Multi-annual variability and homogeneity of drought streamflow deficit

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Variabilität und Homogenität von Niederwasser-Volumsdefiziten

Introduction

Hydrological droughts and low flows are very important components of a river regime. They have a great impact on areas with restricted water resources and concomitant water balances. Water shortages are determined by many factors that are influential over time. Therefore, in the context of observed and predicted climatic changes, many lowland areas are partly affected or seriously put at risk from water deficits due to demands from public services, industry, agriculture, forestry, as well as water ecosystems degradation. Results of hydrological analyses of drought and low flows at a longterm, multiple year scale might provide efficient resource management during hydrological extremes, as well as assist with prevention and risk management strategies.

Drought and low flows are well-known hydrological phenomena. However various methods define these processes in different ways. One approach is based on a threshold level, where runoff deficit periods are selected when runoff values are below the established limit. Its two basic parameters are low flow duration and deficit volume (Figure 1).

There are two methodological approaches allowing analysts to select the threshold: conventional (connected with water management) or statistical. The former approach as-

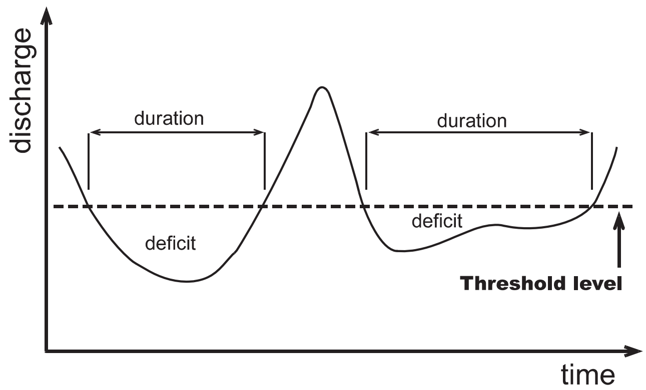

Figure 1: Basic parameters of a hydrological drought
Abbildung 1: Bestimmende Größen des Niederwasserabflusses

Zusammenfassung

Ziel des Beitrags ist die Analyse der Variabilität von Niederwasserabflüssen und deren bestimmender Größen. Die Festlegung der Niederwasserperioden erfolgte nach einem Schwellenwertansatz, wobei die 70%-Perzentile der Abflussdauerlinie als Grenzwert herangezogen wurde. An 22 Pegel-Stationen der Einzugsgebiete der Flüsse Warta, Pilica and Bzura erfolgten Abflussanalysen für den Zeitraum 1951–2000.

Schlagwörter: Hydrologische Trockenperiode, Niedrigwasserabfluss, Mehrjährige Variabilität und Homogenität von Abfluss.

Summary

The aim of this contribution has been to analyze multi-annual variability of drought streamflow deficit as well as to indicate some its determinants. The determination of low flow periods and estimation of the streamflow deficit were based on the threshold level method, where the seventieth percentile from the flow duration curve was used as the criterion. Basic calculations were made for daily discharge series at 22 gauging stations situated in the basins of the Warta, Pilica and Bzura River over the time period 1951–2000. Analysis involved multi-annual tendency and homogeneity of streamflow deficit determinatives, homogeneity interruptions and autocorrelation. Also investigated was the question of a relationship between factors which are crucial for hydrological drought development.

Key words: Hydrological drought, low flows, multi-annual runoff variability and homogeneity.

sumes that the threshold should be derived from a flow duration curve such as the percentile Q_{70} or Q_{90} (Hisdal et al. 2004). The latter uses the minimum annual daily discharge in the calculation of SNQ (mean minimum runoff), WNQ (maximum runoff out of the minima) or ZNQ (median minimum runoff), cf Ozga-Zielińska (1990).

