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ASSESSMENT OF METEOROLOGICAL AND HYDROLOGICAL DROUGHT IN TORUN (CENTRAL POLAND TOWN) IN 1971-2010 BASED ON STANDARDIZED INDICATORS

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ABSTRACT
In the paper, the occurrences of meteorological and hydrological drought in Toruń, Poland in the years of 1971-2010 were analyzed as well as the relationship between both droughts. The analysis was done based on the indicator assessment method where Standardized Precipitation Index (SPI) was used as an index of the meteorological drought and Standardized Water Level Index (SWI) and Standardized Runoff Index (SRI) were indices that characterized the hydrological drought. The values of chosen indices were calculated on the base of monthly precipitation sum P (mm) measured in Toruń and average monthly water level WL (cm) and runoff R ($m^3 \cdot s^{-1}$) recorded on the Vistula River gauge in Toruń. The calculations of indices were made in cumulated periods of 6, 12, and 24 months. It was determined that the number of meteorological and hydrological drought periods decreases along with increasing of the accumulation period. At the same time, the length of drought period increases. It was particularly visible for the periods of 12 and 24 months, in which meteorological drought was shorter than the corresponding hydrological drought. Based on the correlation indices' values, it was determined that the most strong relations between both types of drought took place between SPI-24 and SWI-24 as well as between SPI-24 and SRI-24. The indicator assessment seems to be useful in the drought monitoring and early drought warning.

Keywords: meteorological drought, hydrological drought, indexes of drought, Vistula basin

1 INTRODUCTION

Drought is one of the most adverse natural phenomena, which cause significant economic and social losses. Generally, droughts have been classified into four categories (meteorological, agricultural, hydrological and socioeconomic) based on the system affected and the time scale in which the drought impacts become evident (Wilhite and Glantz 1985). The result of meteorological drought, which is characterized by periodic significant decrease or lack of precipitation, is a disruption of functions of natural and agricultural ecosystems as well as troubles causing serious hydrological imbalances that adversely affect production systems and consumption. A hydrological drought is defined as a decrease in the availability of water in all its forms within the land phase of the hydrological cycle, which includes streamflow, groundwater, reservoirs and lakes. Hydrological droughts often last for a long time and their influences may be visible even in the subsequent hydrological seasons.

The catchment reaction to lack of precipitation is different and mainly depends on physio-geographic features of the catchment (permeability, topography, land use and land cover), climatic conditions (mainly precipitation and evaporation) and the regulation of water (Lorenzo-Lacruz et al., 2013; van Loon and Laaha 2014). They may delay the beginning of the hydrological drought relative to the beginning of meteorological drought for several months (Kępińska-Kasprzak 2015). According to Lorenzo-Lacruz et al. (2013), the most severe hydrological droughts do not always occur in areas with the lowest effective rainfall because their severity is also influenced by other factors, like amount of water consumed by the industry and society, effectiveness of water management and meteorological conditions in river's upper reaches.

In many parts of Europe, especially in the south and in the middle of the continent, yet since 1970s until now, a gradual increase of number of droughts has been observed (Bordi et al., 2009).

The problem of more frequent drought threats pertains to the area of Poland as well (Skowera and Puła 2004; Somorowska and Piętka 2012; Czernecki and Miętus 2015). At the end of the 20th century, in the many parts of Polish middle lowlands, frequent cases of dry spells in spring (Apr-Jun) were found; the maximum of tem was observed in May. In the summer time (Jul-Sep), the drought areas were extended to the other geographic regions of Poland and they often lasted longer than in previous decades. The Somorowska's studies (2009) showed that values of the Palmer Drought Severity Index (PDSI) on large areas of Poland in the period of 1991-2000 were smaller than in the reference period of 1961-1990. This result proves that numbers of hydrological droughts were increased.

In the region East Wielkopolska allotted by Woś (2010), which includes areas of Kuiavia and Bydgoszcz-Toruń regions, drought occurrences are significant economic and social problem too. In this an agricultural lowland region with poor hydrographic network ones of the lowest annual (Jan-Dec) and seasonal (Apr-Sept) sum of precipitation in Poland have been recorded (Łabędzki 2007; Bartczak et al., 2014a). Lack of precipitation also causes numerous hydrological droughts of the surface waters (Gorączko et al., 2013; Kubiak-Wójcicka 2012) and, in rare cases, of underground waters (Ilnicki et al., 2012).

