MISCELLANEA GEOGRAPHICA
WARSZAWA 2002 Vol. 10

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THE SEARCH FOR THE PERIODICITY AND THE TENDENCIES IN THE EXTREME WATER STAGE OF VISTULA RIVER DURING THE LAST CENTURY

The extreme water stage of the hydrological system of a drainage basin, corresponding to the magnitudes of the low and high discharges, have been the subject of study of numerous research teams (Mikulski, 1962; *Ekstremalne*..., 1987; Stachy et al., 1996). The frequency and amplitude of the phenomena investigated underwent a change due to human impact, which disturbed the equilibrium of the hydrological systems, accelerating the circulation of matter and energy in them (Starkel, 1996).

The issue of extreme events is particularly important with regard to the monitoring of system's behaviour in conditions of the strongest inputs from the hydrometeorological and anthropogenic factors. The registering of the extreme stage of the hydrological system during the low and high discharges is usually done ex post, while the forecast results uniquely from the identification of causes: excess or shortage of precipitation, the date of the ice breaking, or the lengths and rates of thermal changes during the periods without precipitation. The monitoring of the catastrophic events in the hydrological system can be carried out through observation of the extreme water stage in particular years. The longer the time series of observations that is available to us, with the higher precision we can predict these events.

The flooding floods, and low flow of Vistula occur, according to the opinions of Z. Mikulski (1962) and J. Stachy et al. (1996), once in a couple or a dozen years, and have a differentiated character. When we know the extreme water stage in particular years, we can forecast the potential periods of increased hazard of the floods or low flow of the rivers. Identification of causes and analysis of trends in climate changes is especially advisable in the context of forecasting of the extreme events in the system. The assessment of the variability of the extreme phenomena was most often done using probability theory. It was rather rare to refer to the mathematical description of the long-term fluctuations and to the search for the trends appearing in the series of values registering the extreme states of the system, constituting the objective of the present paper.