Study area and data

The study area consisted of three river basins – the Warta, Pilica and Bzura – located in the central part of Poland. A set of 22 water-gauges situated in these basins were selected for analysis (Figure 2). All of the gauges, encompassing small and medium autochthonous catchments, reflected simple regimes of small rivers in homogeneous basins, as well as more complex regimes in larger basins of heterogeneous water courses. Basic calculations were made on daily discharge series from the period 1951–2000, measured by the Polish Institute of Meteorology and Water Management. To estimate streamflow deficit the threshold method was applied, where, as a significant limitation level, the percentile Q_{70} from flow duration curve was accepted. As a result, two basic parameters were calculated for each year: the annual sum of drought streamflow deficit volume (S_{def}) and number of days with a streamflow deficit (L_{def}).

Multi-annual variability and tendency

Multi-annual variability of streamflow deficit volume and its duration was analyzed on the base of variation coefficient (Figure 3A). The average value of the streamflow deficit was rather high – at the level of 0.9 – however, there did not appear to be large differences between the catchments (0.8–1.2). Nor was there a spatial factor influencing this value, mainly due to the small differentiation inside the group of investigated cases (Figure 3B).

Number of days when the streamflow deficit was more stable in the multi-year than the deficit volume is shown in Fig 3A. Here the annual average value in particular catchments changed between 106 and 110 days only. The mean variation coefficient for all investigated cases reached the level of 0.65 and ranged from 0.5 to 0.85. It is worth noticing that in every case, multi-year variability of the streamflow deficit was higher than its duration (Figure 3B). With respect to multi-annual variability, this might indicate determiners that operate at macro- and meso-scales (e.g. climate conditions) are more important than local factors.

The multi-annual tendency and duration of streamflow deficit was estimated by a linear trend equation, tested on 5% level. Only 9 cases were statistically significant (Figure 3B). A significant tendency appeared in the central part of the investigated area, especially in the Widawka and Ner basins. In the first case it is attributed to effects from the Bełchatów opencast mine activity and drainage of deposits

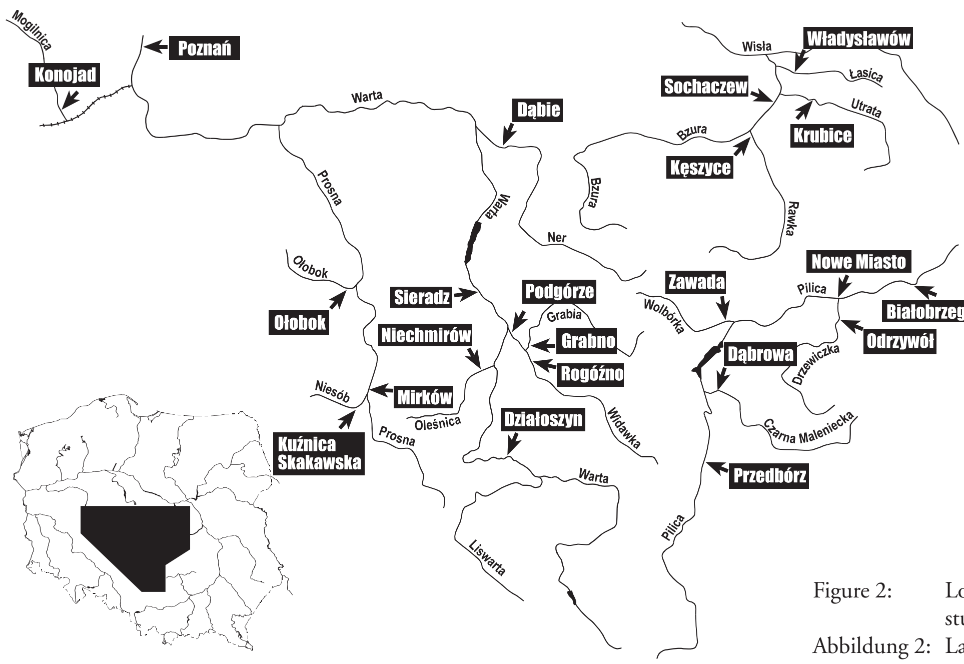

Figure 2: Locations of the water-gauges used in the study
Abbildung 2: Lage der verwendeten Abflussmessstellen

