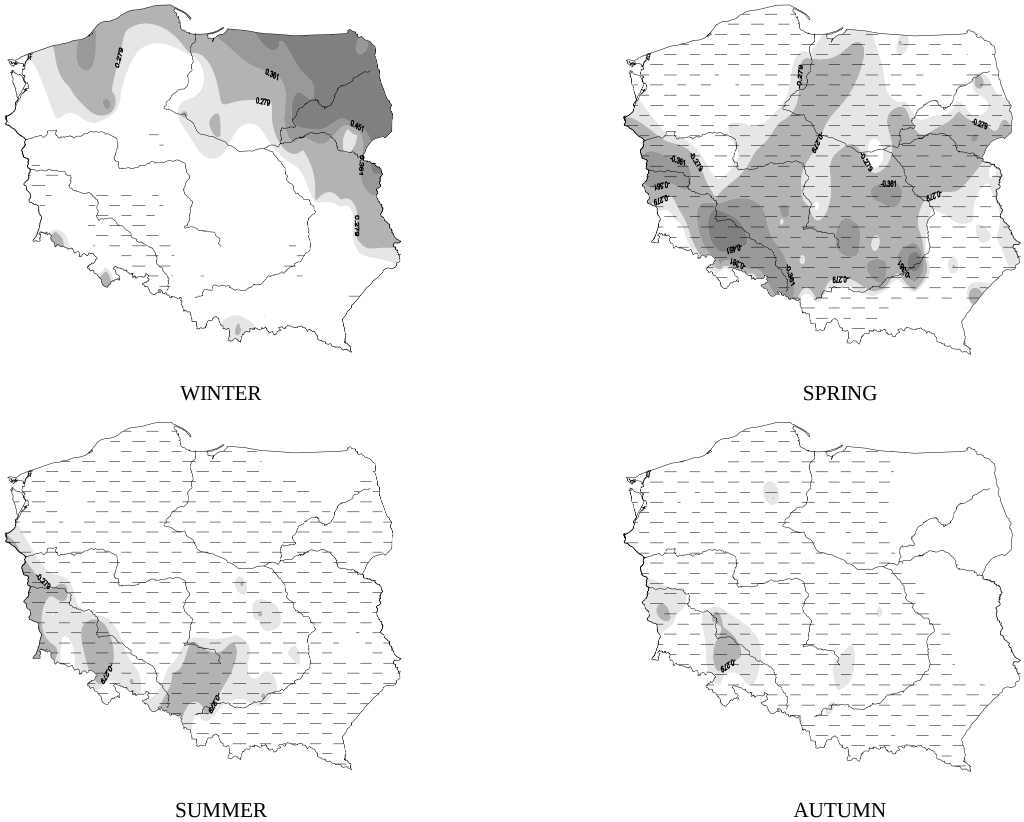
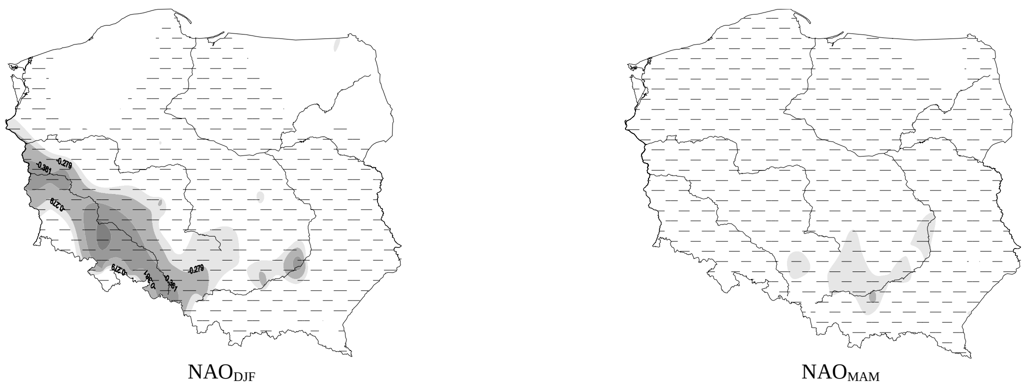
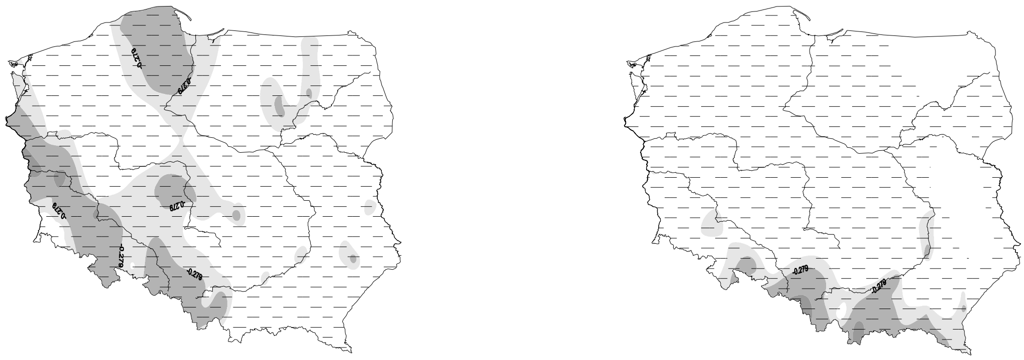


