FOLIA GEOGRAPHICA
SERIES GEOGRAPHICA-PHYSICA
Vol. XLI 2010: 49–58
ISSN 0071-6715

# EXTREME FLOOD EVENTS IN THE DUNAJEC RIVER DRAINAGE BASIN (CARPATHIAN MTS.)

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An increasing number of threats induced by floods is being observed in the Dunajec River drainage basin. An extreme flood event (EFE) is being defined as one producing discharge larger than the sum of mean daily discharge and ten standard deviations. Data from 20 Dunajec sub-basins with areas ranging from 58.4 to 5316 km$^2$ were analyzed. They represent four categories of sub-basins based on their surface area: small, medium, large, and very large. The variability and the spatial distribution of EFEs as well as the link between EFEs and large scale climatic phenomena (NAO) were studied. Strong intra-month variability during some months and in some sub-basins was detected. Finally, statistically significant relationships between winter Hurrell indices and EFE discharges were calculated.

Key words: floods, North Atlantic Oscillation, linear correlation analysis, Monte Carlo method

## 1. INTRODUCTION

River runoff possesses a particular significance in the geographic environment. It is representative of both precipitation and snowmelt, thereby it combines temperature and precipitation variations. On the other hand, river discharge directly impacts numerous anthropogenic activities. Extreme hydrological events such as droughts and floods affect many aspects of human life. They are influenced by a combination of natural factors – one of their main large scale driving forces is air circulation. Maximum river discharge, in particular, poses a considerable risk in terms of flood threats. The direct impact of some of floods events includes the loss of human life and damage to property. Finally, extreme flood events also affects other environmental processes such as soil erosion, hillslope movement, and changes in plant cover.

## 2. OBJECTIVES

The main purpose of this paper is to present an analysis of the temporal and spatial variability of extreme flood events in the Dunajec River drainage basin. Relationships between macroscale air circulation phenomena and river response were examined both in small and large sub-basins with respect to the North Atlantic Oscillation (NAO). The NAO is one of the most prominent airflow patterns controlling atmospheric circulation variability in Poland and plays an important role as an indirect factor influencing river discharge there (Degirmendžić *et al.* 2000; Kożuchowski 2003). A negative NAO episode in the winter is associated with higher than usual flow during snowmelt season. A positive NAO episode is associated with higher than usual flow at the end of summer and at the beginning of autumn (Kaczmarek 2002, 2003; Limanówka *et al.* 2002, Pociask-Karteczka 2006, Pociask-Karteczka *et al.* 2002–2003, Styszyńska 2002). The specific objective of this paper is to define the threshold discharge of extreme flood event taking into consideration 10-days discharge averages. Hydrological information about river discharge for particular 10-day periods of selected months is valuable and important for different kinds of human activity (agriculture, tourism) as well as water management.

## 3. RESEARCH SUB-BASINS

The Dunajec River (L=247 km) is one of the longest tributaries of the Vistula River. Its drainage basin (A=6798 km$^2$) includes the Tatra Mts. – the highest mountain range in the Carpathian mountain chain – with Mt. Gerlach (2655 m a.s.l.) as the highest peak. The investigated area is located in southern Poland and northern Slovakia. The location of the Carpathians in Europe is quite distinct – the mountain chain forms the boundary between two different zones of NAO influence.

The surface areas of the investigated sub-basins range from 58.4 to 5316 km$^2$ (Fig. 1, Table 1). They have been grouped into four categories according to sub-basin surface area: Category A (small sub-basins; <100 km$^2$), Category B (medium sub-basins; 100–300 km$^2$), Category C (large sub-basins; 300–1000 km$^2$), and Category D (very large sub-basins; >1000 km$^2$).

The sub-basins of interest represent flow regimes typical for mountain rivers with two maxima. Snowmelt is the most consistent of factors determining water level peaks in March and April. Rainfall peaks occur in July and August. Some rivers possess one prolonged peak as a result of late snowmelt being extended by early summer rain. Summer rainfall and floods vary more in terms of occurrence, number, and intensity (Chełmicki *et al.* 1998–1999, Dobija 1981).