Generally, a drought event may be characterized by three main properties: drought duration, accumulated deficit, and drought intensity. Accumulated deficit, often referred to as drought magnitude, is defined as the sum of the single deficits, *i.e.* the deviations of the water supply variable from the water demand threshold, over the drought duration, whereas drought intensity is the ratio of the accumulated deficit and the drought duration (Cancelliere et al., 2003; Nam et al., 2015).

There is a wide range of drought indices applied to identify and monitor meteorological and hydrological drought as well as to research their relationships (McKee et al., 1993, 1995; Bąk and Łabędzki 2002; Łabędzki 2007; Lorenzo-Lacruz et al., 2013; Haslinger et al., 2014; Łabędzki and Bąk 2014b; Bachmair et al., 2015; Nam et al., 2015). The decision to apply a particular indicator usually depends on the aim of the application, the ability to reproduce the spatial and temporal features of the drought occurrence, as well as on the availability of the data required for its calculation (Tokarczyk and Szalińska 2014). The Standardized Precipitation Index (SPI) is a useful and often used in purpose of determination of meteorological drought parameters. Commonly used indices of hydrological drought are: Standardized Water Level Index SWI and Standardized Runoff Index SRI (Shukla and Wood 2008; Bordi et al., 2009; Lorenzo-Lacruz et al., 2013; Sahoo et al., 2015). Some authors use SRI as Streamflow Drought Index (SDI) (Nalbantis and Tsakiris 2009; Vicente-Serrano et al., 2012; Rimkus et al., 2013; Tabari et al., 2013) or as Standardized Streamflow Index (SSI) (Barker et al., 2015).

In the opinion of various authors, the drought indices are valuable and practical utility for drought monitoring and assessment of complicated relations between climate parameters and not climate-related ones (Rossi 2003; Tokarczyk and Szalińska 2014). The appointed drought parameters calculated on the basis of long time data of precipitation and selected hydrologic parameters (e.g. water levels, discharge) show the degree of hazard at an analyzed location.

The aim of this study is presentation of methodology for assessment of meteorological and hydrological droughts and their relationships based on indicator assessment and to show the possibility to apply this methodology in drought monitoring system.

2 METHODS

The study is focused on meteorological and hydrological droughts in Toruń, central Poland, in the years 1971-2010. Toruń is located on banks of the Vistula River which is the east border of East Wielkopolska region. Water gauge in Toruń is located on 734.7 km of the river course, its zero point level above the sea level is 31.981 m. The gauge closes the river's basin area of 181033 km^2, which comprises 93.11 % of the whole Vistula's basin area (Kubiak-Wójcicka 2014). The greatest influence on the river's runoff in Toruń have the following tributaries: Narew with Bug, Wkra, Skrwa and Bzura (Figure 1).

The study region is one of the most dry areas in Poland. In the period of 1951-2010 the average annual precipitation in Toruń was 533 mm (Internetowy Atlas, 2015).

Precipitation deficit is the most important cause of hydrological drought. Based on daily water levels of the Vistula River collected at the water gauge in Toruń, it was found that summer low flows in the period of 1951-2010 accounted for about 87% of all low flow time. Average duration of low flow was 18 days in summer, and in winter – 12 days. The largest number of low flows (17) occurred in the period of 2002-2009, when such situation occurred at least once every year. In the period of 1951-1964, eleven low flows were recorded whilst in the period of 1965-1982 there was no case of a low flow (Kubiak-Wójcicka 2012). Most of all days with low flow were observed in September, August and October (Bartczak et al. 2014b). In these months, the hydrological drought often appeared in the region 1 – 2.5 months later than the meteorological drought and it was more extreme in periods of heat wave.

In the paper, the indicator assessment of meteorological and hydrological drought and relations between them is presented. The Standardized Precipitation Index SPI represents meteorological drought (McKee et al. 1993, 1995). The hydrological drought indices are the Standardized Water Level Index SWI and Standardized Runoff Index SRI (Shukla and Wood 2008). The values of the indices were calculated based on monthly precipitation P (mm) in the period of 1971-2001 in Toruń, average monthly water levels WL (cm) and average monthly discharges R ($m^3 \cdot s^{-1}$) of the Vistula River in Toruń.