Fig. 3. Correlations of seasonal flows with the winter NAO index (legend as in Figure 2).

Correlations of annual flows with seasonal NAO indices

Mean annual flows usually show negative correlations with seasonal NAO indices. The strongest negative correlations with NAO_{DJF} are observed on rivers in the upper part of the Oder basin ($p<0.05$). Mean annual flows of lakeland rivers are the only ones to display positive, although statistically insignificant, correlations with NAO_{DJF}. Mean annual flows of all the rivers show negative correlations with NAO_{JJA}, which are statistically significant ($p<0.05$) in south-western Poland (the upper Oder basin, mostly the Sudeten tributaries, and the upper Vistula basin down to the Dunajec), and in the eastern part of the Pomeranian Lakeland (the Łupawa, Słupia, Brda, Wda, Wierzyca).





NAO_{JJA} NAO_{SON}

Fig. 4. Correlations of annual flows with seasonal NAO indices (legend as in Figure 2).

Significant negative correlations ($p<0.05$) of annual flows with NAO_{SON} are only observed on the upper Oder and Vistula, and on the Carpathian tributaries of the Vistula.

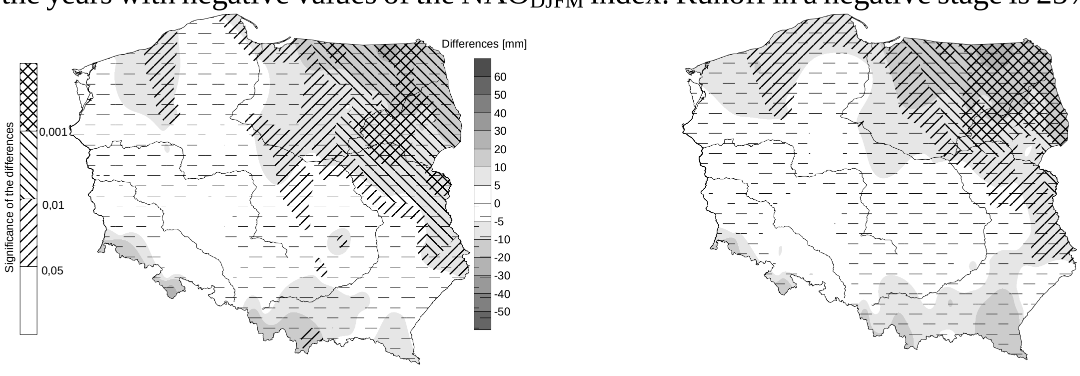
River runoff in the two NAO stages

The strong correlations of the runoff of Polish rivers with the winter NAO index makes it interesting to examine the streamflow and its seasonality (changes in the yearly cycle) in the two NAO stages.