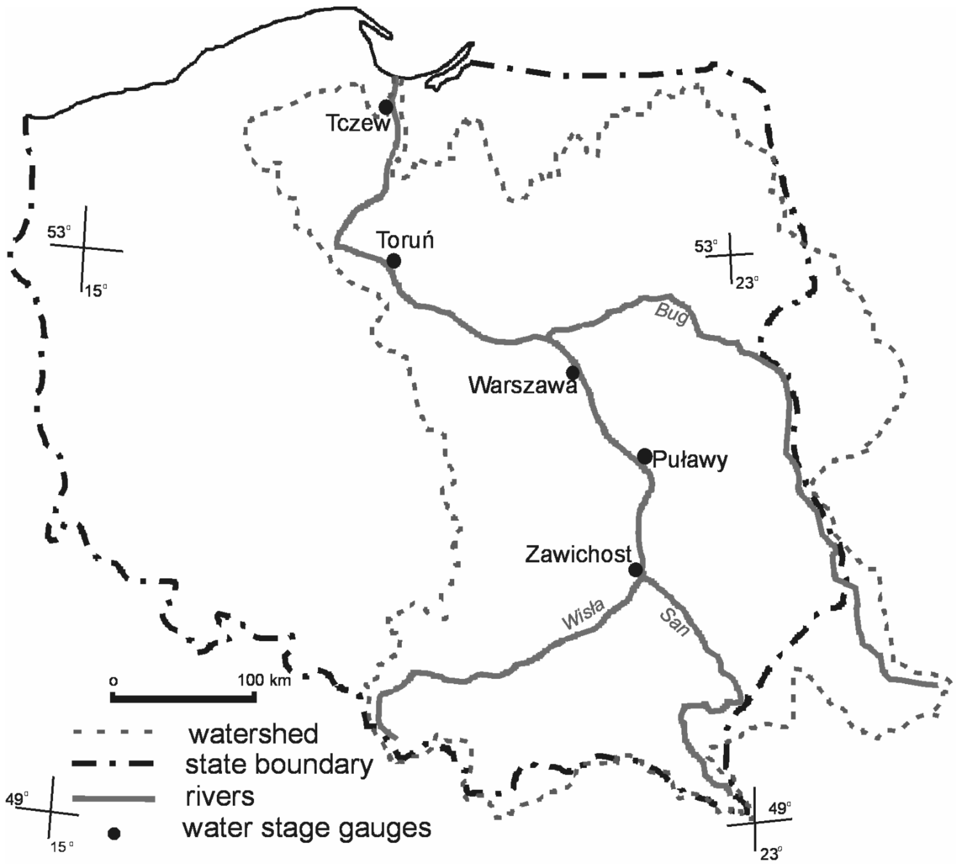

Fig. 1. Distribution of the selected water stage gauging stations in the Vistula river basin.

In order to analyse the long-term fluctuations and trends in the extreme levels of Vistula river the secular time series were collected of the respective values at five hydrological profiles (Fig. 1, Table 1).

Table 1.

Characteristics of the time series of water stage in Vistula river at the selected hydrological profiles

Water level gauging station	Zero level of the water gauge in m.a.s.l. in Kronshtad (Russia)	Initial year of measurements	Length of the series in years
Zawichost	133.38	1841	155
Puławy	113.92	1881	115
Warsaw	76.08	1799	197
Toruń	31.96	1896	100
Tczew	-0.58	1896	100

It should be emphasised that until 1918 the observation and measurement network along Vistula river was managed by the hydrographic services of the three occupational powers (Austria, Prussia, and Russia). The gauges zero was changed, the geodesic reference levels differed, and the water stage was given in non-metric units[1]. Thus, in order to obtain the comparable empirical material all the readings were transformed into the metric units, their values were brought to the currently valid gauge zero of the denivelation system of the Baltic Sea in Kronshtad, and presented in the setting of the hydrological year (November – October). The values missing in the series for Zawichost and Puławy, amounting to a couple of per cent, were added by application of the method of autocorrelation (from the same profile). The uneven length of the time series caused the analysis to be carried out solely on the basis of the one-hundred-years series of the extreme annual values of water stage in Vistula river (1896–1996).

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The method of moving averages, applied to the analysis of the multiannual course of the extreme water stage, does not involve any predefined form of the function approximating the course of a given variable, as this is the case with the regression equations. That is why the analysed secular data series were transformed with the moving 5-, 15- and 25-year averages, smoothing thereby the fluctuations of the periods shorter than the assumed averaging interval.

The analysis of the moving averages, reflecting the variability of the annual maximum water stage at the representative profiles of Vistula river (Fig. 2) makes it possible to state that the divergences from the long-term average are quite small, but synchronous. The rhythm of changes of the multi-annual maximum annual water stage of Vistula in Zawichost and Puławy (the coincidence of the shape of the curve and of the years, in which the average level was crossed) oscillates around the average value and differs from the shape of the consecutive curves in Warsaw, Toruń and Tczew. The course of the maximum levels displays, as a rule, an agreement in the direction of changes with respect to the value of the long-term average in the particular sub-periods of the entire period analysed. The moving curves indicate a clear decline of the maximum water stage below the calculated long-term values during the last 20 years. This decrease deepens downstream the river, as the drained area increases. The character of the course (convexity and concavity) of the curves of the consecutive maximum annual water stage in Vistula river motivates to suppose the existence of one or two fluctuation cycles in the last century.

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[1] 1 New-Polish foot = 0.288 m, 1 Viennese foot = 0.316 m, 1 Russian fathom (7 Russian feet) = 2.13 m.

