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Hydrologic response on atmospheric drought

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Abstract

The main aim of the study concerns the influence of climatic and hydrological droughts formation and intensity of droughts in 6 agricultural catchments located in lowlands of Central Poland. The behaviour of the catchments has been examined with respect to the rate of streamflow during the most severe droughts which occurred in 1966–1995 period. Low flow events were separated according to the selected threshold flow criterion. Uniform truncation criterion of Q70% was applied on daily flow duration curves. The first stage of the study was indication of water supply deficit in selected catchments by the analysis climatic water balance (CWB). Potential evapotranspiration was calculated by Thom-Olivier formula. Next the relationship of cumulated curve of climatic water balance versus discharge reduction curve (Q% discharge expressed as the percentage of time of given discharge) was analysed. The conclusion of the analysis is that the catchments with more impermeable surface need large atmospheric feeding deficit (CWB) to reach the same low flow level as the catchment with relatively more permeable surface. Climatic water balance and discharge reduction values are highly correlated.

Key words: low flows, atmospheric drought, hydrological drought, Polish lowlands

Introduction

Prior researches (Farat et al., 1995, Kasprzyk, 1998, Kasprzyk, Kupczyk 1998) have proved that the highest risk of hydrological droughts in Poland appears in summer half-year in Wielkopolska and Mazowsze regions. The study of hydrological droughts conducted by Farat et al. (1995) concerned 40-year period (1951–1990), Kasprzyk and Kupczyk have taken into account 30-year period (1963–1992).

The aim of the study

The main aim of the study was concerning of the influence of climatic factors on hydrological droughts formation and intensity. The most important aspect of research was indication the moment when influence of climatic conditions on discharge reduction is replaced by hydrogeological conditions.

Intensive hydrological droughts, not analysed in investigations mentioned earlier, which appeared in the middle of 90-ties were included in the study.

The study area and database

The study area consists of 6 agricultural catchments located in lowland of Central Poland (Fig. 1), where the most severe low flows in summer half year appear.

Important criterion in catchments selection was their differentiation in respect of physiographic features: lakeness, permeability and geological substratum.

Arable areas occupy from 41% of surface in Flinta catchment to 83% in Noteć catchment. Dominating type of soils are sand and clay. In Kopel and Mogilnica boulder clay dominates (more than 65% of catchment area), in Flinta catchment sands and gravels of sandr dominate, in other catchments sand and clay sandas dominate but they occupy less than 60% of area.

The basis of study were values of river discharge and meteorological elements in ten days time step in selected years, in which the extreme low flows appeared.

Selection of years with the most severe low flows

The first step of research was selection of years with most severe low flows. In this research low flow is defined as the time, in which flow equals or is smaller than threshold value. Threshold value is determined as 70 percentile discharge computed on the base of sum curve of low flow duration. This explicit definition is the result of research performed within the frame of FRIEND (Flow Regimes from International Experimental and Network Data) and is recommended for low flow calculation (Assessment of the Regional Impact of droughts in Europe, 2001). Selection of years with most severe low flows was made with application of modified criterion proposed by Demuth i Heinrich (1997).

Applied criterion is based on calculation of mean number of days with flow >Q70% in each basin, and selection years, when occurred in more than 60% of all days in summer half year. The subject of further analysis were years, when low flows occurred simultaneously in all selected catchments according to applied criterion. Criterion was fulfilled in following years: 1976, 1979, 1982, 1983, 1989, 1990, 1991, 1992, 1993, (Fig. 2).

Low flows in study catchments appear most often (in most cases) in 180 day of hydrological year – at the beginning of April. The beginning of low flow event corresponds to the beginning of growing season in this part of Poland. Therefore further detailed analysis concerns period April–October.

Catchment response on atmospheric drought

The next stage of research was detailed analysis of each catchment reaction on atmospheric drought. It was made in 9 years (1976, 1979, 1982, 1983, 1989–1993), which were selected as the representative for the most severe hydrological drought conditions.