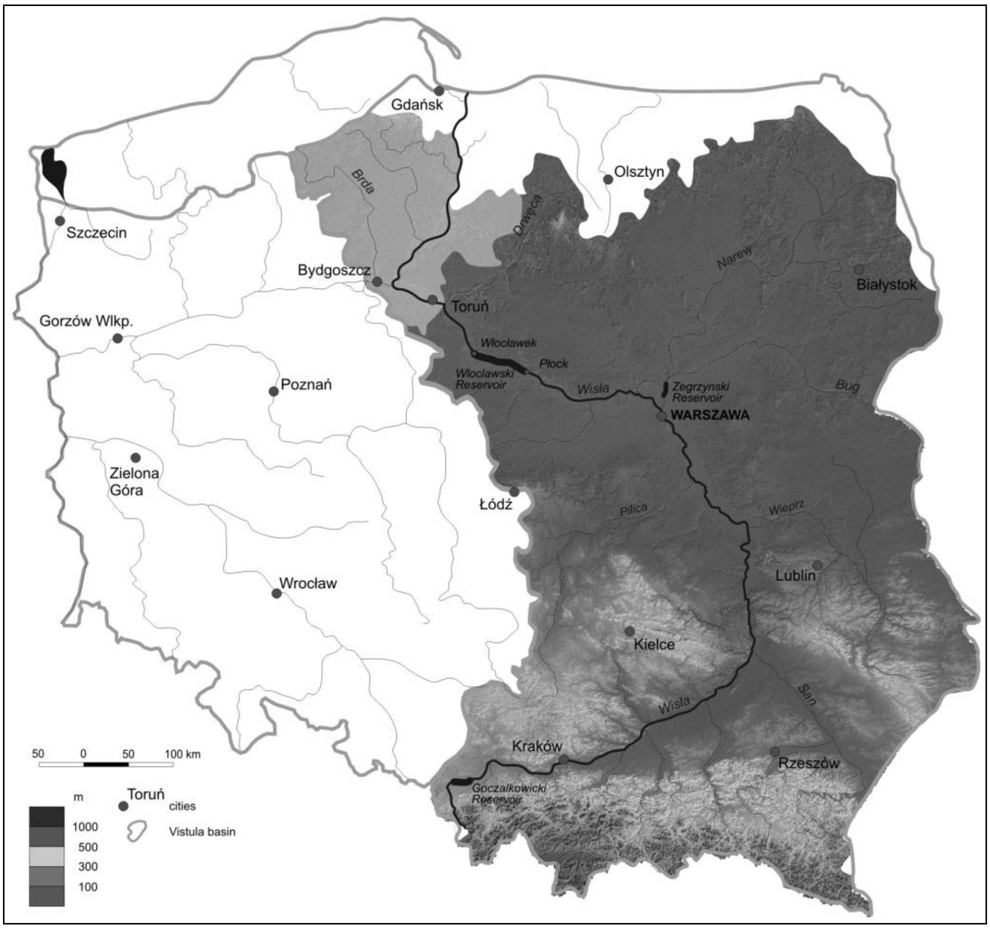

Figure 1. Study area – Vistula basin (Poland)

Generally the above indices are calculated based on the same standardization formula:

$$X = \frac{f(X) - \mu}{\delta}$$

where:

X – selected index (SPI, SWI and SRI)

$f(X)$ – transformed amount of rainfalls, water levels and discharges,

μ – mean value of normalized index X

δ – standard deviation of index X

In order to transform precipitation distribution to the normal distribution in monthly periods the function $\sqrt[3]{x}$ was used and 2-parameter ln function was used to fit historical records of levels water to normalizing function. The normalizing function has been assumed the same 2-parameter ln function to fit historical records of water levels and discharge to normalizing function (Ozga-Zielińska and Brzeziński 1994; Vicente-Serrano et al., 2012). For the indices which values satisfy the condition $X < -1.0$, the common 3-class drought intensity assessment has been assumed: extremely dry (≤ -2,0), severely dry (from -1,99 to -1,50), and moderately dry (from -1,49 to -1,00). Drought events were defined as periods in which index values were continuously negative and with at least one month in the negative series reaching -1.0.

3 RESULTS AND DISCUSSION

In analyzed multi-year period, a small annual precipitation increase (0.14 mm per decade) has been found as well as a decrease of water levels (1.3 cm per decade) and discharges (2.4 $m^3 \cdot s^{-1}$ per decade). In all cases the calculated trends were statistically significant, however a small value of the coefficient of determination r^2 indicates poor fit of the trend line to the observation results.

