Acta Sci. Pol.
Formatio Circumiectus 18 (4) 2019, 103–112
ENVIRONMENTAL PROCESSES

www.acta.urk.edu.pl/pl ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/2019.18.4.103

ORIGINAL PAPER Accepted: 22.11.2019

ANALYSIS OF GROUNDWATER LEVELDECREASE IN REACTION TO METEOROLOGICAL DROUGHT – USING SPI AND STI

Justyna Kubicz

Institute of Environmental Engineering, Wrocław University of Environmental and Life Sciences, Plac Grunwaldzki 24, 50-363 Wrocław

ABSTRACT

Aim of study
The aim of the study was to assess the relationship between groundwater level, drought at aquifer, precipitation deficit and high air temperature.

Materials and methods
The analyses were developed on the basis of data from the Faculty of Agro- and Hydrometeorology Observatory of the Wrocław University of Environmental and Life Sciences in Wrocław-Swojec covering years 1969–2017. Data were provided by measurements of groundwater level as well as temperature and precipitation. Using Standardized Precipitation Index (SPI) for precipitation and Standardized Temperature Index (STI) for temperature, periods with precipitation deficit and raised temperature were identified. The research also determined the relation between these indicators and groundwater level. Drought periods at groundwater level have been estimated using a Standardized Groundwater Level Index (SGI).

Results and conclusions
Analysis of the relationship between STI and the groundwater level showed low correlation. The air temperature as a single factor has no clear impact on the groundwater level at the shallowestaquifer. For precipitation, the strongest relationship appeared between SPI6 and the groundwater level. Seasonal meteorological drought has the greatest impact on decreasing the groundwater level. It was found that an extremely dry period with SPI registered < –2 caused a decrease of the groundwater table in 1969–1970, 1972–1974, 1976, 1978, 1992–1993, while in 1979, 1983–1984, 1989–1992, 1994–1995, 2003, 2004, 2006, 2015 the level dropped due to very high deficits in precipitation with SPI between –2 and –1.5. The decreasing groundwater table, as a result of precipitation deficits, was not always directly connected to droughts at the described groundwater level. The longest periods of groundwater decrease occurred in 1980, 1981, 1986/1987, 1994, 1997/1998, 2000, 2001, 2006/2007, 2017. In addition, 14 periods of extreme drought were recorded.

Keywords: drought, groundwater level, SPI, SGI, STI

INTRODUCTION

Drought is one of the main natural threats to the environment and human populations. Most often droughts are caused by deficits in precipitation during a particular period. Often the impact of precipitation deficit is intensified by high air temperatures. Long periods without any or little precipitation are called meteorological droughts. It is followed by water deficits that spread throughout the hydrological cycle and cause

✉e-mail: justyna.kubicz@upwr.edu.pl

various types of droughts. If a deficit affects groundwater resources, drought may take place at groundwater level (Tallaksen and Van Lanen, 2004).

In the years 1951–2006, the largest meteorological droughts in Poland were recorded in 1951, 1953, 1954, 1963, 1964, 1969, 1976, 1982, 1983, 1984, 1989, 1991, 1992, 1993, 1994, 2000, 2002, 2003, 2005 , 2006. The drought that covered the largest area of Poland (95%) occurred in 1969, and the longest periods of droughts were recorded in 1951–1956 and 1980–1985 (Kędziora et al., 2014).

Subsequent droughts, like the one in 1992, caused a significant decrease in agricultural production and numerous forest fires. As a result of extreme drought in 2006, the decrease in the average national yield of some crops reached as much as 30%. Whereas, the drought in 2008 was reported in 68% of Polish municipalities and in 58% of the country's arable land. In June that year, there were particularly unfavourable conditions for crops due to low precipitation, high air temperature – about 1–1.5° C higher than long-term average – as well as high sunshine duration and low relative humidity. In 2006, according to the General Directorate of the State Forests, the amount of losses caused by meteorological drought totalled PLN 43.5 million (Kędziora et al., 2014).

The drought threat in Poland, among other factors, is a result of relatively low sums of precipitation and high variability of their occurrence (Kleczkowski, 1991; Pasławski, 1992). However, droughts are not only connected to the volume of precipitation in a given period, but also to the volume of precipitation before a drought occurs. Another important factor is the ability of atmosphere to absorb water vapour, also called evaporation. It depends on the temperature and water vapour pressure in the air (Kleczkowski, 1991; Pasławski, 1992).

Meteorological droughts are determined on the basis of the assessment of the deviation of precipitation volume from the median calculated from the average monthly values over a multi-annual period. One of the indicators defining such deviation is the SPI (Standardized Precipitation Index) (McKee et al., 1993). The deviation from the standard temperature, which additionally affects the development of a drought, can also be assessed using a standardized indicator. In such case, the STI (Standardized Temperature Index) (Bloomfield et al., 2019) can be applied.

The aim of the paper is to examine the relationship between the groundwater level represented by the shallowest aqiufer , droughts at groundwater, precipitation deficits and high air temperatures. The analyses were developed on the basis of data from the Faculty of Agro- and Hydrometeorology Observatory of the Wrocław University of Environmental and Life Sciences in Wrocław-Swojec covering years 1969–2017.