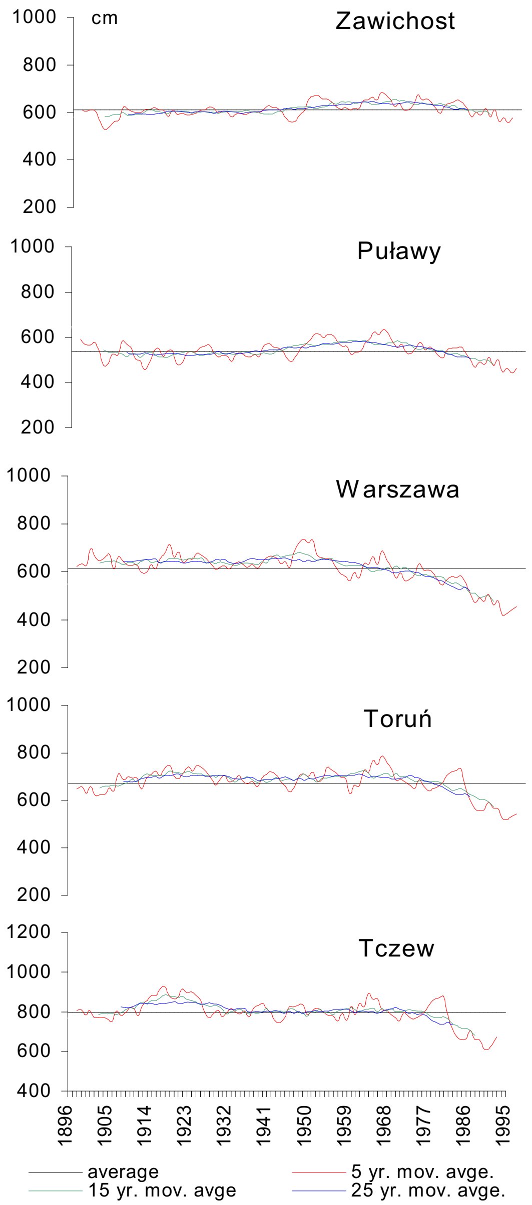

Fig. 2. Moving averages of the annual maximum water stage of Vistula at selected water stage gauging stations.

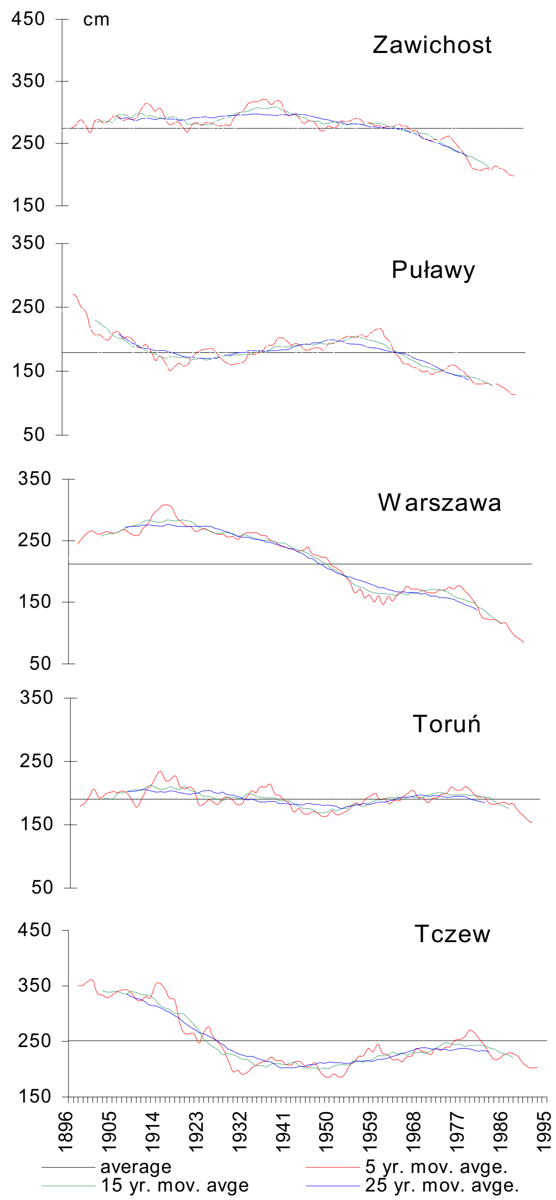

Fig. 3. Moving averages of the annual minimum water stage of Vistula at selected water stage gauging stations.