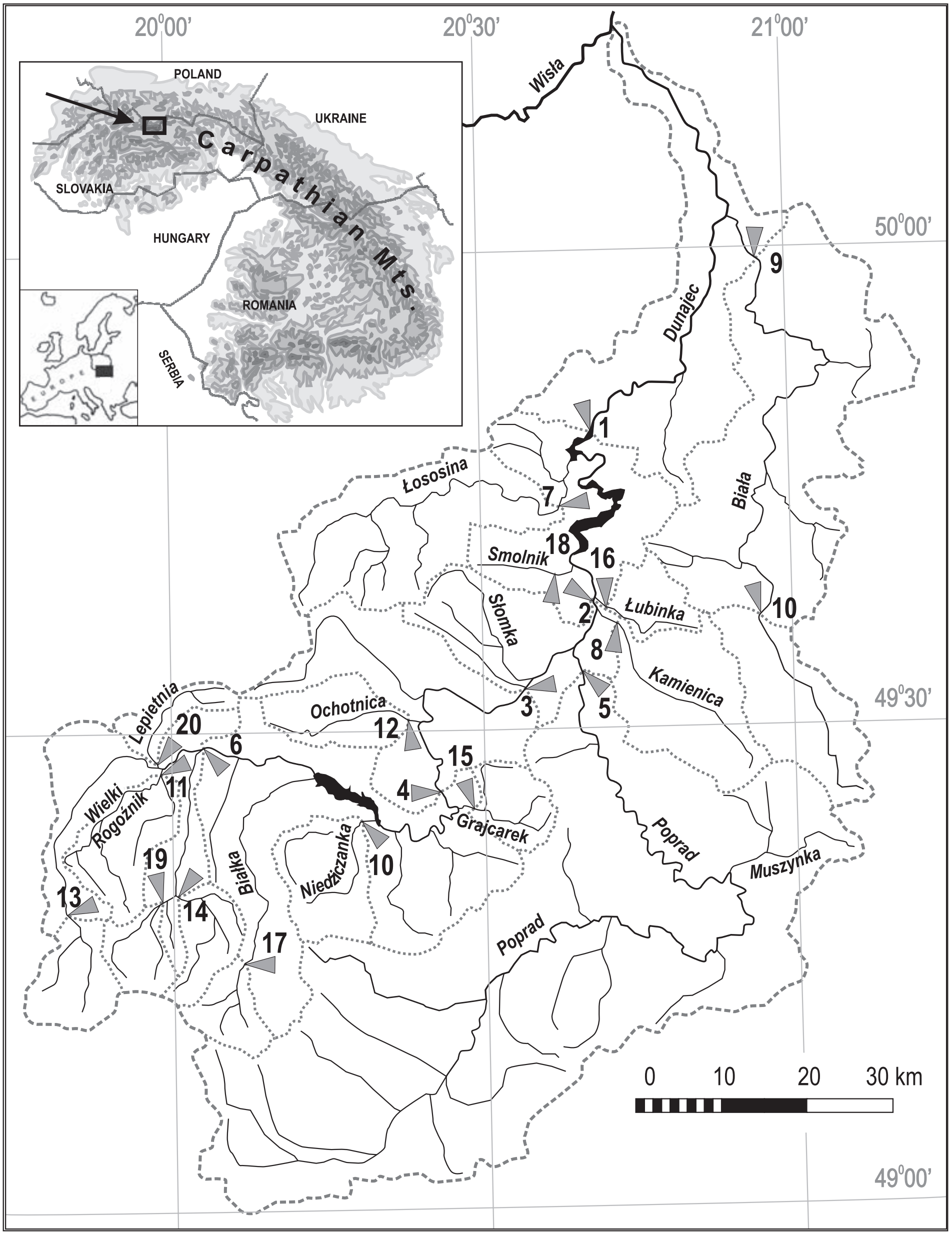


Fig. 1. Area of investigation

Table 1. Investigated sub-basins

| | River – water level gauge | A [km$^2$] | Basin category* | Data sets |
|---|---|---|---|---|
| 1 | Dunajec – Czchów | 5316.4 | D | 1961–2003 |
| 2 | Dunajec – Nowy Sącz | 4341.0 | D | 1951–1997 |
| 3 | Dunajec – Gołkowice | 2046.9 | D | 1984–1997 |
| 4 | Dunajec – Krościenko | 1580.3 | D | 1951–1997 |
| 5 | Poprad – Stary Sącz | 2071.0 | D | 1984–2003 |
| 6 | Dunajec – Nowy Targ (Kowaniec) | 681.1 | C | 1951–2003 |
| 7 | Łososina – Jakubkowice | 342.6 | C | 1964–1983, 1993–1999 |
| 8 | Kamienica – Nowy Sącz | 237.7 | B | 1984–2003 |
| 9 | Biała Tarnowska – Grybów | 209.7 | B | 1964, 1965, 1970–1990, 2001, 2002 |
| 10 | Niedziczanka – Niedzica | 136.4 | B | 1984–2003 |
| 11 | Wielki Rogoźnik – Ludźmierz | 124.3 | B | 1970–1990 |
| 12 | Ochotnica – Tylmanowa | 107.6 | B | 1984–2003 |
| 13 | Czarny Dunajec – Kojsówka | 93.7 | A | 1971–1990 |
| 14 | Poroniec – Poronin | 78.8 | A | 1971–1990 |
| 15 | Grajcarek – Szczawnica | 75.4 | A | 1984–2003 |
| 16 | Łubinka – Nowy Sącz | 66.3 | A | 1984–2003 |
| 17 | Białka Tatrzańska – Łysa Polana | 63.1 | A | 1970–1990, 1996, 2001, 2002 |
| 18 | Smolnik – Klęczany | 63.0 | A | 1984–2003 |
| 19 | Biały Dunajec – Harenda | 58.4 | A | 1964–1990, 1996, 2001, 2002 |
| 20 | Lepietnica – Ludźmierz | 50.7 | A | 1971–1990, 1996, 2001, 2002 |

* A – small sub-basin: < 100 km$^2$; B – medium sub-basin: 100–300 km$^2$; C – large sub-basin: 300–1000 km$^2$; D – very large sub-basin: > 1000 km$^2$