MATERIAL AND METHODS

The data for analysis were provided by daily measurements of the groundwater level, temperature and precipitation taken at the Faculty of Agro- and Hydrometeorology Observatory of the University of Life Sciences in Wrocław-Swojec between 1969 and 2017. Monthly values were estimated on their basis and used for further analysis. Air temperature was measured in a instrument shelter at a height of 2 m using a mercury thermometer. As for precipitation, the daily sum measured by the Hellmann rain gauge was adopted as the basic value. The groundwater level was registered in the observation well during a morning inspection at 7 o'clock. Basic information on the characteristics of the Wrocław-Swojec research station is presented in Table 1, and the vari-

Table 1. Characteristics of observation points

Site	Start of data (year)	End of data (year)	Average annual precipitation (mm)	Average annual temperature (°C)	Groundwater level (m a.s.l.)			Lithology	Type of groundwater table	Land use
					Min.	Max.	Av			
Wrocław-Swojec, Lower Silesia	1969	2017	575	9.1	1.95	0.27	1.16	Sands	Unconfined	Grass

ability of the average annual precipitation sum, average annual air temperature value and the groundwater level are shown in Figure 1.

The main cause of droughts at the groundwater level are periodic precipitation deficits and raised air temperatures, affecting the volume of evapotranspiration (Fiorillo and Guadagno, 2010; Bloomfield et al., 2019). Standardized drought indicators, like SPI and STI, are used to determine the periods of precipitation deficits and raised temperatures in relation to the median value over multi-annual period. Periods of hydrogeological droughts can also be determined by the SGI (Standardized Groundwater Index). These indicators are widely applied and cited in the literature (Bąk and Kubiak-Wojcicka, 2016; Bloomfield et al., 2019; Bąk and Łabędzki, 2014; Kubicz, 2018; Kubicz and Bąk, 2019; Salvador et al., 2019; Wang i in., 2019).

To calculate the standardized SPI, STI, SGI indicators for precipitation, temperature or groundwater level, respectively, after prior normalization of the sequence using the transforming function (respectively: $\sqrt[3]{x}$ – for precipitation, ln – for the groundwater level, the temperature did not require a transforming function) the following formula was applied (McKee et al., 1993):

$$SPI, STI, SGI = \frac{f(X) - \mu}{\delta} \qquad (3)$$

where:

SPI, STI, SGI – standardized indicators [-],
f(*X*) – normalized value of the measured precipitation, air temperature, groundwater level [mm, °C, m b.g.l.],
μ – average value of the normalized series [mm, °C, m b.g.l.],
δ – standard deviation of the normalized series [mm, °C, m b.g.l.].

