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*Original Research*

# Estimating the Occurrence of Trends in Selected Elements of a Small Sub-Mountain Catchment Hydrological Regime

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### Abstract

For this study we investigated the Rzyki G watercourse catchment situated in Andrychów District of Wadowice County in the western part of Poland's Malopolska Region. The basis for the analyses were daily values of precipitation and runoff sums and flow rates in the analyzed watercourse. The empirical data were obtained from systematic precipitation measurement conducted in 1992-2001 by means of a Hellmann rain gauge, and the runoff amounts were determined on the basis of water states registered by limnigraph on a bipartite spillway of a triangle-trapezoid type. The aim of our paper was to assess regularities of selected elements characterizing the hydrological regime of a sub-mountain catchment with dominant agricultural management. The stationarity and variability of monthly precipitation, runoff sums, and runoff coefficients – as well as trends, stationarity, and variability of the flood indicators characterizing maximum stream flows – were analyzed in the paper. Apparent differences appear in cases of variance of the analyzed variables (precipitation variability may be caused by gradual climate warming, whereas higher variability of the runoff in the second half of the multiannual period was determined by precipitation). Due to the changes observed in time series characteristics of the investigated variables, it becomes necessary to analyze the time series not only regarding the occurrence or absence of the trend, as has been done so far, but also considering the other aspects such as the differences between the means or variability of variance. When extreme phenomena are identified at usual lack of a sufficiently long data sequence, the flood rate indicators should be used to comprise much more information than the analysis based only on annual maximum discharge. A significant increase in the annual maximum stream flows was demonstrated for the analyzed multiannual period and for the summer half year, but also higher frequency of flood occurrence in the summer half-year. The observed regularities are typical for the sub-mountain and mountain catchments of the temperate climate and are additionally determined by catchment size.

**Keywords**: catchment, precipitation, runoff, runoff coefficient, flood indicators

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## Introduction

Climatic and hydrological phenomena cause cyclic variability and renewability of water resources [1-3]. Urbanization increases the occurrence of the impermeable layer in the basin area, particularly in urban drainage systems. The situation might be additionally worsened by surface runoff from suburban areas [4].

One of the most significant potential consequences of climate change may be alterations in the regional hydrological cycle and stream flow regimes. Most importantly, changes in the frequency of occurrence and intensity of floods and droughts, which could occur as a result of climate change, have drawn more and more attention from public, government, and academic circles [5-7].

The hydrological cycle regulates the conversion of rainfall into the runoff from the catchment and is responsible for particular elements of water balance and their proportionality in relation to one another. The issue of repeatability of both hydrological and meteorological phenomena, and their regularity in particular (i.e., cyclicality or periodicity) has long been a subject of research [8-10].

Flood estimation and flood design are traditionally based on the assumption that the flood regime is stationary. In particular, flood frequency analysis requires the flood data to be homogeneous, independent, and stationary [11]. Regardless of the existence of temporal periodicity patterns of hydro-meteorological processes, the problem of spatial similarities in the periodicity (not necessarily a very distinct one) is also very interesting. A number of investigations were conducted in recent years to analyze the trends and cycles of stream flows. Tao et al. [12] researched the trends in daily river flows in the Tarim River basin and analyzed the effect of climatic change on the hydrological regime. The study by Villarini et al. [13] did not show any statistically significant changes in the seasonality of the occurrence of maximum annual flows in Central Europe in the past 75 years. The noticed changes in the stationarity of a series of maximum annual flows were mainly caused by anthropogenic factors, although the authors did not exclude the impact of climate change. Mudelsee et al. [14], while examining the long series of daily flows in the rivers Elbe and Oder, showed the reduction in the incidence of maximum flows in the winter half-year and the lack of trend in the summer half-year. On the other hand, Bristan et al. [15], showed increasing trends in flows in 48 rivers in Switzerland. The studies by Kundzewicz et al. [16] demonstrated that there are significant growing trends of maximum annual flows in 11 among the 70 rivers tested in Europe. Banasik and Hejduk [17], based on 48 annual strings of rainfall and runoff in the agricultural catchment of the Zagożdżonka, showed a lack of trend in rainfall and a decreasing trend in runoff (about 1.2 mm per year) using the Mann-Kendall test.

