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Comparative Mountain Hydrology: A Case Study of Wisłok River in Poland and Chaohe River in China

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Abstract: Hydrological processes in river basins of similar size and morphology may differ significantly due to different climatic conditions. This paper presents a comparative analysis of hydrological characteristics of two river basins located in different climatic zones: the Wisłok River Basin in the south-eastern Poland and the Chaohe River Basin in the northern China. The criteria of their choice were similarities in the basin area, main river length and topography. The results show that climate plays a key role in shaping fluvial conditions within the two basins. It is concluded that: 1) precipitation in the Wisłok River Basin is more evenly distributed in the yearly cycle, while in the Chaohe River Basin it is highly concentrated in the few summer months; 2) spring snowmelt significantly contributes to runoff in the Wisłok River Basin, while its role in the Chaohe River Basin is negligible; 3) in the Wisłok River Basin, besides the peak flow in spring, there is also a period of high water in summer resulting from precipitation, while in the Chaohe River Basin there is only one high water period in summer; 4) the Wisłok River Basin shows relatively higher stability in terms of the magnitude of intra- and inter-seasonal discharges; 5) during the multi-year observation period, a decrease in both precipitation and runoff was recorded in the two river basins.

Keywords: comparative hydrology; mountain area; Wisłok River Basin; Chaohe River Basin; seasonal changes; inter-annual changes

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1 Introduction

Comparative analysis is a relatively new, yet important approach in hydrological studies. Its main assumptions were defined within the Third International Hydrological Programme (IHP, 1981; 1985). Liu (1987) concluded that comparative studies enhance our understanding of the hydrological processes occurring in various geographical regions, and increase our predictive ability through the transfer of information obtained in areas sharing similar regional attributes. Woo and Liu (1994) pointed out that over the years each country has evolved different methodological approaches, each with its own strengths and weaknesses. Comparative hydrology offers a vehicle to accelerate communication. On that basis Woo and Liu (1994) provided a case study on mountain hydrology of Canada and China, which indicated that mountain regions have sparse data networks and their hydrological activities reflect large spatial and temporal variations caused by a set of processes, many of which have not been fully examined. Kovács (1984) considered morphology of terrain and climate as decisive factors characterizing regional hydrology and proposed a coordinating matrix for comparative hydrology of watersheds in different climatic zones. The comparative study carried out by Sun *et al*. (2002) suggested that

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climate is the most important factor influencing the watershed water balance, while topography is important in shaping watershed baseflow patterns and storm peak and volume in the southern United States. Peel *et al.* (2001) proved continental differences in the variability of annual precipitation and runoff; they suggested that the continental distributions of evergreen and deciduous vegetation are two main factors causing these differences. Allan *et al.* (2002) examined land use and cover within a series of river valleys of the Venezuelan Andes and agreed that land-use changes within these watersheds are likely to alter hydrology, sediment transport and habitat conditions within river systems, with adverse consequences for aquatic biodiversity. The research results of Musiake (2003) indicated that while the basic concepts of investigating hydrological processes were developed in Europe, more than 60% of the Earth′s population live in the humid climate region influenced by the Asian monsoon. Furthermore, a significant number of people live in mountainous parts of this region. Kondoh *et al.* (2004) mapped hydrological regions in monsoon Asia on the basis of the water budget, while Deans and Munro (2004) analyzed water use by dryland trees in Parklands in Senegal and proved that comparing water use by different tree species provides information that may be useful in guiding species selection for drylands. Araújo and Piedra (2009) provided a comparative approach of two tropical watersheds in a semiarid and humid environment of Brazil and Cuba. Comparative approach was also applied by Roux *et al.* (2010) in an attempt to produce time series of river water height of the Negro River, a tributary of the Amazon River, by means of satellite radar altimetry, while Jebamalar and Ravikumar (2011) carried out a comparison study on the implementation of rainwater harvesting (RWH) structures and the hydrological responses in two different settlements in India and found that the recharge and quality have been improved due to RWH.

As it can be seen from the above review of literature, comparative approach is a widely used method in hydrological studies. The aim of this study is to examine and compare the rainfall-runoff behavior of two river basins located in the mountain areas of Europe and Asia, respectively, thus contributing to the discussion on the further development of comparative hydrology.

2 Study Area

One of the basic requirements of a comparative approach is the selection of areas sharing similar regional attributes to explore overlaps in their hydrological processes and their hydrological responses to these attributes (Woo and Liu, 1994). In this study, two river basins: the Wisłok River Basin (denoted as WRB) in the southeastern Poland and the Chaohe River Basin (denoted as CRB) in the northern China were compared. The criteria of their selection were similarities in area, main river length and relief. Availability of a comparable long-term hydrological data also played an important role in the selection process. The selected characteristics of the studied basins are synthesized in Table 1 and shown in Fig. 1.

According to the geographical regionalization of Poland by Kondracki (2002), the 220-km long Wisłok

Table 1 Main characteristics of Wisłok River and Chaohe River basins

Characteristics	Wisłok River Basin	Chaohe River Basin
Catchment area (km^2)	3516^a (3540^b)	4266^a (6169^b)
Main river length (km)	219	227
River network density (km/km^2)	0.61	0.33
Main river slope (m/km)	2.76	7.96
Relief (m a.s.l.)	166–848	54–1861
Geology	Flysch rocks, loess	Sedimentary and metamorphic rocks
Soil	Brown soil, river soil	Alluvial loam soil
Land use type	Plough land, meadow, forest	Plough land and forest
Vegetation	Deciduous and mixed forests	Coniferous and mixed forests, scrub and grass formations
Köppen climate classification	Cold without dry season and with warm summer (Dfb)	Cold with dry winter and hot summer (Dwa)
Pardé river regime classification	Complex with two or more high water periods	Simple with one high-water and one low-water period