Atmospheric drought was characterized by hydrotermical coefficient of Sielianinow *K:*

$$K = \frac{P}{0.1\sum t}$$

where: P – precipitation, t – mean air temperature in period.

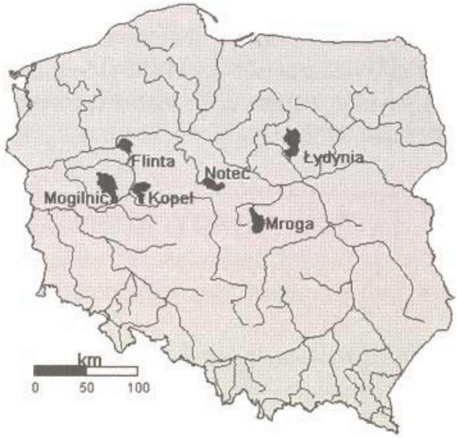

Fig. 1 Location of selected catchments in Poland

Values of precipitation were corrected with use of Jaworski method (1988). Values of Sielianinow coefficient for each catchment were calculated in decade time steps. Next frequency analysis of Sielianinow coefficients was made – the intervals parallel the stages of severity of atmospheric drought according to Prawdzic and Koźmiński classification. It enabled the comparison of atmospheric conditions both among selected catchments and selected years.

Prawdzic i Koźmiński (after Suchorab, 1998), taking into account Sielianinow coefficient, distinguished four typical periods of atmospheric conditions – three of them indicate different severity of atmospheric drought (Tabs. 1, 2).

Tab. 1 Criterion of estimation of atmospheric drought severity

Sielianinow coefficient	Drought severity
> 1.0	No drought (transpiration is lower than precipitation)
0.5–1.0	Small drought (transpiration is higher than precipitation)
< 0.5	Drought (transpiration is twice higher than precipitation)
< 0.3	High Drought (period with extreme deficit of humidity)

Frequency analysis of decade values of Sielianinow coefficient revealed, that about 50% of all decades in analyzed years in each catchment can be characterized as dry (K < 1) (Tab. 2).

Tab. 2 Frequency (%) of Sielianinow coefficient appearance in Flinta catchment

Sielianinow coefficient	1976	1979	1982	1983	1989	1990	1991	1992	1993	Mean in 9 years
> 1	57	52	38	38	29	62	52	29	48	45
0.5–1.0	14	10	24	38	43	10	29	24	29	24
< 0.5*	29	38	38	24	29	29	19	48	24	31
< 0.3	24	24	33	14	10	14	05	33	19	20

* the second stage of drought ("drought") contains the third one ("high drought").

Analysis confirmed, that the highest risk of atmospheric drought is in the western part of Wielkopolska Lowland (Mogilnica and Kopel catchments), the lowest one is in Łydynia catchment. The most dry vegetation periods appeared in years 1982, 1989, 1992 and 1983.

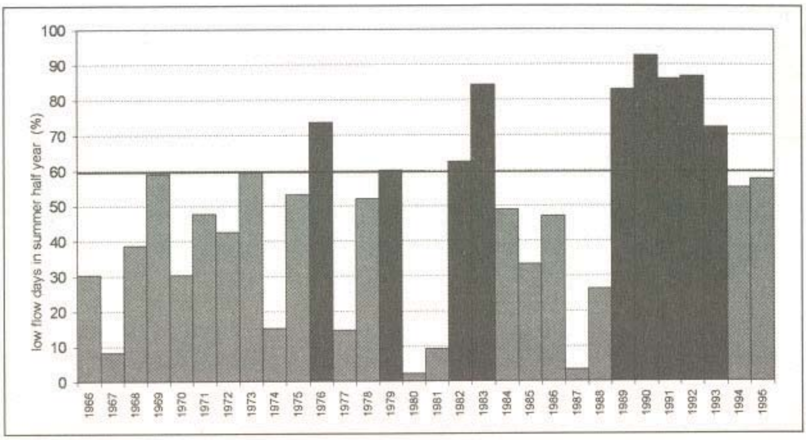

Fig. 2 Mean percentage of days with low flow (Q>Q70%) in number of all days in summer half year, occurring simultaneously in all selected catchments in period 1966–1995. The bold line shows value 60% which was criterion of selection years for further analysis

The next stage of research was analysis of relationship between water supply deficit in dry period and discharge reduction.