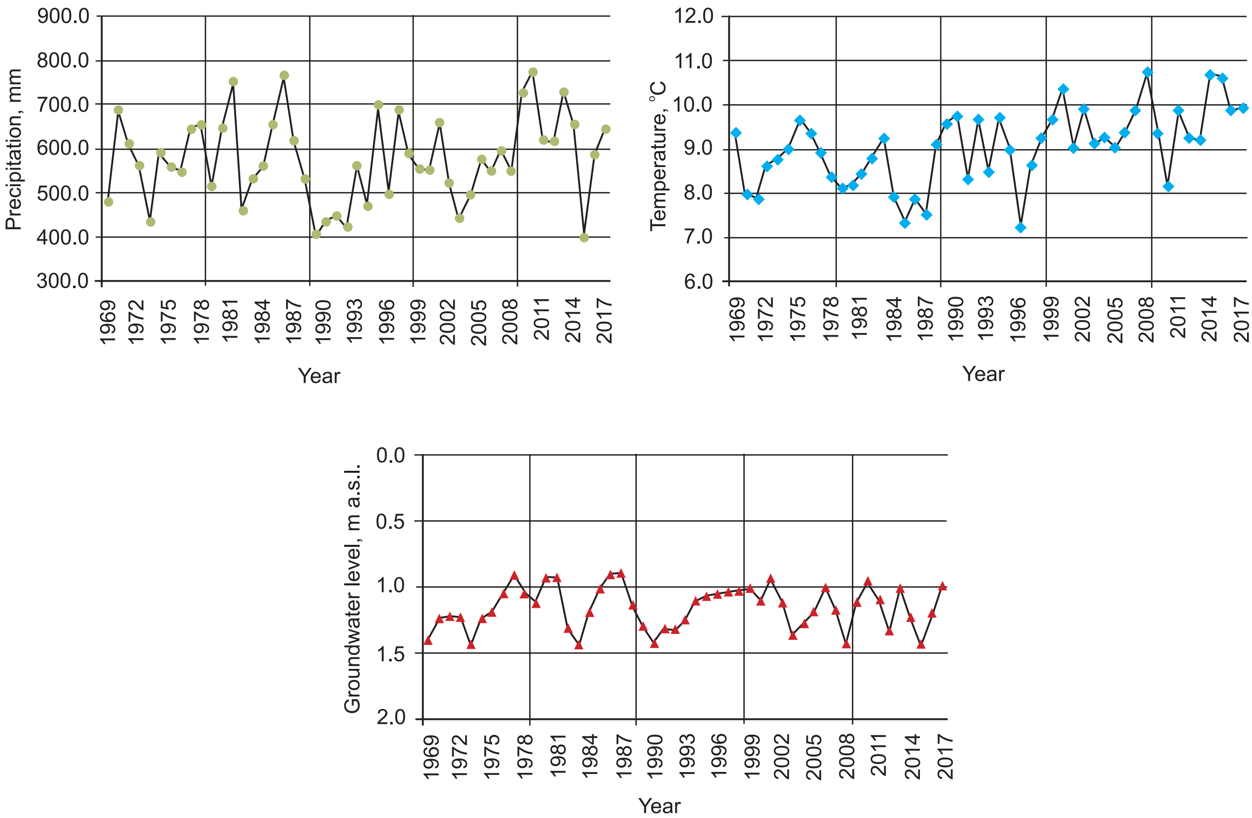
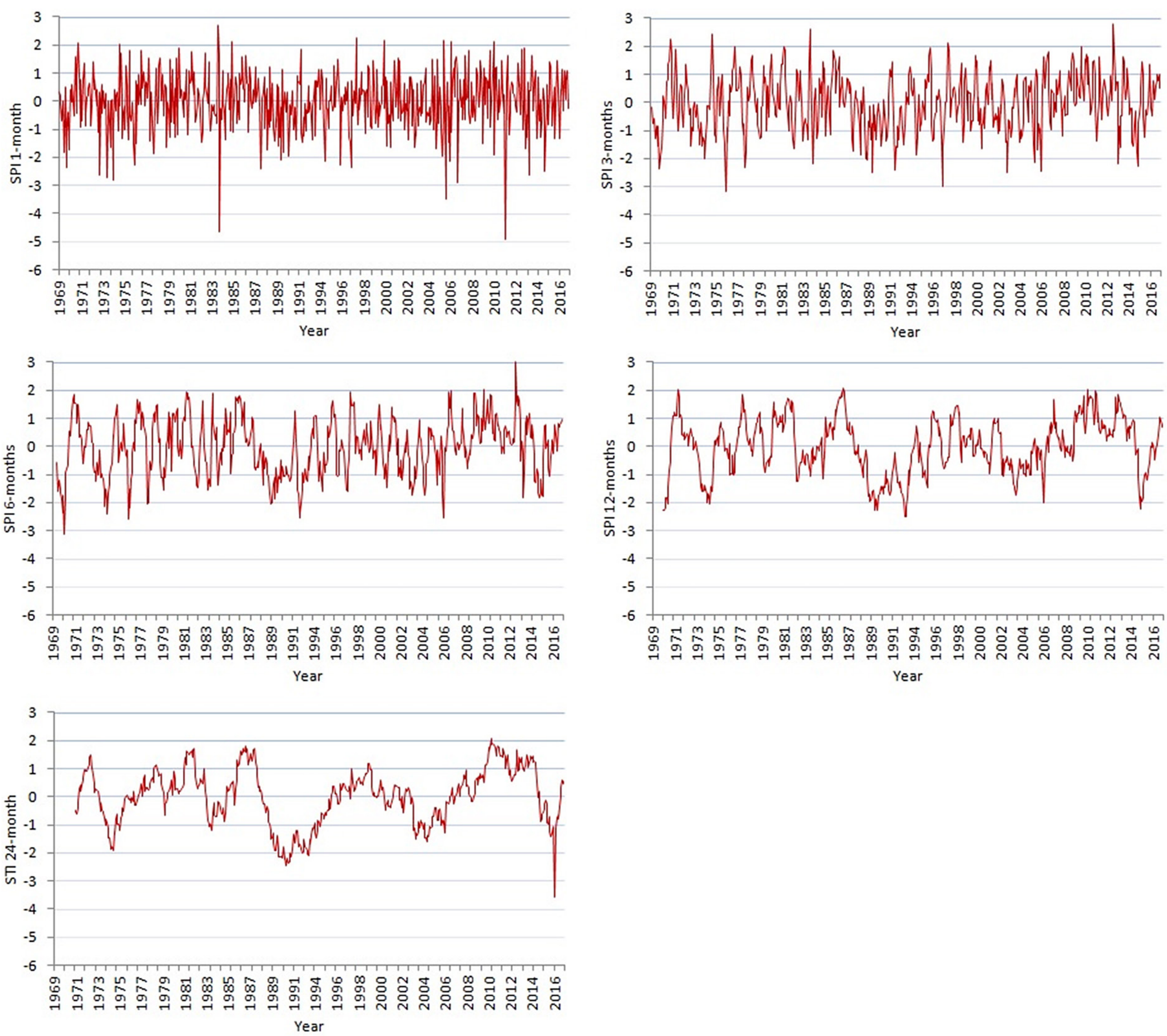


Fig. 1. Average annual precipitation, temperature and groundwater level in 1969–2017