Notes: a, area controlled by gauging station; b, total area

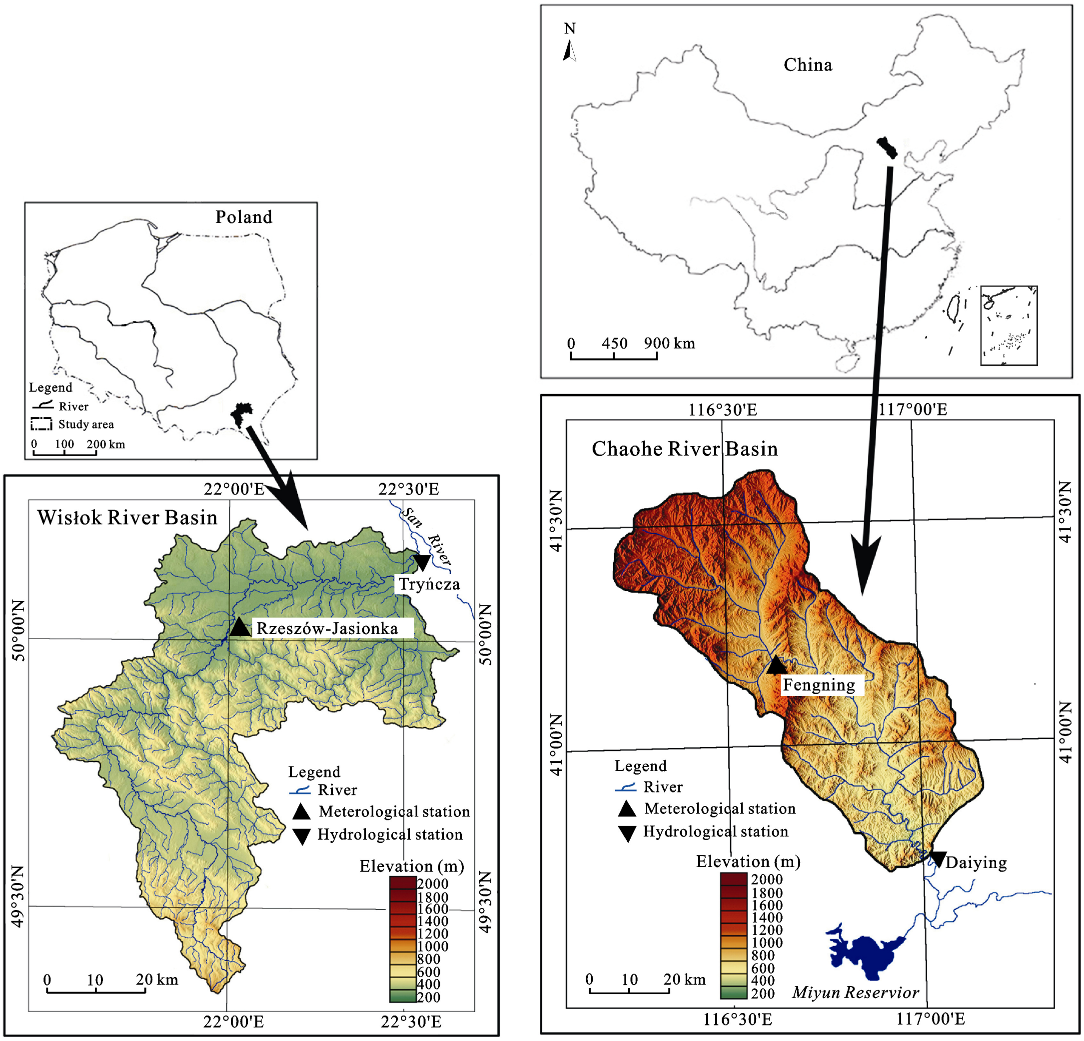

Fig. 1 Location of study areas

River has its source in the Beskid Niski Mountains (up to 900–1000 m a. s. l.), flows north-eastwards, and after crossing the Pogórze Dynowskie area (up to 500 m a. s. l.). It enters the Pradolina Podkarpacka (Carpathian Glacial Valley) (200–280 m a.s.l.), where it empties into the San River, a tributary of the Vistula (Wisła)—the largest and the longest river of Poland (Czarnecka, 2005). In terms of geology, flysch rocks, mostly Tertiary slates and sandstones, are predominant in the upper and middle reaches of the WRB, while the lower reaches occupy the Pleistocene loess formations. Additionally, river valleys are filled in with Holocene gravel (Marks *et al.*, 2006). Brown soils are widespread, with sands and river soils common in the river valleys.

In the land use pattern there is predominance of plough lands and meadows in valleys, with broadleaf and mixed forests located mainly in the uplands of the Beskid Niski and Pogórze Dynowskie areas. The source of the Wisłok River is located in a protected forest area. The population of the WRB is about 390 000. There are two dams on the Wisłok River mainstream: one in the lower reaches, near the city of Rzeszów, constructed in 1973 in order to create an artificial Rzeszowski Reservoir (area: 68.2 ha; volume: 1.8×10^6 m^3) serving as a source of drinking water, and another one in the upper reaches, near the town of Sieniawa, built in 1978, with the Sieniawski Reservoir (area: 1.3 km^2; volume: 13.2×10^9 m^3) mainly for the flood-prevention purposes.

The WRB is situated in the transitional climate zone between the temperate climate in the west and a continental climate in the east. Prevailing (87%) are the westward and north-westward winds bringing humid Atlantic air. The eastward winds (13%) appear mostly in winter, bringing dry and cold air from Asia. According to the Köppen climate classification (Peel *et al.*, 2007), the area has a cold climate without dry season and with warm summer (Dfb). When applying the classification of fluvial regimes by Pardé (1957), the WRB has a complex nivo-pluvial regime with one period of high runoff in spring and one in summer.

The 227-km long Chaohe River rises in the Yanshan Mountain located the north of the North China Plain and flows southwards into the Miyun Reservoir (built in 1958–1960, area of 183.6 km^2, max. volume of 4.375×10^9 m^3), one of the main sources of drinking water for Beijing (Zhu, 1992; Zhu *et al.*, 2011). The stratum lithology is mainly volcano sedimentary series of the Jurassic and metamorphic rocks from the Miyun Cluster (Zhou *et al.*, 2008). Alfisols and eluvial soils are predominant (Wang and Zuo, 2009). Coniferous and mixed forests along with scrub and grass formations are widespread on the slopes, while river valleys are occupied by plough lands (Zhou *et al.*, 2008).

The CRB remains under the influence of the monsoon circulation between the Pacific Ocean and the Asian landmass. Köppen classified its climate as cold with dry winter and hot summer (Dwa) (Peel *et al.*, 2007). The river has simple regime with one period of high water and one period of low water (Pardé, 1957).

3 Data and Methods

3.1 Data sources

In this study, data from meteorological and hydrological stations located in the two basins were analyzed. Data sets collected at Rzeszów-Jasionka meteorological station (50°06′N, 22°03′E, 200 m a. s. l.) in the WRB included: daily maximum, minimum and average temperature, daily precipitation and snow cover depth in the multi-year study period of 1961–2009 (49 years). Daily discharges from the same period were collected at Tryńcza hydrological station (50°09′N, 22°32′E, 167 m a. s. l.), which controls 99.3% of the basin area. Data from the CRB included: daily records of maximum, minimum and average temperature, precipitation and evaporation from the period 1956–2002 (47 years) recorded at Fengning meteorological station (41°14′N, 116°37′E, 683 m a. s. l.). Daily discharges from 1960 to 2002 (41 years) were collected at Daiying hydrological station (40°43′N, 117°09′E, 220 m a. s. l.), which controls 69.1% of the analyzed basin (Fig. 1).

