JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2024.151785
2024, No. 63 (X-XII): 11–18

Relationships between springs yield dynamics and hydrological drought development

Edmund Tomaszewski*, Malwina Kozek-Połomska

University of Lodz, Faculty of Geographical Sciences, Department of Hydrology and Water Management, ul. Narutowicza 88, 90-139 Łódź, Poland

* Corresponding author

RECEIVED 02.04.2024 ACCEPTED 09.08.2024 AVAILABLE ONLINE 08.11.2024

Abstract: This paper presents results of the identification and assessment of relationships between river discharge dynamics and spring yield during severe hydrological drought. The study covered a weekly yield series of eight springs and the daily discharge series of river gauging stations closing catchments including these springs. The investigated area was located in the mountainous, upper reaches of the Dunajec River basin (southern Poland) and the study covered the period 1989–2018. It was assumed that river low-flow is a good indicator of hydrological drought development. Severe streamflow droughts were estimated on the basis of the threshold level method (TLM) at a truncation level of 95% on the flow duration curve (FDC). Spring yield droughts were identified in the same way, however, there were three variants of truncation criteria. Synchronicity between both types of droughts was assessed on the basis of a co-occurrence ratio. To achieve the best fit criteria analysis, time shift steps of the spring yield series in relation to the river discharge series were conducted both for individual springs and for the whole investigated group. The best results of drought co-occurrence were achieved for the spring threshold at a multiannual average yield value, especially in backward and zero time shifts for fissure springs placed in relatively small catchments. Analysis of the course of relative spring drought intensity in following time shifts allowed an indication of the typical behaviours of the aquifer spring regime in relation to hydrological drought development.

Keywords: droughts co-occurrence, spring yield drought, streamflow drought, synchronicity

INTRODUCTION

Drought is one of the most unfavourable hydrometeorological extremes on earth. Commonly, it is defined as an extremely long, dry period which triggers a serious water deficit within a specific area (Nagarajan, 2009). As a result, the limited access to water resources leads to numerous disturbances in water management (agriculture, water supply, hydropower etc.) as well as posing a threat to water ecosystems and natural water aquifers. Drought develops in several phases. The first refers to a precipitation shortage which initiates meteorological drought (Sene, 2010). In practice, this extreme is identified on the base of relative deviations of rainfall parameters from standard values or multiannual means (Łabędzki, 2007). A prolonged lack of precipitation combined with intense evapotranspiration causes a gradual loss of soil moisture which leads to soil drought. Water shortages occurring during intense field works might determine plant degradation or growth restrictions which results in the onset of agricultural drought (Wilhelmi, Hubbard and Wilhite, 2002). Continuous increase of water shortage initiates hydrological drought. Lack of alimentation determines a groundwater table recession which is incessantly drained by river channels and springs (groundwater low-flow). Surface waters which are usually in a hydraulic connection with groundwaters, show a reaction to this process by water table lowering and runoff reduction (river low-flow). In adverse conditions, streams may dry up completely (Hisdal *et al.*, 2001; Smakhtin, 2001).

The most serious problems for water management and the natural environment are caused by severe hydrological drought and the deep low-flows related to it. Therefore, continuous expansion of knowledge about identification, dynamics and directions of hydrological drought development is very important. During severe streamflow drought, a river channel is alimented by groundwaters only. As a result, the hydrogeological regime of groundwater reservoirs during a dry period is crucial from a research point of view. It is worth noting that springs draining particular groundwater systems reflect many features of their regime. Therefore, if we make an assumption that river low-flow is a good indicator of hydrological drought development (Tokarczyk, 2013; Kozek and Tomaszewski, 2022) then the spring yield regime might have a significant relationship with its progression.

The aim of this study is to identify the relationships between river discharge dynamics and spring yield during severe hydrological drought. On this basis, there will be an analysis of which features of the groundwater reservoir regime, drained by river channels, are particularly important for streamflow drought development.

STUDY MATERIALS AND METHODS

STUDY METHODS

The identification of periods of hydrological drought occurrence requires streamflow drought estimation. This was carried out based on the threshold level method (TLM), where a period during which daily discharge attains values below an established limit is defined as a streamflow drought (Hisdal *et al.*, 2004). Its two basic parameters are low-flow duration and deficit volume (Fig. 1a). The advantage of this methodological approach is the possibility to assess physically interpretable parameters such as the precise date of streamflow deficit onset and termination as well as the volume of water shortage during the deficit period which may be used for the estimation of hydrological drought severity. This is particularly important when comparative analyses of synchronicity between different types of water bodies (rivers, lakes, springs etc.) are conducted.

The assumption of an appropriate threshold level is crucial for the method used and the interpretation of the obtained results. There is no objective and automatic method of determining it. Each time, individual research goals must be taken into account and the appropriate criterion adjusted to them. There are two methodological approaches that allow researchers to select a proper threshold: conventional or statistical. The former approach uses usual flows important for the proper operation of water management objects or refers to environmental condition, for example hands-off flow. The latter assumes that the threshold can be derived from a flow duration curve (FDC) such as the percentile, usually from the range Q_{70} or Q_{95} (Hisdal *et al.*, 2004; Raczyński and Dyer, 2020; Choi, Borhardt and Choi, 2022; Teutschbein *et al.*, 2022). For statistical criteria calculation of the *SNQ* (mean minimum runoff), *WNQ* (the largest of the runoff minima) or *ZNQ* (median minimum runoff) are applied (Ozga-Zielińska, 1990).