In January and February, higher flows can be observed in most of Poland in a positive NAO stage (Fig. 5). Deviations of flow figures from the average observed in this NAO stage increase markedly from south-west to north-east, where they reach 125% to 150% of the 1951-2000 mean. The runoff of rivers in the north-eastern region of the country in a positive NAO stage is 150% to 300% of that observed in a negative NAO stage (Fig. 6). This is also the area where statistically most significant differences (even $p<0.01$) appear between the runoff in the years with a positive (NAO+) and a negative (NAO-) NAO_{DJFM} index. In the analysed months big flow differences between periods with extreme values of the NAO_{DJFM} index are observed also in the case of mountain rivers and those of the Pomeranian Lakeland. In January, on some of the rivers they are statistically significant ($p<0.05$), and the runoff in a NAO+ stage is 25% to 50% higher than that in a NAO- stage (Fig. 5).

In March the situation changes. In northern Poland and the mountains in the south the runoff figures in a NAO+ stage are still higher, but statistically significant differences are only recorded in the north-eastern part of the country ($p<0.01$). There the river runoff in a NAO+ stage is more than 175% of that in a NAO- stage. The entire central, lowland, part of the country and the upland region show higher runoff in a negative NAO stage. It is locally 25% higher than that in a positive stage, but the observed differences are usually statistically insignificant.

In April, it is already in the whole of Poland that rivers show markedly higher runoff figures in the years with negative values of the NAO_{DJFM} index. Runoff in a negative stage is 25% higher