3.2 Methods

The hydrological year in Poland lasts from 1 November to 31 October of the next year, and is additionally divided into the winter (1 November–30 April) and summer (1 May–31 October) seasons. In order to facilitate the comparison, such division was also applied in the analyses of the CRB characteristics.

This study consists of two parts: in the first part the analyses of annual changes in precipitation and fluvial regimes in the two basins are carried out, while in the second part inter-annual tendencies are analyzed and compared. That approach allows finding both seasonal and long-term similarities and differences between the WRB and CRB. To make the analysis comparable, in the second part of the study period of 1961–2001, common for the two basins was taken into account. In the trend analysis, the 5-year moving average and the cumulative deviation from the mean methods were applied.

In the analyses of the fluvial regimes, besides the relative values of the discharges (Q), the absolute values, the coefficient of discharge (C_Q), runoff depth (H) and specific discharge (q) were also taken into account. This allowed comparative analyses regardless of the areas occupied by the investigated river basins.

The coefficient of discharge (C_Q), introduced by Pardé (1957), shows seasonal variations of water discharge, and the equation is as follows:

$$C_Q = \frac{\overline{Q_{\mathrm{m}}}}{\overline{Q_{\mathrm{yr}}}} \tag{1}$$

where $\overline{Q_{\mathrm{m}}}$ is average monthly discharge (m^3/s); $\overline{Q_{\mathrm{yr}}}$ is average yearly discharge (m^3/s). If $C_Q > 1$, discharge of a specific month is higher than the yearly average, if $C_Q < 1$, discharge is lower than the yearly average.

In order to compare the yearly course of discharges, the hydrological periods were separated using a method introduced by Rotnicka (1976; 1977; 1988). In that method, separation of the hydrological periods is based on the assumption that particular characteristic (for example, daily specific discharge) is identical or at least similar over a certain period of time. The particular characteristic allows that period of time to be distinguished from the neighboring ones. Therefore, it is possible to define the boundaries of a particular time series. The elementary time unit is a 5-day period called pentad. The hydrological year consists of 73 pentads, each representing five values of daily specific discharges. The grouping characteristic is described by the variable x, which is the probability distribution of occurrence of daily specific discharges.

In this study, the similarity of probability distributions of daily specific discharges was determined by using the two-sample Kolmogorov-Smirnov test. The test statistic is as follows:

$$D_{n1n2} = \sup|F_{n1}(x) - F_{n2}(x)| \tag{2}$$

where D_{n1n2} is the two-sample Kolmogorov-Smirnov test statistic; F_{n1} and F_{n2} are the empirical distribution functions of the first and the second samples (pentad), respectively.

The H_0 hypothesis is rejected at level α if:

$$\sqrt{\frac{n1n2}{n1+n2}}D_{n1n2} > \lambda_\alpha \tag{3}$$

where λ_α is the critical value for each level of α.

As a result of the H_0 hypothesis testing ($\alpha = 0.05$), the similarities between all possible pairs of probability distributions of the annual pentad sets are defined. This provides a basis for constructing a square matrix of similarity diagrams for the annual sets of pentads. The obtained diagrams show the internal structure and relationships between the pentads in terms of similarity of their characteristics (specific discharges), allowing to distinguish the hydrological periods. That method was applied, among others, by Wrzesiński (1999) and Sobkowiak (2009).

Finally, on the basis of the daily discharges, the probability distributions of the maximum discharges at the analyzed gauges were calculated and compared using the QMAXP method proposed by the Institute of Meteorology and Water Management in Warsaw. In that method, besides the probabilities of the largest winter $p_w(z)$ and summer $p_s(z)$ discharges, also the probability distribution of the maximum annual discharge $p_A(z)$ is determined as the probability of alternative of two non-exclusive (inseparable) and independent events:

$$p_A(z) = p_w(z) + p_s(z) - p_w(z)p_s(z) \tag{4}$$

where $p_A(z) = P(Z > z)$, exceedance probability of the maximum annual (winter or summer) discharge z; $p_w(z) = P(X > z)$, exceedance probability of the maximum winter discharge $x = z$; $p_s(z) = P(Y > z)$, exceedance probability of the maximum summer discharge $y = z$.

Details of the calculation procedure are described in Ozga-Zielińska *et al*. (1999). Selected climatic and fluvial regime characteristics of the two basins are shown in Table 2 and Table 3.

Table 2 Main climatic characteristics of Wisłok River Basin and Chaohe River Basin

Characteristics	WRB	CRB
Absolute max./min. temperature/amplitude (℃)	34.5/–35.8/70.3	40.5/–28.6/69.1
Average max./min. temperature/amplitude (℃)	12.8/3.5/16.3	14.2/0.0/14.2
Average daily temperature (℃)/CV	8.1/0.93	6.7/0.53
Average yearly precipitation (mm)/Me/CV	646.8/652.4/0.19	476.9/474.0/0.21
Precipitation of winter months (Nov.–Apr.) (mm)/percentage of yearly precipitation (%)	217.9/33.7	33.3/7.0
Precipitation of summer months (May–Oct.) (mm)/percentage of yearly precipitation (%)	429.3/66.3	443.6/93.0
Max./min. yearly precipitation (mm)/CV	1008.6/381.1/5.2	705.9/289.5/4.9
Max. 24 h precipitation (mm)	62.2	85.4
Average number of days with/without precipitation (d)	164.3/201.0	79.9/285.4
Wettest month: average precipitation (mm)/CV	July: 90.6/0.51	July: 141.5/0.44
Driest month: average precipitation (mm)/CV	February: 29.4/0.60	December: 1.2/1.55
Month with largest number of days with precipitation: (d)	December: 16.0	July: 16.0
Month with smallest number of days with precipitation: (d)	October: 11.6	December: 1.0
Months with snow	November–March (sporadically October and April)	NA
Average number of days with snow cover (d)	68.6	NA
Max. daily snow cover depth (cm)	53	NA
Max. monthly cumulative snow cover depth (cm)	2811	NA
Min. monthly cumulative snow cover depth (cm)	100	NA
Evaporation (mm)/aridity coefficient	418.4/0.65	421.0/0.88

Notes: WRB, Wisłok River Basin; CRB, Chaohe River Basin. Me, median; CV, coefficient of variation; NA, not available

Table 3 Main fluvial regime characteristics of Wisłok River Basin and Chaohe River Basin