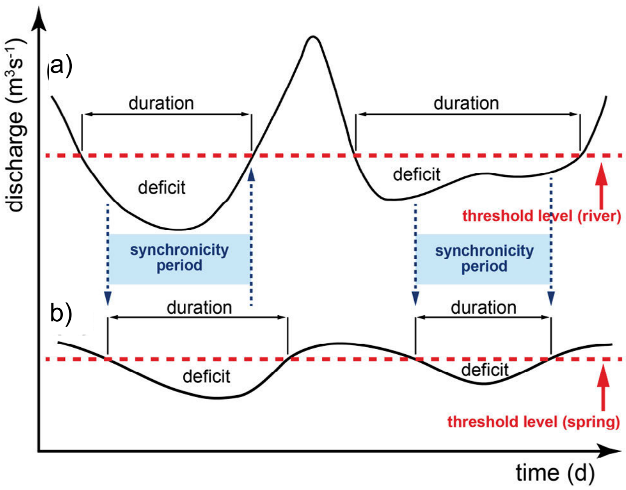

Fig. 1. Basic parameters of: a) streamflow drought, b) spring yield drought; source: own elaboration

For this research, percentiles from the FDC, which is widely used for low-flow analysis, have been taken into consideration. The percentile of 95 was established as the truncation level for streamflow droughts because it is recommended as a good estimator of severe hydrological drought. Moreover, the fourteen-day period was taken as the minimum streamflow drought duration to avoid a random fluctuation of flow (Yevjevich, 1967; Hisdal *et al.*, 2004; Tomaszewski, 2012; Tomaszewski and Kubiak-Wójcicka, 2021)

Estimated volumes of streamflow drought deficit (in m^3) are not fully comparable, similarly to river discharge, because of different stream drainage (catchment) area. For this reason, calculated deficits were transformed into relative deficits (*DWN*) according to the Equation (1) (Tomaszewski and Kozek, 2021):

$$DWN = \frac{DN}{DN_{\max}} 100\% \tag{1}$$

where: *DWN* = relative drought streamflow deficit (%); *DN* = volume of drought streamflow deficit for a given period (m^3); $DN_{\max}$ = volume of maximum possible drought streamflow deficit for a given period, i.e. when the river discharge equals 0 (m^3).

This characteristic is fully comparable for catchments of various sizes because it is based on measurements from a specific gauging station only. The presented parameter evaluates the intensity of the drought deficit as well as indirectly indicating the level of water resources drained during the low-flow season. When the estimated value reaches 100%, the riverbed should be completely dried up without any flow.

An analogous procedure was applied to estimate the drought deficit in the spring yield series. Three variants of truncation level were chosen because the application of TLM for spring drought has never, to the author's knowledge, appeared in the literature. It should be emphasised that springs are a very good estimator of the quantity, quality and regime of groundwater collected in aquifers. There are numerous very interesting analyses regarding the estimation of static and dynamic water resources on both the regional and local scale (e.g. Korkmaz (1990), Chełmicki *et al.* (2011), Bartnik and Moniewski (2018), Mudarra, Hartmann and Andreo (2019), Ezea *et al.* (2022), Deng *et al.* (2023), Yabusaki and Asai (2023)), however, no assessment of groundwater resources shortage based on spring discharge analysis during drought periods has previously been conducted.

Based on this approach it should be possible to ascertain which criterion is more accurate in assessing the relationship between spring and streamflow drought. Selected thresholds were 70% ($Thr_{70\%}$) and 95% ($Thr_{95\%}$) of FDC as well as the average value of multiannual yield (Thr_{av}). For identified drought periods, their durations, deficit volumes and relative deficits were estimated (Fig. 1b).

In the final step, synchronicity of streamflow and spring drought was assessed. The assessment was made on the basis of the co-occurrence ratio (Eq. 2):

$$CoR = \frac{NoD_{SPR}}{NoD_{STR}} 100\% \tag{2}$$

where: CoR = co-occurrence ratio (%); NoD_{SPR} = number of days with spring drought during corresponding streamflow drought (d); NoD_{STR} = streamflow drought duration (d).

For every identified period of streamflow drought, the co-occurrence ratio was estimated (Eq. 2). Its value equal 100% means a total synchronicity of both types of droughts. Reducing the value of the index results from a smaller number of days with spring drought, for example CoR = 50% describes a situation when during a given streamflow drought period only half days reflect spring drought whereas other yields take values higher than the established threshold level.

STUDY MATERIALS

The study area is located in the southern part of Poland, in the upper reaches of the Dunajec River basin (Fig. 2). It covers the central part of the Polish Carpathians where average specific discharge varies between 10 and 50 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Michalczyk, 2017) and annual precipitation achieve totals ranging from 750 to 1800 mm (Kożuchowski, 2017). Eight springs were selected for investigation, characterised by various hydrogeological conditions and different yield dynamics (Tab. 1). Each one possesses a weekly discharge series, measured and published by the Polish Geological Institute – National Research Institute (Pol. Państwowy Instytut Geologiczny – PIB). Basic data, taken for this study, were initially prepared by Bartnik and Moniewski (2018). For the established research period 1989–2018, there were, in some cases, observation gaps in different places of the multi-year series but they were no shorter than 24 years. The weekly spring discharge series has been interpolated linearly to daily step to compare with the daily stream flow series.

