Temporal and spatial variability of drought in mountain catchments of the Nysa Klodzka basin

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Abstract This paper presents drought assessments on the basis of a climatic water balance and with the application of a three-parameter model of hydrological drought. Analysis of the spatial range and temporal variability of drought phenomena was carried out for the Nysa Klodzka River basin for 1951–2003. The crucial information for hydrological drought assessment delivers the probability of low flow extreme. The low flow extreme characterizes the maximum deficit volume and duration. The two dimensional Bivariate Generalized Pareto Distribution (BGPD) was applied to estimate the extreme values of the low flow deficit volumes and duration probabilities.

Key words Nysa Klodzka River, Poland; drought; climatic water balance; low flow extreme; Bivariate Generalized Pareto Distribution

INTRODUCTION

Drought assessment is a complex problem for which many influencing factors should be taken into consideration, as well as the areal extent and duration aspects of drought. The droughts that have occurred in Poland in recent years have increased the interest in the issues of mitigation of drought consequences in agriculture, economic activities, as well as in the community. Studies including extreme phenomena such as a drought, with spatial and temporal variable scales, constitute the basis for creating state-of-the-art decision support tools that can be used for effective reduction of droughts. The potential impacts of climatic change and variability, according to the 1996 report of the IPCC (Burn *et al.*, 2002), indicate that the frequency and severity of drought events could increase as a result of changes in both precipitation and evapotranspiration.

In this study an effort has been made to describe the space–time variability of drought in the Nysa Klodzka River basin.

AREA OF STUDY

The Nysa Klodzka River is the left side tributary of the Odra River and therefore it plays an important role in the water management of the Odra River basin. Recognition of water resources during drought conditions, when groundwater yield is the only source of river supply, is very significant given the great diversity of basin geological structures.

The headwater area of the Nysa Klodzka River basin is mountainous and composed of crystalline rocks, and is an important groundwater reservoir, characterized by considerable underground runoff and slow groundwater resources bailing (Tarka, 1997). A significant part of the basin, the middle part of the basin area, is composed of Quaternary sediments with average resources. In the south-western division of the basin, a Cretaceous aquifer with high potential groundwater resources occur (Chudowski, 1976).

Moreover a cascade of four reservoirs, which have a significant influence on the discharge formation of the Nysa Klodzka River, is located in the basin.

METHODOLOGY

Climatic water balance

In this study, drought assessment was made on the basis of the climatic water balance (CWB) and with the application of a three-parameter model of low flow.

The first drought indicator is the atmospheric drought phase. The CWB was applied as an index characterizing the deficiency of water during this phase. It is the difference between

precipitation and potential evaporation. The Nysa Klodzka River basin is characterized by its diversity of climatic conditions. The CWB includes water relations that appear in selected catchments, taking into consideration both income of water from the atmosphere and losses in the form of evaporation. The CWB was calculated for the time period 1966–2003.

Threshold level method

The extent of the occurrence of a meteorological drought causes in the first step agricultural drought and then hydrological drought. The manifestation of hydrological drought is low flow in the river. The definition of a hydrological drought, criteria for drought event separation, and methods of derivation of drought indices have been used in accordance with the criteria recommended by Tallaksen & van Lanen (2004). The threshold level method was established as percentiles from the recession curve ($Q_{0;25\%}$). Q_0 is the initial discharge and it corresponds with the threshold value where surface runoff is substituted by subsurface runoff.

To obtain the probability distribution of the maximum low flow, the two-dimensional Bivariate Generalized Pareto Distribution (BGPD) (Tajvidi, 1996) was used.

