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Original Research

Statistical Characteristics of Riverflow Variability in the Odra River Basin, Southwestern Poland

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Abstract

We have analyzed the statistical characteristics of riverflow variability in the Odra River basin in southwestern Poland. In particular, we have examined the daily discharge time series recorded at 15 sites from November 1971 to October 2006. The skewness and kurtosis values of the time series are computed to determine if the empirical distribution of the data follows a normal distribution. The empirical distributions of all the time series are found to be non-Gaussian. The kurtosis values are interpreted in terms of intermittency, and together with skewness they are found to be significantly correlated with morphometric properties of the subbasins. In addition, several theoretical probability distributions are fitted to the riverflow data at each site. Among them, the 5-parameter Wakeby distribution is found to provide the best overall fit. Subsequently, the Wakeby distribution is used to calculate the return periods. Finally, the trend and stationarity around a trend of the various riverflow time series are assessed using the Cox-Stuart and Phillips-Perron (Dickey-Fuller) statistical tests. A decreasing trend is found in the daily discharge data at all sites, but there is no evidence of nonstationarity around the trend over the time span of the data record. A good understanding of the statistical characteristics of riverflow fluctuations in the Odra River basin is essential for water resources planning and management, including flood control and prediction in SW Poland.

Keywords: riverflow, Odra River, time series, extreme value distributions, trend, stationarity

Introduction

Riverflow in a specific geographical region is affected by rainfall, evaporation, topography, lithology, vegetation heterogeneity and other factors, including regional and global climatic fluctuations [1-3]. Estimation of riverflow variability is important for many practical purposes, particularly in water resources management. These include reservoir operations, irrigation management, hydroelectric power generation, flood and drought control, and recreational sports. Specifically, knowledge of temporal variability in riverflow can be used to assess extreme events of floods and droughts [4]. Development of appropriate mathematical and statistical models of riverflow variability may lead to a better understanding of riverflow dynamics and aid in forecasting and strategic planning for control of catastrophic events. The purpose of this paper is to investigate the statistical properties of riverflow variability in the Odra River basin in souhwestern Poland.

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There have been many studies on riverflow variations in basins around the world to determine the types of probability distributions that govern the riverflow patterns. Among others, Yevjevich [5] examined 140 river basins worldwide and observed that the annual streamflow in about 70% of the basins follows a normal distribution. Finlayson and McMahon [6] investigated the annual average streamflow at 974 sites in different regions of the world and concluded that at approximately 60% of these sites the streamflows can be described by a normal distribution. However, they also found that in only about 31% of sites in Australia and South Africa the streamflow can be approximated by a normal distribution. These studies indicate that for many locations, depending on geography and climatic conditions, streamflow may as well be governed by other types of distributions. For example, Markovich [7] examined annual streamflow at 446 sites throughout the United States and showed that it is best fitted by the gamma distribution. Lof and Hardison [8] analyzed the annual average streamflow across 22 water resources regions in the United States. They concluded that the normal distribution applies to the streamflows in a few states, the lognormal distribution in a few other states, and the Weibull distribution in the remaining states. More recently, Vogel and Wilson [9] examined 1,455 sites throughout the U.S. and demonstrated that the Pearson type III (P3) distribution best fits the U.S. annual minimum streamflows, whereas P3, log-Pearson type 3 (LP3) and 3-parameter lognormal (LN3) distributions are all acceptable distributions for modeling annual average streamflows. In addition, Kroll and Vogel [10] analyzed low-flow time series across the U.S., and recommended P3 and LN3 distributions at the intermittent and nonintermittent (perennial) sites, respectively. The U.S. Water Resources Council [11] advocates the use of log-Pearson Type III distribution as the appropriate model for analysis of annual peak series data.

Several researchers have examined the statistical properties of Canadian streamflows. Among them, Yue and Wang [12] identified the types of probability distributions for riverflows in different climatic regions of Canada. They showed, that depending on the region, one or more of the following distributions can be used to characterize riverflow variability: P3, LP3, LN3, and the generalized extreme value (GEV) distribution. In a recent study, Arbelaezi and Castro [13] indicated that in order to model discharges accurately, it is sometimes necessary to use more flexible distributions than those mentioned above. They found the 5-parameter Wakeby distribution to be the most suitable model for describing low-flow discharges in some ungauged basins in Colombia.

Trends in hydrologic data are also analyzed by many researchers [14-16]. There are several methods for trend detection such as the Cox-Stuart (C-S) test [15, 16], and the Mann-Kendall (M-K) test [14, 17]. Using the M-K test, Zhang et al. [18] estimated the long-term trend in 50 years of historical discharge data of the Yellow River in China. Kundzewicz et al. [19] also applied the M-K test to evaluate the trend in the annual maximum flows in various rivers throughout the world.

The Odra River, the focus of the present paper, is the second largest river in Poland. It has experienced 13 major floods since 1880 [20]. The major floods in the 20th century occurred in 1902, 1903, 1977, 1985 and 1997 [21]. Among them, the flood of July 1997 has been the most devastating [22, 23]. During this flood, 115 people died in the Czech Republic and Poland [24], and the economic loss in both countries is estimated to be nearly $ 6 bilion (U.S.).

In view of the fact that the Odra River is prone to flooding, there has been a great deal of interest in modeling and forecasting its temporal variability. Among others, De Roo at al. [25, 26] applied the physically-based LISFLOOD model for flood simulation within the Odra River basin. This model was subsequently extended by Gouweleeuw et al. [27]. For the simulation of the Odra River flow in its upper and middle reaches, Butts et al. [28] used the MIKE SHE framework, an advanced integrated hydrological modeling system. Mengelkamp et al. [29] used the Surface Energy and Water Balance (SEWAB) approach to simulate the discharge variability at sites located along the Odra River. Niedzielski [30] analyzed the discharge time series in the Odra River basin to predict extreme flows using multivariate autoregressive stochastic models. A nonstationary approach was used by Strupczewski et al. [31] for flood frequency modeling of Polish rivers. They discovered trends in their mean values and variances and fitted the optimal probability distributions to the annual maximum riverflow data. Van Gelder et al. [32] also found appropriate probability distributions to the annual maximum discharge time series of the Odra River basin to evaluate extreme events.