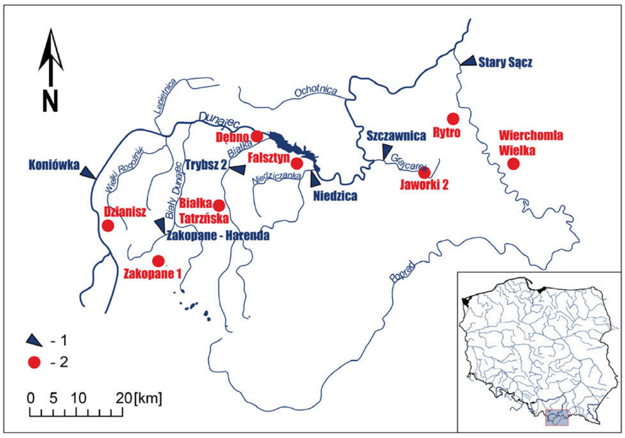

Fig. 2. Map of study area; *1* = river gauging station, *2* = spring; source: own elaboration

A river gauging station was selected for each spring, closing such a catchment which included the selected spring (Fig. 2). All gauging stations have available daily discharge series in the period 1989–2018, published by the Institute of Meteorology and Water Management – National Research Institute (Pol. Instytut Meteorologii i Gospodarki Wodnej – PIB).

RESULTS AND DISCUSSION

In accordance with the established criteria, 55 severe streamflow drought episodes in all gauging stations in the period 1989–2018 have been identified. They occurred mainly in the winter and summer–autumn season. The longest winter low-flow lasted 100 days whereas during the warm half-year its maximum duration was 75 days. For estimation, the most severe periods of hydrological drought, corresponding to spring yield droughts in three truncation variants were assessed. The co-occurrence ratio calculated for the identified episodes is characterised by very different distributions depending on the threshold criteria (Fig. 3).

Table 1. Basic features of the investigated springs

Locality	Elevation (m a.s.l.)	Type	Lithology	Stratigraphy	Q_{av} ($dm^3 \cdot s^{-1}$)
Dzianisz	945	fissure	sandstones and shales	Eocene and Oligocene	1.70
Zakopane 1	908	fissure	limestones	Eocene	18.76
Białka Tatrzańska	725	fissure	sandstones and shales	Oligocene	0.20
Dębno	531	porous	sands, gravels and pebbles	Quaternary	10.43
Falsztyn	648	fissure	limestones	Middle Jurassic and Lower Cretaceous	0.94
Jaworki 2	630	fissure	limestones	Middle Jurassic and Lower Cretaceous	0.08
Wierchomla Wielka	495	fissure	sandstones and shales	Eocene	0.76
Rytro	480	fissure	sandstones and shales	Eocene and Oligocene	0.08

Explanation: Q_{av} – multiannual average spring yield.
Source: own elaboration.

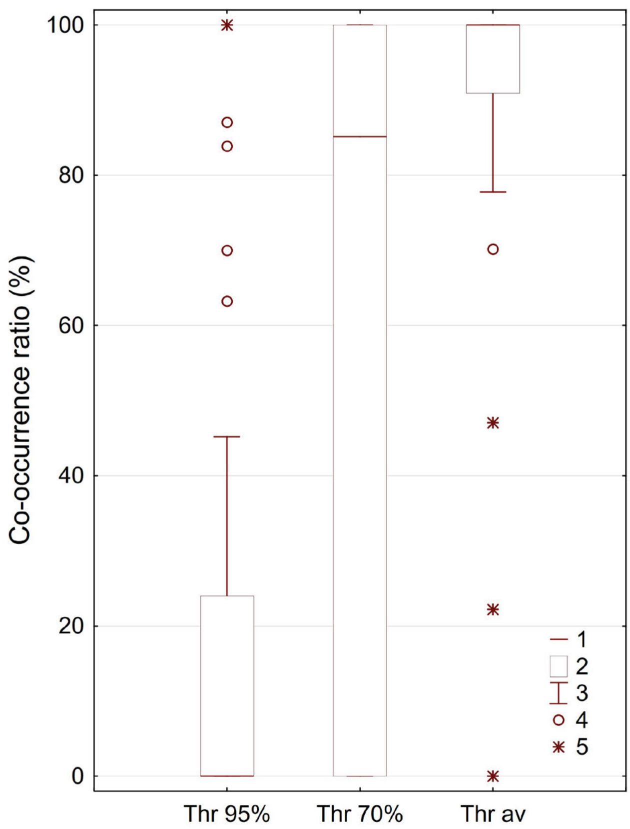

Fig. 3. Distribution of co-occurrence ratio between streamflow drought and spring drought at the threshold: $Thr_{95\%}$, $Thr_{70\%}$ = percentile of the flow duration curve, Thr_{av} = multiannual average yield; *1* = median, *2* = range between first and third quartile, *3* = range limited by 1 quartile deviation, *4* = outliers under 1.5 quartile deviation, *5* = extremes over 1.5 quartile deviation; source: own study

Spring droughts at the threshold level of 95% are non-synchronic with river droughts. At least half of the streamflow droughts had no equivalents in spring droughts and almost 75% of them did not exceed 20% of the co-occurrence ratio. It is worth noting that with this criterion, droughts in springs occur much less frequently than in rivers. It follows from the fact that such low spring yield corresponds to groundwater alimentation by the river channel which is defined as the baseflow on the master recession curve (curve limit) (Jokiel, 1994; Tallaksen, 1995). As a result, river discharges only attain such extreme low flows very rarely.