Traditionally, simple or multiple linear regression, including autoregression (AR) and autoregressive moving average (ARMA), are used to analyze the time series of hydro-meteorological data [18]. Further developed models include possible periodic components, temporal and/or spatial disaggregation. The periodic autoregressive moving average (PARMA) model and periodic autoregressive (PAR) model are widely used to model hydrologic time series [19] by constructing a separate model for each season. In practice, the trends of time series of hydro-meteorological data are identified by means of non-parametric tests: Mann-Kendall test, Mann-Kendall-Sneyers test, Daniels trend Test, and Spearman correlation coefficient [5, 20-24]. Trend analyses requires long records to distinguish climate change, preferably in excess of about 50 years [25]. Sometimes metadata are not available for records. Notwithstanding such limitations, stream flows represent the integrated response to all the hydrometeorological processes occurring throughout a catchment [26]. Therefore, a number of indicators helpful for data trend analysis are used in practice. A commonly used index is the annual maximum daily mean stream flow, which is the largest daily mean flow that occurs annually [1]. However, in several years the annual maximum daily flow may be of such modest magnitude that it cannot really be called a flood. Therefore, another option to choose is a flood index series including all independent events that exceed a threshold so that the series contains a certain number of events per year on average. In the latter approach such a data set – called the peak-over-threshold (POT) series – may contain more than one entry from one year and none from another year [26]. POT consists of a series of independent daily mean stream flows that exceed a certain threshold (this threshold is the same throughout the time series). The POTs have to be proper peaks, i.e., the stream flow both before and after the peak has to be lower than at the peak itself. Two POT indices describing flood magnitude were used: the POT1 magnitude (POT1 mag.) and the POT3 magnitude (POT3 mag.). The magnitude of the threshold was set so that on average one and three POT events, respectively, were selected per year [16, 27].

Previous research conducted on the regularities of hydrometeorological phenomena time series focused on large catchments. No research has been carried out on changes in the hydrological regime during the multiannual periods in catchments with areas of several km$^2$. Due to the character of these catchments (including fast response to precipitation), they may pose a hazard to the local communities inhabiting these watercourse valleys. Therefore, it is crucial to learn the regularities in the hydrological regimes in these catchments. The above statement indicates the aim of the paper, i.e., the estimation of regularities in selected elements characterizing the hydrological regime of a catchment with prevalent agricultural management. We analyze two issues of the catchment hydrological regime in this paper: i) stationarity and variability of monthly precipitation and runoff sums and runoff coefficients, and ii) trends, stationarity, and variability of the indicators characterizing maximum stream flows.

## Investigated Area

The investigations were conducted in the Rzyki G watercourse in Rzyki village (Andrychów District in Wadowicki County in the western part of Malopolskie Province; Fig. 1). Considering its geographical location, the region where the discussed catchment is situated belongs to the Beskid Mały Mts. The Rzyki G watercourse catchment is part of the Wieprzówka River catchment, the right bank tributary to the Skawa River.

The catchment, with an area of 47.50 ha and average width of 0.525 km, has a slightly elongated compact shape. There is only one watercourse, 0.575 km flowing in a clearly formed valley closer to its eastern border, therefore the river network density is 1.21 km·km$^{-2}$. The catchment area is situated at the altitude of 393-475 m a.s.l, but the hypsometric interval from 40 to 440 m a.s.l prevails definitely, constituting 72.2% of its area. Mean weighted average altitude is 425 m a.s.l., whereas the average land slope is 12.2%. Terrain with land slope between 5 and 18% prevails in the catchment, altogether covering almost 68% of its area, whereas terrain with a land slope above 27% occupies 8.5% of total area. Location height and land slopes evidence the sub-mountain character of the catchment, where the northeastern and southwestern slope aspects are dominant [28].