The moving averages of the minimum annual levels of Vistula show essential differences with respect to the curves resulting from the smoothing of the maximum levels (Fig. 3). The annual minimum water stage at all the water gauge profiles remain above the secular average value in the first part of the one-hundred-year period analysed, the length of this part depending upon the location of the profile. The moving averages have a similar rhythm of changes of minima in Warsaw, Toruń and Tczew. There is an obvious agreement of appearance of the highest minimum values at the beginning of the 20^{th} century and in the 1970s, and the decrease in the 1940s. The courses of the moving averages at the Zawichost and Puławy profiles are different, with the trends observed in Puławy being opposite to those for the remaining profiles. In Zawichost, Warsaw and Tczew a single long-term period is observed, though of varying length, during which annual minimum water stage remain, respectively, below and above the average for the entire time interval considered.

The course of the moving averages allows for the supposition that in the case of the upper and middle stretches of Vistula the minimum water stage have a different character of periodicity than along the lower Vistula. The cycles at the profiles of lower Vistula are clearer, but shorter, while at the profiles of upper Vistula they are longer, but less pronounced. In all the analysed profiles the annual minimum water stage of Vistula display the same direction of changes during the last 20 years – a distinct decrease. The 15- and 25-year moving averages usually coincide, defining quite long (at least 30 year long) periods of changes in the extreme water stage. The periodicity of the changes in the maximum water stage is less pronounced than for the minimum water stage. The disagreement of the fluctuations in the same profiles and years is also often observed.

TRENDS IN THE EXTREME ANNUAL WATER STAGE

The theory of time series (Box, Jenkins, 1983) was made use of in the analysis of the changes in the extreme annual water stage. The theory assumes that the time series is composed of the set of elements, consecutive in time, which can be described with the equation

$$X(t) = X_r(t) + X_t(t) + X_p(t),$$

where:

$X_r(t)$ – random component,
$X_t(t)$ – linear trend,
$X_p(t)$ – periodicity of the function.

It was assumed, conform to the approach frequently applied by other researchers, e.g. by Ciepielowski (1996), that there exist linear trends of the long-term changes in selected elements. This is the simplest way allowing for the quantitative description of variability of the element in question in the adopted time interval. The trend was analysed of changes in the annual maximum and minimum water stage in a river, understood as the gradual change of the average value.

The equation of the linear trend was estimated using the standard estimation error (minimum value), the coefficient of determination (the maximum value), the t-test and the F-test. In order to determine the statistical significance of the results obtained the significance intervals for $\alpha = 0.95$ were provided. For the time series analysed with measurement number equal $n = 100$ and the adopted significance level $\gamma = 0.05$, the critical value of the t-test is 1.98 and of the Fisher test – 3.09. Hence, the values of the statistic $t > 1.98$ and of $F > 3.09$ correspond to the statistically significant linear trends of the changes in the extreme annual water level values during the century (Table 2).

Table 2.

Coefficients of the regression equation of the extreme annual water stage of Vistula river and the appraisal of significance

Water level gauge	Regression coefficients		Limits of the significance interval for coefficient a		t-test	F test	Determination coefficient R^2	
	a	b					Linear function	Polynomial of 6^{th} degree
maximum water stage								
Zawichost	0.32	592.07	-0.15	0.79	1.35	1.83	0.02	0.11
Puławy	-0.20	535.18	-0.84	0.44	-0.63	0.39	0.00	0.13
Warsaw	-1.42	692.91	-2.05	-0.80	-4.51*$_o$	20.32*$_o$	0.16	0.27
Toruń	-0.71	709.25	-1.43	0.01	-1.96	3.85*	0.04	0.20
Tczew	-1.11	851.65	-1.92	-0.30	-2.71*$_o$	7.35*$_o$	0.07	0.19
minimum water stage								
Zawichost	-0.74	311.09	-0.98	-0.53	-6.86*$_o$	47.04*$_o$	0.32	0.59
Puławy	-0.82	220.23	-1.03	-0.61	-7.74*$_o$	59.85*$_o$	0.38	0.71
Warsaw	-1.36	306.92	-1.61	-1.11	-10.82*$_o$	117.03*$_o$	0.52	0.88
Toruń	-0.19	199.79	-0.38	0.00	-2.01*	4.05*	0.04	0.22
Tczew	-1.26	315.06	-1.59	-0.93	-7.64*$_o$	58.43*$_o$	0.37	0.73