In this paper we investigate riverflow variability in SW Poland by analyzing the daily discharge time series at 15 sites located along the upper and middles sections of the Odra River for the period from November 1971 to October 2006. In order to characterize the statistical properties of riverflow fluctuations, we use the skewness and kurtosis measures. We also link these measures with the basic morphometric features of each subbasin, which are determined using the Geographic Information System (GIS) tools. We then fit theoretical probability distributions, such as the GEV distribution, generalized Pareto (GP) distribution, generalized logistic (GL) distribution, and the Wakeby distribution to the daily discharge data. As the Odra River is regulated by several hydro-technical infrastructures that modify the flood wave [21], we describe the human interventions and evaluate their impact on the statistical results. As the Odra River is regulated by hydro-technical infrastructure such as reservoirs that modify the flow [21], we describe these human interventions by calculating the percentage maximum upstream storage capacity of the reservoirs with respect to the mean annual flow at the various sites and estimate the extent of regulation. In order to better describe the riverflow characteristics, trends and stationarity around trends are assessed using the Cox-Stuart and the Phillips-Perron statistical tests.

A good understanding of the statistical properties of riverflow patterns in the Odra River basin is essential for water resources management, including flood control and prediction in SW Poland. The skewness and kurtosis mea-

Table 1. Upstream storage capacity as percentage of the mean annual flow in the upper and middle Odra River basin between 1971 and 2006.

Gauge	Basin area above gauge [km^2]	Height [m a.s.l.]	Ratio of maximum upstream reservoir volume to mean total annual flow [%]
Chalupki	4,596	192.60	28.7
Krzyzanowice	5,870	184.66	21.5
Miedonia	6,738	176.28	18.6
Malczyce	26,860	95.03	20.7
Scinawa	29,605	86.72	18.5
Klodzko	1,084	281.48	X
Nysa	3,253	179.30	31.9
Skorogoszcz	4,499	139.85	26.3
Olawa	957	124.83	X
Bialobrzezie	165	159.48	X
Kraskow	686	176.28	6.8
Swierzawa	136	256.67	X
Cieszyn	424	266.94	X
Lenartowice	1,084	172.43	67.4
Staniszcze Wielkie	1,099	187.52	0.4

X – no large reservoirs upstream.

sures allow us to make a better assessment of the peak flow events as well as riverflow intermittency in the regional scale. Estimation of trends, stationarity, and the probability distribution can be crucial for modeling and predicting flood wave propagation.

Study Area and Data

Upper and Middle Odra River Basin and Database

The Odra River, the second largest river in Poland, forms an integral part of the Central European drainage network. It originates at the foothills of the Sudetes Mountains in the Czech Republic, and flows northward through Polish territory into the Baltic Sea (Fig. 1). The length of the river is 854 km, including both Polish and Czech sections. The upper Odra River and its left tributaries are located in southwestern Poland and drain the Sudetes Mountains. The maximum elevation of the Sudetes Mountains is approximately 1,602 meters above sea level. The rivers draining the Sudetes are prone to serious flooding that may occur after extreme rainfall, and snowmelt leads to frequent flooding in the lowland areas of Nizina Slaska in SW Poland.

We have examined 15 sites located along the Odra River basin in SW Poland (Table 1, Fig. 1). Most of them are located within the Nizina Slaska Lowland, but there are also a few sites located in the hilly areas of the Fore-Sudetic Block, the Sudetes and the Carpathian Mountains.

Fig. 1. Study area and the distribution of hydrological gauges under study.

The time series of daily discharge for the 15 sites are obtained from:

(1) the Hydrological Yearbooks of Surface Waters 1972-1982, and

(2) the Geoserver established within project No. PBZ-KBN-086/P04/2003 financed by the Polish Ministry of Science and Higher Education.

The data spans the time interval from November 1971 to October 2006, and covers several rain- and snowmelt-induced flood events. The biggest floods during this period happened in August 1977 and July 1997, and were driven by heavy rainfall in all SW Poland with extreme values recorded mainly in the mountains [21, 22, 33].

Human Interventions in the Upper and Middle Odra River

As noted in the Introduction, there have been significant human interventions along the Odra River basin. After the great flood in 1903, 32 weirs and 32 sluices were constructed [21]. The Odra River itself is channeled between Kedzierzyn Kozle (SE sector of the study area) and Brzeg Dolny (NW sector of the study area) [34]. The regulation works include channels and embankments that aim at reducing the flood waves at some places. There are 15 polders in the Odra River valley and 12 dry reservoirs along its tributaries which were constructed to reduce the maximum discharge during floods [21]. There are also several dams and reservoirs within the study area, e.g. in Nysa. There are a total of 24 reservoirs in the Odra River basin (both in the Polish and Czech parts of the basin) that enable storage of 931 million m^3 [21].

More recently, the construction of the Raciborz reservoir has been extensively discussed [20]. There is also a plan to construct the Kamieniec Zabkowicki reservoir [21]. According to Dziubek et al. [35], the idea of building water reservoirs appeared in the late 19th century as a direct consequence of floods in 1894, 1897, 1902, and 1903. After the flood in July 1997 many hydro-technical constructions were rebuilt. Several new constructions were introduced, i.e. 3 weirs, 2 polders, and 2 flood reservoirs [21].