The analyzed catchment is covered by relatively shallow and skeletal dystrophic brown soils developed as a result of Carpathian flysh weathering. Regarding the soil types, silt clays, clay silts, light and heavy loams dominate. These are soils characterized by considerable compactness and high capillary capacity, but low drainability and permeability. The main land use in the Rzyki G catchment is agriculture (Fig. 1), and ploughlands prevail visibly (constituting 68.7%) followed by grasslands (16.2% which occur along the watercourse valley), and forests and forested areas (8.4% – mainly slopes with 20% inclination situated in the eastern part of the catchment).

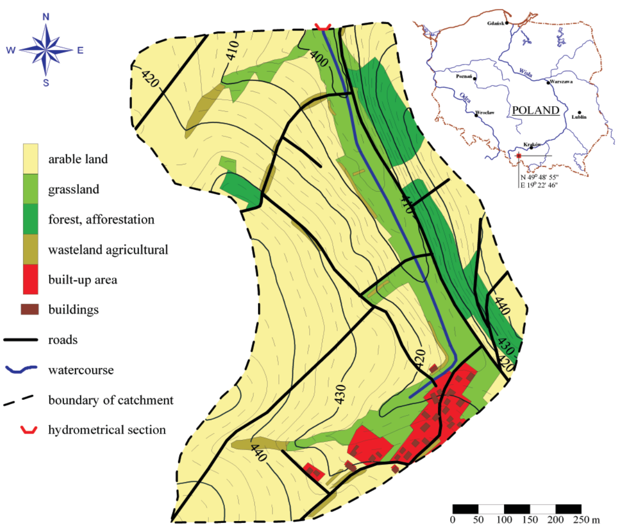


Fig. 1. Location and land use of the Rzyki G watercourse catchment.

## Methods

The basis for the analyses connected with an estimation of the hydrological regime in the analyzed catchment were daily precipitation, runoff, and flow rate values for the 1992-2001 multiannual period. The results were obtained from the precipitation measurements conducted systematically by means of a Hellmann rain gauge and runoff determined on the basis of the river stages registered by a limnigraph on a bipartite spillway of the triangle-trapezoid type. The daily values of runoff layers in millimetres were computed from the rating curves, taking into consideration the area of the Rzyki G catchment. We calculated monthly precipitation and runoff sums based on the input data as well as the values of the runoff coefficient. Subsequently, the analyses were conducted on statistical homogeneity of data, variance alterations, and occurrence of periodicity.

### Statistical Homogeneity of Data

The Kruskal-Wallis non-parametric test was used to test the homogeneity of monthly precipitation and runoff sums and the runoff coefficient. The core of the test is ranking the ordered elements of all samples and calculating the sum of ranks for each sample. If we test a hypothesis that all samples that originate from one general population (homogenous) is true, then the sums of ranks for individual samples should not differ considerably. The statistics used in this test to create the critical area has Pearson limit range $\chi^2$ with k-1 degrees of freedom, where k is the number of compared samples [29]. Therefore, the Kruskal-Wallis test of the sum of ranks served for the verification of $H_0$ hypothesis that k samples of size $n_i$ (i = 1, 2, … k) and free distributions with continuous distribution functions $F_1(x)$, $F_2(x)$, …, and $F_k(x)$ originate from one general population. In the discussed case, the sequence of the monthly sums of analyzed variables was divided into two samples k = 2 with the size of 60 elements each. $H_0$ hypothesis is verified on the significance level α = 0.05.

### Variability of Variance

The hypothesis about the equality of variances of two populations was analyzed by means of F statistics, described by the following formula:

$$F = \frac{\overline{S_1^2}}{\overline{S_2^2}} \tag{1}$$

…with $n_1$ being 1 and $n_2$ being 1 degrees of freedom, and where $\overline{S_i^2}$ denotes unbiased estimators of variance of appropriate populations at the assumption of the normality of distribution [30]. The calculations assumed the division of the data sequence into two populations numbering 60 elements. $H_0$ hypothesis about the equality of variances was verified on the significance level α = 0.05.