Characteristics	WRB	CRB
Average annual discharge (m^3/s)	25.5	7.57
Kurtosis of annual discharge	0.67	3.18
Coefficient of skewness of annual discharge	0.53	1.71
Average annual volume of discharged water (10^6 m^3)	804.72	238.89
Average annual runoff depth (mm)	228.4	56.0
Average annual specific discharge ($dm^3/(s\cdot km^2)$)/Me ($dm^3/(s\cdot km^2)$)/CV	7.24/4.63/0.30	1.77/0.91/0.68
Average specific discharge of winter semester (Nov.–Apr.) ($dm^3/(s\cdot km^2)$)/percent of yearly discharge (%)	4.21/58.2	0.44/24.6
Average specific discharge of summer semester (May–Oct.) ($dm^3/(s\cdot km^2)$)/percent of yearly discharge (%)	3.03/41.8	1.33/75.4
Highest specific discharge month ($dm^3/(s\cdot km^2)$)/CV	March: 13.08/0.49	August: 7.34/1.11
Lowest specific discharge month ($dm^3/(s\cdot km^2)$)/CV	September: 4.47/ 0.74	May: 0.35/0.57
Runoff coefficient	0.35	0.12

Notes: WRB, Wisłok River Basin; CRB, Chaohe River Basin. Me, median; CV, coefficient of variation

4 Results and Discussion

4.1 Intra-annual changes of precipitation and runoff

Analysis results of data collected in Table 2 and Table 3 suggested that rainfall is a key factor shaping the hydrological responses in the WRB and CRB. In the WRB also the role of snowfall has to be underlined. In both basins the maximum monthly sums of precipitation are recorded from June to August (Fig. 2). However, in the WRB, precipitation during those three months accounts only for 38.8% of the annual value, while in the CRB, it is as high as 71.0%. The temporal difference is even more obvious if one compares the percent share of precipitation of the summer semester (May–October) in the annual total: it is equal to 66.4% in the WRB and 93.0% in the CRB, respectively. Interestingly, in the WRB the distribution of the monthly sums of precipitation is not fully correspondent with the distribution of the number of days with precipitation: despite the highest sums observed in summer, the highest number of days with precipitation is recorded in winter (December and January) (Fig. 2).

Additionally, the maximum sums of precipitation of the summer months in the WRB are not reflected in the maximum discharges: in the WRB, they are observed in two spring months of March and April, what is closely related to high contribution of snowmelt enhanced by relatively low evaporation in that period. Dynowska (1971), who analyzed the role of snow in the fluvial regime of rivers in Poland, concluded that in the spring season the percent share of the water supply to rivers

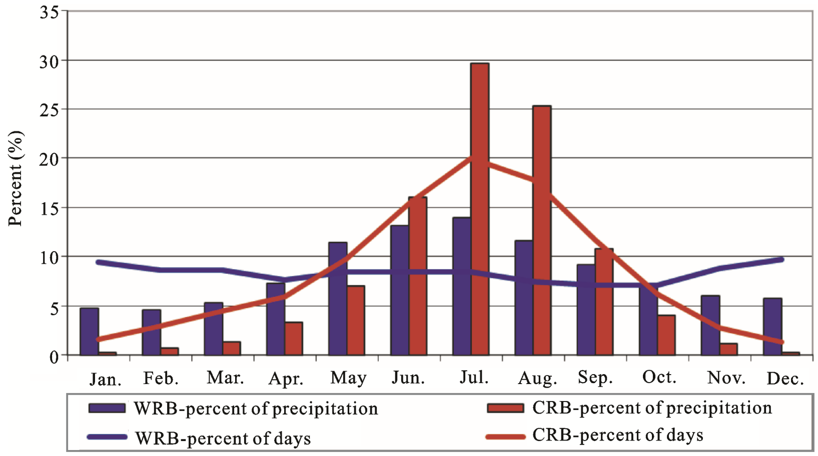

Fig. 2 Percent share of days with precipitation and of sums of precipitation in Wisłok River Basin (WRB) and Chaohe River Basin (CRB) in yearly cycle

from snowmelt in the WRB is 30%–40% and that the spring floods are generated by a combination of snowmelt and rainfall events. On average, snow cover in the WRB appears in October–November and lasts until March–April of the next year. Estimations by Dynowska (1971) also proved that contribution of the subsurface supply of rivers in the WRB is relatively lower (up to 40%), mostly due to the predominant presence of the flysch rocks and the steep slopes enhancing the surface flow. The highest (up to 50%) contribution occurs in winter, because of the snow retention, while the lowest (30%–40%) is in spring (snowmelt) and in summer (intense rainfall and evaporation). Relatively higher contribution of the groundwater recharge in autumn results from lower precipitation. In the CRB, the snowmelt contribution to the runoff seems to be negligible due to its sporadic appearance and sublimation. Therefore, the role of the monsoon circulation is predominant in the river feeding.

The constructed similarity matrices confirm relatively large differences in the yearly course of discharges of the two rivers (Fig. 3).

Kovács (1989) proposed to compare regional differences in river flow regimes using the duration curve as the accumulated form of the empirical frequency distribution or the duration surfaces, determined for each month separately, to describe the seasonal fluctuations in the water regime. On those grounds the frequency distribution histogram (Fig. 4) and the duration surfaces of the specific discharges in pentads (Fig. 5) recorded in the multi-year observation periods at the studied gauges were plotted. As it can be seen in Fig. 4, the CRB shows specific discharges highly concentrated (94.3%) from 0 dm^3/(s·km^2) to 5 dm^3/(s·km^2), while for the WRB there are only 54% records in that range.

As expected, the computed duration surfaces (Fig. 5) show that the largest specific discharges of the CRB occur in July and August, with the maximum baseflow around mid-October and the minimum in the first half of June. As to the WRB, the largest specific discharges are expected in July as a result of heavy rains, followed by those in March and April due to the snowmelt; the baseflow of the specific discharges reaches its maximum in March, while the minimum in late September and in October. This finding confirms the complex nivo-pluvial regime of the WRB concluded by Dynowska (1971).