In order to quantify the impact of human interventions on the flow, we have computed the percentage maximum upstream storage capacity of the reservoirs with respect to the mean annual flow at the various sites. At a few sites, there are no reservoirs located upstream. At the remaining sites, the flow that can be stored in the reservoirs varies between 0.4% and 31.9% (Table 1). The only exception is the Lenartowice site, for which maximum potential storage can reach 67%. In practice, however, the mean annual volumes measured in the reservoirs are far from reaching the maximum. Thus, the similar ratio with respect to annual mean reservoir volumes would exhibit lower values. The channel works have some impact on the daily flow, but the reservoirs have a much greater influence, and these values show the extent of discharge modification caused by regulation. The interpretation of the results at the sites, where the flow can be considerably influenced by the upstream reservoirs, should be considered with caution (Table 1).

Methods

Statistical Measures and Probability Distributions

Statistical measures of the riverflow time series can be given in terms of the mean, standard deviation, skewness and kurtosis. For a time series $x = (x_1,..., x_n)$, they are defined as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \qquad s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}, \tag{1}$$

$$S = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{s^3}, \quad K = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4}{s^4}. \tag{2}$$

Here $\bar{x}$, s, S, and K are the mean, standard deviation, skewness and kurtosis, respectively. A nonzero skewness implies deviation from a Gaussian distribution and is a measure of the asymmetry of the pdf, reflecting preferred fluctuations in the time series. If the skewness is positive (negative), the pdf will be skewed to the right (left). Large positive skewness indicates that the values of the discharge are generally less than their mean, with occasional large excursions to values greater than the mean. The kurtosis is a measure of the flatness of the probability density function (pdf). A value of kurtosis different from 3 indicates deviation from a Gaussian distribution. A pdf with $K > 3$ is more peaked with a heavy tail, and is referred to as super-Gaussian, whereas a pdf with $K < 3$ is more flat than a Gaussian pdf in appearance, and is referred to as sub-Gaussian.

Furthermore, the kurtosis of the pdf measures the degree of intermittency in the time series [36, 37]. Intermittency refers to a phase of quiescence interrupted by an active phase [38]. In the case of riverflows, intermittency implies periods of low flow (or no flow) intervened with short periods of high flows. In particular, an excess kurtosis ($K > 3$) indicates short periods of large fluctuations and is indicative of intermittency. In general, the larger the kurtosis, the higher is the degree of intermittency.

The probability density functions of these intermittent flows exhibit a characteristic heavy tail. The heavy-tail character can be modeled by several theoretical probability distributions such as the LN3, GL, GEV, GP, and the 5-parameter Wakeby distribution. As will be shown below, among them, the Wakeby distribution provides the best overall fit.

The pdf of the 5-parameter Wakeby distribution is given by the following expression [39]:

$$f(x) = \frac{[1 - F(x)]^{\delta+1}}{\gamma + \alpha[1 - F(x)]^{\beta+\delta}}, \tag{3}$$

...where α, β, γ, δ are shape parameters, and $F(x)$ is its cumulative distribution function (cdf). The inverse of the cdf of the Wakeby distribution is defined as $x(F)$, and it is given by:

$$x(F) = \xi + \frac{\alpha}{\beta}[1-(1-F)^{\beta}] - \frac{\gamma}{\delta}[1-(1-F)^{-\delta}], \quad (4)$$

...where ξ is a location parameter, and
(1) $\xi \le x < \infty$ if $\delta > 0$, $\gamma \ge 0$;
(2) $\zeta \le x \le \xi + \alpha / \beta - \gamma / \delta$ if $\delta < 0$, $\gamma = 0$.

The above parametrization is due to Hosking [40] and it is different from that used by other authors [41]. In fact, the parameterization (3) shows the Wakeby distribution as an extension of the generalized Pareto distribution and gives estimates of the parameters that are more stable under small perturbations of the data [41]. In order that $x(F)$ in Eqn (4) represents an inverse cdf, the conditions $\gamma \ge 0$ and $\gamma + \alpha \ge 0$ should be imposed. In addition, the following other restrictions must apply among the various parameters:
(i) either $\beta + \delta > 0$ or $\beta = \gamma = \delta = 0$,
(ii) if $\alpha = 0$ then $\beta = 0$,
(iii) if $\gamma = 0$ then $\delta = 0$ [40, 42].

Because of its flexible nature, the Wakeby distribution can be used to describe a natural process with several contributing factors (rainfall, snowmelt) that should otherwise be modeled by a mixture of several distributions. Since its introduction, the Wakeby distribution has been used in several hydrological and hydrometeorological studies [13, 43-46].

Testing Hypotheses

The trend in a time series can be assessed using the Cox-Stuart (C-S) test [47]. The null hypothesis H_0 is: there is no trend in the data. In order to apply the C-S test, one needs to divide the time series $x = (x_1,..., x_n)$ into two subsets $x^{(1)}$ and $x^{(2)}$ of length n_0. A time series $x^{(1)}$ comprises of first $n/2$ elements of x, and $x^{(2)}$ corresponds to the second half of the data set (even n case). If n is an odd number, the middle element of x shall be skipped.

The test statistics are defined for $i = 1, 2, 3,..., n_0$ as:

$$T = \sum_{i=1}^{n_0} X_i \ , \quad (5)$$

...where

$$X_i = \begin{cases} 1 & if \quad x_i^{(1)} < x_i^{(2)}, \\ 0 & if \quad x_i^{(1)} > x_i^{(2)}. \end{cases} \quad (6)$$

The probability distribution of T is binomial $b(n_0, p)$, where p is a probability of 'success.' If one assumes that H_0 is true, the probability law of T is $b(n_0, 0.5)$. If the alternative hypothesis H_1 allows both increasing and decreasing trends, the rejection of H_0 is based on the upper and lower tails of the cumulative distribution function $F(t)$ of the test statistics T, $t = 1,..., n_0$. The M-K test that is commonly used in hydrology is not applied here, because it tests for the null hypothesis of no trend or serial correlation in the time series. As a result, significant autocorrelations in hydrologic data may lead to misinterpretation [48].