## 4. DATA

Data from 20 river profiles were analyzed (Table 1). Data verification was performed for the purpose of identifying heterogeneity. The following data have been taken into consideration:

- 10-day river discharge averages for the warm season, i.e. from April to September for the 1951–2003 time period (the length of data sets varies according to data availability);
- Hurrell's winter NAO index and monthly NAO values (December, January, February, March) (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

Using 10-day river discharge values tends to be more appropriate for the analysis of river flow dynamics in medium and large basins and sub-basins. 10-day averages represent large scale climatic influence on extreme hydrological processes more accurately than do daily maxima. This may be caused by short-term rain events resulting from local weather conditions – mainly air masses convection (Cebulak 1998–1999).

## 5. METHODS

An extreme flood event (EFE) is one which differs from an ordinary hydrological event by an order of magnitude. The EFEs considered in this paper are defined as ones which exceed a certain threshold discharge $Q_{EMax}$ (Ozga-Zielińska 1990). This threshold value has been specified based on a statistical approach that describes the dispersion of daily river discharges, i.e. a standard deviation. This approach assumes that an EFE might not occur every year. The threshold value $Q_{EMax}$ was calculated according to this formula:

$$Q_{EMax} = Q_M + 10\ STD \tag{1}$$

where:
$Q_{EMax}$ – the threshold value of EFE,
$Q_M$ – mean daily river discharge,
$STD$ – standard deviation of the daily discharge data set.