Average annual precipitation in Toruń in the years 1971-2010 was 545 mm and in vegetation period (Apr-Sep) – 350 mm. The moist years were: 1980 (845 mm) and 2010 (832 mm), and the driest year was 1989 (312 mm). In the same years 1980 and 1989 were similarly measured 682 mm and 142 mm in vegetation period. These results were similar to the data achieved by other authors, who analyzed precipitation distribution in the Bydgoszcz-Toruń region and in the Kuiavia region (Bąk et al. 2012; Bartczak et al. 2014a). The driest month was Mar 2009 when monthly precipitation was approximately 1 mm while Jun 1980 was the wettest month (299 mm).

The average annual discharge of the Vistula River in Toruń was 911 $m^{3}\cdot s^{-1}$ with maximum 3335 $m^{3}\cdot s^{-1}$ (Apr 1979) and minimum 271 $m^{3}\cdot s^{-1}$ (Aug 1992). In vegetation period, the average monthly discharge was changing in the range 592 $m^{3}\cdot s^{-1}$ (1992) to 1961 $m^{3}\cdot s^{-1}$ (2010); its average value was 992 $m^{3}\cdot s^{-1}$.

Average annual water level of Vistula River in Toruń in the analyzed multi-year period was 318 cm; the highest water level was recorded in 1980 (410 cm) and the lowest in 2003 (243 cm). The above statistics for summer were: average – 311 cm, maximum – 432 cm (1980), minimum – 235 cm (2007). The highest monthly average water level was recorded in Apr (413 cm) and the lowest in Sep (254 cm) (Kubiak-Wójcicka 2012; Gorączko et al. 2013). In Apr 1971 the water level of the Vistula river in Toruń reached 631 cm while in Sep 2003 it fell down to 140 cm.

The statistics of analyzed meteorological and hydrological droughts are presented in Table 1. It was found that as the accumulation period was increased, the number of periods with meteorological and hydrological droughts decreased and, at the same cumulative time, the duration of both kinds of drought were increased. The longest meteorological drought lasted 48 months (SPI-12; Jun 1989-Jul 1993) while the longest hydrological drought lasted 86 months (SRI-12; Mar 2003-May 2010). The intensity of all droughts was changing between -0.9 and -1.3.

Table 1. Statistics of meteorological and hydrological droughts in Toruń (1971-2010) source: own study

Parameters of droughts	*SPI*-6	*SPI*-12	*SPI-24*	*SWI-6*	*SWI-12*	*SWI-24*	*SRI-6*	*SRI-12*	*SRI*-24
	Value (Period)	Value (Period)	Value (Period)	Value (Period)	Value (Period)	Value (Period)	Value (Period)	Value (Period)e	Value (Period)e
Event numbers	23 (-)	9 (-)	6 (-)	11 (-)	5 (-)	3 (-)	6 (-)	3 (-)	3 (-)
The longest duration (months)	16 (III.96 – I.97)	50 (VI.89 – II.93)	48 (IX.89 – II.93)	48 (IV.90 – III.94)	65 (V.91 – X.96)	76 (VII.90 – X.96)	51 (XII.05 – II.10)	86 (III.03 – V.10)	80 (VII.90 – X.96)
Average duration of drought (months)	5.1 (-)	16.7 (-)	16.0 (-)	5.8 (-)	6.5 (-)	9.0 (-)	5.8 (-)	7.2 (-)	7.2 (-)
Maximum magnitude of drought	-19.4 (VI.89 – VI.90)	-51.4 (VI.89 – II.93)	-64.1 (IX.89 – II.93)	-53.0 (VI.89 – II.93)	-65.0 (V.91 – X.96)	-86.0 (VII.90 – X.96)	-32.0 (IV.90 – III.94)	-9.,0 (III.03 – V.10)	-101.0 (VII.90 – X.96)
Minimum value of index	-2.7 (VIII.89)	-2.6 (IX.89 II. 90)	-2.3 (XII.83 I.84)	-2.2 (V.84)	-1.8 (X.85)	-1,8 (X.92)	-2.3 (XII.05 II.10)	-2.2 (X.85)	-1.8 (XI.04)
Average intensity of drought	-1.1 (-)	-1.0 (-)	-1.3 (-)	-1.0 (-)	-0.9 (-)	-0.9 (-)	-1.0 (-)	-1.0 (-)	-1.1 (-)

An analysis of the simultaneous occurrence of all analyzed droughts (SPI + SWI + SRI) showed that in chosen cumulative periods there were 27, 46 and 43 such months. The common droughts were appearing most often in the years 1984-85 and 1991-93. In mid 1990s and at the beginning of the new century, series of common long-time hydrological droughts (SWI + SRI) were observed.