### Periodicity of the Time Series

The aim of this analysis is to decompose the complex time series containing cyclic components into several basic sinusoidal functions (sine and cosine) with specific wavelengths. The analysis may reveal a few periodic cycles of different wavelengths, which at first appeared in the tested time series to be more or less random walking. A general model of the spectral function may be described by the multiple regression function [31]:

$$X_t = a_0 + \sum [a_k \cdot \cos(\lambda_k \cdot t) + b_k \cdot \sin(\lambda_k \cdot t)]$$

$$\text{for } k \in (1, q) \tag{2}$$

…where $X_t$ is random variable in time t, $a_0$ is constant term, $a_k$ and $b_k$ are regression coefficients, $\lambda_k$ is frequency, t is time, and q is number of variables in the model related to the number of data within the set.

The results of spectral analysis are presented as a periodograph that was smoothed by the transformation of the weighted moving average using Hamming's method to remove random fluctuations. The periodograph shows how the variance of the time series is decomposed into individual frequencies. Spectral analysis was performed using STATISTICA 12.0 software.

### Trends in Flood Magnitude

Seven flood indicators were included in this study (Table 1). These comprise annual maximum stream flow series (AMAX) as well as POT. Annual daily mean discharge is the largest daily mean stream flow that occurs in each hydrological year. In addition to the annual flood time series, seasonal time series were derived, distinguishing between winter (1 November-30 April) and summer (1 May-31 October). POT series of daily mean flow with on average three (POT3) events occurring per year were used to analyze flood trends.

Due to a short data sequence, analysis of the flood trend indicators used Spearman rank correlation coefficient test. The essence of the test is ranking the sample elements in a chronological sequence and ranking the same elements of the sample in a growing sequence. The value of rank differences between the same elements of the chronological and growing sample sequence evidences the occurrence or absence of a trend in the sample. If the verified hypothesis that the sample does not have the trend is true, then the value of rank differences should differ considerably from 0 value. The statistics used in this test have t-Student distribution with n being 2 degrees of freedom. Spearman rank correlation coefficient $R_s$ is expressed by the following formula [30]:

$$R_s = 1 - \frac{6}{n\,(n^2 - 1)} \sum_{i=1}^{n} d_i^2 \tag{3}$$

…where:

$$d_i = range\ (X_i - i;\ X_i, i = 1, 2, \ldots, n) \tag{4}$$

The significance of correlation coefficient $R_s$ has been verified at significance level α = 0.05.

## Results and Discussion

### Monthly Precipitation and Runoff Sums and Runoff Coefficients

Annual mean precipitation sum over 1992-2001 was 900 mm and the summary runoff layer was 408 mm, which in result gave an average runoff coefficient of 45%. The result is compatible with values of runoff coefficients of 41-54% obtained from the hydrological research conducted in Poland's Spisz Region [9] and in three sub-mountain catchments situated on Wadowickie Plateau [32] in the vicinity of the Rzyki G catchment. The highest precipitation (1,194 mm) occurred in 2001 and the lowest (661 mm) in 1992. Considering the runoff layer, as in case of precipitation, its highest value (555 mm) was noted in 2001. On the other hand, the lowest summary runoff of

Table 1. Flood indicators used in studies [modified after 25].

| Flood indicator | Abbreviation | Description |
|---|---|---|
| Annual maximum daily mean discharge [$dm^3 \cdot s^{-1}$] | AMAX | Maximum discharge for each hydrological year (1 Nov-31 Oct) |
| Annual winter maximum daily mean discharge [$dm^3 \cdot s^{-1}$] | WMAX | Maximum discharge for each hydrological winter (1 Nov-30 April) |
| Annual summer maximum daily mean discharge [$dm^3 \cdot s^{-1}$] | SMAX | Maximum discharge for each hydrological summer (1 May-31 Oct) |
| POT magnitude [$dm^3 \cdot s^{-1}$] | POTM | Discharge peak over threshold (on average X events per year) |
| POT frequency | POT3F | Annual number of discharge peaks over threshold (on average three events per year) |
| Summer POT frequency | SPOT3F | Annual number of summer discharge peaks over threshold |
| Winter POT frequency | WPOT3F | Annual number of winter discharge peaks over threshold |