10-day river flow averages were analyzed and a coefficient of variation $(C_v)$ was calculated for each 10-day period for selected months. The following formula was used:

$$C_v = STDD / Q_{MD} \tag{2}$$

where:
$STDD$ – standard deviation of 10-day averages,
$Q_{MD}$ – average 10-day discharges.

Linear correlation analysis for 10-day discharge averages and winter and monthly NAO indices was performed. Only results with a statistical significance of 95% were taken into consideration. Furthermore, the significance of these correlations was analysed using the Monte Carlo Method (Koronacki, Mielniczuk 2006).

## 6. RESULTS

The analysis of the data indicates that the 10-day periods most frequently affected by EFEs in the Dunajec River drainage basin are the third 10-day period of July (31 EFEs), the second 10-day period of June (26 EFEs), and the second 10-day period of July (22 EFEs) (Table 2). The above 10-day periods may be described as the most flood-prone periods of the year.

Table 2. Number of EFEs during selected 10-day periods in investigated sub-basins

| Month | April | | | May | | | June | | | July | | | August | | | September | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10-day period | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Number of EFEs | 3 | - | 4 | 16 | 4 | 17 | 6 | **26** | 11 | 19 | **22** | **31** | 21 | 2 | 16 | 6 | - | 1 |

Analysis of 10-day hydrological data sets has shown very strong intra-month variability. This variability is prevalent during some months and in some sub-basins – particularly small ones. For example, the coefficients of variation ($C_v$) of 10-day discharge averages in the Lepietnica–Ludźmierz sub-basin for the first, second, and third 10-day periods of July are 0.88, 0.64, and 1.21, respectively. In the Biały Dunajec–Harenda sub-basin, coefficients of variation for the first, second, and third 10-day periods of July are 0.74, 0.8, and 1.4, respectively.

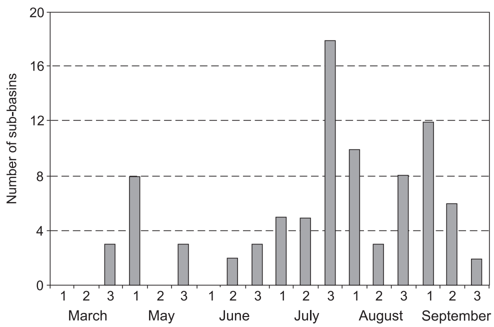


Fig. 2. Number of sub-basins with a mean 10-day discharge coefficient of variation $C_v > 1$

10-day discharge averages tend to have a wide range of values. The highest coefficient of variability was calculated for the third 10-day period of August in Wielki Rogoźnik–Ludźmierz ($C_v$ = 2.03), and the lowest one for the second 10-day period of April in Poroniec – Poronin ($C_v$ = 0.3). The most variable 10-day periods in most of the investigated sub-basins are the third 10-day period of July and the first 10-day period of September (Fig. 2). For the third 10-day period of July, the variability coefficient $C_v$ for 10-day discharge averages is >1.0 in the case of 18 sub-basins while for the first 10-day period of September, this is true for 12 catchments. It is quite interesting that for the second 10-day period of July (number of EFEs = 22; Table 2) variability is very high ($C_v$ >1.0) for only five sub-basins: small (Poroniec–Poronin, Klęczany–Smolnik, Łubinka–Nowy Sącz), medium (Biała Tarnowska–Grybów), and large (Łososina–Jakubkowice). It is also important to note that most of the sub-basins in this group are small.

The number of sub-basins with a much lower level of variability ($C_v$< 0.5) is small: 50% of sub-basins are characterized by very low variation coefficients in the third 10-day period of April and the second 10-day period of May (Table 3).

Five sub-basins during the third 10-day period of June are characterized by very low values of $C_v$. Two of them belong to the small sub-basin category (Czarny Dunajec–Kojsówka, Białka–Łysa Polana) and three of them represent very large sub-basins (Dunajec–Krościenko, Dunajec–Gołkowice, Dunajec–Czchów).