As McKee (McKee et al., 1993) has indicated, three drought classes were adopted in the range of negative values of SPI and SGI: moderate (for –1.5 < SPI < –1.0), strong (for –2.0 < SPI < –1.5) and extreme (for SPI ≤ –2). For the range of positive values of the STI, periods were divided in terms of temperature: moderately hot (for 1.5> STI > 1.0), very hot (for 2.0 > STI > 1.5), extremely hot (for STI ≥ 2). Standardized indicators were calculated for various periods of accumulation of a given phenomenon, from 1 to 24 months (an example for SPI and STI is shown in Fig. 2a)

a)



b)

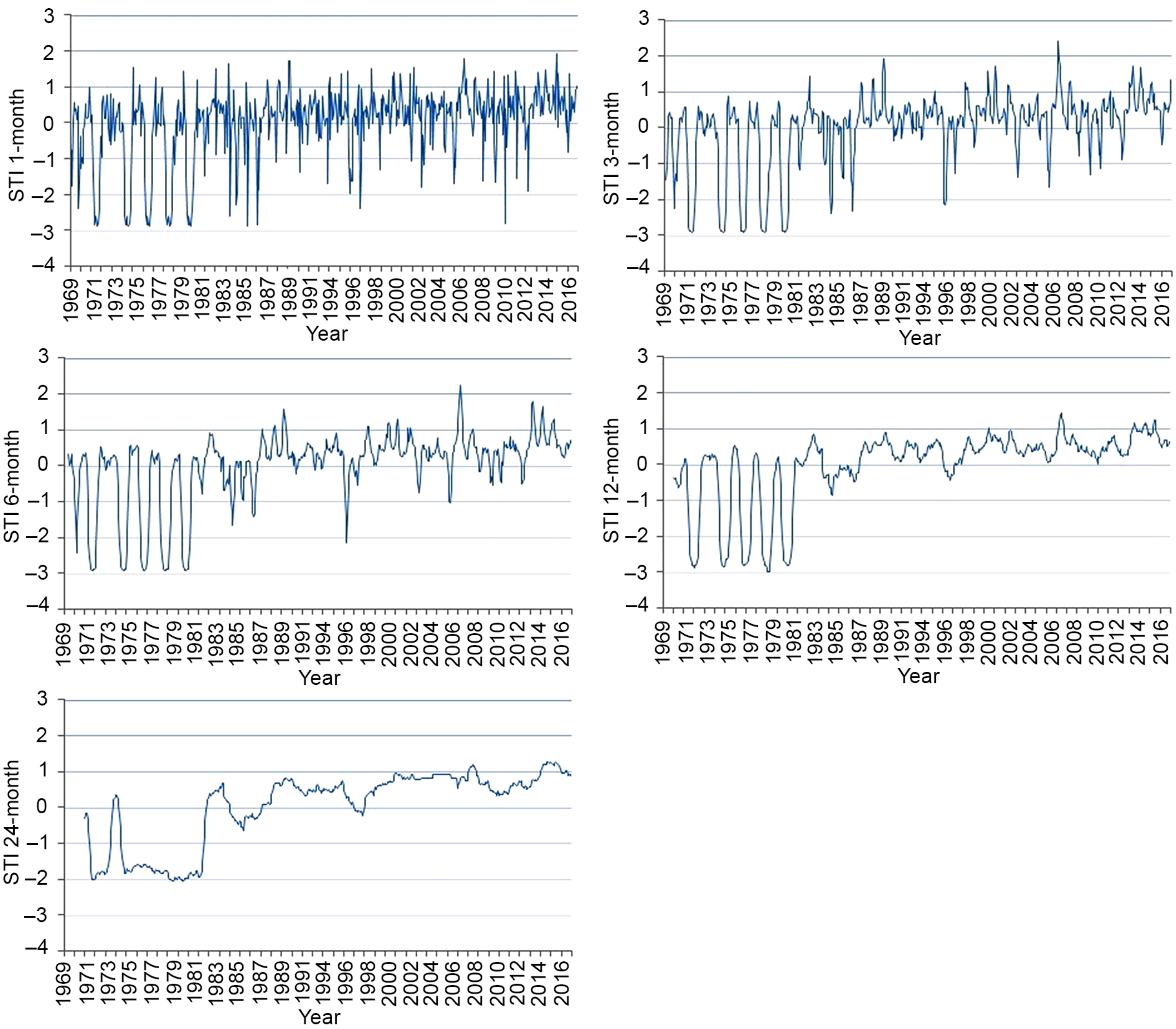


Fig. 2. SPI (a) and STI (b) computed for various periods of 1, 3, 6, 12 and 24 months

RESULTS AND DISCUSSION

In order to assess the relationship between the groundwater level and SPI and STI, a correlation coefficient *r* was calculated for the average monthly values of the groundwater level and standardized indicators in the previous months with different accumulation periods (from 1 to 24). This analysis indicated the largest correlation between the groundwater level and SPI6 (absolute value was 0.55). This proves that seasonal meteorological droughts take the greatest part in lowering the groundwater level in the Wrocław-Swojec research area. Further research on the impact of meteorological droughts on the groundwater level in this area should focus on assessing the relationship between seasonal precipitation deficits and the groundwater level. Analysis of the relationship between the groundwater level and STI showed a low degree of correlation between