that started in the middle of the 1970s. As a result, all water from main was consistently pumped into the Widawka River channel, which resulted in a higher and more regular discharge, as well as the gradual recession of the streamflow deficit. In the second case, the Ner system channels take water and municipal wastes discharged from the agglomeration of Łódź. Water for this city is taken from a different basin and transported over the main watershed lying between the Vistula and Oder rivers. Because of the city's development, the results in streamflow deficit regime are very similar to the previous case – higher and more regular discharge, streamflow deficit gradually reduced. It appears that determining factors are mainly connected with local scale water management, for example industry or public utilities, rather than climatic factors, which are relatively less important.

Homogeneity

A very interesting question is the homogeneity of conditions determining the occurrence of streamflow deficits. This can be analyzed using the double mass curve (Searcy, Hardison, 1960), which shows the relationship between the cumulated variable of an annual streamflow deficit and cumulated variable of an annual number of days with a streamflow deficit (Figure 4). Breaks which appear on the curve indicate changes in relations between conditions determining this process.

Figure 4A shows an example of 13 cases out of 22 that demonstrate 2 breaks on the curve. It is interesting that the second break appeared near 1989 in every case. It indicates that the beginning of the 1990s was very important for low flow regimes over the whole investigated area. In periods between breaks, the streamflow deficit volume was relatively decreasing and its duration was increasing. It resulted in periods with lower volume and variability of the streamflow deficit. There were also series with 1 break (see Figure 4B).

The double mass curve took a very interesting shape for rivers of the central part of the investigated area (Figure 4C). However there are no breaks year by year instead showing continuous changes in relations between variables. As previously explained, the origin of this is the anthropogenic activity connected with opencast mine draining or water management in the agglomeration of Łódź that caused a progressive reduction of drought streamflow deficit in relation to its duration time. There were also a few homogeneous series (see Figure 4D).

Most cases demonstrate two interruptions of homogeneity, where the second break occurred in the beginning of the 1990s (Figure 5). Years of the first interruption diverge much more and indicate the rate of getting out of severe hydrological droughts in the 1950s (Tomaszewski 2009), where different delaying is caused mainly by hydrogeological conditions and water management in the catchments. Special inhomogeneity in the central part of the investigated area (in grey) is connected with anthropogenic activities (industry, municipal water management) and curves with continuous changes. Homogeneous series were located mainly in the upper course of the Pilica River basin. It is worth noticing that in this area there were not statistically significant trends and groundwater alimentation derives from capacious reservoirs. It might lead to the conclusion that this is the territory of the most stable low flow regime in central Poland.