Spring droughts at the threshold level of 70% are much more synchronous where half of the investigated cases are characterised by a co-occurrence ratio higher than 85% (Fig. 3). Distribution of *CoR*, compared to the previous one, is much more symmetric and platykurtic without outliers or extremes. The observed dispersion of values results from a different recession pace in river and spring discharges during the dry weather curve (recession coefficient) which is determined by individual, regional dependencies between the hydrogeological conditions of the groundwater reservoir drained by the spring and the structure of river channel alimentation in the catchment (Korkmaz, 1990; Jokiel, 1994; Tallaksen, 1995).

The highest synchronicity was observed for spring drought identified on the basis of the average multiannual yield truncation level (Fig. 3). At least half of the streamflow droughts had a full time coincidence with spring droughts and almost 75% of them exceeded 90% of the co-occurrence ratio. Such a good relationship is an obvious effect of the higher frequency of spring droughts, however, it was also proved that average spring yield is a good estimator of river channel groundwater alimentation (Tomaszewski, 2007) which is significantly connected to streamflow drought beginning and development (Hisdal *et al.*, 2004; Yildirim and Aksoy, 2022; Ying *et al.*, 2024).

The process of water resource recession during dry weather has different determinants for aquifers drained by springs and for river catchments. The main differentiating factor in this case is the time and pace of discharge recession as well as changes in their dynamics. The significance of these differences was assessed using the co-occurrence ratio in time shifts of spring droughts in relation to streamflow droughts. A weekly shift step was assumed. The spring yield series was moved one and two weeks back as well as one and two weeks ahead. The analysis was carried out for two truncation criteria only (Fig. 4). The threshold for spring yield of 95% was excluded because of very low synchronicity (Fig. 3).

The co-occurrence ratio for the threshold of average spring yield with a large advance shows a dichotomous distribution (Fig. 4). About 80% of identified drought episodes are fully synchronic whereas the others occupy the entire variability range.

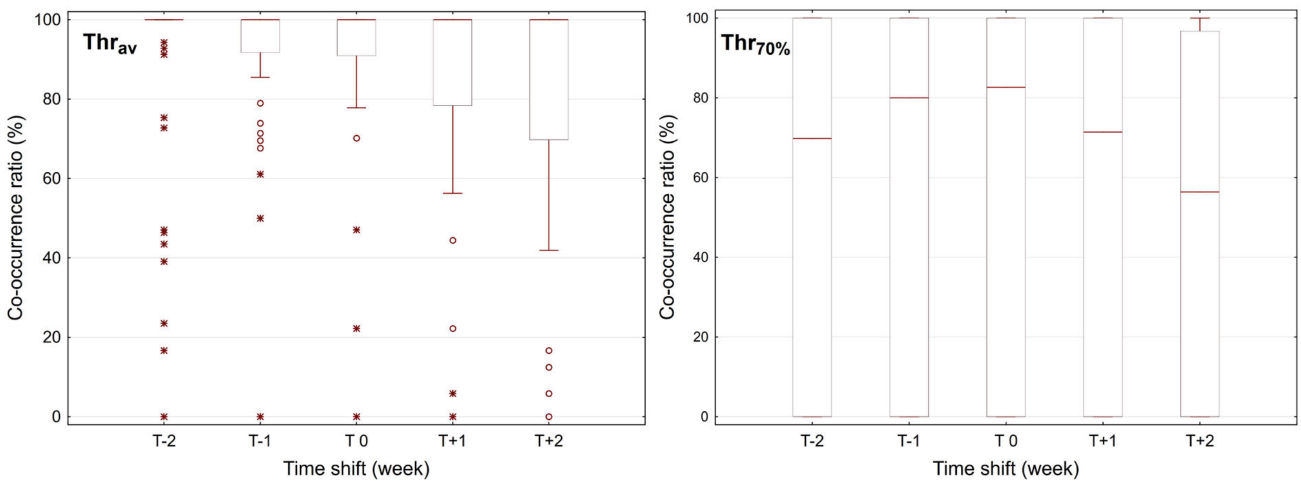

Fig. 4. Distribution of co-occurrence ratio between streamflow drought and spring drought at the multiannual average (Thr_{av}) and 70% of FDC (flow duration curve) ($Thr_{70\%}$) threshold in weekly time shifts of spring yield series; other of sign. as in Fig. 3; source: own study

When the time shift delays, the median of the *CoR* constantly maintains a value of 100% but the share of cases with lower co-occurrence increases. As a result, spring droughts at this threshold start earlier than in rivers, however, individual features of their yield regime determine significant co-occurrence differentiation during flow recession lengthening. At the spring yield threshold of 70%, the highest drought coincidence is observed in the step without time shift. The level of co-occurrence is less than in the previous case but time shifts reflect quasi normal distribution. It can be concluded that analyses conducted at this truncation level have less application importance but greater cognitive value because they reflect better relations (proportions) between the spring regime and the severe phase of streamflow droughts.