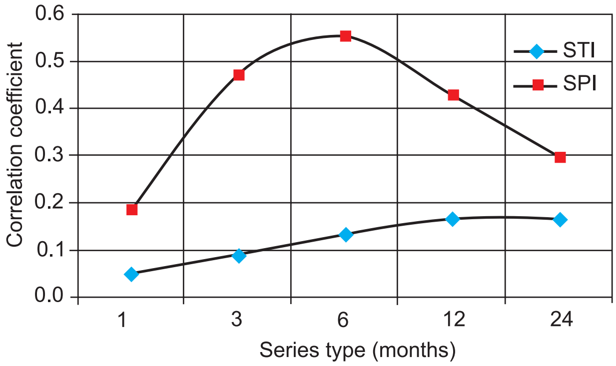


Fig. 3. Results of the correlation between monthly groundwater level series vs SPI and STI, computed for different time scales (1–24 months)

cumulative periods of temperature raised in relation to median and the groundwater level. This led to the conclusion that air temperature as a single factor has no clear influence on the groundwater level at the shallowest aquifer. Its impact should be analysed in connection with other factors affecting, for example, the volume of evapotranspiration. The further part of the study omits the influence of temperature.

According to the definition given by McKee (1993), it is assumed that in the dry season all SPI values are negative, however at least one month shows values that are less than or equal to –1. Drought is interrupted when the index value rises above zero.

It was found that SPI6 with values equal to –1, –1.5 or –2 roughly corresponds (depending on the specifics of a month) to 200, 180, 120 mm of accumulated precipitation from the previous 6 months. In the case of the Wrocław-Swojec research station, this volume of semi-annual precipitation can also be considered as the minimum amount of precipitation necessary to avoid droughts of varying intensity.

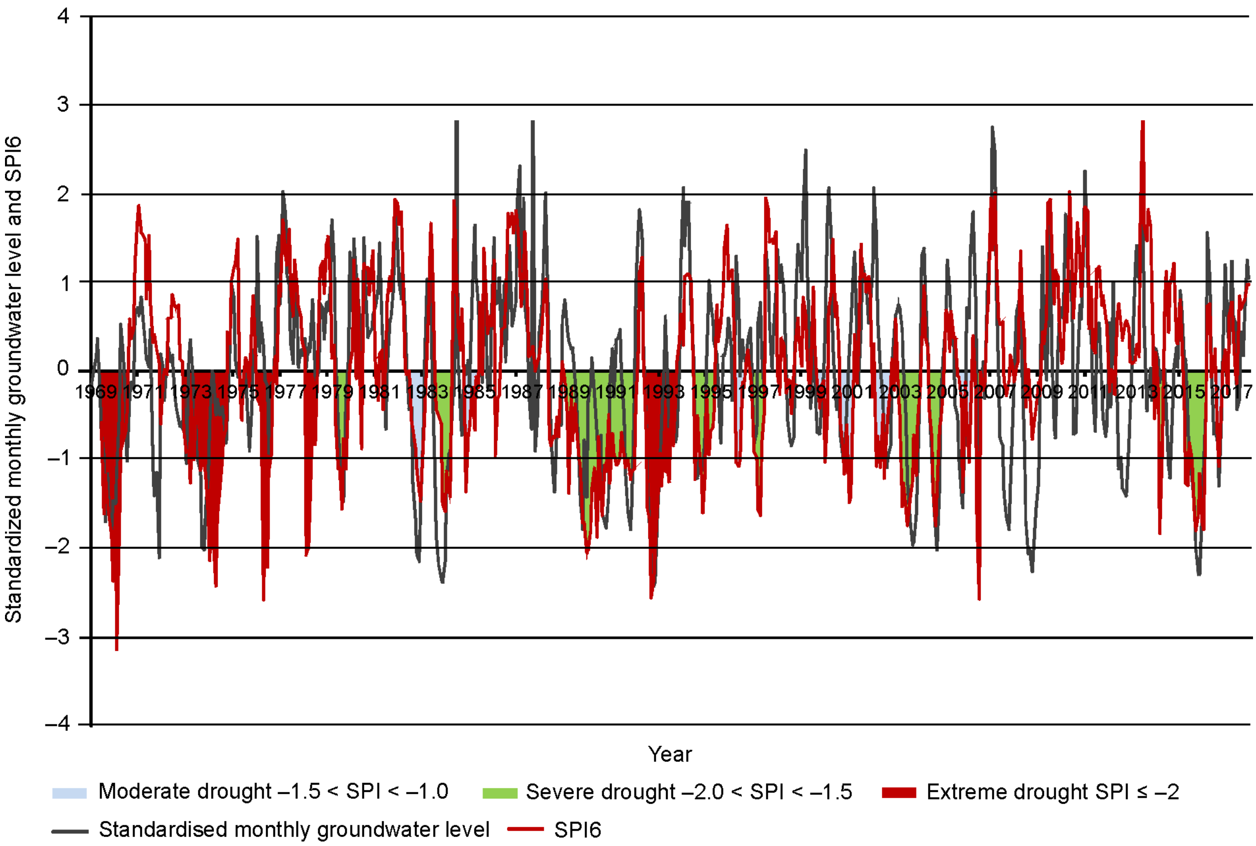


Fig. 4. Standardized monthly mean groundwater level and SPI6 in period 1969–2017 (drought categories are distinguished by colour)