JANUARY FEBRUARY

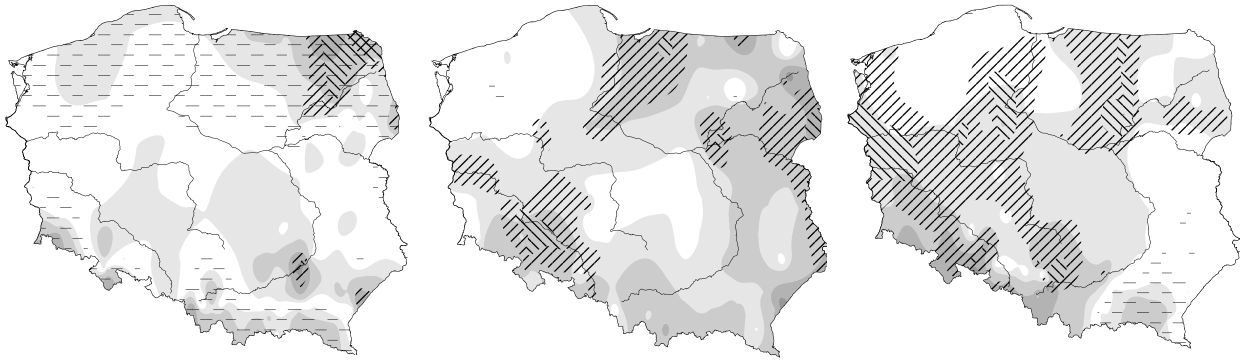


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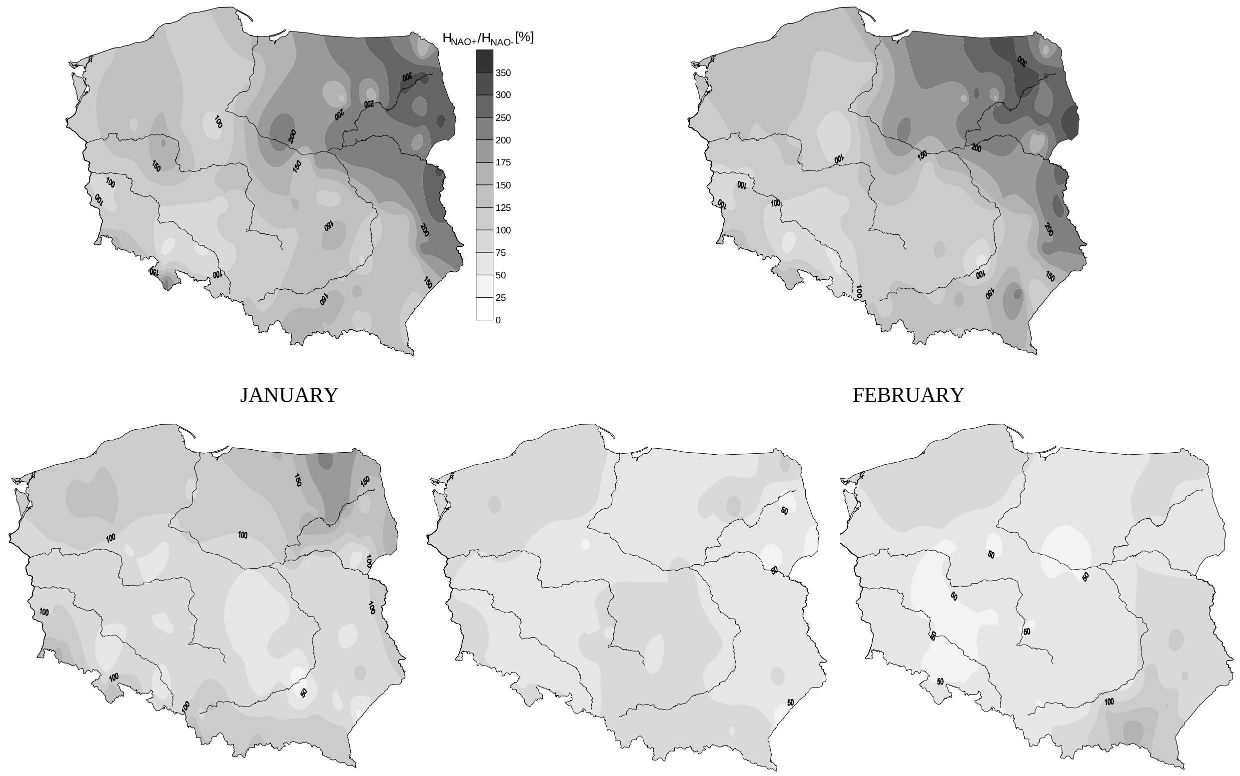
Fig. 5. Differences in monthly flows between a positive and a negative NAO stage and the results of a test of the statistical significance of the differences.



MARCH APRIL MAY

Fig. 6. Deviations of monthly flows (in %) in the different NAO stages (the H_{NAO-} = 100%).

than that observed in a positive stage on rivers of the upper and middle Oder and middle Warta basins, in the western part of the Mazurian Lakeland, and the eastern part of the Vistula basin below the mouth of the San, where locally it can be even more than 50% higher. The rivers of those regions also display the most statistically significant ($p<0.05$) differences in flows in the two NAO stages. Those observed in a negative NAO_{DJFM} stage are also 25% to more than 50% higher than the average flows from the years 1951-2000.

A similar situation occurs in May, with clearly higher flows in a negative NAO_{DJFM} stage observed on rivers in the central and western parts of the country. Flows are then more than 25%, and locally even 50%, higher than in a NAO+ stage. There is also an expansion of the area of statistically significant flow differences ($p<0.05$), now covering most of this region with the exception of the central part of the Pomeranian Lakeland and the river catchments between the

Warta and the Vistula. Though still higher in a negative NAO stage, the runoff decreases in the eastern part of the country, while in the south-east, from the Poprad to the San, higher flows are observed in a positive NAO_{DJFM} stage, but the differences are not statistically significant.

In June, on most of the rivers the runoff is still higher in a negative NAO stage, but statistically significant differences are only observed on some rivers in the upper Warta and Noteć basins. On lakeland rivers and those in the upper part of the Wisłoka system, slightly higher flows are recorded in a positive NAO stage. A similar situation also occurs in the next months (VII-IX): flows are still higher in a negative NAO stage, but a growing area in the east of the country is characterised by higher flows in a positive stage. Also, no statistically significant differences are noted between flows in the two NAO stages. From November, an increasingly bigger region in the north and east of the country, and in December also the catchments of the Sudeten and the Silesian Beskids, show higher runoff figures in a positive NAO stage. Statistically significant differences ($p<0.05$) in the flows observed in the two NAO stages are only recorded on rivers of the Biebrza basin.