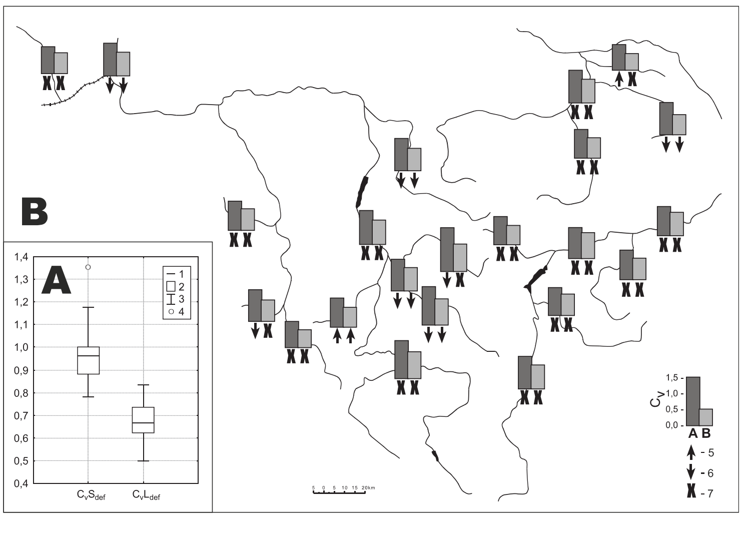

Figure 3: Multi-annual variability and tendency of drought streamflow deficit volume and its duration (1951–2000)
A: Distribution of the annual drought streamflow deficit variation coefficient (C_vS_{def}) and its duration variation coefficient (C_vL_{def}), 1 – median, 2 – 25–75%, 3 – range below 1.5 quartile deviations, 4 – outliers
B: Space differentiation of variation coefficient (C_v) of: A – annual drought streamflow deficit volume, B – annual number of days with streamflow deficit, 5 – statistically significant upward trend, 6 – statistically significant downward trend, 7 – statistically insignificant trend

Abbildung 3: Variabilität und Dauer des Abflussvolumsdefizit des Zeitraums 1951–2000

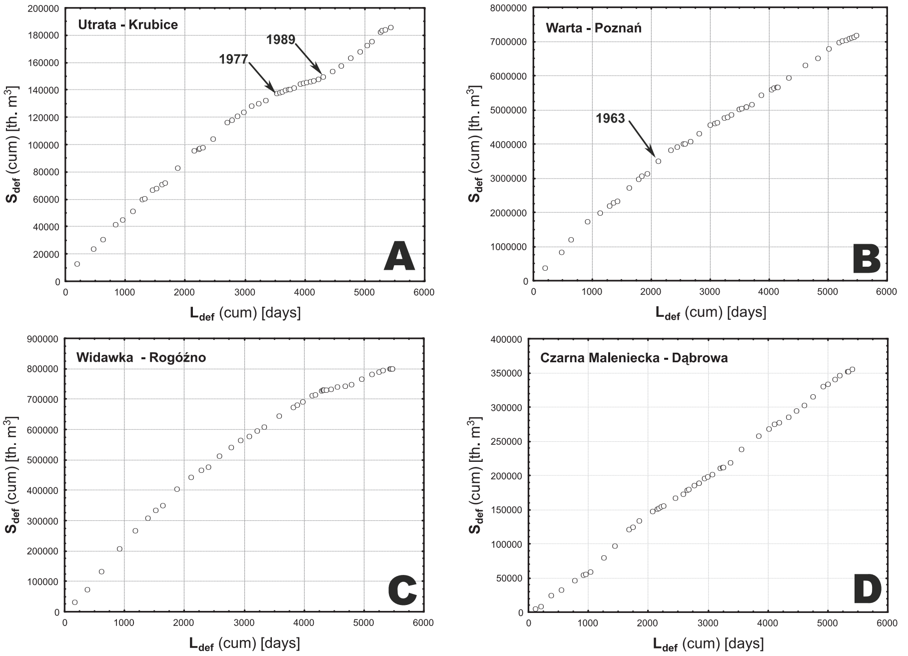

Figure 4: Examples of double mass curve (1951-2000): S_{def} (cum) – cumulated annual drought streamflow deficit volume, L_{def} (cum) – cumulated annual number of days with streamflow deficit

Abbildung 4: Doppelsummenkurve zwischen jährlichem Abflussvolumsdefizit S_{def} und Anzahl der Niederwassertage L_{def}