In order to test for stationarity around a trend, one may apply the Phillips-Perron test [49]. The null hypothesis corresponds to non-stationarity, i.e. there exists a unit root in an autoregressive model. The alternative hypothesis H_1 is equivalent to stationarity around the trend. To perform the Phillips-Perron test, one must apply the Dickey-Fuller (D-F) statistics [50]:

$$\Delta y_t = at + b + \varepsilon y_{t-1} + z_t \quad (7)$$

Here Δy_t is the first difference operator, $at + b$ is a linear trend, $\varepsilon = \phi - 1$, z_t is white noise, and ϕ is an autoregressive coefficient of the first order autoregressive process AR(1).

Results and Discussion

The basic statistical parameters such as the mean, standard deviation, coefficient of variation, skewness and kurtosis of the daily discharge time series at each of the fifteen sites are listed in Table 2. The mean daily discharge varies approximately between 0.5 and 182 m^3/s, and tends to be rather small at sites located along the Odra River tributaries and quite large at sites located along the main river. In particular, downstream locations of both the Odra River and its largest tributary in the study area, Nysa Kłodzka, exhibit the highest mean daily flows. Standard deviation of the daily discharge time series varies approximately between 0.8 and 133 m^3/s and is also higher at downstream locations. The coefficient of variation is found to be between 0.61 and 1.88 at the various sites; note that the flow recorded at sites located in hilly areas or in the mountains is much more variable than at downstream lowland sites (Table 2).

As mentioned earlier, the kurtosis of the empirical distribution function of a time series provides a quantitative measure of its intermittency. It can be seen in Table 2 that at all 15 sites the kurtosis (which is 3 for a normal distribution) has values much higher than 3. The lowest and highest values of the kurtosis are 12.05 and 731.10, at Lenartowice and Nysa, respectively. A larger value of kurtosis implies a more intermittent flow pattern. Thus we see that the most intermittent flows occur at sites that are located in the mountainous and hilly areas. Indeed, at those sites the kurtosis values are typically higher than 100.

The empirical distribution functions of the discharge time series at all sites under study are heavy-tailed. The heavy-tail property of the data is characterized by skewness and kurtosis. From Table 2, note that the skewness values range from 2.29 at Lenartowice to 20.46 at Swierzawa. Positive skewness implies that the probability density function has a right tail. Higher values of skewness are reported for sites situated in the mountains or in foothills. This may be due to the fact that peak flows are rather more severe in the mountains than in the lowland. Our analysis shows that skewness and kurtosis measures are linked in describing the intermittency patterns. Indeed, the Pearson correlation coefficient is found to be statistically significant (p-value of $1.4\ 10^{-8}$) and equal 0.96. This indicates that the intermittent flows in the study area are typically right-skewed.

Table 2. Basic statistics of daily riverflow time series from upper and middle Odra River basin.

Site	Mean [m³/s]	Standard deviation [m³/s]	Coefficient of variation	Skewness	Kurtosis	Mean elevation in subbasin above a site [m a.s.l.]	Mean slope in subbasin above a site [degrees]
Chalupki	42.58	55.41	1.30	9.29	186.72	483.23	1.90
Krzyzanowice	56.93	68.12	1.20	10.59	260.64	457.08	1.82
Miedonia	65.80	76.34	1.16	9.34	208.60	432.06	1.65
Malczyce	157.12	127.08	0.81	6.34	83.56	298.18	0.98
Scinawa	182.28	133.45	0.73	5.04	54.78	290.09	0.98
Klodzko	13.06	15.99	1.22	12.57	352.69	565.37	2.94
Nysa	28.28	32.22	1.14	19.12	731.10	481.46	2.50
Skorogoszcz	34.30	38.19	1.11	9.85	177.09	396.51	1.87
Olawa	3.79	3.13	0.83	6.02	57.73	197.66	0.51
Bialobrzezie	0.48	0.81	1.69	9.46	142.35	243.92	0.92
Kraskow	4.41	7.77	1.76	12.14	223.49	380.34	1.77
Swierzawa	1.18	2.22	1.88	20.46	612.85	422.45	1.92
Cieszyn	8.68	13.00	1.50	9.25	174.65	539.73	3.01
Lenartowice	6.37	3.86	0.61	2.29	12.05	272.41	0.47
Staniszcze Wielkie	7.03	7.13	1.01	5.80	78.74	241.98	0.28

It has also been found that the skewness and kurtosis values can be associated with topographic patterns of the subbasins. For each site and its upstream contributing area, we have calculated the mean elevation and mean slope (Table 2). This is done using the USGS HYDRO1k digital elevation model and GIS methods. The Pearson correlation coefficients between skewness and mean elevation or mean slope are found to be 0.58 and 0.65, respectively. These correlations are statistically significant at the significance level of 0.05. Similar relationships are found for kurtosis, with the statistically significant correlation coefficients ranging between 0.58 and 0.62. This finding confirms that the non-Gaussian riverflow dynamics is more evident in the hilly and mountainous areas with diversified topography. Thus, geomorphology appears to be an essential factor controlling the riverflow intermittency and the heavy-tail discharge dynamics.

Finally, we try to fit several theoretical probability distributions to the daily discharge data. These include the 3-parameter family of distributions such as the LN3, GL, GEV, GP, and the 5-parameter Wakeby distribution [40]. Among them, the 5-parameter Wakeby distribution is found to model the discharge data most accurately.