Seasonal flows

Similar regularities are observed when analysing seasonal flows in the two NAO_{DJFM} stages. In winter (mean runoff of the months XII-II) decidedly higher flows are observed on most of the Polish rivers in a positive NAO stage. In the north-east they are then 2-3 times higher than in a NAO- stage, and the observed differences are highly significant statistically ($p<0.001$) (Fig. 7, 8). Only some rivers of the upper and middle Oder basin and the upper Noteć basin display higher flows in a negative NAO stage, but the differences are small and statistically insignificant.

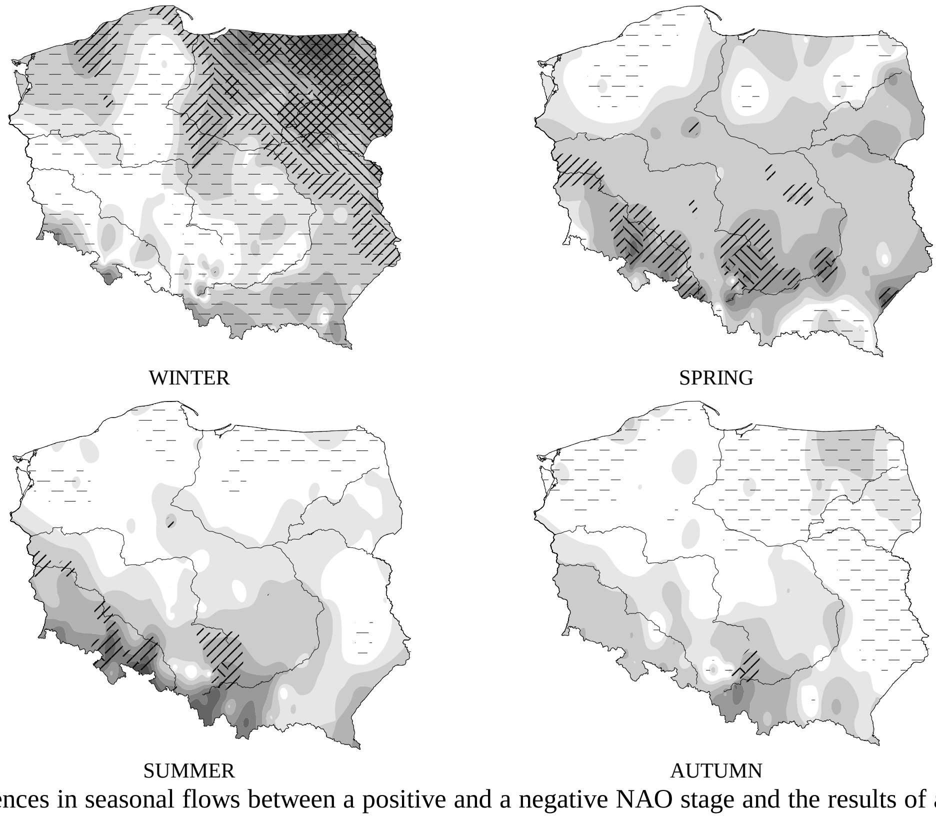


Fig. 7. Differences in seasonal flows between a positive and a negative NAO stage and the results of a test of the statistical significance of the differences (legend as in Figure 5).

On most of the Polish rivers, spring and summer flows have higher values in a negative NAO_{DJFM} stage. Flows observed in this stage exceed those in a positive stage, especially in the central part of the country, by 25% to 50%. However, statistically significant differences ($p<0.05$) are recorded for only some of the rivers of the upper and middle parts of the Oder basin. There are a few lakeland rivers with a runoff greater in a positive NAO stage in those seasons, but the observed differences are not statistically significant.

In autumn (IX-XI) there is a decided increase in the area of the country, mostly east of the Vistula and the central part of the Pomeranian Lakeland, in which higher flows are observed in a positive NAO_{DJFM} stage. Locally, in the north-eastern part of the country the flows can then be even 50% higher than those in a negative stage, but the observed differences are not statistically significant. In the remaining area the flows in a negative stage exceed those in a positive stage, but again the observed differences are not statistically significant.