The two basins show clear differences also if the Pardé′s coefficient of discharge is applied (Fig. 6): the

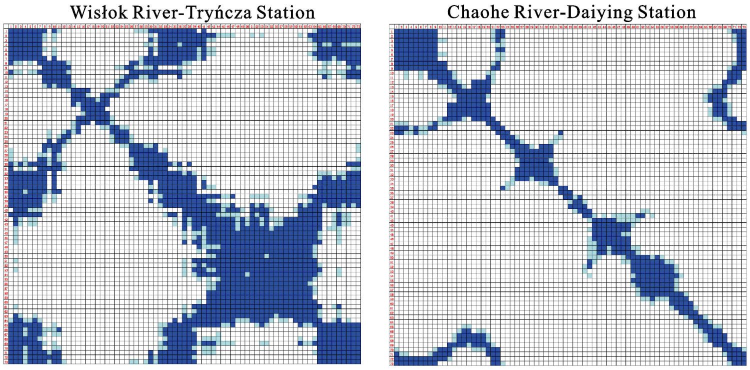

Fig. 3 Similarity matrices of specific discharges of Wisłok River Basin and Chaohe River Basin (in pentads)

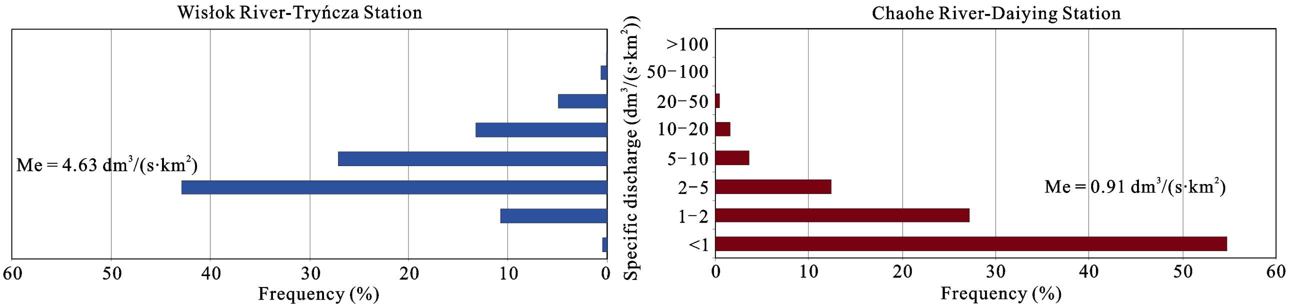

Fig. 4 Frequency distribution of specific discharges in Wisłok River Basin and Chaohe River Basin. Me, median

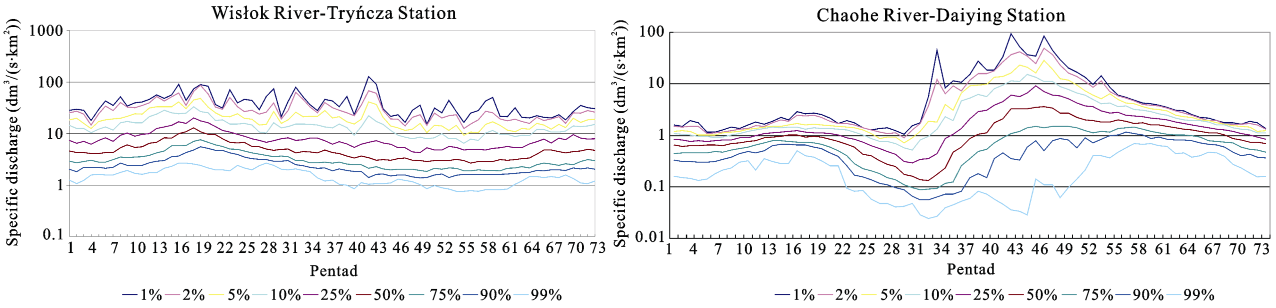

Fig. 5 Duration surfaces of specific discharges of Wisłok River Basin and Chaohe River Basin

WRB has discharges above the mean (C_Q = 1.6–1.8) in spring (March–April), mostly as a result of the snowmelt contribution. From May on, they rapidly decrease to reach the minimum (C_Q = 0.6) in autumn (September–October). Despite relatively high rainfall in summer, the discharges of that period are lower than the annual average due to high evaporation and the plants′ interception. As for the CRB, the highest (C_Q = 2.1–3.7) coefficients of discharge are concentrated in summer (July–August), to be below the yearly average through the rest of the year; the minimum (C_Q = 0.2) is in May, in accordance with the monsoon circulation pattern.

Table 4 and Fig. 7 present the maximum (specific) discharges with the defined exceedance probability calculated using the QMAXP program. The ratios of $Q_{\max, 99.9}$ to $Q_{\max, 0.01}$ are: 1 ∶ 41.8 (winter), 1 ∶ 41.2 (summer) and 1 ∶ 30.8 (annual) in the WRB, and 1 ∶ 8.2 (winter), 1 ∶ 118.1 (summer) and 1 ∶ 118.1 (annual) in the CRB, respectively. The dispersion of the extreme values suggests remarkably higher stability of the WRB than that of the CRB in terms of the magnitude of the seasonal and annual maximum discharges.

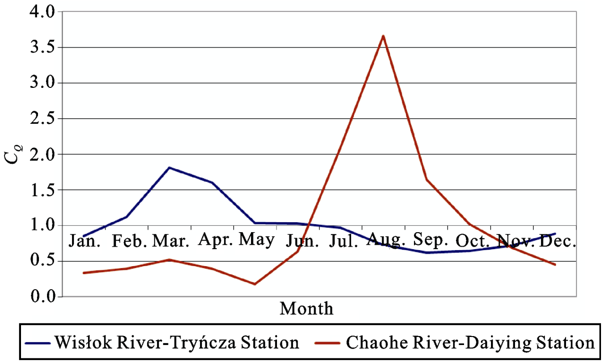

Fig. 6 Distribution of monthly coefficients of discharge (C_Q) in Wisłok River Basin and Chaohe River Basin

4.2 Inter-annual changes of precipitation and runoff

In contrast to the clearly seen differences in the seasonal distribution of precipitation and runoff, the multi-year changes in both basins show similar decreasing trends (Fig. 8).

From Fig. 9, it can be found that during 1961–2001 the annual sums of precipitation in the WRB were mostly below the average level, particularly in the second half of that period. Similar changes were observed by Brzeźniak (2003), who investigated anomalous precipitation in the WRB in the second half of the 20th century. At the same time, the average precipitation in the CRB shows cumulative values higher than the mean of 1961–1983, to be mostly below the average during 1984–2001. The precipitation patterns are reflected in the long-term changes of the specific discharges in the two basins.

The results of this study reveal that in mountain areas sharing similar environmental attributes (such as basin area, main river length and topography), climate (and more specifically rainfall and snowfall) is the decisive factor shaping the observed hydrological responses. Although further research is needed, available data on snow cover in the WRB suggest that the decreasing precipitation and runoff may also be related to the observed climate fluctuations. The duration of the snow and ice cover and their thickness are commonly used indicators of the climate warming (Skowron 1997; Magnuson *et al.* 2000; Marszalewski and Skowron, 2006; Jensen *et al.* 2007; Choiński *et al.* 2010). Figure 10 illustrates the decreasing number of days with snow and the cumulative snow cover depth in the WRB in the multi-year period of 1961–2009.