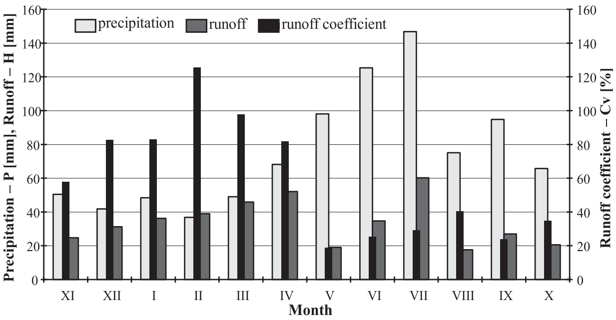


Fig. 2. Average monthly precipitation and runoff sums and runoff coefficient values in 1992-2001.

268 mm occurred in 1993. Analysis of the runoff coefficient values revealed that its highest value (57.9%) evidenced the catchment's lowest retention capacity in 1992, whereas 1998 was characterized by the highest retention capacity because the lowest value of the runoff coefficient (32.8%) was registered in that year. Fig. 2 shows monthly mean precipitation, runoff, and runoff coefficient values over the investigated multiannual period.

Precipitation value averages for the multiannual period were higher for the summer half-year than in winter. However, this did not translate proportionately into the runoff amount, whose higher values were usually registered in winter months. Also, the values of runoff coefficient were much higher in the winter half-year. Only in February did mean value of this coefficient exceed 100% (Fig. 2), which was connected with the snowmelt from previous months.

Computations conducted using the Kruskal-Wallis test demonstrated that there were no marked differences in the medians of the analyzed variable in 1992-96 and 1997-2001 (Table 2). This testifies that all values of the analyzed variables originate from the same general population. The absence of changes in the precipitation course regarding the medians affects a similar lack of significant differences in the medians of the precipitation and runoff coefficient. So no additional factor appeared, which might have influenced the course of precipitation and runoff medians in the analyzed catchment over the investigated multiannual period. Therefore, it may be said that the catchment is characterized by a natural hydrological regime. Quite a different situation occurs regarding the analysis of variability of precipitation variance, runoff, and runoff coefficients during 1992-97 and 1997-2001. In this case the $H_0$ hypothesis about a lack of significant differences between the variances (Table 2) had to be rejected at the significance level $\alpha = 0.05$. This may be the reason

Tabela 2. Values of $\chi^2$ and F statistics for monthly precipitation, runoff sums, and runoff coefficients.

| Variable | Values of test statistics and probability of the test (p) | | | |
|---|---|---|---|---|
| | $\chi^2$ | p | F | p |
| Precipitation | 0.833 | 0.361 | 2.715 | **0.000*** |
| Runoff | 2.700 | 0.103 | 2.530 | **0.000** |
| Runoff coefficient | 0.000 | 1.000 | 2.330 | **0.001** |