For the sake of brevity, only the results for Wakeby distribution are presented below. To illustrate the results, we have chosen the following four sites: Chalupki, Scinawa, Swierzawa, and Staniszcze Wielkie. The time series of the daily discharge at these sites are plotted in Fig. 2, and the histograms of the empirical distributions and the fitted Wakeby distributions are shown in Fig. 3. It is apparent from Fig. 3 that the Wakeby distribution models the data quite well, especially for higher discharge. Some misfit can be observed for low flows around the modal values, where the Wakeby distribution tends to overshoot. We have assessed the goodness-of-fit of the Wakeby distribution using a probability-probability (P-P) plot that compares the empirical cumulative distribution function of a dataset with a specified theoretical cumulative distribution function. P-P plots have been used in a wide variety of applications [51, 52]. For the daily discharge data examined here, the P-P plots show that the Wakeby distribution fits the data quite well. For brevity the P-P plots are not presented here.

The fitted Wakeby distributions have been used to calculate the exceedance probability, i.e. the probability that the daily discharge X exceeds a specified value x, $P(X > x) = 1 - F(x)$. For the purpose of illustration, two specific threshold values (x) have been selected:

(a) the maximum daily discharge of the flood of August 1977, and

(b) the maximum daily discharge of the flood of July 1997.

The exceedance probabilities are expressed in terms of return periods at different sites (Table 3). We note from this table that, for the August 1977 threshold, the return period for the site Cieszyn is 611 days in 100,000 days (about 274 years). The corresponding figures for the other 14 sites are lower than 87 days in 100,000 days. For the larger threshold discharge values of the July 1997 flood, the return periods are reduced to 40 days in 100,000 days and less at many sites.

Regarding the analysis of trend, the values of the C-S statistics for the various riverflow time series are found to

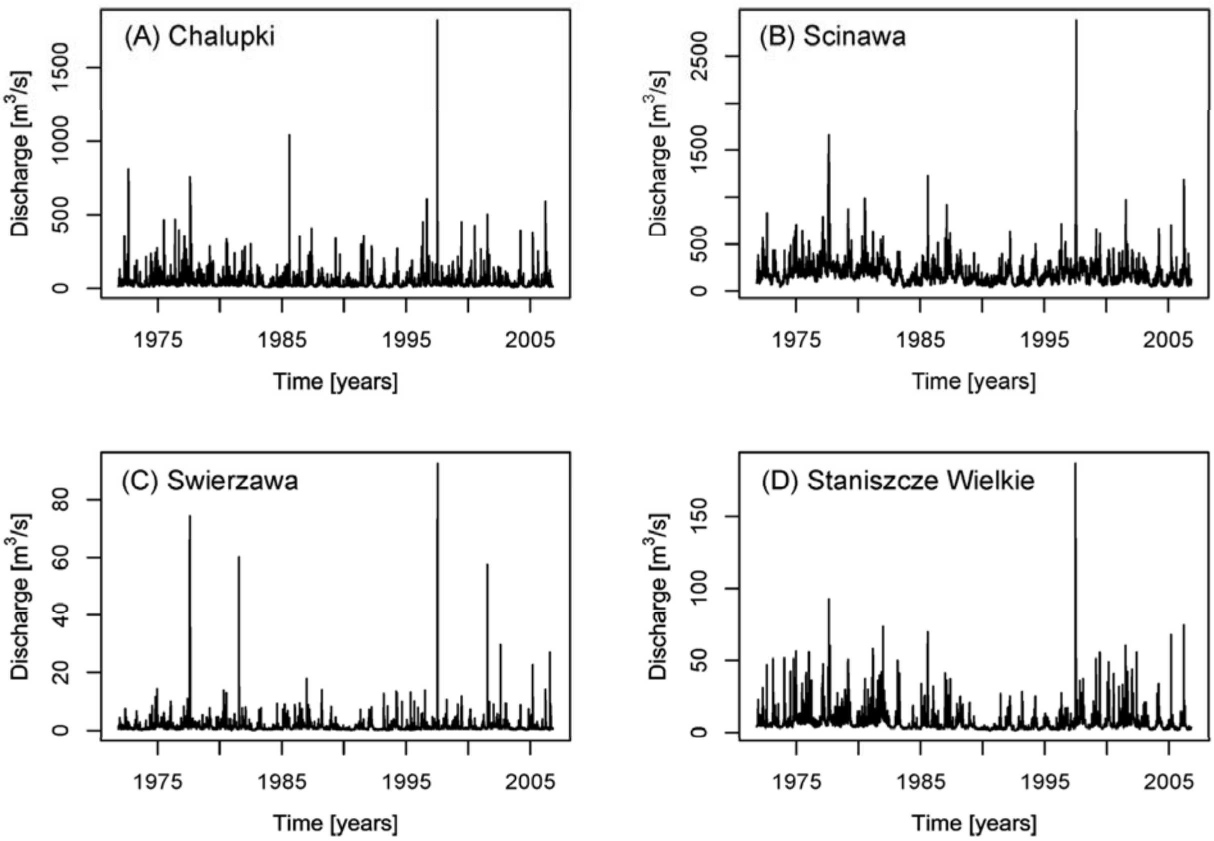

Fig. 2. Daily discharge time series from November 1971 to October 2006; (A) Chalupki; (B) Scinawa; (C) Swierzawa; (D) Staniszcze Wielkie.