Table 3. Number of sub-basins with low coefficients of variation for particular 10-day periods ($C_v < 0.5$)

| Month | April | | | May | | | June | | | July | | | August | | | September | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10-day period | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| $C_v$<0.5 | 3 | 7 | **10** | 4 | **8** | 3 | 2 | 2 | 5 | 1 | 1 | - | 1 | - | - | - | 1 | 2 |

There are some years when there is a very high number of EFEs. The years 1973 (14 EFEs), 1983 (12 EFEs), and 1989 (21 EFEs) are examples. According to the classification system of circulation periods researched by Degirmendžić *et al.* (2000), the above mentioned years were characterized by very strong zonal flow during the winter only. The intensity of zonal flow may be expressed using the NAO index. A number of relationships were identified based on an analysis of Hurrell's index and 10-day discharge averages. In many cases, correlation coefficients were very low and statistically insignificant. However, the number of significant correlation coefficients for 10-day discharges and the NAO index for December (NAO-12) is higher than the number of correlation coefficients between 10-day discharges and the winter NAO index. Unfortunately, not many of them are referred to as "summer flood periods" as they are mostly based on 10-day periods from April, May, and September. As the hydrological data sets used were not extensive, it was important to check the random character of each calculated correlation coefficient. Hence, the real confidence level (RCL) was calculated for correlation coefficients by applying the Monte Carlo method (Koronacki, Mielniczuk 2006; Table 4).

## 7. CONCLUSIONS

The extreme flood event threshold taken into consideration in this paper is based on the standard deviation of daily discharges data series. Strong intra-month variability during some months was detected based on 10-day discharge averages. Analysis of these values makes it possible to forecast the occurrence time of an EFE with more temporal accuracy.

It may be stated, that the third 10-day period of July and the second 10-day period of June are the periods most frequently affected by EFEs in the Dunajec River drainage basin (flood-prone periods). The 10-day periods experiencing the most variability in most of the investigated sub-basins are the third 10-day period of July and the first 10-day period of August. The coefficient of variation is high for small, medium, and large sub-basins. It is important to note that most of the affected sub-basins are small in area.

Some sub-basins and some 10-day periods (third 10-day period of April, second 10-day period of May, third 10-day period of June) are characterized by low values of coefficients of variation.

Table 4. Correlation coefficient (α ≤ 0.05)/RCL (real confidence level) between the winter NAO index (a) and the December NAO index (b) and 10-day discharge averages; number of sub-basins based on Table 1