Establishing the threshold Thr_{av} for spring yield drought as best fitted to appearance and changes of streamflow drought, an analysis of the co-occurrence ratio for individual springs on the basis of this criterion was performed (Fig. 5). In general, springs located in relatively small river catchments (Dzianisz, Zakopane, Białka Tatrzańska, Jaworki 2) showed high synchronicity between both types of droughts. The porous spring in Dębno, which is located on an alluvial apron in the interfluve of the Dunajec River and Białka stream, had a high co-occurrence of droughts in back time shifts only. *CoR* estimated for delayed shifts decreased, which might be determined by a faster reaction to alimentation shortage by Quaternary aquifer horizons drained by this spring than in the fissured aquifers that dominate the river catchment area. Moreover, during severe hydrological droughts, alluvial groundwater dynamics might be determined by local, temporary hydrometeorological conditions which will modify their recession pace significantly. Very similar conditions appeared in the Falsztyn spring.

Different reactions for hydrological drought development and significant co-occurrence decrease have been observed in springs located in Wierchomla Wielka and Rytro (Fig. 5). It is worth noting that they belong to a large catchment where the river alimentation during hydrological drought depends on the groundwater regime of the lower part of the catchment as well as being under the influence of the runoff features formed in its upstream part. As a result, co-occurrence between both types of droughts varies significantly and depends on episode duration, pattern of hydrometeorological conditions and season of appearance. However, the median of *CoR* for Wierchomla Wielka spring is equal to 100% in all time shifts and for the Rytro spring it does not fall below 80%, which indicates that drought synchronicity in these cases is significant and the perturbations indicated above are rather unique in nature and occur in delayed time shifts.

The last stage of the analysis concerned the assessment of spring yield drought intensity during the development of hydrological drought. For this reason, spring drought episodes identified at the threshold Thr_{av} were selected. The second condition of selection was 100% of a co-occurrence ratio in all 5 time shift steps. For each episode, relative yield drought deficit has been estimated, according to Equation (1). During analysis four types of spring drought severity development were identified. Some of investigated springs were characterised by a very long time of yield recession (Fig. 6A). Relative drought