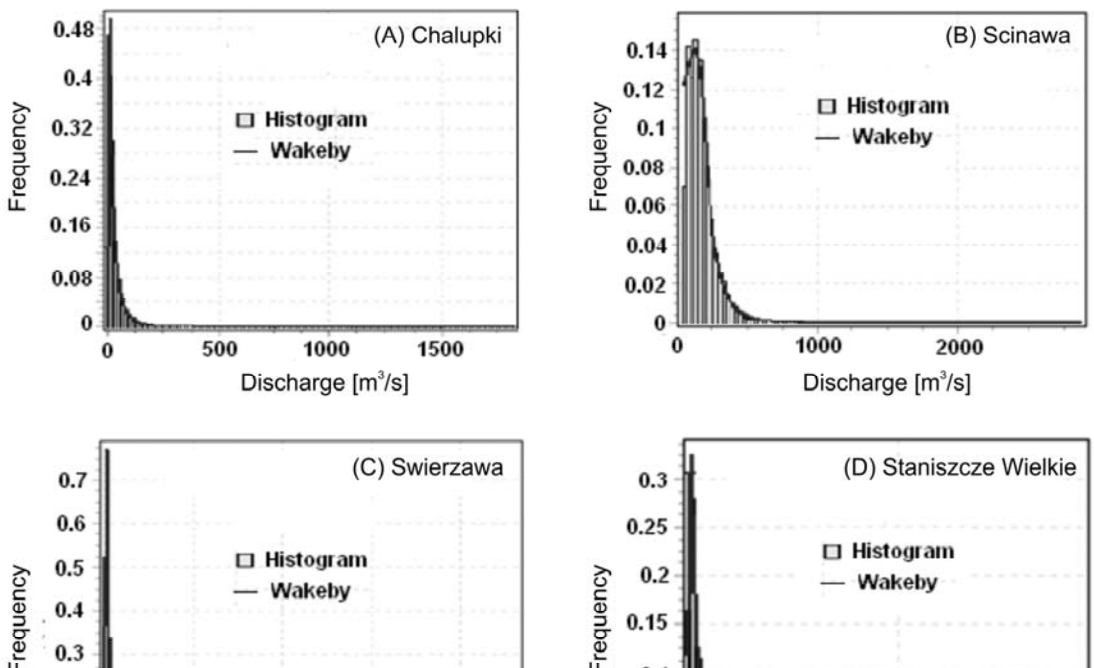

Fig. 3. Comparison between histograms of daily discharge data and the Wakeby densities; (A) Chalupki; (B) Scinawa; (C) Swierzawa; (D) Staniszcze Wielkie.

Table 3. Return periods determined using the Wakeby distribution for maximum discharges recorded in August 1977 and July 1997.

Site	River	Maximum discharge in 1977	Return period threshold - maximum discharge in 1977 [days-in-100,000 days]	Maximum discharge in 1997	Return period threshold - maximum discharge in 1997 [days-in-100,000 days]
Chalupki	Odra River	760.0	59	1,820.0	5
Krzyzanowice	Odra River	844.0	52	2,620.0	1
Miedonia	Odra River	956.0	60	2,800.0	2
Malczyce	Odra River	1,490.0	71	3,020.0	7
Scinawa	Odra River	1,660.0	68	2,880.0	14
Klodzko	Nysa Klodzka	394.0	8	693.0	2
Nysa	Nysa Klodzka	272.0	17	1,500.0	0
Skorogoszcz	Nysa Klodzka	495.0	87	1,180.0	22
Olawa	Olawa	52.2	67	53.4	64
Bialobrzezie	Sleza	17.6	30	15.3	40
Kraskow	Bystrzyca	181.0	13	227.0	7
Swierzawa	Kaczawa	74.4	10	92.7	7
Cieszyn	Olza	70.1	611	298.0	13
Lenartowice	Klodnica	38.3	63	48.3	19
Staniszcze Wielkie	Mala Panew	92.6	68	187.0	8

be between 2,161 and 3,019 (Table 4). The null hypothesis (no trend) is thus rejected against the alternative hypothesis of a declining trend. This finding holds for each discharge time series at the significance level of 0.001 or lower, and may be interpreted as the consequence of high discharges in the 1970s and low discharges between 1985 and 1995. On the regional scale, the southern catchments of the Baltic Sea drainage basin demonstrate similar trends [53]. This is caused by a significant decrease of precipitation in the southern subbasins of the Baltic Sea drainage basin and increase in evapotranspiration.

The values of the D-F statistics for the test of stationarity around a trend vary between -50.9 and -16.3 (Table 4), which means that all 15 riverflow time series are stationary around a trend (at the significance levels of 0.01 or smaller). The rejection of the null hypothesis and, as a result, accepting stationarity around a trend is essential for autoregressive modeling.

These two test results partially confirm those of previously reported studies. Indeed, Absalon and Matysik [54] found that during the period 1970-2000, discharges along the upper Odra River reveal a decreasing but statistically insignificant trend.

Concluding Remarks

We have characterized the statistical properties of riverflow variability in SW Poland by analyzing the daily discharge data at 15 sites in the Odra River basin for from November 1971 to October 2006. We found that the riverflow time series at these sites exhibit various degrees of temporal intermittency, and each time series follows a super-Gaussian distribution. In addition, it is found that the skewness and kurtosis values of the empirical distributions can be linked to surface topography of the subbasins in the study area. We have also fitted several theoretical probability distributions to the daily discharge data. Among them, the 5-parameter Wakeby distribution was found to provide the best overall fit. From the fitted Wakeby distribution, return periods were estimated using the threshold discharge levels of the August 1977 and July 1997 flood events. The daily discharge time series at all 15 sites exhibit statistically significant declining trends during the study period. This may be explained by relatively high discharges in the 1970s and low discharges in the period 1987-1996. The daily riverflow time series are also found to be stationary around a trend. A good understanding of the statistical characteristics of riverflow variability in the Odra River basin may be useful for water resource planning and management, including flood control and prediction.

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Table 4. Cox-Stuart (test statistics *T*) and Phillips-Perron (test statistics *D-F*) tests applied for daily riverflow time series from south-western Poland recorded between 1971 and 2006. P-values are indicated by: p↑ (for inclining trend), p↓ (for declining trend), and *p* (for stationarity).