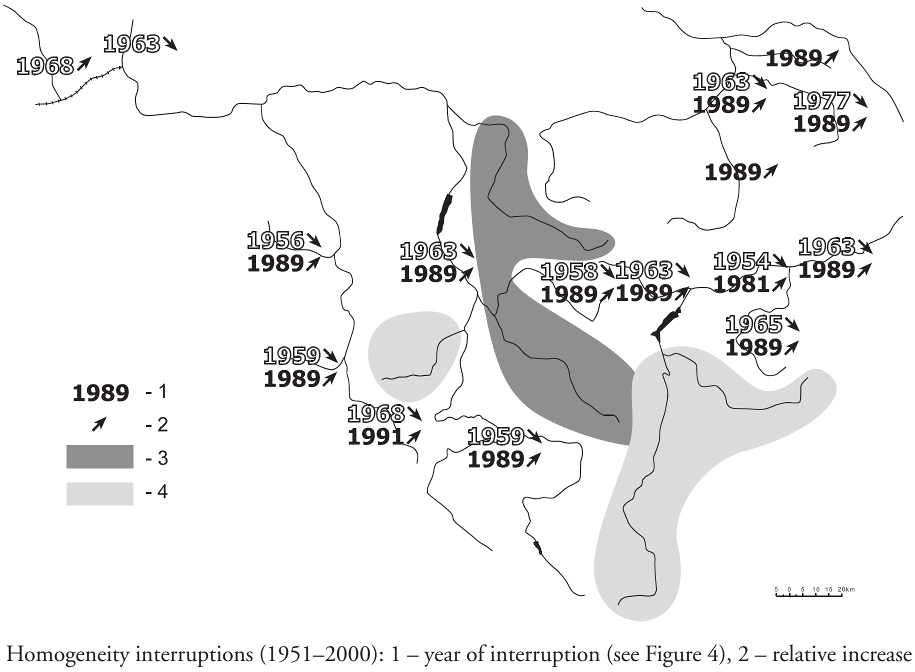

Figure 5: Homogeneity interruptions (1951–2000): 1 – year of interruption (see Figure 4), 2 – relative increase or decrease in drought streamflow depth with respect to duration in the period following the interruption, 3 – area of continuous changes in relations between depth and duration of deficit events (see Figure 5C), 4 – area of homogeneous series

Abbildung 5: Unterbrechung der Homogenitätseigenschaften (1951–2000)

Inertia

The analysis of streamflow shortage inertia, based on autocorrelation (Kendall 1984), gave promising results. First autocorrelation coefficient (shift = 1, 1 year in this case) enabled identifying information about low flow formation that is transmitted year by year. In every case its value was quite strong and statistically significant (Figure 6I) and seems to be determined by groundwater reservoirs regime. Equally interesting was an analysis of autocorrelation functions in successive shifts. It was possible to group investigated cases into 3 types. The first concerns systems with a "long memory" of water shortage periods where homogeneous periods lasted 9–11 years, and are connected with basins where rate of recession and renewal of groundwater resources is rather low (Figure 6A). The second type demonstrates very "short memory" – about 3–4 years (Figure 6B). The third one was rather difficult to interpret. It seems that stress occurs there over some separated short periods, perhaps connected with an activity of some special conditions, for example lakes, which are of importance to water retention (Figure 6C).

Summary

In summary, it is useful to present a diagram showing streamflow deficit variation in relation to its inertia and number of homogeneity interruptions (Figure 7). It is interesting that in all three outlined groups there is a variety of interruption types. Moreover, low variation and low inertia in group *a* as well as high values of these variables in group *c* indicate that in the catchments with low groundwater resources, streamflow deficit appeared much more regularly than in basins with higher and more stable groundwater resources.

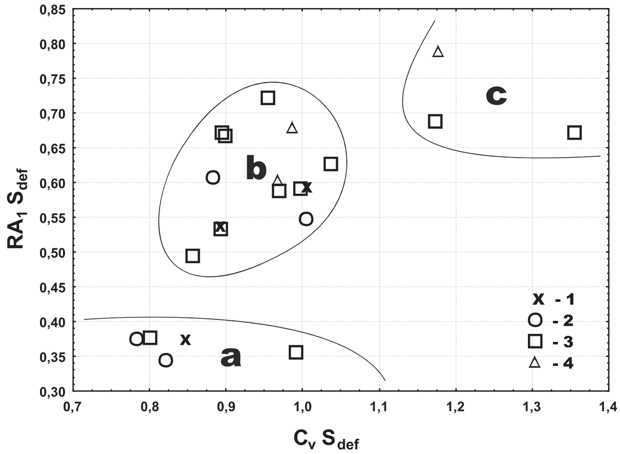

Figure 7: Relationship between drought streamflow deficit volume variation coefficient (C_vS_{def}) and first autocorrelation coefficient of streamflow deficit volume (RA_1S_{def}) – (1951–2000)
Homogeneity: 1 – no interruptions, 2 – one interruption, 3 – two interruptions, 4 – continuous changes (see Figure 4)