Additionally, starting from the 1970s and the 1980s both the WRB and the CRB have undergone significant

Table 4 Probability distribution of maximum winter and summer discharges (m^3/s) and specific discharges ($dm^3/(s \cdot km^2)$) (in parenthesis) at investigated stations

Probability *P* (%)	Winter (November–April)		Summer (May–October)		Alternative (November–October)	
	WR	CR	WR	CR	WR	CR
99.9	34.27 (9.75)	2.52 (0.59)	24.87 (7.07)	16.01 (3.75)	46.55 (13.24)	16.01 (3.75)
99.5	43.10 (12.26)	2.69 (0.63)	25.75 (7.32)	16.12 (3.78)	57.90 (16.47)	16.12 (3.78)
99.0	48.30 (13.74)	2.82 (0.66)	26.75 (7.61)	16.31 (3.82)	64.63 (18.38)	16.31 (3.82)
98.5	51.93 (14.77)	2.93 (0.69)	27.70 (7.88)	16.55 (3.88)	69.33 (19.72)	16.55 (3.88)
98.0	54.83 (15.59)	3.02 (0.71)	28.63 (8.14)	16.82 (3.94)	73.09 (20.79)	16.82 (3.94)
95.0	66.6 (18.94)	3.44 (0.81)	33.93 (9.65)	18.98 (4.45)	88.32 (25.12)	18.98 (4.45)
90.0	79.52 (22.62)	3.94 (0.92)	42.44 (12.07)	23.99 (5.62)	104.98 (29.86)	23.99 (5.62)
80.0	99.12 (28.19)	4.73 (1.11)	59.66 (16.97)	37.88 (8.88)	130.09 (37.00)	37.88 (8.88)
70.0	116.64 (33.17)	5.42 (1.27)	78.08 (22.21)	56.48 (13.24)	152.33 (43.32)	56.48 (13.24)
60.0	134.39 (38.22)	6.09 (1.43)	98.51 (28.02)	80.26 (18.81)	174.65 (49.67)	80.26 (18.81)
50.0	153.76 (43.73)	6.76 (1.58)	121.89 (34.67)	110.48 (25.90)	198.73 (56.52)	110.48 (25.90)
40.0	176.30 (50.14)	7.49 (1.76)	149.69 (42.57)	149.58 (35.06)	226.37 (64.38)	149.58 (35.06)
30.0	204.58 (58.19)	8.32 (1.95)	184.56 (52.49)	202.36 (47.44)	260.42 (74.07)	202.36 (47.44)
20.0	244.25 (69.47)	9.35 (2.19)	232.35 (66.08)	279.79 (65.59)	306.99 (87.31)	279.79 (65.59)
10.0	314.10 (89.33)	10.87 (2.55)	311.42 (88.57)	417.34 (97.83)	385.47 (109.63)	417.34 (97.83)
5.0	388.57 (110.51)	12.19 (2.86)	388.11 (110.38)	558.95 (131.02)	464.47 (132.10)	558.95 (131.02)
2.0	496.45 (141.20)	13.74 (3.22)	486.87 (138.47)	750.00 (175.81)	571.71 (162.60)	750.00 (175.81)
1.0	586.47 (166.80)	14.81 (3.47)	560.01 (159.27)	896.49 (210.15)	656.30 (186.66)	896.49 (210.15)
0.5	684.69 (194.74)	15.81 (3.71)	632.07 (179.77)	1044.20 (244.77)	745.32 (211.98)	1044.20 (244.77)
0.2	828.50 (235.64)	17.04 (3.99)	725.91 (206.46)	1240.88 (290.88)	872.95 (248.28)	1240.88 (290.88)
0.1	948.93 (269.89)	17.93 (4.20)	795.97 (226.39)	1390.50 (325.95)	948.93 (269.89)	1390.50 (325.95)
0.05	1080.34 (307.26)	18.77 (4.40)	865.34 (246.11)	1540.69 (361.16)	1080.34 (307.26)	1540.69 (361.16)
0.02	1272.43 (361.90)	19.83 (4.65)	956.09 (271.93)	1739.98 (407.87)	1272.43 (361.90)	1739.98 (407.87)
0.01	1432.89 (407.53)	20.60 (4.83)	1024.08 (291.26)	1891.19 (443.32)	1432.89 (407.53)	1891.19 (443.32)

Notes: WR, Wisłok River; CR, Chaohe River

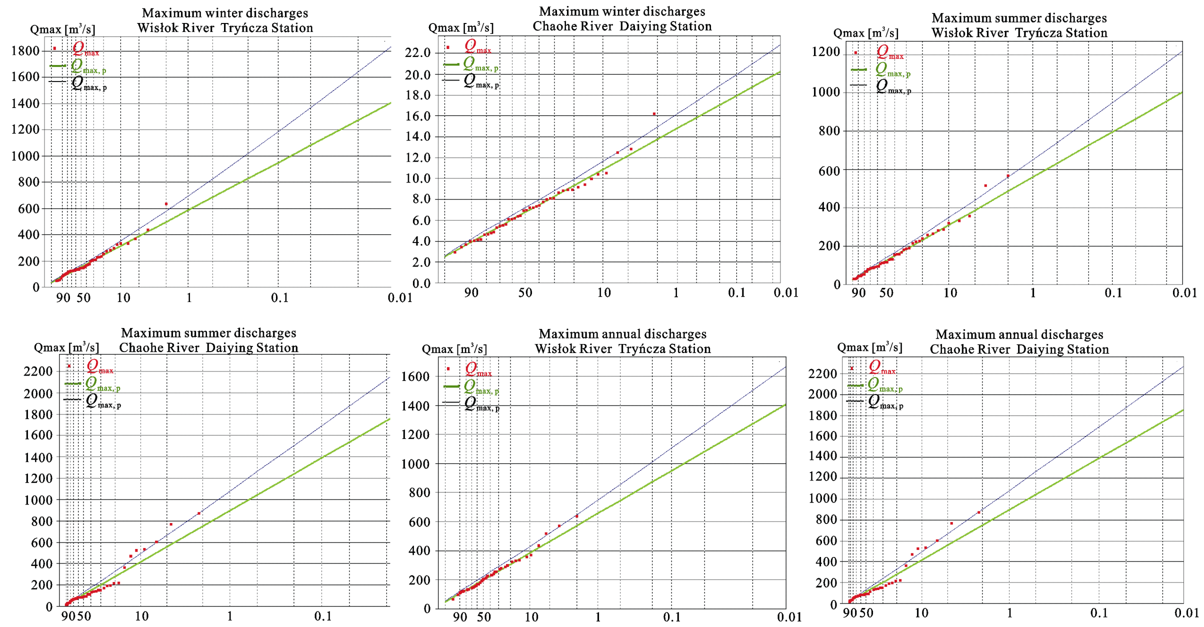

Fig. 7 Distribution of maximum discharges with defined exceedance probability at investigated stations