***bold font** indicates statistically significant values for $\alpha = 0.05$

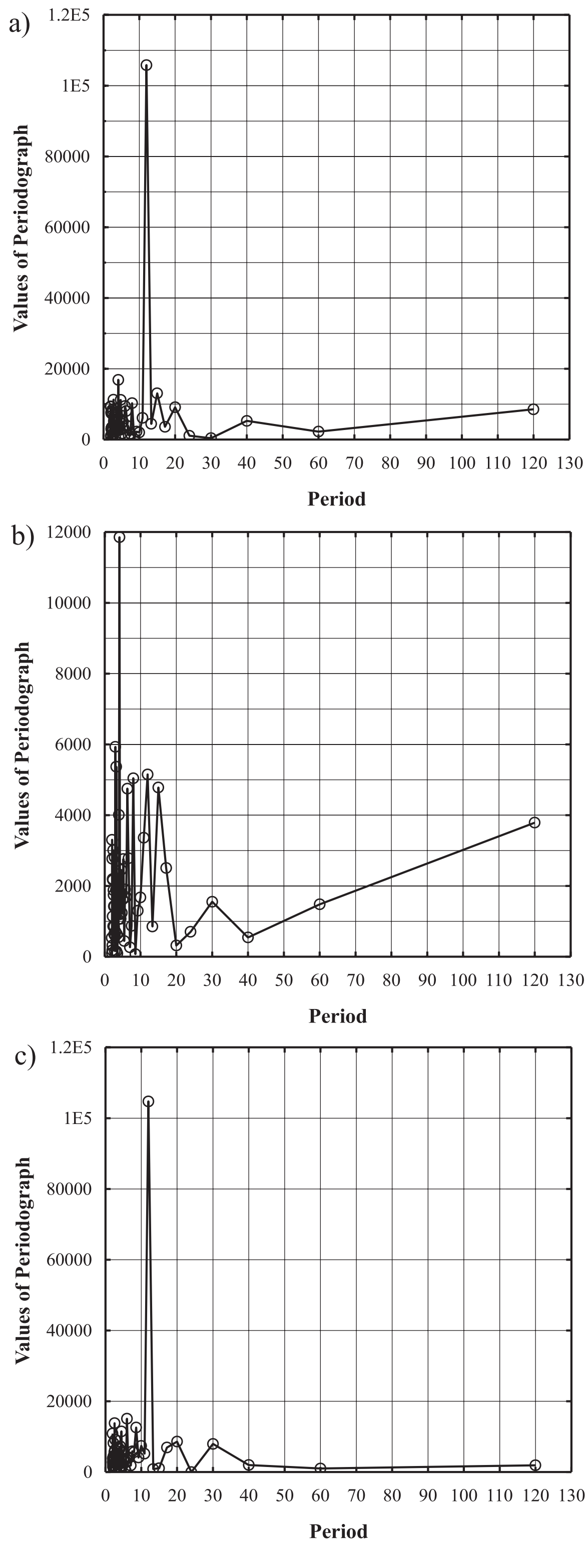


Fig. 3. Periodograph: a) monthly precipitation sums, b) monthly sum of runoff, and c) mean monthly values of runoff coefficient.

Table 3. Values of Spearman rank (Rs) correlation coefficients and their significance for the individual flood indicators.

| Flood indicator | AMAX | WMAX | SMAX | POTM | POT3F | WPOT3F | SPOT3F |
|---|---|---|---|---|---|---|---|
| Rs | **0.636*** | 0.115 | **0.758** | 0.345 | 0.582 | -0.287 | **0.745** |
| Probability of the test (p) | **0.048** | 0.751 | **0.011** | 0.328 | 0.078 | 0.422 | **0.013** |

*__bold font__ indicates statistically significant values for α = 0.05

why during the second period (1997-2001) precipitation, runoff, and the runoff coefficient values revealed an apparently greater variability as compared with the previous period of 1992-96. Most probably, precipitation was a determining factor in increased runoff variability. A phenomenon of more frequent extreme rainfalls connected with the occurrence of long sequences of rainfall periods has been often observed recently [33]. The increase in variability of both precipitation and runoff may lead to far more frequent flood events and low-flow periods, which may result in a greater number of extremely high flood flows and very low flows during drought periods. An additional factor that may increase the runoff amount is a change in catchment management, mainly through