* regression significant at the significance level $\gamma = 0.05$

$_o$ regression significant at the significance level $\gamma = 0.01$

The calculated linear regression equations of the extreme annual water stage, presented in Table 2, display strong statistical significance, but at the same time a weak dependence of the described variable upon time (R^2). That is why an attempt was made of describing the extreme water stage of Vistula with polynomials of higher degrees. The polynomial of the 6^{th} degree turned out to be most advantageous.

The equations of linear regression of the maximum water stage of Vistula (Fig. 4) display a clear downward tendency (between 0.2 and 1.5 cm per annum) at all profiles, except for Zawichost, this tendency being most distinct

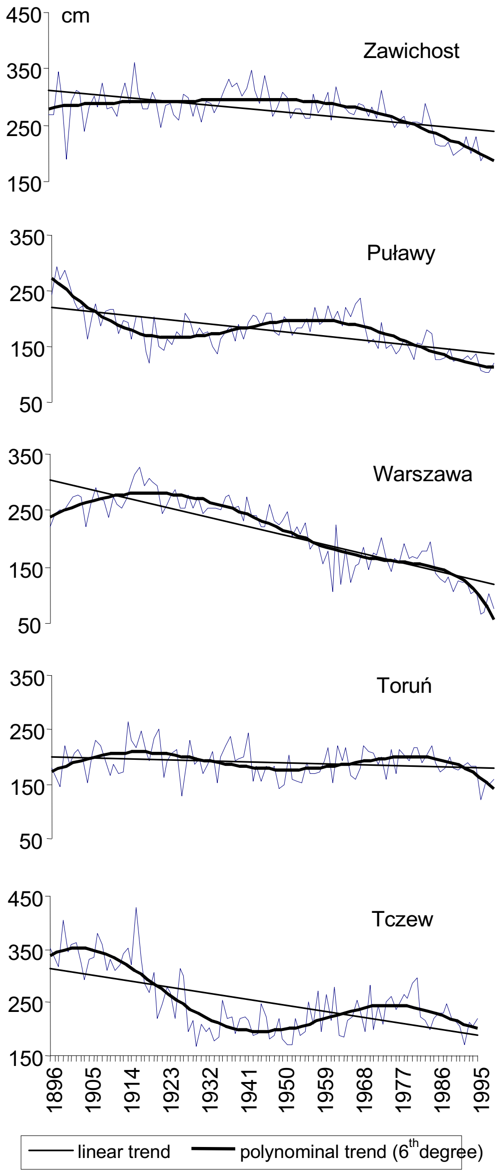

Fig. 4. Linear and nonlinear trends of the annual maximum water stage of Vistula at selected water stage gauging stations.