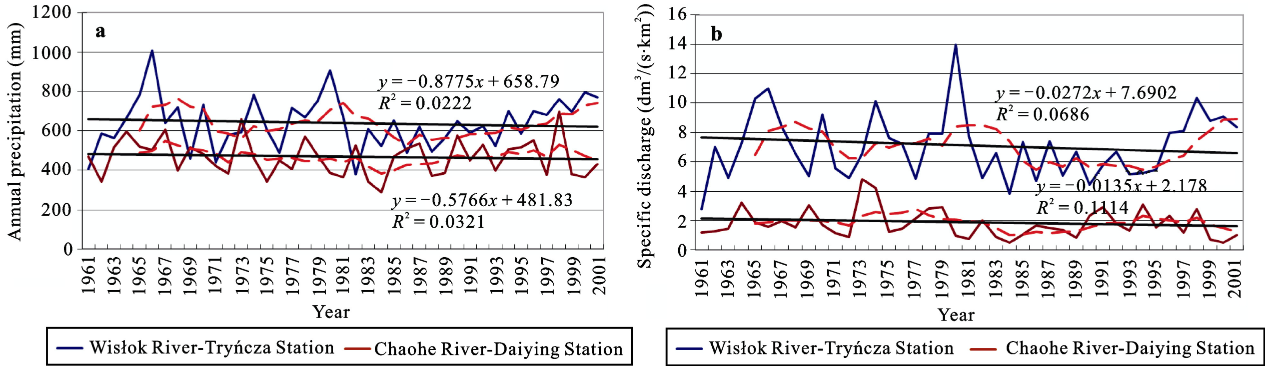

Fig. 8 Trends of precipitation (a) and specific discharges (b) at investigated stations

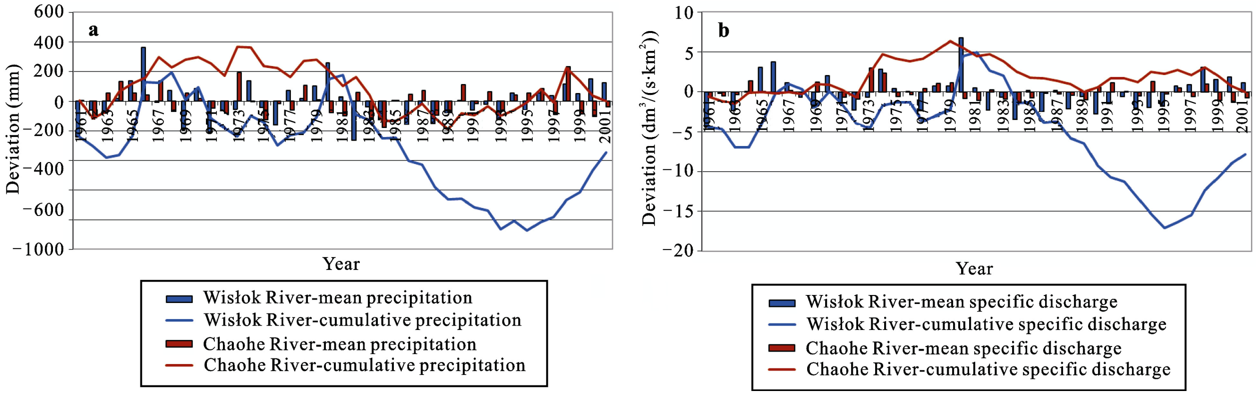

Fig. 9 Cumulative deviations from mean values for yearly precipitation (a) and specific discharges (b) at investigated meteorological stations

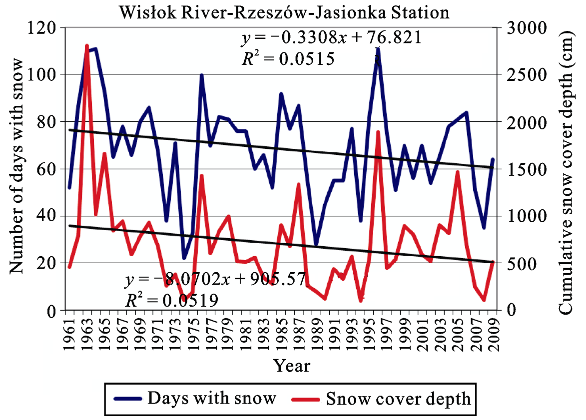

Fig. 10 Number of days with snow and cumulative snow cover depth in Wisłok River Basin

changes in their water resources development, including construction of reservoirs and extensive water use for agricultural, industrial and domestic purposes. Thus, it would be also worthy to analyse under the comparative approach the human influence on changes in the rainfall-runoff patterns in the two basins.

5 Conclusions

In this study, a comparative approach was applied to explore the rainfall-runoff behavior of two river basins of similar size, main river length and relief, located in different climatic zones. The obtained results suggest that rainfall and snowfall are the driving forces of the observed processes. There are clear differences in the seasonal course of the hydrological responses. Main conclusions obtained are as follows:

(1) Precipitation in the WRB is more evenly distributed in the yearly cycle, while in the CRB it is highly concentrated in few summer months.

(2) Snowmelt in spring period significantly contributes to runoff in the WRB, while its role in the CRB is negligible.

(3) Besides the peak flow in spring, there is also a period of high water in summer resulting from precipitation in the WRB; in the CRB there is only one high water period in summer.

(4) The WRB has relatively higher stability in terms

of the magnitude of intra- and inter-seasonal discharges.

(5) During the multi-year observation period, a decrease in both precipitation and runoff was recorded in the WRB and CRB, which may reflect the observed climate fluctuations along with the increasing human impact in the two basins.

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References

Allan J D, Brenner A J, Erazo J *et al*., 2002. Land use in watersheds of the Venezuelan Andes: A comparative analysis. *Conservation Biology*, 16(2): 527–538. doi: 10.1046/j.1523-1739.2002.02301.x

Araújo J A, Piedra J I G, 2009. Comparative hydrology: Analysis of a semiarid and a humid tropical watershed. *Hydrological Processes*, 23(8): 1169–1178. doi: 10.1002/hyp.7232

Brzeźniak E, 2003. Anomalous precipitation in Wisłok River Basin in the half-century 1951–2000. *Problems of Development of Mountain Areas*, 49: 19–35.