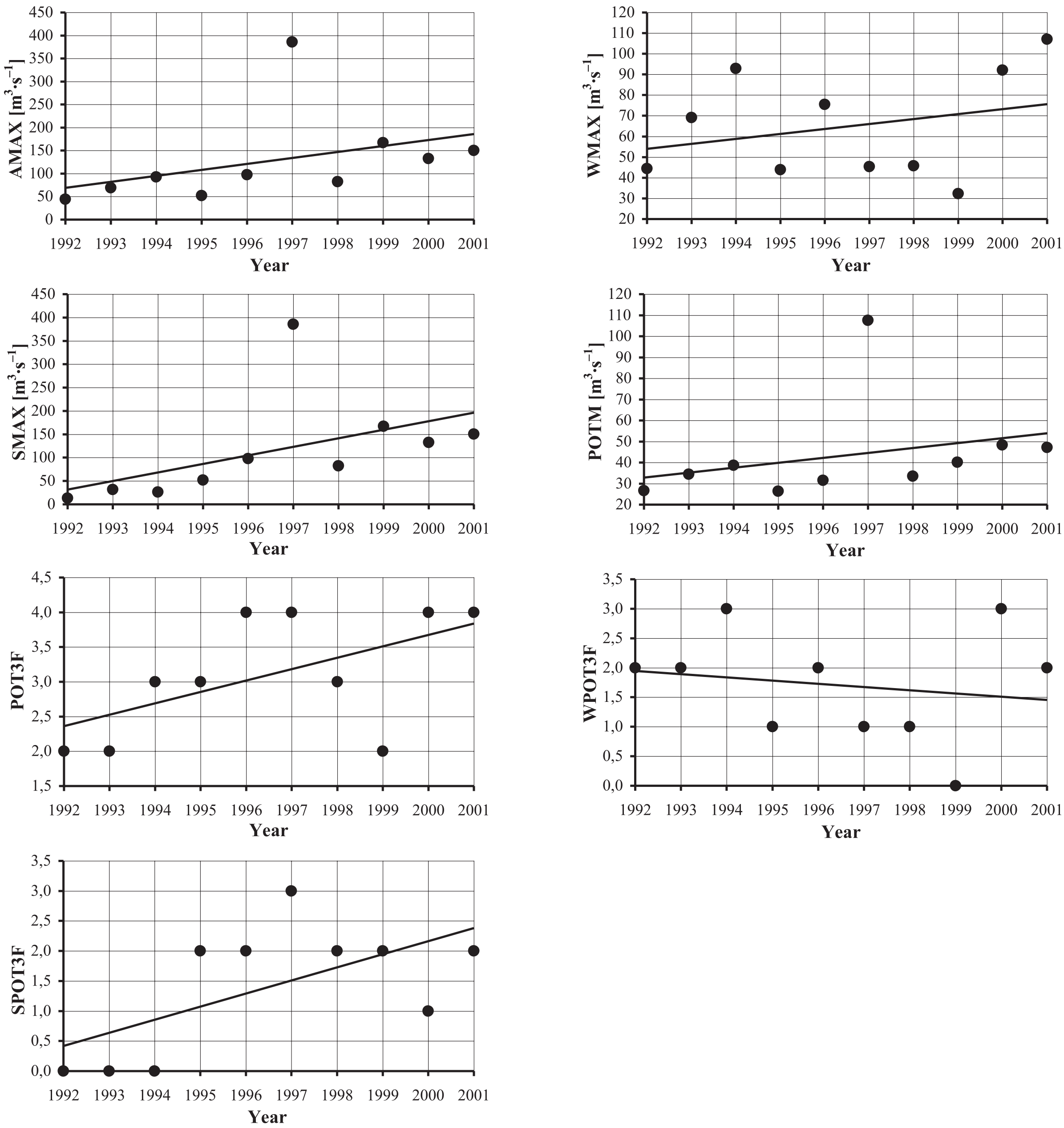


Fig. 4. Variability of flood coefficient values in 1992-2001.

a greater degree of sealing and a change of catchment character. According to Dong et al. [34], in catchments with gentle land slopes precipitation sums influence the runoff amount more than the change in catchment management. On the other hand, Jokiel and Tomalski [35] claim that the runoff system becomes more complicated and more dependent on individual characteristics of the catchment and anthropopressure regarding the processes affecting runoff formation.

An important issue in the identification of the regularities connected with the river hydrological regime is the analysis of the hydrometeorological element periodicity. Fig. 3 presents the results of Fourier spectrum analysis in the form of monthly periodic graphs of precipitation and runoff sums and runoff coefficients in the analyzed catchment. In the case of atmospheric precipitation, their periodicity of 12 months is visible (Fig. 3a). The runoff regime is slightly more complicated (Fig. 3b). In this case an apparent four-month runoff cycle occurs, but additional 2-, 3-, 6-, and 8-month cycles are clearly visible. A much less predictable runoff regime in relation to rainfall may be caused by soil conditions, catchment management, and size, which influence the speed of catchment response to rainfall. Surface runoff dominates the runoff from the investigated catchment, which is additionally determined by the precipitation amount. The factors mentioned above affect the observed runoff cycles. The periodograph of the runoff coefficient is much more regular (Fig. 3c) and its course is very similar to the precipitation periodograph. The observed cycling of the runoff coefficient is 12 months, which may unanimously indicate that precipitation is the determining factor influencing runoff from a microcatchment.