| No | | April | | | May | | | June | | | July | | | August | | | September | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | – | – | – | 0.3/3.3 | – | – | – | – | -0.37/1.8 | -0.32/3.9 |
| 2 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.26/3.6 | – | – | – |
| | b | – | – | – | – | – | – | – | – | 0.3/2.2 | – | – | 0.24 /0.5 | – | – | – | – | – | -0.28/3.2 |
| 3 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.32/5.8 | -0.39/2.3 | – |
| | b | – | 0.35/3.4 | – | – | – | – | – | – | 0.39/2.1 | – | – | – | – | – | – | -0.37/2.0 | -0.44/0.5 | -0.43/1.2 |
| 4 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.27/40 | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | – | – | – | – | – | 0.23/4.9 | – | – | -0.31/2.71 | -0.33/1.67 |
| 5 | a | – | – | – | – | – | – | 0.41/3.3 | – | – | – | – | -0.41/3.9 | – | – | – | -0.38/4.5 | -0.61/0.1 | -0.48/1.5 |
| | b | 0.51/0.6 | 0.47/1.6 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.47/0.9 | – |
| 6 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | 0.3/1.2 | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | 0.23/4.4 | – | – | – | – | – | – | -0.24/3.5 | -0.3/1.1 | -0.25/3.2 |
| 7 | a | – | – | – | – | – | – | – | – | – | | | | – | 0.38/4.8 | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | – | – | – | 0.39/4.1 | – | – | – | – | – | – |
| 8 | a | – | – | – | 0.41/3.3 | – | 0.48/1.4 | – | – | – | – | – | – | – | -0.41/3.8 | – | – | -0.54/0.5 | -0.56/0.4 |
| | b | 0.57/0.3 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.43/1.9 | – |
| 9 | a | – | – | – | 0.48/0.4 | – | – | – | – | – | – | – | – | -0.36/3.8 | – | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | – | 0.31/4.6 | – | – | – | – | 0.32/0.44 | – | – | – |
| 10 | a | – | – | – | – | – | – | – | – | – | – | – | -0.39/4.0 | – | – | – | – | – | – |
| | b | 0.46/2.5 | 0.41/3.5 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.5/0.8 | -0.36/4.5 |
| 11 | a | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | – | – | – | – | – | – | – | 0.41/2.9 | – | – | – | 0.42/2.5 | -0.49/1.1 | – | – | – | – | – |
| 12 | a | – | – | – | – | – | – | – | – | – | – | – | -0.45/2.1 | -0.39/4.8 | -0.46/2.0 | – | – | -0.54/0.3 | -0.55/0.4 |
| | b | 0.6/0.4 | 0.53/0.7 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.47/0.3 | -0.52/0.4 |
| 13 | a | – | 0.39/4.4 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | – | – | – | – | 0.43/3.1 | – | 0.44/2.4 | 0.66/0.1 | 0.44/2.6 | – | – | – | – | – | – | – | – | – |
| 14 | a | – | – | – | 0.44/3.3 | – | – | – | 0.41/3.5 | – | – | 0.39/4.5 | – | – | – | – | – | – | – |
| | b | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| 15 | a | – | – | – | 0.41/3.4 | – | -0.42/3.0 | – | – | – | – | – | -0.39/4,6 | – | -0.41/3.4 | – | – | -0.55/0.3 | -0.56/0.3 |
| | b | 0.51/0.8 | 0.5/1.1 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.46/0.6 | -0.4/3.4 |
| 16 | a | – | – | – | 0.39/0.41 | – | -0.52/4.1 | – | – | – | – | – | – | -0.52/0.8 | – | – | -0.4/3.7 | -0.52/0.5 | -0.53/0.6 |
| | b | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.46/0.3 | -0.47/1.3 |
| 17 | a | 0.4/1.5 | 0.5/0.3 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | – | – | – | – | 0.33/3.9 | – | 0.32/4.3 | – | – | – | – | – | – | – | – | -0.35/2.4 | -0.32./4.3 | – |
| 18 | a | – | – | – | – | – | -0.63/0.7 | – | – | – | – | – | -0.59/1.9 | -0.56/2.3 | – | – | -0.5/4.2 | -0.61/2.0 | -0.62/1.4 |
| | b | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.54/2.0 | -0.63/0.4 | -0.58/1.5 |
| 19 | a | 0.37/2 | 0.33/3.4 | – | 0.4/1.1 | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | 0.33/3.8 | 0.39/1.6 | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.32/3.8 | -0.44/0.6 | -0.48/0.3 |
| 20 | a | – | – | -0.39/3.1 | 0.39/3.3 | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| | b | 0.41/2.5 | 0.37/3.9 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | -0.37/4.0 | -0.51/0.6 |

– insignificant correlation coefficient (α ≤ 0.05)

Statistically significant relationships between Hurrell's winter index, the NAO-12 index, and EFE discharges were identified. They are mostly based on 10-day periods in April, May, and September. Higher than usual discharge during spring and early summer 10-day periods and lower than usual discharge during 10-day periods in September and August are associated with a positive NAO phase during the preceding winter. River discharge in small and medium sub-basins during the third 10-day period of July is also associated with a positive NAO phase during the preceding winter. The above mentioned relationships may be helpful in the evaluation of streamflow response to winter NAO changes.

## ACKNOWLEDGEMENTS

The project was supported by the Polish Committee for Scientific Research (PBZ-KBN-086/PO4/2003).

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