Water supply deficit in selected catchments was estimated as a modified climatic water balance (CWB)

$$\mathrm{CWB} = P - E_p \quad \text{(mm)}$$

where: P – corrected precipitation, E_p – reference crop evaporation.

Mean ten days values of climatic water balance were calculated in period April–October for each basin in nine selected years. Ten day period was assumed as optimal for CWB analysis and its relationships with low flows.

Rainfall measurements were taken from pluvial stations located in the basins and their surroundings; mean spatial values of precipitation for each basin were calculated by Thiessen method.

Potential evaporation, originally occurring in CWB calculations, was replaced by *reference crop evaporation*. Reference crop evaporation was calculated by Thom-Olivier formula (Shuttleworth, 1992) on the basis of meteorological data taken from representative meteorological station located nearest to the basin.

$$E_p = \frac{\Delta}{\Delta + \gamma^*} \cdot (R_n - G) + \frac{\gamma}{\Delta + \gamma^*} \frac{900}{T + 275} U_2 D$$

where: E_p – reference crop evaporation, Δ – slope of the saturated water vapour pressure versus temperature curve (hPa/°C), γ – psychrometric constant (hPa/°C), R_n – net radiation exchange (MJ); G – measured or estimated soil heat flux (MJ); T – air temperature (°C); U_2 – wind speed at altitude 2 m (m/s); D – vapour pressure deficit (kPa).

Next step was calculating of cumulated decade values of CWB in each basin.

Daily values of discharge were expressed as the percentage of time of given discharge reduction curve (Q%) in period April–October for each basin and they were generalized into decade values.

Intensity of relationship between river discharge (Q%) and water supply deficit (cumulated CWB) was estimated by correlation coefficient (Tab. 3). The highest values of mean correlation coefficient in 9 dry years were in Noteć and Kopel catchments (r = –0.77). In separate years its value exceeded even –0.90. Low values of correlation coefficient were the reason of elimination Mroga catchment from further analysis.

Tab. 3 Values of correlation coefficient r between river discharge (Q%) and cumulated climatic water balance in six catchments in nine dry years

Catchment	Year									Mean
	1976	*1979*	*1982*	*1983*	*1989*	*1990**	*1991*	*1992*	*1993*	
Flinta	–0.68	–0.88	–0.71	–0.69	–0.83	–0.28	–0.69	–0.73	–0.24	–0.64
Kopel	–0.82	–0.68	–0.76	–0.68	–0.79	–0.73	–0.59	–0.69	–0.76	–0.72
Łydynia	–0.75	–0.76	–0.80	–0.72	–0.77	0.13	–0.67	–0.59	–0.83	–0.64
Mogilnica	–0.76	–0.70	–0.90	–0.72	–0.72	–0.30	–0.64	–0.63	–0.74	–0.68
Noteć	–0.86	–0.83	–0.85	–0.85	–0.83	–0.71	–0.20	–0.90	–0.91	–0.77
Mean	–0.78	–0.77	–0.81	–0.73	–0.79	–0.38	–0.56	–0.71	–0.69	–0.69

* Low flow in 1990 was not caused by atmospheric drought but not renewed underground retention after drought in 1989.

Analysis of correlation coefficients revealed that the strongest influence of the climatic water balance on low flows appears in the first year of hydrologic drought (years 1976, 1979, 1982, 1989); in next years of drought duration this relationship is much weaker (Fig. 3, 4).

In the first year of drought river flow reduces as a result of increasing water supply deficit and reduction of shallow groundwater reservoirs, caused by evaporation (Fig. 5, 6).