Bivariate Generalized Pareto Distribution

Let $\left\{A_i^{(1)}, A_i^{(2)}\right\}_{i=1,\ldots,n}$ be a sequence of mutually independent identically distributed random variables with distribution function $F(x,t)$. These are defined in the one dimensional case as $(M_n^{(1)}, M_n^{(2)}) = (\max_{i=1,\ldots,n} A_i^{(1)}, \max_{i=1,\ldots,n} A_i^{(2)})$. If for each $a_n^{(1)} > 0, a_n^{(2)} > 0, b_n^{(1)}, b_n^{(2)}$ the limit:

$$\lim_{n\to\infty} \Pr\left(\frac{M_n^{(1)} - b_n^{(1)}}{a_n^{(1)}} \le x, \frac{M_n^{(2)} - b_n^{(2)}}{a_n^{(2)}} \le t\right) = G(x,t) \tag{1}$$

exists and if $G(x,t)$ is a non–degenerate distribution function, then $G(x,t)$ is a Bivariate Generalized Extreme Value Distribution (Resnick, 1987; Coles 2001). According to Tajvidi (1996), $H = H(x,t)$ belongs to the family of BGPD with positive support if:

$$\overline{H}(x,t) = \frac{-\ln G(x+x_0, t+t_0)}{-\ln G(x_0,t_0)}, \quad x,t > 0 \tag{2}$$

$$H(x,t) = \begin{cases} 1-\overline{H}(x,t), & \text{where} \quad x,t>0, \\ 0, & \text{otherwise} \end{cases}$$

for some extreme values distribution G with (x_0, t_0) in support of G. It can be also shown that (Tajvidi, 1996):

$$\overline{H}(x,t) = 1 - H(x,t) = \Pr\left((D_M, T_M) \not\le (x,t)\right) = \left(\frac{\overline{F}_d^p(x) + k\overline{F}_d^{p/2}(x)\overline{F}_t^{p/2}(t) + \overline{F}_t^p(t)}{\overline{F}_d^p(0) + k\overline{F}_d^{p/2}(0)\overline{F}_t^{p/2}(0) + \overline{F}_t^p(0)}\right)^{\frac{1}{p}} \tag{3}$$

where:

$$\overline{F}_d(x) = \left(1 - \alpha_d \kappa_d (b_d + x)\right)^{1/\kappa_d}, \quad \overline{F}_t(t) = \left(1 - \alpha_t \kappa_t (b_t + t)\right)^{1/\kappa_t}, \tag{4}$$

$0 \le k \le 2(p-1)$, $p \ge 2$, $\kappa_d, \kappa_t \in (-1;0)$, $\alpha_d, \alpha_t > 0$, belongs to the BGPD family. Note that the distribution functions $F_d(x), F_t(t)$ are Univariate Generalized Pareto Distributions (UGPD) and they describe each of the indices separately.

RESULTS

The spatial variability of CWB in the Nysa Klodzka River basin during the period 1966–2003 is shown in Fig. 1. The CBW undergoes variability from the mountainous part of the basin (highest value) to the lowland (negative value), and presents the background for low flow processes.

Fig. 1 The spatial variability of CWB in the Nysa Klodzka River basin in 1966–2003.

In this study the low flow maximum analysis was carried out down the Nysa Klodzka River. The estimated results for selected gauging station are shown in Fig. 2 and 3. They present the estimated two dimensional probability plots of extreme low flow deficit volumes and durations.

The shift lines in general divide the observed low flow events into two groups. The first one consists of many "low" low flows, while the second one contains a smaller number of higher low flows. Such a difference confirms the earlier assumed non-homogeneity of the observed low flow values. It means that these lower low flows are caused by different hydrological processes than the higher ones. The group of lower low flows exemplifies seasonal phenomenon, whereas the second