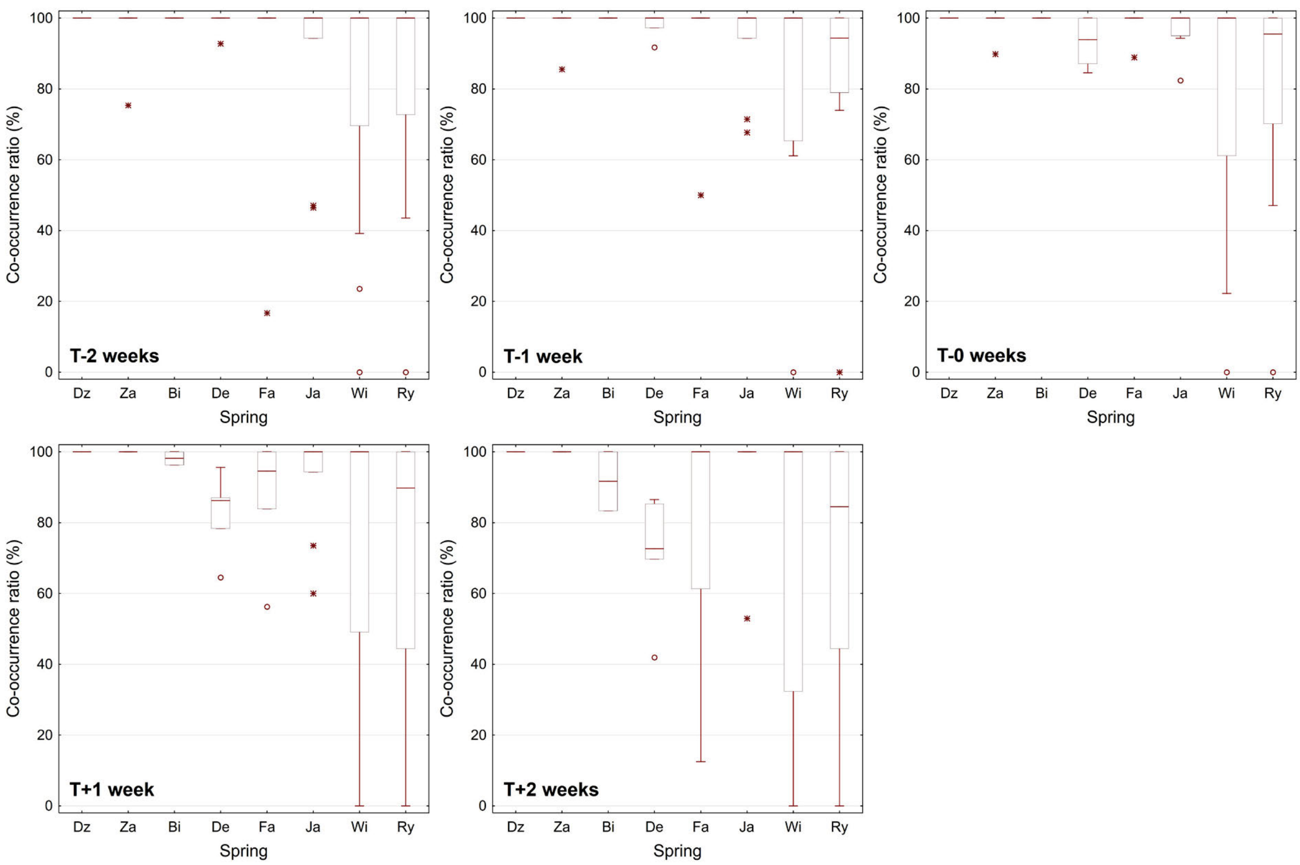

Fig. 5. Distribution of co-occurrence ratio between streamflow drought and spring drought at the multiannual average threshold in weekly time shifts of spring yield series; spring locality: Dz = Dzianisz, Za = Zakopane, Bi = Białka Tatrzańska, De = Dębno, Fa = Falsztyn, Ja = Jaworki, Wi = Wierchomla Wielka, Ry = Rytro; other of sign. as Fig. 3; source: own study

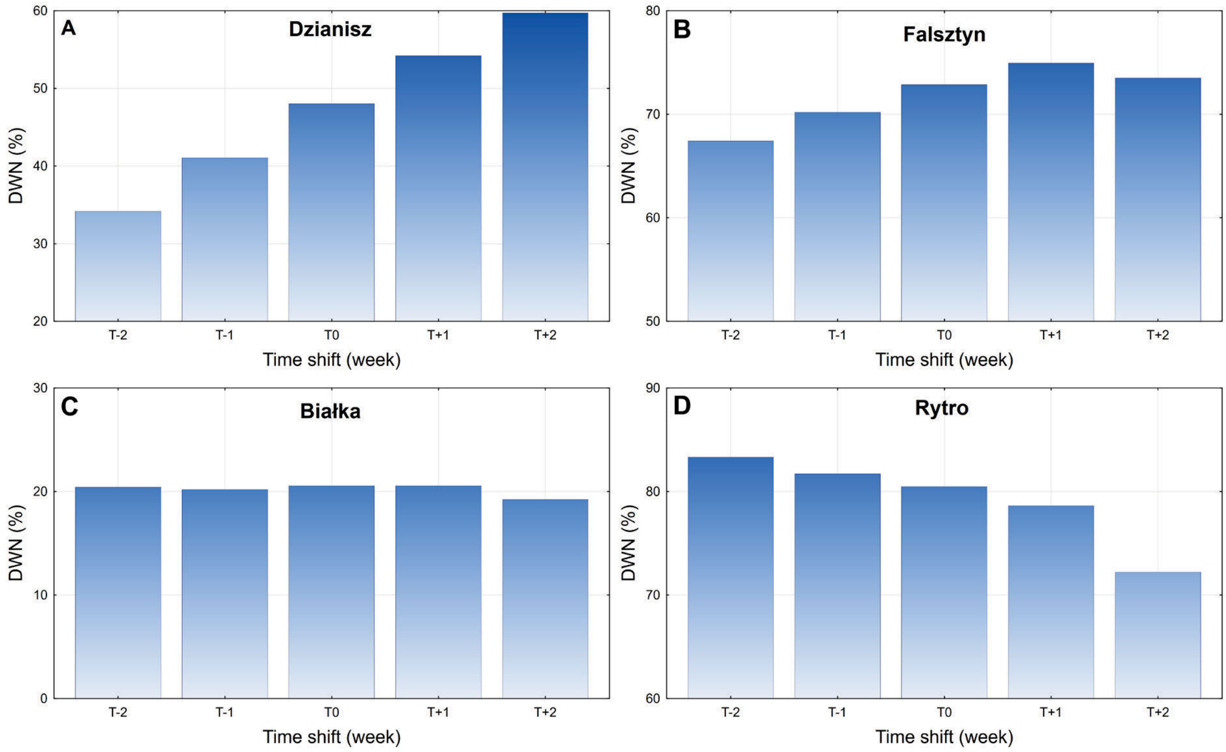

Fig. 6. The examples of the course of relative spring drought deficits (*DWN*) in following time shifts; source: own study

deficits increased during time shift delay. As a result, there were no synchronous changes during hydrological drought termination. Spring drought was still developing at this moment because the reaction time of the aquifer, drained by the spring, to resource renewal was much longer than the whole aquifers in the catchment on average. In the next analysed type, time of yield recession was also very long, however, delayed reaction to hydrological drought termination has been notified which is probably determined by the hydrogeological structure of the spring which more similar to the main groundwater reservoirs drained in the catchment than in previous type (Fig. 6B). In some springs a moderately high value of *DWN*, similar in all time shifts, was discovered (Fig. 6C). Such a feature should be connected with a stable multiannual yield where the high capacity of an aquifer drained by a spring is characterised by a very slow pace of recession and renewal of water resources. The last identified type reflected a totally inverted spring reaction to hydrological drought development (Fig. 6D). This might be determined by the aforementioned differences in alimentation regime between upstream and downstream of the catchment or results from the vertical and horizontal range of the spring aquifer going beyond reach of the catchment.