Site	River	Cox-Stuart			Phillips-Perron	
		T	p↑	p↓	*D-F*	*p*
Chalupki	Odra River	2797	1.00	<0.001	-26.3	<0.01
Krzyzanowice	Odra River	2769	1.00	<0.001	-27.0	<0.01
Miedonia	Odra River	2798	1.00	<0.001	-26.0	<0.01
Malczyce	Odra River	2269	1.00	<0.001	-17.2	<0.01
Scinawa	Odra River	2340	1.00	<0.001	-16.3	<0.01
Klodzko	Nysa Klodzka	2985	1.00	<0.001	-50.9	<0.01
Nysa	Nysa Klodzka	2737	1.00	<0.001	-24.1	<0.01
Skorogoszcz	Nysa Klodzka	2725	1.00	<0.001	-18.7	<0.01
Olawa	Olawa	2770	1.00	<0.001	-21.9	<0.01
Bialobrzezie	Sleza	2238	1.00	<0.001	-39.9	<0.01
Kraskow	Bystrzyca	2598	1.00	<0.001	-32.5	<0.01
Swierzawa	Kaczawa	2486	1.00	<0.001	-46.6	<0.01
Cieszyn	Olza	3019	1.00	<0.001	-41.6	<0.01
Lenartowice	Klodnica	2193	1.00	<0.001	-25.6	<0.01
Staniszcze Wlkielkie	Mala Panew	2161	1.00	<0.001	-21.6	<0.01

of R 2.0.1 - A Language and Environment and additional packages are acknowledged. The digital elevation model USGS HYDRO1k was used in this study. We would like to thank the two anonymous reviewers whose insightful comments and suggestions have led to a significant improvement of this paper.

References

1. BORDIGNON S., LISI F. Nonlinear analysis and prediction of riverflow time series. Environmetrics **11**, 463, **2000**.
2. GOBENA A.K., GAN T.Y. Low-frequency variability in Southwestern Canadian streamflow: Links with large-scale climate anomalies. International Journal of Climatology **26**, 1843, **2006**.
3. SEN A.K. Complexity analysis of riverflow time series. Stochastic Environmental Research and Risk Assessment **23**, 361, **2009**.
4. MARSH T.J., DALE M. The UK floods of 2000/01 - a hydrometeorological Appraisal. CIWEM Journal **16**, 180, **2002**.
5. YEVJEVICH V. Fluctuations of wet and dry years Part I: Research data and mathematical models. Proc Hydrology Days, Paper No. 1, Colorado State University, Fort Collins, CO, **1963**.
6. FINLAYSON B.L., MCMAHON T.A. Global Runoff. Encyclopedia of Earth System Science. Vol. 2. Academic Press, San Diego, California, USA, **1992**.
7. MARKOVICH R.D. Probability of best fit to distributions of annual precipitation and runoff. Hydrological Paper No. 8. Colorado State University, Fort Collins, CO, **1965**.
8. LOF G., HARDISON C.H. Storage requirements for water in the United States. Water Resources Research **2**, 232, **1966**.
9. VOGEL R.M., WILSON I. Probability distribution of annual maximum, mean, and minimum streamflows in the United States. ASCE Journal of Hydrologic Engineering **1**, 69, **1996**.
10. KROLL C.N., VOGEL R.M. Probability distributions of low streamflow series in the United States. ASCE Journal of Hydrologic Engineering **7**, 137, **2002**.
11. U.S. Water Resources Council, Guidelines for determining flood flow frequency: Revised Bulletin 17B of the Hydrology Committee, U.S. Water Resources Council, **1982**.
12. YUE S., WANG C.Y. Possible regional probability distribution types of Canadian streamflow by L-moments. Water Resources Management **18**, 425, **2004**.
13. ARBELAEZI A., CASTRO L.M. Low flow discharges regional analysis using Wakeby distribution in an ungauged basin in Colombia. Proc Hydrology Days, Colorado State University, pp. 198-208, **2007**.
14. HAMED K.H. Enhancing the effectiveness of prewhitening in trend analysis of hydrologic data. Journal of Hydrology **368**, 143, **2009**.
15. BOUCHARD A., HAEMMERLI J. Trend detection in water quality time series of LRTAP-Quebec network lakes. Water, Air, and Soil Pollution **62**, 89, **1992**.
16. DIRMEYER P.A., BRUBAKER K.L. Evidence for trends in the Northern Hemisphere water cycle. Geophysical Research Letters 33, L14712, doi:10.1029/2006GL026359, **2006**.