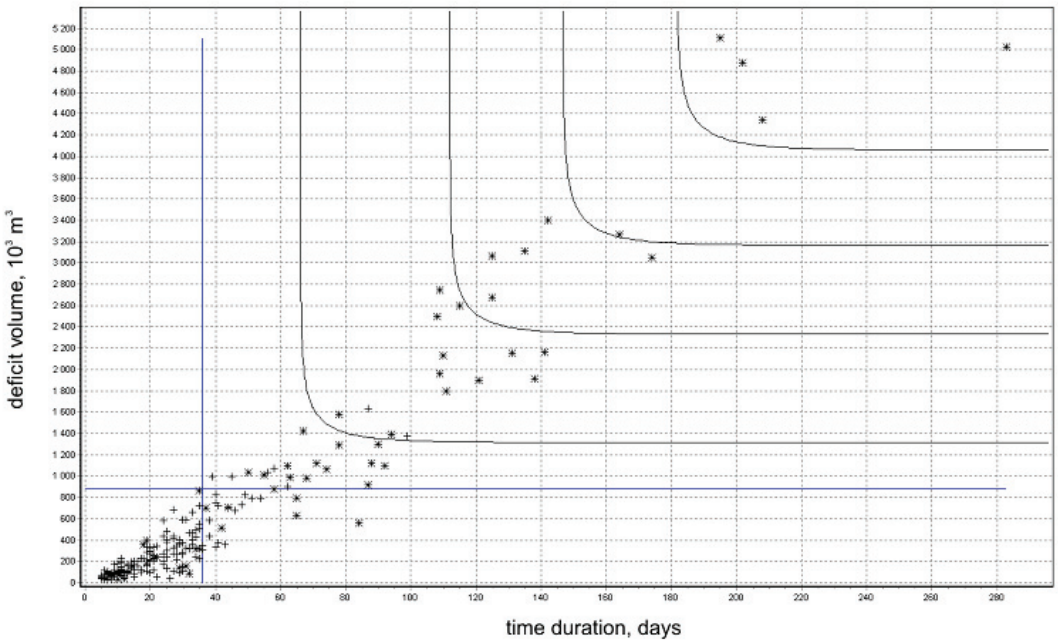

Fig. 2 The Nysa Klodzka River, Miedzylesie gauge, fitting of annual low flows to the Bivariate Generalized Pareto Distribution. (Asterisks denote the observed annual or summer maximums of deficits or durations, crosses refer to other significant observed droughts. Straight lines depict the estimated best shift parameters. The quantile curves constant value probability lines determine the areas laying left or below them which estimated probabilities of non-exceedence are equal to 50, 80, 90 and 95%).

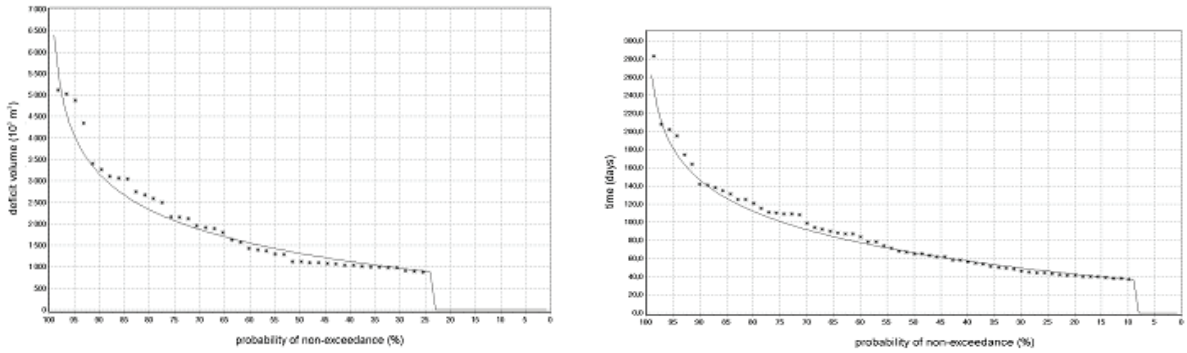

Fig. 3 The Nysa Klodzka River, Miedzylesie gauge, and annual low flows – fitting into marginal distributions of the low flow maximum deficit volume (left side) and duration (right side).

group consists of longer duration linking two or more seasons. Exception are low flows observed at gauging stations located downstream of the cascade of reservoirs. The reservoir's management leads to homogeneity of low flows and there is not a distinct division between the two groups.