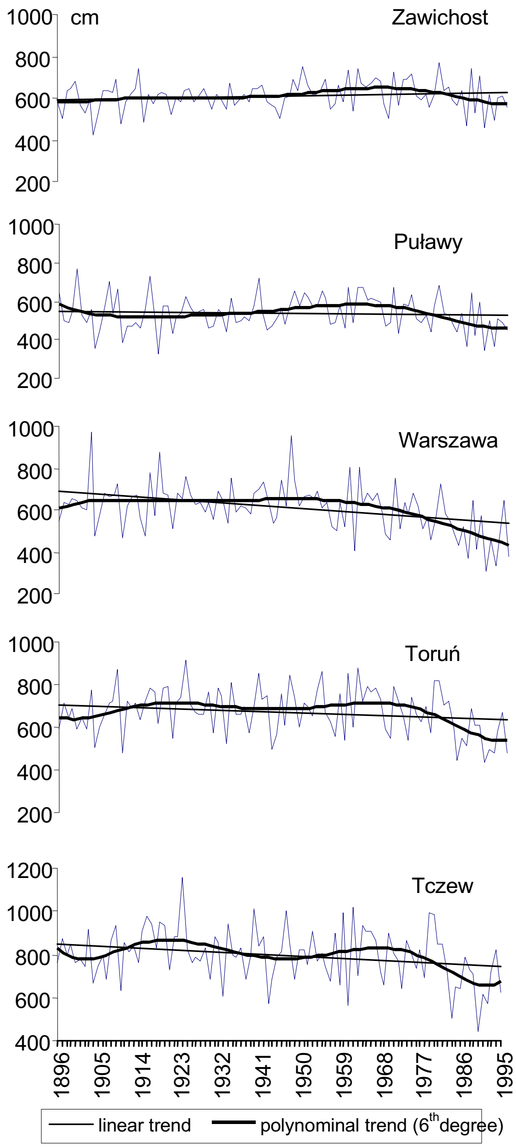

Fig. 5. Linear and nonlinear trends of the annual minimum water stage of Vistula at selected water stage gauging stations.

in Warsaw and Tczew, and somewhat weaker in Puławy and Toruń. A part of them is statistically significant with probability of 95%, or even 99%. In case of the Zawichost profile a distinct positive trend in the water stage is pronounced – contrary to that for the minimum levels. The very low value of the coefficient of determination (R^2), being the measure of fitness of the equation, motivated to make an attempt of obtaining a more precise description of the variability in time with the help of polynomials of higher degrees. Application of the polynomial of the 6^{th} degree allowed for a better determination of the rhythm of temporal changes in the extreme states of the element considered in the particular sub-periods of the last century (Table 2). The nonlinear trend, with the help of which the long-term changes in the maximum water stage are presented, is very smooth, much more distinct in the last decade. It is the weakest, but synchronous, in Zawichost and Puławy, the strongest, but also synchronous, in Tczew and Toruń. Besides, an important temporal agreement can be noticed between the extreme values of the function identified and the extremes observed in the case of minimum water stage.

Quite high values of the determination coefficient were obtained in case of equations of linear regression of the minimum annual water stage of Vistula (Fig. 5), which display also the downward tendency of 0.2 to 1.9 cm per annum for the selected gauges. This tendency is the strongest in Warsaw and Tczew, weaker in Zawichost and Puławy, and least distinct in Toruń.

Linear trends, applied in the mathematical description of the extreme water stage of Vistula are negative in the majority of gauges. The gradient of the temporal trend is, however, different in some cases. The nonlinear trend allows, in the majority of cases, for the distinction of two maximums, which do not appear as synchronous in all the gauges analysed. The most distinct temporal coincidence is seen in the long-term course of the minimum water stage of Vistula between Warsaw and Tczew. Two periods followed after them, distinct through appearance of maximums of the function, occurring in different years than in the earlier commented profiles of lower Vistula. The minimum water stage in Zawichost, representing the conditions of upper Vistula, were changing in a much milder manner. The smooth, almost parabolic course of the nonlinear trend, with a maximum in the 1960s, informs of the relatively stable minimum water stage of Vistula in the last one hundred years. The strongest dispersion of the extreme values of the annual water stage were observed in Tczew and Warsaw, smaller in Puławy, and smallest in Toruń and Zawichost.

It should be emphasised that the rhythm of changes is different, both when we compare the same kinds of extremes (minima or maximums) for the consecutive profiles downstream the river and when we compare the various kinds of extreme values for the same river profile. The identified decreasing trends in the course of the highest annual floodings of Vistula are also confirmed by J. Stachy et al. (1996).

Summing up, let us indicate that the limit water stage at the analysed water gauge profiles of Vistula river have been changing during the last century with a clear domination of the downward tendencies. The answer to the question of the essential causes of these changes within the particular parts of the drainage basin, and their associations with climatic fluctuations, and the anthropogenic pressure variations, will constitute the subject matter of a separate study.

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