Figure 4 shows the SPI6 (best correlated with groundwater level) and the standardized monthly value of the groundwater level at the Wrocław-Swojec research station. It was noticed that extremely dry periods caused a decrease of the groundwater level in 1969–1970, 1972–1974, 1976, 1978, 1992–1993. The lowering of the groundwater level in 1979, 1983–1984, 1989–1992, 1994–1995, 2003, 2004, 2006, 2015 was associated with very high precipitation deficits. The most extreme periods were recorded in 1983, 1992, 2008.

The decreasing groundwater level that results from precipitation deficits was not always directly connected to droughts at the studied groundwater level. The calculation of the SGI for each month allowed determining the periods of groundwater drought. It was noted that the longest periods of groundwater deficits occurred in 1980, 1981, 1986/1987, 1994, 1997/1998, 2000, 2001, 2006/2007, 2017 (see: Fig. 5). The research discovered 20 periods of extreme groundwater droughts (see: Fig. 6). The greatest took place in June 2013, when the SGI fell to below –4. Slightly weaker drought took place in spring 2007. Only in individual months droughts associated with precipitation deficits and droughts in groundwater coincided. This does not mean that hydrogeolog-

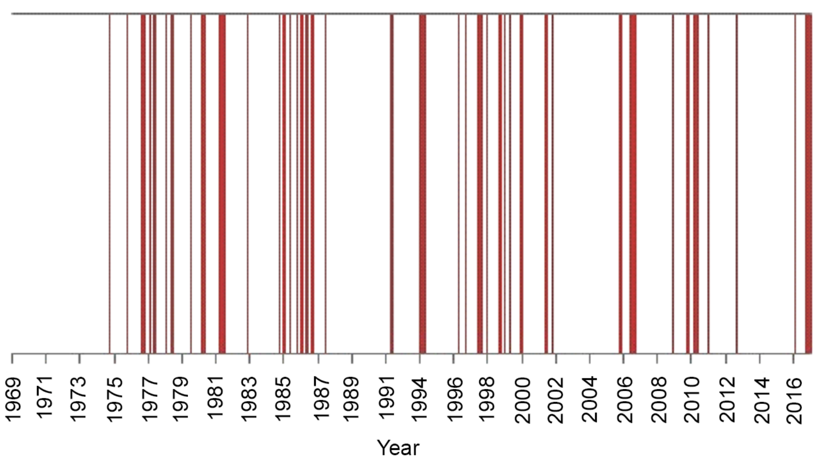


Fig. 5. Graphical representation of duration of groundwater droughts in period 1969–2017

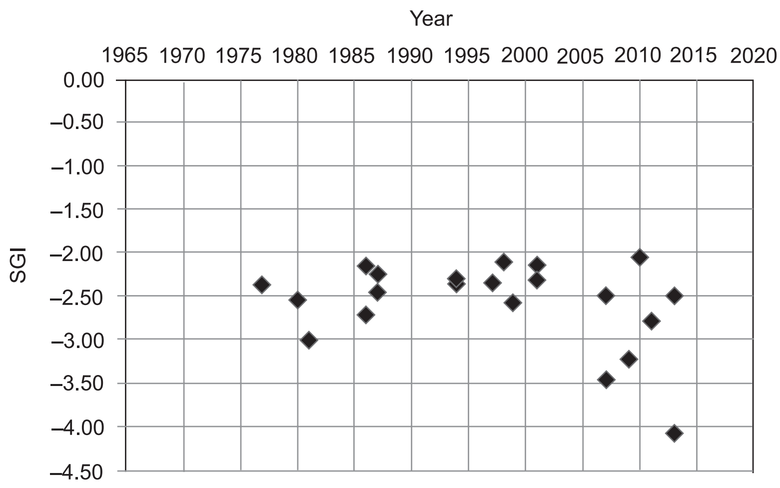


Fig. 6. Graphical representation of extreme groundwater droughts in period 1969–2017

ical drought is not a direct consequence of precipitation deficits. On this basis, it should be pointed out that periodic deficits of groundwater are conditioned by more factors.