Taking the marginal distributions of the estimated BGPD, the probability of each of the examined maximum values of the indices was computed. In Fig. 3 the probabilities of the non-exceedence of the low flow extreme deficit volumes and durations are presented. In the next step, deficit as well as duration, from every gauge upstream of the cascade reservoirs were compared. The deficit volume was depicted in the relative form with reference to the runoff. Such an approach allows a comparison of deficit volumes of consecutive basins. The results are presented in Fig. 4. It turned out that only the Bystrzyca Klodzka profile has a different route indicating dissimilar development and shaping of low flows. The deficit of low flows in the form of relative for the same probability is significantly higher at Bystrzyca Klodzka than the rest of profiles. For example the deficit volume with 50% probability of non-exceedence at BystrzycaKlodzka gauge amounts to 34 whereas at Miedzylesie and Bardo it is about 22. It is concerns both the deficit volume and duration. It may be caused by the specific location of the gauge and the local faulting tectonics and discontinuous fold structures. This location can be characterized by the high bedrock permeability and water support differed from the remaining part of the river.

Furthermore in order to characterize the temporal variation of low flow, the time period 1955–2003 was divided into two sequences: 1955–1984 and 1974–2003. Then the probability distributions for the periods were compared for every sub-basin. In Miedzylesie, the divided periods have a similar pattern (Fig. 5) whereas Bystrzyca Klodzka has a clearly different form in the 1955–1974 period for both deficit and duration (Fig. 6). It means that low flows that occurred in these periods do not have the same characteristics. The deficit volume is much higher and the duration longer. The results of deficit volume with probability 50% and 70% of non-exceedence and for duration for every gauging station on Nysa Klodzka River are presented in Tables 1 and 2.

Table 1 The relative deficit volume with 50% ($D_{v,50\%}$) and 70% probability of non-exceedence ($D_{v,70\%}$) for gauging stations on Nysa Klodzka River.

Gauging station	Period 1955–2003	Period 1974–2003	Period 1955–1984
$D_{v,50\%}$			
Miedzylesie	22.5	16.8	21.1
Bystrzyca Klodzka	34.3	24.2	8.40
Klodzko	00.0	8.27	21.2
Bardo	21.3	8.13	10.0
$D_{v,70\%}$			
Miedzylesie	32.0	25.1	30.7
Bystrzyca Klodzka	46.0	34.7	14.4
Klodzko	29.4	13.6	31.0
Bardo	29.9	13.4	15.8

Table 2 The duration of low flow with 50% ($T_{50\%}$) and 70% probability of non-exceedence ($T_{70\%}$) for gauging stations on Nysa Klodzka River.

Gauging station	Period 1955–2003	Period 1974–2003	Period 1955–1984
$T_{50\%}$			
Miedzylesie	66.1	47.6	61.8
Bystrzyca Klodzka	87.4	60.8	00.0
Klodzko	61.4	00.0	00.0
Bardo	71.5	21.8	31.3
$T_{70\%}$			
Miedzylesie	91.7	69.4	87.8
Bystrzyca Klodzka	115.0	84.8	00.0
Klodzko	82.7	40.4	71.8
Bardo	97.1	35.1	48.3