Abbildung 7: Beziehung zwischen dem Variationskoeffizienten des Abflussvolumsdefizit (C_vS_{def}) und dessen ersten Autokorrelationskoeffizienten (RA_1S_{def})

The preference of the interruptions number appears only in relation to the number of significant subsequent autocorrelation shifts (Figure 8). A very long inertia, up to 10 years, is determined by strong anthropogenic impacts and continuous changes in the double mass curve.

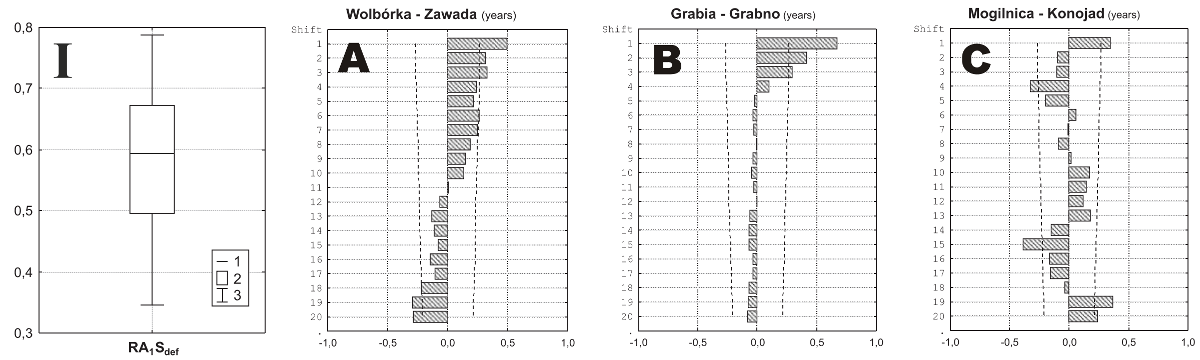

Figure 6: Distribution of the first autocorrelation coefficient of annual drought streamflow deficit (I) and its autocorrelation in subsequent shifts (A, B, C) 1 – median, 2 – 25–75%, 3 – range below 1.5 quartile deviations

Abbildung 6: Boxplot-Verteilung des ersten Autokorrelationskoeffizienten der jährlichen Abflussvolumsdefizitwerte

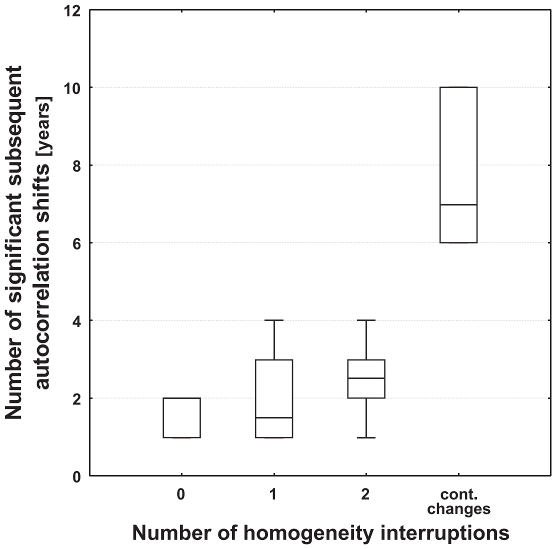

Figure 8: Distribution of number of significant subsequent autocorrelation shifts in relation to number of homogeneity interruptions (1951–2000).

Abbildung 8: Verteilung der Anzahl der signifikanten Autokorrelationsintervalle und den Unterbrechung der Homogenitätskriterien (1951–2000).

Acknowledgments

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