17. MANN B. Nonparametric tests against trend. Econometrica **13**, 245, **1945**.
18. ZHANG Q., XU C.-Y., YANG T. Variability of water resources in the Yellow River basin of past 50 Years, China. Water Resources Management **23**, 1157, **2009**.
19. KUNDZEWICZ Z.W., GRACZYK D., MAURER T., PIŃSKWAR I., RADZIEJEWSKI M., SVENSSON C., SZWED M. Trend detection in riverflow series: 1. Annual maximum flow. Hydrological Sciences Journal **50**, (5), 797, **2005**.
20. FAGANELLO E., ATTEWILL L. Flood management strategy for upper and middle Odra River fasin: feasibility study of Raciborz Reservoir. Natural Hazards **36**, 273, **2005**.
21. DUBICKI A., MALINOWSKA-MAŁEK J., STROŃSKA K. Flood hazards in the upper and middle Odra River basin – A short review over the last century. Limnologica **35**, 123, **2005**.
22. DUBICKI A., SŁOTA H., ZIELIŃSKI J. (Eds) The Odra Basin – a monograph of the July 1997 flood, IMGW, Warsaw, **1999** [In Polish].
23. KUNDZEWICZ Z.W. Is the Frequency and Intensity of Flooding Changing in Europe? Chapter 3, **2005**.
24. BARREDO J.I. Major flood disasters in Europe: 1950–2005. Natural Hazards **42**, 125, **2007**.
25. DE ROO A., ODIJK M., SCHMUCK G., KOSTER E., LUCIEER A. Assessing the effects of land use changes on floods in the Meuse and Oder catchment. Physics and Chemistry of the Earth **26**, 593, **2001**.
26. DE ROO A., SCHMUCK G., PERDIGAO V., THIELEN J. The influence of historic land use changes and future planned land use scenarios on floods in the Oder catchment. Physics and Chemistry of the Earth **28**, 1291, **2003**.
27. GOUWELEEUW B.T., THIELEN J., FRANCHELLO G., DE ROO A.P.J., BUIZZA R. Flood forecasting using medium-range probabilistic weather prediction. Hydrology and Earth System Sciences **9**, (4), 365, **2005**.
28. BUTTS M.B., OVERGAARD J., VIAENE P., DUBICKI A., STROŃSKA K., SZALINSKA W., LEWANDOWSKI A., OLSZEWSKI T., KOLERSKI T. Flexible process-based hydrological modelling framework for flood forecasting-MIKE SHE. In: Proceedings of the International Conference "Innovation, advances and implementation of flood forecasting technology" Tromso, Norway, 17–19 October **2005**.
29. MENGELKAMP H.-T., WARRACH K., RUHE C., RASCHKE E. Simulation of runoff and streamflow on local and regional scales. Meteorology and Atmospheric Physics **76**, 107, **2001**.
30. NIEDZIELSKI T. A data-based regional scale autoregressive rainfall-runoff model: A study from the Odra River, Stochastic Environmental Research and Risk Assessment **21**, 649, **2007**.
31. STRUPCZEWSKI W.G., SINGH V.P., MITOSEK H.P. Non-stationary approach to at-site flood frequency modelling. III. Flood analysis of Polish rivers. Journal of Hydrology **248**, 152, **2001**.
32. VAN GELDER P.H.A.J.M., VAN NOORTWIJK J.M., DUITS M.T. Selection of probability distribution with a case study on extreme Oder River discharges. In: safety and reliability **2**, 1475, **1999**.
33. DUBICKI A. Characterisation of causes, progress, and magnitude of the flood in 1977 in upper and middle Odra River basin. In: Jahn A, Kowaliński S (Eds) Flood in 1977 and its consequences for Lower Silesia. PAN Oddział we Wrocławiu, Komisja Nauk o Ziemi, Wrocław, pp. 27-40, **1979** [In Polish].
34. KOZIARSKI S. Navigational function of the Odra river. Czasopismo Geograficzne **LXVIII** (2), 155, **1997** [In Polish].
35. DZIUBEK A.M., KOWAL A.L., NALBERCZYŃSKI A., SZYMAŃSKA H. (Eds) Water resources management of the upper and middle Odra River. Regionalny Zarząd Gospodarki Wodnej we Wrocławiu, Wrocław, **1993** [In Polish].
36. CONSOLINI G., DE MICHELIS P. Non-Gaussian function of AE-index fluctuations: Evidence for time intermittency. Geophysical Research Letters **25**, 4087, **1998**.
37. MAHRT L. Intermittency of atmospheric turbulence. Journal of the Atmospheric Sciences **46**, 79, **1999**.
38. BRUNO R., BAYASSANO B., PIETROPAOLO E., CARBONE V., VELTRI P. Effects of intermittency on interplanetary velocity and magnetic field fluctuations anisotropy. Geophysical Research Letters **28**, 3185, **1999**.
39. JOHNSON N.L., KOTZ S., BALAKRISHNAN N. Continuous Univariate Distributions - Vol. 1, Wiley, New York, **1994**.
40. HOSKING J.R.M. The Wakeby distribution. Research Report RC12302, IBM Research Division, Yorktown Heights, New York, **1986**.
41. LANDWEHR J.M., MATALAS N.C., WALLIS J.R. Estimation of parameters and quantiles of Wakeby distributions. Water Resources Research **15**, 1361, **1979**.
42. KOTZ S., JOHNSON N.L., READ C.B. Encyclopedia of Statistical Sciences, Vol. 9, Wiley, New York, USA, **1988**.
43. HOUGHTON J.C. Birth of a parent: the Wakeby distribtion for modeling flood flows. Water Resources Research **14**, 1105, **1978**.
44. GRIFFITHS G.A. A theoretically based Wakeby distribution for annual flood series. Hydrological Sciences Journal **34**, 231, **1989**.
45. PARK J.S., JUN H.S., KIM R.S., OH J.H. Modeling summer extreme rainfall over the Korean peninsula using Wakeby distribution. International Journal of Climatology **21**, 1371, **2001**.
46. SU B.D., KUNDZEWICZ Z.W., JIANG T. Simulation of extreme precipitation over the Yangtze river basin using Wakeby distribution. Theoretical and Applied Climatology, doi: 10.1007/s00704-008-0025-5, **2008**.
47. McCUEN R.H. Modeling hydrologic change-statistical methods, Lewis Publishers, Boca Raton, **2003**.
48. HAMED K.H., RAO A.R. A modified Mann-Kendall trend test for autocorrelated data. Journal of Hydrology **204**, 182, **1998**.
49. PERRON P. Trends and random walks in macroeconomic time series. Journal of Economic Dynamics and Control **12**, 297, **1988**.
50. DICKEY D.A., FULLER W.A. Distribution of the Estimators for autoregressive time series with a unit root. Journal of the American Statistical Association **74**, 427, **1979**.
51. GNANADESIKAN R. Methods for Statistical Data Analysis of Multivariate Observations. 2nd ed. Wiley, New York, **1997**.
52. HOLMGREN E. C. The P-P plot as a method of comparing treatment effects. Journal of the American Statistical Association **90**, 360, **1995**.
53. GRAHAM L.P. Climate Change Effects on River Flow to the Baltic Sea. Ambio **33**, 235, **2004**.
54. ABSALON D., MATYSIK M. Changes in water quality and runoff in the Upper Oder River basin. Geomorphology **92**, 106, **2007**.