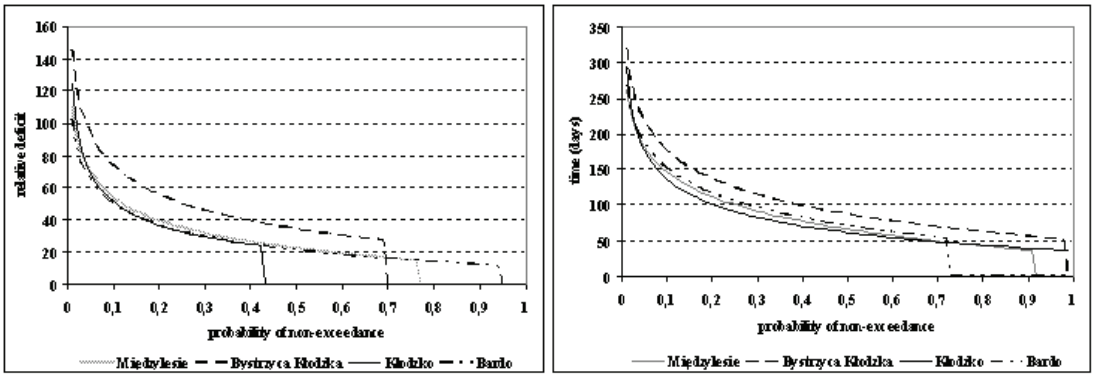

Fig. 4 The Nysa Klodzka River, Miedzylesie, Bystrzyca Klodzka, Klodzko, Bardo gauges down the river; an annual low flows route of the low flow maximum deficit volume and duration marginal distributions.

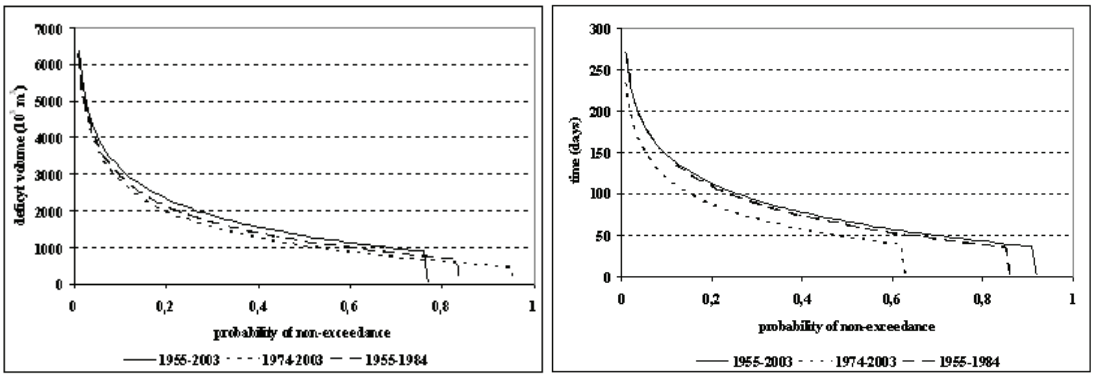

Fig. 5 Route of the low flow maximum deficit volume and duration marginal distributions for the Nysa Klodzka River, Międzylesie gauge for selected periods: 1955–2003, 1955–1984 and 1974–2003.

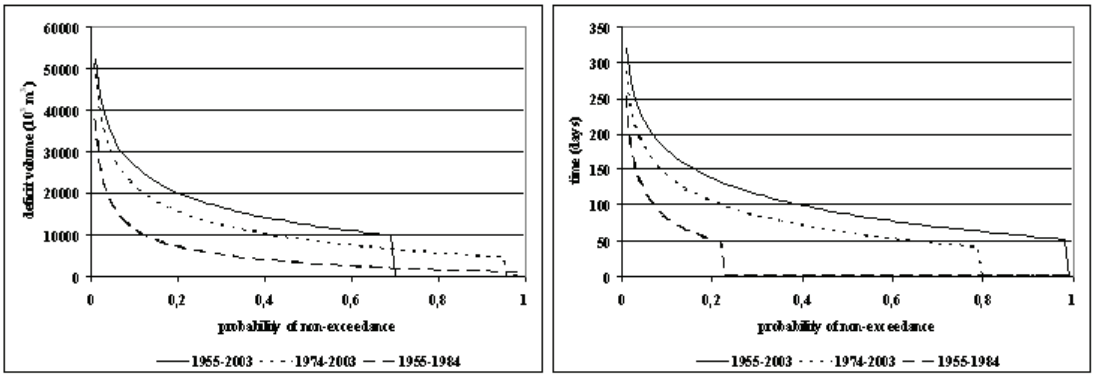

Fig. 6 Route of the low flow maximum deficit volume and duration marginal distributions for the Nysa Klodzka River, Międzylesie gauge for selected periods: 1955–2003, 1955–1984 and 1974–2003.

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