In next years of drought the main reason of occurring low flow is weak groundwater storage renewal in winter–spring period and small groundwater supply to the river in vegetation period.

In the first year, when low flow occur, there are distinct differences in hydrological reaction of catchments on similar values of CBW, caused by different geological conditions. The big similarity of hydrological reaction of catchments on similar values of CBW occurred in Kopel, Mogilnica and Noteć.

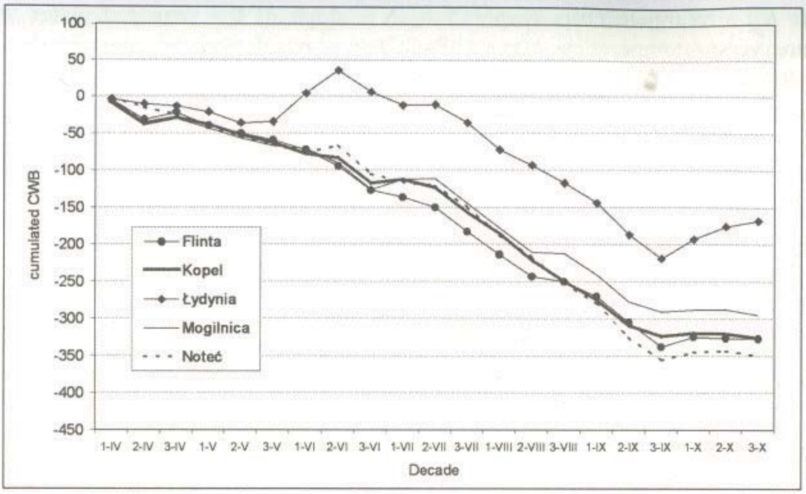

Fig. 3 Cumulated decade values of CWB in period April–October 1989

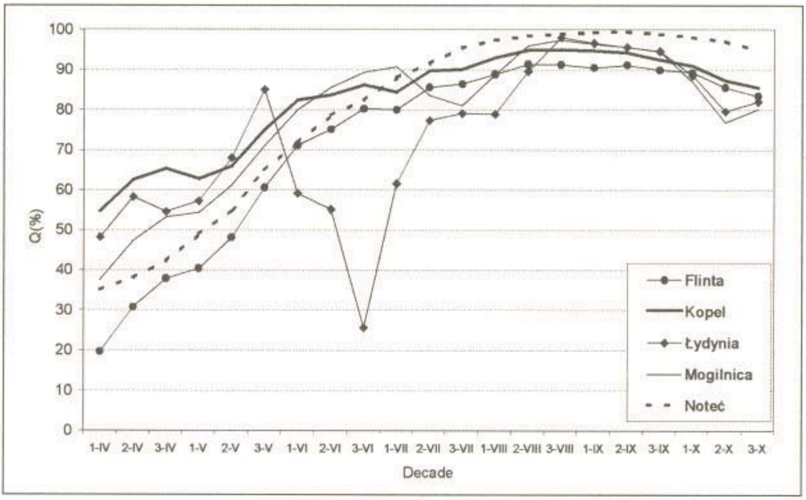

Fig. 4 Decade values of discharge expressed as the percentage of time of given discharge reduction curve (Q%) in period April–October 1989

The trials of mathematical description of river discharge in vegetation period versus climatic water balance showed, that logarithm function is the best fitted. Application of logarithm function required transforming negative values into positive ones, according to the formula:

$$CWB' = -CWB + 10$$

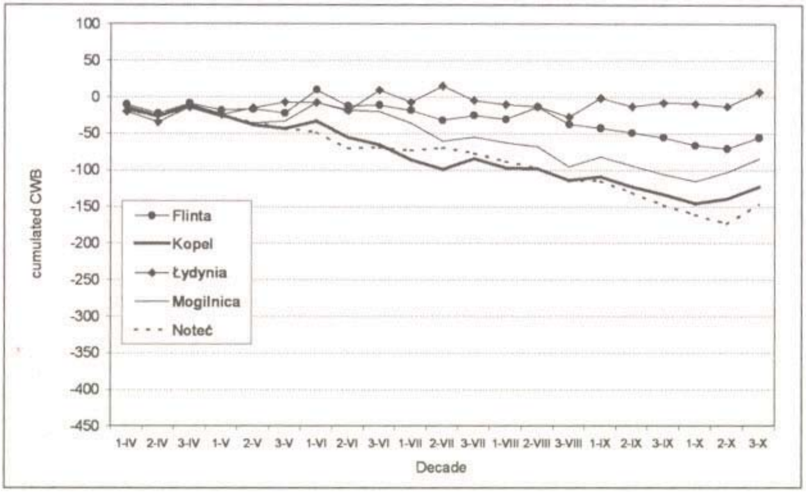

Fig. 5 Cumulated decade values of CWB in period April–October 1990

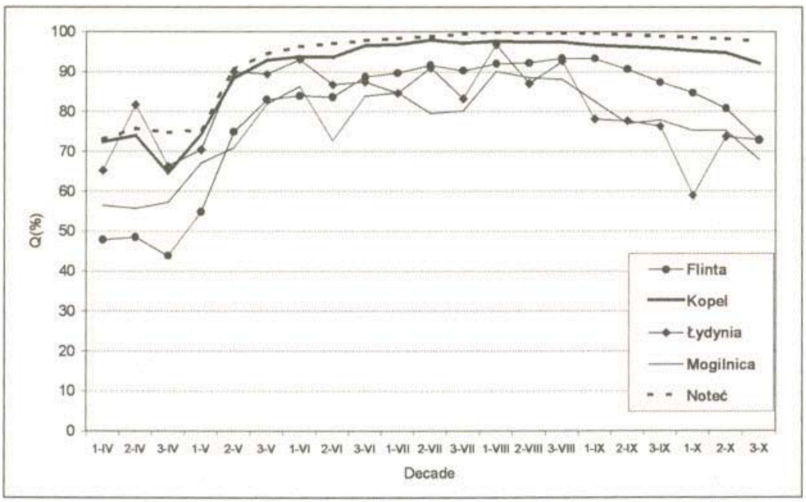

Fig. 6 Decade values of discharge expressed as the percentage of time of given discharge reduction curve (Q%) in period April–October 1990

Values of cumulated CWB in vegetation periods in selected dry years were between 8 mm–439 mm.

Coefficients of determination of logarithm function were from 0.58 in Łydynia cachment to 0.77 in Noteć catchment (Tab. 4).

Tab. 4 Equations of logarithm functions describing relationship between river discharge (Q%) and cumulated climatic water balance

Catchment	Equation*	R^2
Flinta	$Q\% = 17.283 \ln(CBW') + 1.8146$	0.63
Kopel	$Q\% = 20.914 \ln(CBW') - 27.513$	0.69
Łydynia	$Q\% = 21.114 \ln(CBW') - 20.706$	0.58
Mogilnica	$Q\% = 24.511 \ln(CBW') - 46.227$	0.70
Noteć	$Q\% = 25.126 \ln(CBW') - 43.998$	0.77

* For $CBW' = -CBW + 10$

These equations let foresee rate of discharge reduction on the basis of assumed water supply deficit in given basin.

Values of discharge (Q%) corresponding to CWB values were calculated on the basis of logarithm equations. It enabled to estimate values of water supply deficit when each basin reach low flow threshold Q70% (Tab. 5).

Tab. 5 Values of cumulated water balance calculated on the basis of logarithm function equations for discharge Q70% and Q90%*

Discharge	Flinta	Kopel	Łydynia	Mogilnica	Noteć
Q70%	–42	–96	–63	–105	–84
Q90%	–154	–265	–179	–249	–197

* Values of cumulated climatic water balance put into logarithm equations in order to obtain values of discharge Q70% and Q90%

During the first phase of discharge reduction (till gaining Q70%), big similarity of discharge reduction characterizes catchments: Mogilnica, Kopel i Noteć. These catchments are similar in respect to soil types, infiltration conditions and land use.