Choiński A, Kolendowicz L, Pociask-Karteczka J *et al*., 2010. Changes in lake ice cover on the Morskie Oko Lake in Poland (1971–2007). *Advances in Climate Change Research*, 1(2): 71–75. doi: 10.3724/SP.J.1248.2010.00071

Czarnecka H, 2005. *Atlas of the Hydrographic Division of Poland*. Warsaw: IMGW Publishing House, 117. (in Polish)

Deans J D, Munro R C, 2004. Comparative water use by dryland trees in Parklands in Senegal. *Agroforestry Systems*, 60(1): 27–38. doi: 10.1023/B:AGFO.0000009402.06475.81

Dynowska I, 1971. *Types of River Regimes in Poland*. Kraków: PWN, 152. (in Polish)

IHP (International Hydrological Programme), 1981. *Third Session of the Intergovernmental Council*. Paris, Fourth Session, 28–29 August 1981.

IHP (International Hydrological Programme), 1985. IHP-III Project 4.9. *Textbook on Comparative Hydrology Relating to the Various Hydrological Regimes of the World*: *Consolidation and Development of Information*. Paris, 17–20 June 1985.

Jebamalar A, Ravikumar G, 2011. A comparative analysis of hydrologic responses to rainwater harvesting—A case study. *Indian Journal of Science and Technology*, 4(1): 34–39.

Jensen O P, Benson B J, Magnuson J J *et al*., 2007. Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. *Limnology and Oceanography*, 52(5): 2013–2026. doi: 10.4319/lo.2007.52.5.2013

Kondoh A, Harto A B, Runtunuwu E *et al*., 2004. Hydrological regions in monsoon Asia. *Hydrological Processes*, 18(16): 3147–3158. doi: 10.1002/hyp.5754

Kondracki J, 2002. *Regional Geography of Poland*. Warsaw: PWN, 440. (in Polish)

Kovács G, 1984. Proposal to construct a coordinating matrix for comparative hydrology. *Hydrological Sciences Journal*, 29(4): 435–443. doi: 10.1080/02626668409490961

Kovács G, 1989. Techniques for inter-regional comparison. In: Falkenmark M *et al*. (eds). *Comparative Hydrology. An Ecological Approach to Land and Water Resources*. Paris: UNESCO, 140–143.

Liu Changming, 1987. A research of comparative hydrology. *Acta Geographica Sinica*, 42(2): 182–188. (in Chinese)

Magnuson J J, Robertson D M, Benson B J *et al*., 2000. Historical trends in lake and river ice cover in the northern Hemisphere. *Science*, 289(5485): 1743–1746. doi: 10.1126/science.289.5485.1743

Marks L, Ber A, Gogołek W *et al*., 2006. *Geological Map of Poland 1：500 000*. Warsaw: Polish Geological Institute.

Marszelewski W, Skowron R, 2006. Ice cover as an indicator of winter air temperature changes: Case study of the Polish Lowland lakes. *Hydrological Sciences Journal*, 51(2): 336–349. doi: 10.1623/hysj.51.2.336

Musiake K, 2003. Hydrology and water resources in monsoon Asia: A consideration of the necessity of establishing a standing research community of hydrology and water resources in the Asia Pacific region. *Hydrological Processes*, 17(14): 2701–2709, doi: 10.1002/hyp.1428

Ozga-Zielińska M, Brzeziński J, Ozga-Zieliński B, 1999. *The Rules for Calculating the Largest Annual Discharges of A Defined Probability of Recurrence in Designing Hydro-engineering Objects. Long Sets of Discharge Data*. Warsaw: Institute of Meteorology and Water Management. (in Polish)

Pardé M, 1957. *Rivers*. Warsaw: PWN, 236. (in Polish)

Peel M C, Finlayson B L, McMahon T A, 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5): 1633–1644. doi: 10.5194/hess-11-1633-2007, 2007

Peel M C, McMahon T A, Brian L F *et al*., 2001. Identification and explanation of continental differences in the variability of annual runoff. *Journal of Hydrology*, 250(1–4): 224–240. doi: 10.1016/S0022-1694(01)00438-3

Rotnicka J, 1976. The separation of hydrological periods and description of river regimes by comparison of probability distribution of water stages by pentads. *Quaestiones Geographicae*, 3: 79–102.

Rotnicka J, 1977. *The Theoretical Bases of Separation of Hydrological Periods and Analysis of River Regime—An Example of River Prosna*. *Vol. 18*. Warsaw-Poznań: PTPN Publishing House, 94. (in Polish)

Rotnicka J, 1988. *Taxonomic Bases of Classification of River Regime*. Poznań: UAM Publishing House, 130. (in Polish)

Roux E, da Silva J S, Getirana A C V *et al*., 2010. Producing time series of river water height by means of satellite radar altimetry—A comparative study. *Hydrological Sciences Journal*, 55(1): 104–120. doi: 10.1080/02626660903529023

Skowron R, 1997. *Temporal-spatial Differentiation of Temperature of Surface Waters of Lakes of Northern Poland*. UMK: Toruń. (in Polish)

Sobkowiak L, 2009. *Floods on the Yangtze River in the Sichuan Basin and Three Gorges Area. Vol. 39*. Poznań: PTPN Publishing House, 132. (in Polish)

Sun G, McNulty S G, Amatya D M *et al.*, 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the southern US. *Journal of Hydrology*, 263(1–4): 92–104. doi: 10.1016/S0022-1694(02)00064-1

Wang Jingai, Zuo Wei, 2009. *Geographic Atlas of China*. Beijing: China Cartographic Publishing House, 368. (in Chinese)

Woo M K, Liu C M, 1994. Mountain hydrology of Canada and China: A case study in comparative hydrology. *Hydrological Processes*, 8(6): 573–587. doi: 10.1002/hyp.3360080608

Wrzesiński D, 1999. *Seasonal Structure of Runoff in the Warta River Basin and Its Environmental Conditions*. *Vol. 25*. PTPN Poznań: Publishing House. (in Polish)

Zhou H Z, Chi Y B, Wang Z Y *et al.*, 2008. A study on surface water resources in Chaobaihe Basin of Beijing based on Beijing-1 microsatellite data. *The International Archives of the Photogrammetry*, *Remote Sensing and Spatial Information Sciences XXXVII*, *Part B*.

Zhu Daoqing, 1992. *Great Dictionary of River Network of China*. Qingdao: Qingdao Publishing House, 642. (in Chinese)

Zhu Junfeng, Liu Wenzhong, Suo Huixia, 2011. Preliminary analysis on hydrological correlation of Daiying Hydrologic Station. *Haihe Water Resources*, 2: 44–48. (in Chinese)