The strongest relationships have been found in the relations SPI-24 → SWI-24 ($r = 0.39$) and SPI-24 → SRI-24 ($r = 0.53$). In the periods, when all kinds of droughts simultaneously appeared, the relationships were stronger ($r > 0.5$); the maximum of the correlation coefficient ($r = 0.73$) was found for relations SPI-24 → SWI-24. These calculations were done with an assumption that the threshold of a moderate drought is -1.0; this value corresponds to 16% probability of appearing of this drought intensity class.

Based on the values SWI and SRI, it can be concluded that during long-term deficiency of precipitation, the levels of water in the Vistula river in Torun were more stable than the discharges. The reason for this discrepancy were external non-climatic factors. One of them is directly related to the existence of the dam and hydroelectric power station in Włocławek. The Włocławek Reservoir is a typical lowland dam reservoir with quick water exchange. An average water retention time is only 5.2 days (Gierszewski et al. 2013). The reservoir mitigates Vistula's floods only minimally but it is more useful in periods of very low water levels (small values of SWI).

The second parameter which has significant influence on Vistula's river discharge, especially in periods of small discharges caused by hydrological drought, is a river's drainage of underground water. In the Toruń area, there is the Major Groundwater Basin (GZWP-14), which encompasses large resources of freshwater. That underground basin stretches on both sides of Vistula and covers 354 km^2. It was created as a result of especially favorable hydro-geological conditions in quaternary sediments (sands, river gravel and glacial water gravel), of thickness reaching from a dozen to above 30 m (Kleczkowski 1990; Pomianowska 1999). During long term periods of lack of precipitation the recharge coming from deeper groundwater levels is small and constant, which is the reason for small SRI values.

In occasional cases, the intensity of hydrological drought may be mitigated as a result of temporary inflow to the main riverbed of the water coming from significant precipitation in other parts of river's basin or in the area of Toruń. Tokarczuk and Szalińska (2014) compared the impact of meteorological drought on hydrological drought in mountainous regions and lowlands of Poland and found differences. Mountain rivers were characterized by high dynamics of rainfall and hydrological conditions, both in terms of excess and shortages of rainfall. Rate of change in lowland areas is much slower, and the intensity of hydrological drought is more dependent on external factors. According to van Loon and Laaha (2015), more than 30 factors may impact water regime in the main riverbed.

The practical side of the presented method is possibility to use it to monitor meteorological and hydrological drought in Toruń in the future. Treating the analyzed period of 1971-2010 as a reference data, and based on current measurements, it is possible to calculate the values of SPI, SWI and SRI and thus to determine actual class of drought intensity. For example, in January, a moderate meteorological drought appeared when 24-month sum of precipitation at the end of this month was lower than 923 mm. Similarly, for hydrological drought, the sum of water levels didn't exceed 6739 cm or the sum of discharges were less than 18997 $m^3 \cdot s^{-1}$.

4 CONCLUSION

On the basis of the applied method, periods of meteorological and hydrological droughts in Toruń in the years 1971-2010 have been determined. The monthly values of drought indices SPI, SWI and SRI were calculated as cumulative sums of precipitation, average monthly water levels and discharges recorded in periods of 6, 12 and 24 months. It was found that the number of droughts was decreasing along with increasing length of an accumulation period. On the basis of the values of correlation coefficients between SPI→SWI and SPI→SRI, it was found that the strongest, however small, relationships between meteorological and hydrological droughts appeared in the longest, 24-month accumulation period. Smaller correlation coefficients were found when all values of indices were analyzed. They were a little higher in the periods of simultaneous appearance of all kinds of drought.

According to the authors, the probable cause of weak correlation between droughts in Toruń are non-climate factors. The main one is an influence of the dam in Włocławek on the variability of water levels. The presented methodology seems to be useful in drought monitoring system too. Based on comparison between current measurement data (cumulative sums) and threshold values of drought intensity classes which were calculated in the long term reference period, the actual values of indices and the drought intensity class can be determined.

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