CONCLUSIONS

Analysis of the relationships between spring and streamflow droughts in a mountainous catchment area indicated several conclusions, among which are methodological and environmental ones. Assessment of spring yield droughts may be conducted using the threshold level method, where multiannual average spring discharge as a truncation level (Thr_{av}) shows the best fit to hydrological drought in the river catchment. A median of co-occurrence ratio equal to 100% proved the best applicability of this criterion. Worse synchronicity between both types of droughts was achieved in forward time shifts of the spring yield series in relation to river discharge which resulted from individual features of hydrogeological aquifer structures determining the flow recession process during dry weather. Springs located in small catchments were characterised by a higher co-occurrence of droughts than in larger basins. Analysis of the course of relative spring drought intensity in following time shifts allowed an indication of the typical behaviours of the aquifer spring regime in relation to hydrological drought development. The relatively high accuracy of drought co-occurrence estimation encourages the use of this methodology in other geographical regions as an assessment support tool for hydrological drought development.

The methodology used to assess the synchronicity of the development of severe hydrological drought gives unambiguous results and it seems that it can be used in other geographical regions. Conducting this type of research in other areas may verify the results obtained here and reveal the existence of a broader spectrum of relationships and factors determining the development of drought, related primarily to the existence of other hydrogeological types of groundwater reservoirs in different hydroclimatic conditions. This also applies to the impact of climate change on the development of hydrological drought. However, this type of analysis requires a larger sample of research objects.

The main limitation of the conducted research is the rare and very uneven distribution of springs and other types of groundwater outflows. They dominate in areas with well-developed erosion relief, i.e. in the mountains and highlands. Therefore, in lowland catchments it will be possible mainly to analyse case studies, rather than regional investigations. Moreover, spring yields are often not monitored systematically, but in areas where groundwater reservoirs occur in fissured and karst rocks, springs are the only reliable estimator of the groundwater regime.

FUNDING

The project was supported by state budget funds granted by the Minister of Education and Science in Poland within the framework of the "Excellent Science II" Program. The paper prepared for the "5th Crenology Conference. Springs – an underestimated phenomenon of nature".

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Bartnik, A. and Moniewski, P. (2018) "Wieloletnia i sezonowa zmienność wydajności źródeł Sudetów i Karpat [Multiannual and seasonal diversity of spring discharge in the Sudetes and Carpathians]," *Prace Geograficzne*, 125, pp. 7–26. Available at: https://doi.org/10.4467/20833113PG.18.013.9536.

Chełmicki, W. *et al.* (2011) "Distribution, discharge and regional characteristics of springs in Poland," *Episodes*, 34(4), pp. 244–256. Available at: https://doi.org/10.18814/epiiugs/2011/v34i4/003.

Choi, W., Borchardt, S.A. and Choi, J. (2022) "Human influences and decreasing synchrony between meteorological and hydrological droughts in Wisconsin since the 1980s," *Annals of the American Association of Geographers*, 112(1), pp. 36–55. Available at: https://doi.org/10.1080/24694452.2021.1883416.

Deng, Y. *et al.* (2023) "Groundwater recharge mechanisms in a vegetated epikarst spring catchment using water isotopes methods," *Carbonates and Evaporites*, 38(19), pp. 1–9. Available at: https://doi.org/10.1007/s13146-022-00844-8.

Ezea, V.C. *et al.* (2022) "A multi-criteria approach to drinking and irrigation water assessment of spring water in Igbo-Etiti, Nigeria," *Applied Water Science*, 12, 220, pp. 1–20. Available at: https://doi.org/10.1007/s13201-022-01747-8.

Hisdal, H. *et al.* (2001) "Drought event definition," in S. Demuth and K. Stahl (eds.) *Assessment of the regional drought impact of droughts in Europe*. Freiburg: Institute of Hydrology, University of Freiburg, pp. 17–26.

Hisdal, H. *et al.* (2004) "Hydrological drought characteristics," in L.M. Tallaksen and H.A.J. van Lanen (eds.) *Hydrological drought. Processes and estimation methods for streamflow and groundwater. Developments in Water Science*, 48. Amsterdam: Elsevier, pp. 139–198.

Jokiel, P. (1994) *Zasoby, odnawialność i odpływ wód podziemnych strefy aktywnej wymiany w Polsce [Groundwater resources, renewal and flow in the active exchange zone in Poland]. Acta Geographica Lodziensia*, 66–67. Łódź: Łódzkie Towarzystwo Naukowe.

Korkmaz, N. (1990) "The estimation of groundwater recharge from spring hydrographs," *Hydrological Sciences Journal*, 35, pp. 209–214. Available at: https://doi.org/10.1080/02626669009492419.

Kozek, M. and Tomaszewski, E. (2022) "Dynamics of hydrological droughts propagation in mountainous catchments," *Miscellanea Geographica*, 26, pp. 111–124. Available at: https://doi.org/10.2478/mgrsd-2022-0002.

Kożuchowski, K. (2017) "Opady atmosferyczne [Precipitation]," in P. Jokiel, J. Pociask-Karteczka and W. Marszelewski (eds.) *Hydrologia Polski [Hydrology of Poland]*. Warszawa: PWN, pp. 36–44.

Łabędzki, L. (2007) "Estimation of local drought frequency in Central Poland using the standardized precipitation index *SPI*," *Irrigation and Drainage*, 56, pp. 67–77. Available at: https://onlinelibrary.wiley.com/doi/10.1002/ird.285 (Accessed: March 14, 2024).