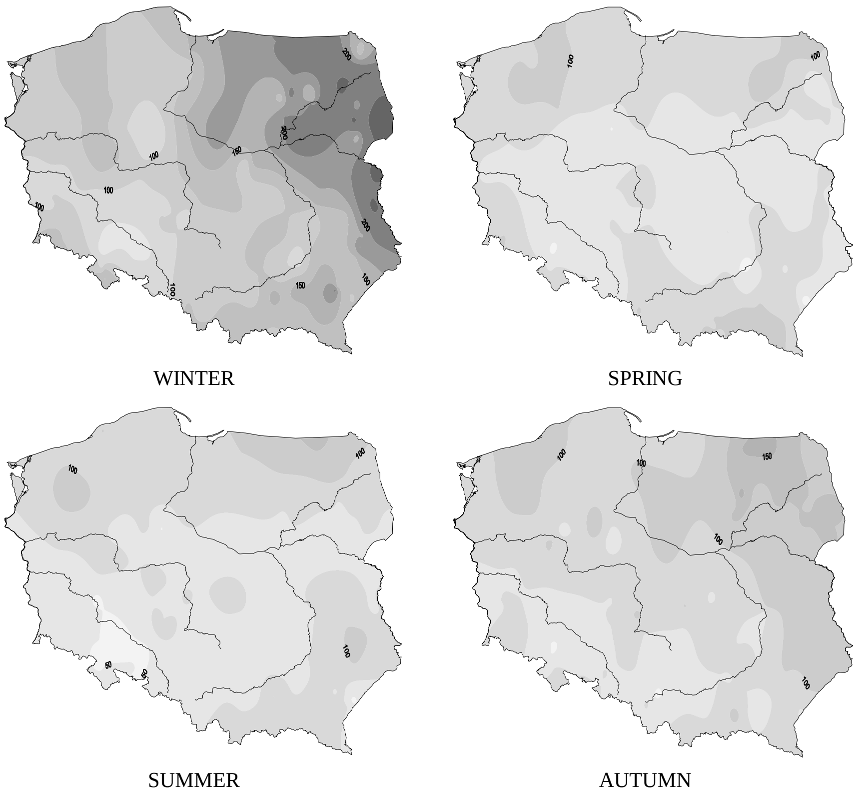


Fig. 8. Deviations of seasonal flows (in %) in the different NAO stages (the H_{NAO-} =100%), legend as in Figure 6.

Classification of rivers in terms of the magnitude of seasonal deviations of flows between a positive and a negative NAO_{DJFM} stage

Five groups of rivers were distinguished on the basis of the similarity of deviations of their seasonal runoff between the different NAO_{DJFM} stages (Fig. 9).

Group 1 embraces rivers flowing in the north-eastern part of Poland (the Guber, Gołdapa, Biebrza, upper Narew, and Krzna). They are characterised by winter flows that are decidedly higher, 160% on average, in a positive NAO stage than in a negative one. Also higher in a positive NAO stage are autumn flows, 40% on average. In turn, spring and summer flows are smaller in this stage and constitute about 80% of the runoff observed in a negative NAO stage (Fig. 10).

Group 2 includes the rivers of the Mazurian Lakeland, middle parts of the Narew and Bug basins, and the upper Wieprz basin. The nature of the relationships of the seasonal flows of those rivers and the two NAO stages is similar to those observed in the rivers of group 1. Winter and autumn flow figures in a positive NAO stage are again higher than those recorded in a negative one, but not so markedly - 100% and 20%, respectively.

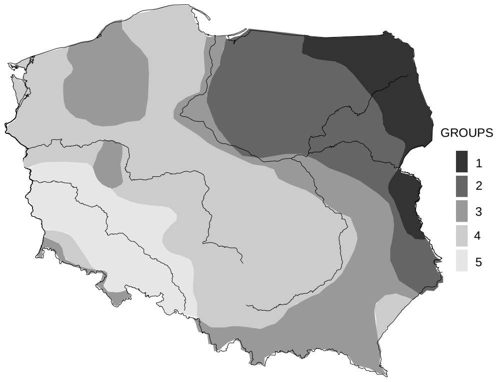


Figure 9. Typological classes of rivers distinguished on the basis of the similarity of deviations of their seasonal runoff between the different NAO_{DJFM} stages.