Meteorological droughts do not always have a decreasing effect on the groundwater level and do not threaten the aeration zone. The reaction time of the groundwater level to a precipitation deficit depends on the length of the period of shortage. It can be interrupted by external factors, especially of an anthropogenic nature, as indicated by research by Khan et al. (2008). Mohammadi Ghaleni and Ebrahimi (2011) and Chamanpira et al. (2014). Human activity had no impact on the grounwater level in the studied case, and the Wrocław-Swojec research station is reliable for assessing the influence of dry periods and periods with temperature above the median value on groundwater level. Precipitation deficits are the main cause of droughts at groundwater level (Tallaksen and Van Lanen, 2004; Van Loon and Laaha, 2015). Not all factors causing droughts in groundwater were assessed for the Wrocław-Swojec research station, the research focused on precipitation and temperature. It concluded that the relationship between groundwater droughts and precipitation deficits is not direct. In other words, no linear relationship between droughts caused by precipitation deficits and groundwater droughts has been proven. Meteorological droughts usually do not imply hydrogeological droughts occurring at the same time. It was proven that air temperature as a single factor has no clear impact on the groundwater level at the shallowest aquifer. Its influence should be studied against other factors connected to, for example, the volume of evapotranspiration. Tallaksen and Van Lanen (2004), Van Lanen et al. (2013) and Van Loon (2015) came to similar conclusions. In studies on shallow groundwater they proved that evapotranspiration has a large, though non-linear effect on the formation of groundwater droughts.

With reference to the information of Kędzior (2014), it was found that nationwide meteorological droughts in the years 1980–1985, 1992, 2006 had an impact on droughts at the groundwater level in the area of the Wrocław-Swojec research station. Groundwater deficits due to meteorological droughts from 1992 and 2006 appeared with a delay of about one year.

SUMMARY AND CONCLUSIONS

SPI, STI, SGI indicate a deviation from a median of accumulated values of precipitation, temperature and groundwater level measured over a given time. They provide data on periods with deficits (negative SPI) or excess precipitation (positive SPI), particularly cold (negative STI) or hot (positive (STI) periods and groundwater level below (negative SGI) or above (positive SGI) a median.

Analysis of the relationship between the Standardized Temperature Index and the groundwater level showed a low degree of correlation. As for precipitation, the largest and statistically significant relationship was registered between SPI6 and the groundwater level (assuming a significance level of $p = 0.05$). This proves that seasonal meteorological droughts have the greatest impact on lowering the groundwater level in the Wrocław-Swojec research station.

It was found that an extremely dry period caused a decrease of the groundwater level in 1969–1970, 1972–1974, 1976, 1978, 1992–1993, while in 1979, 1983–1984, 1989–1992, 1994–1995, 2003, 2004, 2006, 2015 the level dropped due to very high deficits of precipitation. The most extreme periods of decreasing groundwater levels were recorded in 1983, 1992, 2008. Only in 1983 and 1992 drops in groundwater levels occurred at the same time as precipitation deficits.

Decreasing groundwater levels that result from precipitation deficits were not always directly connected to droughts at the described groundwater level. Only in individual months droughts associated with precipitation deficits and droughts in groundwater coincided.

Based on the analysis of the SGI, it was noticed that the longest periods of groundwater deficits were in 1980, 1981, 1986/1987, 1994, 1997/1998, 2000, 2001, 2006/2007, 2017. There were 14 periods of extreme drought (the strongest occurred in June 2013).

REFERENCES

Bak, B., Kubiak-Wojcicka, K. (2016). Assesment of meteorological and hydrogeological drought in Toruń (Central Poland town)in 1971–2010 based on standardized indicators. 3rd International Conference Water Resources and Wetlands, 164–170.

Bąk, B., Łabędzki, L. (2014). Prediction of precipitation deficit and excess in Bydgoszcz Region in view of predicted climate change. Journal of Water and Land Development, 23, 11–19.

Bloomfield, J.P., Marchant, B.P., McKenzie, A.A. (2019). Changes in groundwater drought associated with anthropogenic warming. Hydrology and Earth System Sciences, 23,1393–1408. DOI:10.5194/hess-23-1393-2019.

Chamanpira, G.H., Zehtabian, G.H., Ahmadi, H., Malekian A.(2014). Effect of Drought on Groundwater Resources; a Study to Optimize Utilization Management (Case Study: Alashtar Plain). Bulletin of Environment, Pharmacology and Life Sciences, 3(10), 48.

Fiorillo, F., Guadagno, F. M. (2010). Karst spring discharges analysis in relation to drought periods, using the SPI. Water resources management, 24(9), 1867–1884.

Kędziora, A., Kępińska-Kasprzak, M., Kowalczak, P., Kundzewicz, Z. W., Miler, A. T., Pierzgalski, E., Tokarczyk, T. (2014). Zagrożenia związane z niedoborem wody. Nauka, 1.

Khan, S., Gabriel, H. F., Rana, T. (2008). Standard precipitation index to track drought and assess impact of rainfall on watertables in irrigation areas. Irrigation and Drainage Systems, 22(2), 159–177.

Kleczkowski, A. (1991). Zagrożenia i bariery rozwoju w gospodarce wodnej. Polska w obliczu współczesnych wyzwań cywilizacyjnych. Komitet Prognoz „Polska w XXI wieku" przy Prezydium PAN. Warszawa: PAN.

Kubicz, J. (2018). TLM method and SGI index as indicator of groundwater drought. Acta Scientiarum Polonorum -Formatio Circumiectus, 17, 127–136. DOI:10.15576/ASP.FC/2018.17.1.127.