Michalczyk, Z. (2017) "Odpływ średni, zmienność w czasie i zróżnicowanie przestrzenne [Average runoff, time changeability and spatial differentiation]," in P. Jokiel, J. Pociask-Karteczka and W. Marszelewski (eds.) *Hydrologia Polski [Hydrology of Poland]*. Warszawa: PWN, pp. 153–160.

Mudarra, M., Hartmann, A. and Andreo, B. (2019) "Combining experimental methods and modeling to quantify the complex recharge behavior of karst aquifers," *Water Resources Research*, 55, pp. 1384–1404. Available at: https://doi.org/10.1029/2017WR021819.

Nagarajan, R. (2009) *Drought assessment*. Dordrecht: Springer.

Ozga-Zielińska, M. (1990) "Niżówki i wezbrania – ich definiowanie i modelowanie [Droughts and floods – their definition and modeling]," *Przegląd Geofizyczny*, 1–2, pp. 33–44.

Raczyński, K. and Dyer, J. (2020) "Multi-annual and seasonal variability of low-flow river conditions in southeastern Poland," *Hydrological Sciences Journal*, 65(15), pp. 2561–2576. Available at: https://doi.org/10.1080/02626667.2020.1826491.

Sene, K. (2010) *Hydrometeorology. Forecasting and applications*. Dordrecht–Heidelberg–London–New York: Springer.

Smakhtin, V.U. (2001) "Low flow hydrology: A review," *Journal of Hydrology*, 240, pp. 147–186. Available at: https://doi.org/10.1016/S0022-1694(00)00340-1.

Tallaksen, L.M. (1995) "A review of baseflow recession analysis," *Journal of Hydrology*, 165(1–4), pp. 349–370. Available at: https://doi.org/10.1016/0022-1694(94)02540-R.

Teutschbein, C. *et al.* (2022) "Streamflow droughts in Sweden: Spatiotemporal patterns emerging from six decades of observations," *Journal of Hydrology: Regional Studies*, 42, 101171, pp. 1–26. Available at: https://doi.org/10.1016/j.ejrh.2022.101171.

Tokarczyk, T. (2013) "Classification of low flow and hydrological drought for a river basin," *Acta Geophysica*, 61, pp. 404–421. Available at: https://doi.org/10.2478/s11600-012-0082-0.

Tomaszewski, E. (2007) "Kilka uwag o zastosowaniu metody źródeł reprezentatywnych do oceny wielkości oceny zasilania podziemnego rzeki [A few remarks about application of the representative springs method]," in P. Jokiel, P. Moniewski and M. Ziułkiewicz (eds.) *Źródła Polski. Wybrane problemy krenologiczne [Springs of Poland. Selected crenological problems]*. Łódź: Wydział Nauk Geograficznych Uniwersytetu Łódzkiego, pp. 163–171.

Tomaszewski, E. (2012) "Wieloletnia i sezonowa dynamika niżówek w rzekach środkowej Polski [Multiannual and seasonal dynamics of low flows in rivers of central Poland]," Łódź: Wydawnictwa Uniwersytetu Łódzkiego. Available at: https://dspace.uni.lodz.pl/xmlui/handle/11089/41804 (Accessed: March 14, 2024).

Tomaszewski, E. and Kozek, M. (2021) "Dynamics, range, and severity of hydrological drought in Poland," in M. Zeleňáková, K. Kubiak-Wójcicka and A.M. Negm (eds.) *Management of Water Resources in Poland. Springer Water*. Cham, Switzerland: Springer Nature, pp. 229–252. Available at: https://link.springer.com/chapter/10.1007/978-3-030-61965-7_12 (Accessed: March 14, 2024).

Tomaszewski, E. and Kubiak-Wójcicka, K. (2021) "Low-flows in Polish rivers," in M. Zeleňáková, K. Kubiak-Wójcicka and A.M. Negm (eds.) *Management of water resources in Poland. Springer Water*. Cham, Switzerland: Springer Nature, pp. 205–228. Available at: https://link.springer.com/chapter/10.1007/978-3-030-61965-7_11 (Accessed: March 14, 2024).

Wilhelmi, O.V., Hubbard, K.G. and Wilhite, D.A. (2002) "Spatial representation of agroclimatology in a study of agricultural drought," *International Journal of Climatology*, 22, pp. 1399–1414. Available at: https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.796 (Accessed: March 14, 2024).

Yabusaki, S. and Asai, K. (2023) "Estimation of groundwater and spring water residence times near the coast of Fukushima, Japan," *Groundwater*, 61(3), pp. 431–445. Available at: https://doi.org/10.1111/gwat.13288.

Yevjevich, V. (1967) "An objective approach to definitions and investigations of continental hydrologic drought," *Hydrology Paper*, 23. Fort Collins, Colorado: Colorado State University.

Yildirim, I. and Aksoy, H (2022) "Intermittency as an indicator of drought in streamflow and groundwater," *Hydrological Processes*, 36(6), e14615, pp. 1–17. Available at: https://doi.org/10.1002/hyp.14615.

Ying, Z. *et al*. (2024) "Developing a conceptual model of groundwater – Surface water interactions in a drought sensitive lowland catchment using multi-proxy data," *Journal of Hydrology*, 628, 130550. Available at: https://doi.org/10.1016/j.jhydrol.2023.130550.