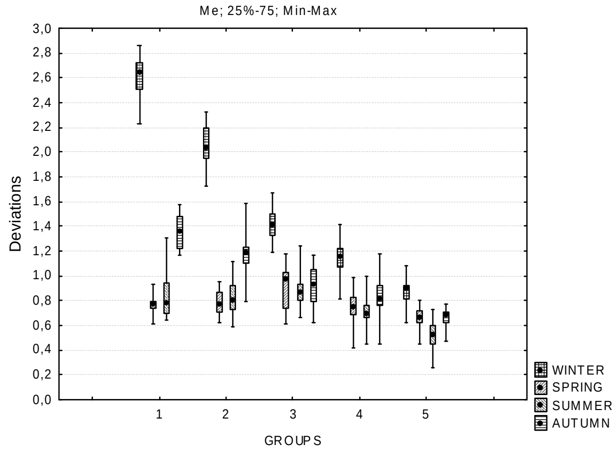


Figure 10. Differences in the deviations of seasonal flows between a positive and a negative NAO_{DJFM} stage in the river groups.

Group 3 embraces rivers of the upper Vistula basin (the Carpathian tributaries of the Vistula), the Sudeten, rivers of the middle Vistula basin (the Wieprz, Utrata, Vistula below the mouth of the Wieprz), and those of the central part of the Pomeranian Lakeland. In a positive NAO stage flows on those rivers in the winter season are on average 40% higher. Flows in the remaining seasons are as a rule higher in a negative stage. The smallest differences are observed in the spring runoff, with mountain and lakeland rivers showing then slightly higher flows, 5% on average, in a positive NAO stage. Flows in the summer and autumn seasons are about 10% higher in a negative stage.

Group 4 embraces rivers of a large part of the country west of the Vistula, with the exception of the upper and middle parts of the Oder basin and the rivers of the Pomeranian Lakeland classified in group 3. Their winter runoff is also higher in a positive NAO stage, 20% on average. In the remaining seasons, higher flows are observed in a negative stage - in spring 25%, in summer 30%, and in autumn 20%.

Group 5 includes the rivers of the upper and middle Oder basin (with the exception of its mountain sections). In a negative NAO stage, higher flows are observed in all the seasons - 10% on average in winter, 30% in spring and autumn, and even 50% in summer.

CONCLUSIONS

The research results have confirmed a strong effect of the North Atlantic Oscillation on the runoff volume of the Polish rivers. The calculated correlation coefficients show the observed dependences to display great temporal and spatial differences.

The winter NAO index shows the strongest correlations with flows in the winter and spring seasons, the correlations being usually positive in winter and negative in spring. In the winter months - January, February and March, the most statistically significant positive relations can be observed on rivers in the north-east and north of the country. The flows in those regions in a positive NAO stage are then more than 25% higher than the average (mean flows from the years 1951-2000) and more than 100% higher than in a negative stage. In the spring months, statistically significant negative correlations in April hold for the runoff of rivers in north-eastern

Poland and the middle parts of the Oder and Warta basins, and in May, rivers of almost the entire country with the exception of the east and south-east. In those areas streamflow in a negative NAO stage is more than 25% higher than the average, and more than 50% higher in a positive NAO stage. In the remaining months, on most of the analysed rivers the relations are usually not significant statistically. Still, negative correlations predominate markedly, and only in the eastern and north-eastern parts of the country positive correlations dominate.

The obtained results show that the North Atlantic Oscillation has the greatest effect on streamflow in the winter-spring months, i.e. in the period when the most abundant water resources are being formed in Poland. Hence, in a positive NAO stage, one might expect a considerable buildup of the water resources in the winter months, mostly in the north-east, and their marked dwindling almost throughout the entire country in spring. The diversity of environmental conditions in the catchments of the analysed rivers gives the observed relationships a different character, which was confirmed by the typological classification of the rivers by deviations of their seasonal flows in a positive and a negative NAO_{DJFM} stage. The results of the grouping made it possible to distinguish five regions in Poland differing in the magnitude of seasonal flows observed in the years with extreme winter values of the NAO index.

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