Kubicz, J., Bąk, B. (2019). The Reaction of Groundwater to Several Months' Meteorological Drought in Poland. 187–195.

McKee, T.B., Doesken, N.J., Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society Boston, MA. 179–183.

Mohammadi-Ghaleni, M., Ebrahimi, K. (2011). Assessing impact of irrigation and drainage network on surface and groundwater resources—Case study: Saveh Plain, Iran. In ICID 21st International Congress on Irrigation and Drainage, 15–23 October 2011, Tehran, Iran.

Pasławski, Z. (1992). Hydrologia i zasoby wodne dorzecza Warty. Konferencja naukowa na temat: Ochrona i racjonalne wykorzystanie zasobów wodnych na obszarach rolniczych Wielkopolski. Koreferaty i wnioski. Poznań, 5–28.

Salvador, C., Nieto, R., Linares, C., Diaz, J., Gimeno, L. (2019). Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013. Science of the Total Environment, 662, 121–133. DOI:10.1016/j.scitotenv.2019.01.217

Tallaksen, L.M., Van Lanen, H.A. (2004). Hydrological drought: processes and estimation methods for streamflow and groundwater. Elsevier.

Van Lanen, H.A.J., Wanders, N., Tallaksen, L.M., Van Loon, A.F. (2013). Hydrological drought across the world: impact of climate and physical catchment structure. Hydrology and Earth System Sciences, 17, 1715–1732. DOI:10.5194/hess-17-1715-2013.

Van Loon, A.F. (2015). Hydrological drought explained. Wiley Interdisciplinary Reviews-Water, 2, 359–392. DOI:10.1002/wat2.1085.

Van Loon, A.F., Laaha, G. (2015). Hydrological drought severity explained by climate and catchment characteristics. Journal of Hydrology, 526, 3–14. DOI:10.1016/j.jhydrol.2014.10.059.

Wang, L., Yu, H., Yang, M., Yang, R., Gao, R., Wang, Y. (2019). A drought index: The standardized precipitation evapotranspiration runoff index. Journal of Hydrology, 571, 651–668. DOI:10.1016/j.jhydrol.2019.02.023.

OBNIŻENIE POŁOŻENIA ZWIERCIADŁA WÓD PODZIEMNYCH JAKO REAKCJA NA SUSZĘ METEOROLOGICZNĄ – ANALIZA Z ZASTOSOWANIEM SPI I STI

ABSTRAKT

Cel pracy

Celem badań była ocena zależności między położeniem zwierciadła wód podziemnych, wystąpieniem suszy w tym poziomie wodonośnym a niedoborem opadów i wysoką temperaturą powietrza.

Materiał i metody
Analizy wykonano opierając się na danych z Wydziałowego Obserwatorium Agro i Hydrometeorologii Wrocław-Swojec Uniwersytetu Przyrodniczego we Wrocławiu z lat 1969–2017. Dane do analiz stanowiły pomiary położenia wód podziemnych oraz temperatury powietrza i opadu. Posługując się standaryzowanymi wskaźnikami opadu SPI oraz temperatury STI, wyznaczono okresy z niedoborem opadów oraz podwyższoną temperaturą. Określono zależność pomiędzy wskaźnikami a poziomem wód podziemnych. Za pomocą standaryzowanego wskaźnika poziomu położenia wód podziemnych SGI wyznaczono okresy wystąpienia suszy w poziomie wód podziemnych.

Wyniki i wnioski
Analiza zależności pomiędzy STI a położeniem zwierciadła wód podziemnych wykazała niewielki stopień korelacji. Temperatura powietrza jako pojedynczy czynnik nie ma wyraźnego wpływu na poziom położenia zwierciadła wód podziemnych najpłytszego poziomu wodonośnego. W przypadku opadów największa zależność wystąpiła pomiędzy SPI6 i położeniem zwierciadła wód podziemnych. Sezonowa susza meteorologiczna ma największy wpływ na obniżenie poziomu zwierciadła wód. Stwierdzono, że ekstremalnie suchy okres z obserwacjami SPI<–2 spowodował obniżenie położenia zwierciadła wód gruntowych w latach 1969–1970, 1972–1974, 1976, 1978, 1992–1993, natomiast w latach 1979, 1983–1984, 1989–1992, 1994–1995, 2003, 2004, 2006, 2015 było to związane z bardzo dużym niedoborem opadów o SPI z zakresu od –2 do –1.5. Obniżenie zwierciadła wody podziemnej powstałe na skutek niedoboru opadu nie zawsze łączyło się z bezpośrednim wystąpieniem suszy w opisywanym poziomie wód gruntowych. Najdłuższe okresy niedoboru wód podziemnych wystąpiły w latach 1980, 1981, 1986/1987, 1994, 1997/1998, 2000, 2001, 2006/2007, 2017. Dodatkowo stwierdzono 14 okresów suszy ekstremalnej.

Słowa kluczowe: susza, SPI, STI, SGI, poziom wód podziemnych