## Flood Indicators

In view of recent flooding, detection of trends in time series of flood data is of scientific interest and practical importance. This is essential for planning future flood protection systems, where system design is traditionally based on the assumption of stationarity in hydrological processes such as river stage or discharge [16]. Furthermore, the work attempts to analyze the trends in hydrological characteristics connected with extreme stream flow phenomena. Table 3 presents the results of investigations of the monotone trend conducted by means of Spearman rank correlation coefficient for the indicators of flood in the analyzed catchment, and Fig. 4 shows the analyzed hydrological indices over the 1992-2001 multiannual period.

Conducted analysis revealed that annual maximum daily mean discharge AMAX, annual summer maximum daily mean discharge SMAX, and summer POT frequency SPOT3F reveal an increasing and statistically significant monotone trend. The other indicators, i.e., annual winter maximum daily mean discharge WMAX, POT magnitude POTM, and winter POT frequency WPOT3F reveal an increasing but statistically insignificant trend. The only indicator, i.e., winter POT frequency WPOT3F, is characterised by a decreasing but statistically insignificant trend over the analyzed multiannual period (Table 3). While analyzing the AMAX, SMAX, and POTM indicators, one may clearly see their considerable similarity (Fig. 4).

In the first place one outstanding point is visible, which occurred in 1997. In that year one of the most severe floods in the last several dozen years occurred in Poland, which caused an apparent increase in stream flows. In 1997 AMAX in the analyzed catchment was 385.8 $dm^3 \cdot s^{-1}$. In the same year, precipitation sum in the investigated catchment was 930 mm, i.e., 3% higher than the average precipitation over the multiannual period 900 mm. Such high discharge in 1997 occurred in July, when the rainfall sum was 347 mm and proved the highest precipitation sum for the whole analysed period. This constituted 38% of normal precipitation for 1992-2001, 37% of total rainfall for 1997, and 236% higher than the mean precipitation sum for July. Moreover, it may be seen in the presented figures that summer maximum stream flows prevailed among the AMAX, as evidenced by a very similar course of dependencies for AMAX and SMAX. In fact, over the analysed multiannual period winter, maximum stream flow occurred only in 1994. The analysis of the frequency of flood occurrence based on POT3F and SPOT3F indicators revealed an apparent increasing trend, which evidences a higher frequency of flood events in the individual years. Four floods per year were identified in the final years of the analysed multiannual period, but they happened more frequently in the winter than in the summer half-year. Higher-frequency of flood events during the last part of the analysed multiannual period were undoubtedly associated with the growth of variance of the precipitation sums and therefore their greater variability. Higher variability of precipitation may be indirectly caused by the growing air temperature [36-37].

## Conclusions

A statistical analysis of the precipitation time series, runoff amounts, and flood indices in a small sub-mountain catchment with agricultural management was conducted in the paper on the basis of the empirical data for 1992-2001. The analyses revealed that differences appear regarding the variance of the analysed variables. For atmospheric precipitation the variability may be due to a gradually warming climate. On the other hand, higher runoff variability in the second part of the multiannual period was determined by precipitation. In connection with the changes of the studied variable time series' characteristics, it becomes necessary to analyse the time sequences not only regarding the occurrence or absence of the trend, as in the present case, but it is also crucial to consider other aspects such as the differences between the means or variability of variance. In the case of the identification of extreme phenomena at the usual lack of sufficiently long data sequences, flood indicators should be used that contain much more information than the analysis based only on the annual maximum discharges. In this situation, using the analysis based on the POT series seems helpful. In the investigated multiannual period a significant increase was demonstrated in the annual maximum stream flows and summer discharges, as well as in the frequency of flood events in the summer half-year. The observed regularities are typical for the mountain and sub-mountain catchments of a temperate climate, but they are also determined by catchment size.

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