Discharge reduction in Flinta catchment is quite different – it is more rapid due to sands and gravels what ensure good infiltration conditions. Discharge of Flinta reduces to threshold Q70% when climatic water balance equals 42 mm, in the case of Mogilnica – when CWB equals –105 mm, what is a big difference.

Shape of logarithm function curves reveals that clear relationship between river discharge and climatic water balance disappear when discharge gains Q70%–Q80%. It corresponds to the end of the phase of hydrologic drought when river discharge is determined by climatic factors and the beginning of the phase when further discharge reduction is determined mainly by hydrogeological conditions of the catchment.

Conclusion

Climatic water balance and discharge reduction values in lowland catchments are highly correlated. Relationship between river discharge and water supply deficit can be described by logarithm function curve.

In the first year of low flow occurrence, the main factor regulating discharge reduction is water supply deficit, in next years of drought the main reason causing low flow is the groundwater storage renewal in winter–spring period and magnitude of groundwater supply to the river in vegetation period, resulting first of all from retention capabilities of underground catchment.

When river discharge gains Q70%–Q80%, then the phase of hydrological drought caused by climatic factors is finished and the phase when further discharge reduction is determined mainly by hydrogeological conditions of the catchment begins.

The catchments with more impermeable surface need large atmospheric feeding deficit (CWB) to reach the same low flow level as the catchment with relatively more permeable surface.

The presented results are part of doctoral thesis conducted by professor Elżbieta Kupczyk and they are also contribution to research within Low Flow Group of International Hydrological Programme of UNESCO.

References

DEMUTH, S., HEINRICH, B. (1997): Temporal and spatial behaviour of drought in south Germany. [In:] FRIEND'97 – Regional hydrology: concepts and models for sustainable water resource management. A. Gustard, S. Blazkova, M. Brilly, S. Demuth, J. Dixon, H. Van Lanen, C. Llasat, S. Mkhandi, E. Servat. IAHS Publ. no 246.

FARAT, R., KĘPIŃSKA-KASPRZAK, M., KOWALCZAK, P., MAGER, P. (1995): Susze na obszarze Polski w latach 1951–1990. Seria Gosp. Wodna i Ochr. Wód, z. 16. IMGW.

JAWORSKI, J. (1988): Charakterystyka obiegu wody w zlewni Regi. Wiad. IMGW, T. XI (XXXII), z. 1–2.

KASPRZYK, A. (1998): Fizycznogeograficzne uwarunkowania susz hydrologicznych w Polsce. Doctoral thesis, Kielce, WGSR UW.

KASPRZYK, A., KUPCZYK, E. (1998): Ocena podatności systemu zlewni rzecznej na występowanie niżówek o znacznym deficycie odpływu. [In:] Hydrologia u progu XXI wieku. ed. A. Magnuszewski i U. Soczyńska. Konf. Hydr. 24–27. 09. 1996, Warszawa, Wyd. Retro-Art.

POKOJSKI, W. (2002): Wpływ warunków fizycznogeograficznych na kształtowanie się przepływów niżówkowych rzek nizinnych w Polsce. Doctoral thesis, WGiSR UW, Warszawa

Assessment of the Regional Impact of Droughs in Europe, Final Report (2001), ed. S. Demuth and K. Stahl. Univ. of Freiburg, Germany.

SHUTTLEWORTH, W.J. (1992): Evaporation. [In:] Handbook of hydrology, ed. D. R. Maidment. McGraw--Hill.

SUCHORAB, J. (1998): Dni posuszne w Lublinie w okresie wegetacyjnym w świetle współczynnika hydrotermicznego Sielianinowa. [In:] Problemy współczesnej klimatologii i agrometeorologii regionu lubelskiego, ed. M. Nowosad. Lublin, Wyd. UMCS.