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Original Research

The Reaction of Groundwater to Several Months' Meteorological Drought in Poland

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Abstract

Our article presents the results of research aimed at determining the effect of precipitation on the level of the groundwater table and the impact of meteorological drought on the hydrogeological groundwater level in the area of Kujawy and Wielkopolska in the years 1981-2015. Monthly sums of precipitation came from Bydgoszcz and Poznan. Underground water table levels were measured by the Geological Institute in the area of Kujawy, near Bydgoszcz (Solec Kujawski and Jagodowo) and in the area of Wielkopolska (Stęszew and Czachurki). The drought periods were determined on the basis of standardized precipitation index (SPI), meteorology drought, and standardized groundwater level (SGI) in four time scales (6, 12, 24, and 48 months).

The results confirmed the findings of other authors that there is no linear relationship between the terms of meteorological drought and hydrogeological groundwater drought. The relatively low value of correlation coefficients between SPI and SGI indices show that the groundwater droughts are affected by other factors independent of rainfall. The relationships between the climatic conditions and the level of the water table as well as groundwater droughts were determined by the properties of the aquifer.

Keywords: meteorological drought, groundwater drought, SPI, SGI, correlation

Introduction

In economic, social, and environmental terms drought is recognized as one of the most damaging natural disasters [1]. It is generally believed that climate change has caused a marked increase in the frequency of droughts in the northern hemisphere since the 1970s. The expansion of areas affected by this phenomenon for longer dry periods and an increase in their intensity are still being observed [2-4]. Problems with access to water sources are the cause of social conflicts, which intensified especially in the early 21st century [5-6]. Droughts cause problems mainly with access to surface water resources, generate losses in agriculture, and often contribute to irreversible changes in ecosystems dependent on water [7-8]. As other important effects of drought, a number of forest fires and increased mortality, especially in periods of heat waves, may be mentioned [9-10].

In literature there is no uniform definition of a drought, since there are different reasons for its formation [11]. Most often it is assumed that it is a period of significantly reduced precipitation, which results in restrictions on water accessibility [12-15]. In our latitudes, intensity of draught increases due to high temperature and increased evaporation [16-18].

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An important and still little-known aspect of the impact of drought on the environment is the reaction of the groundwater to meteorological drought, especially in those areas where the drought is common. Diverse environmental geological conditions play an important role in these relationships. Wielkopolska and Kujawy are among the driest regions in Poland, as confirmed by several observations and studies carried out since the mid-19th century [19-25]. Meteorological droughts in these regions often appeared in the last two decades of the 20th century and early 21st century. Numerous scenarios of climate change foresee that they will also appear in the next decades in the first half of this century [26-28]. The drought in Wielkopolska in 1992 is an example of the impact of meteorological drought on groundwater. This caused a drastic reduction of the water level in Warta and the groundwater table in the water intake Mosina, near the agglomeration of Poznań. The drought also caused damage in a national park and Rogalin Landscape Park [29].

Monitoring hydrogeological conditions in Poland has been carried out since 2006 by the National Hydrogeological Service within the framework of National Environmental Monitoring. Statistically processed monitoring data of the groundwater heads and spring rates are reported by the Quarterly Bulletin of Groundwater issued by Polish Geological Institute – National Research Institute. In parallel, National Water Management is also running a project titled "Developing plans to counter the effects of drought in river basin areas." Its main task is to propose mitigation and prevention measures to limit the negative impact of drought on society, the environment, and the economy [32]. In addition, the project collects evidence of the drought spells in Poland and identifies the regions particularly exposed to the appearance of drought.

Investigating the effect of meteorological drought on hydrogeological drought has already been conducted in the UK, the Netherlands, and some other countries. Currently, most of this type of research is carried out using the indicator method. In the national literature examples of work that examined, among others, the relationships between the meteorological drought [19, 36] and hydrological drought [37] can also be found. Standardized precipitation index (SPI) was used in the case of meteorological droughts, which were calculated on the basis of long-term (at least 30 years), rainfall in the case of most droughts, which is calculated on the basis of long-term, at least 30 year rainfall measurement sequences. In the case of hydrogeological drought the standardized groundwater level (SGI) that often appears in literature may be used [40-41]. In this case it is also recommended to use the longest possible measurements of the groundwater table. In the case of both droughts, SPI and SGI allow for the adoption of the same methodology of preparation measurement data, calculating the values of indicators and using the same classification of drought intensity, and setting the parameters of drought, like the beginning and end of an occurrence and its duration and intensity. The research concern regarding relationships between both droughts was carried out in different time scales of 1 to 48 months [42-43].

Research conducted by Bloomfield and Marchant [40] van Loon [1] and Kumar [43] in the area of Great Britain, Germany, and the Netherlands showed no linear relationship between current rainfall and the current level of the groundwater table. In some Asian regions often affected by meteorological drought, a significant correlation between rainfall and the level of groundwater table was found at the end of a 24-month meteorological drought [44]. These authors examining the relationship using indicators SPI and SGI accumulating periods of rainfall (6, 12, 24, and 48 months) and the average monthly water level showed a relationship between both droughts, and also a delayed reaction of the aquifer to the lack of precipitation.

The aim of the article was to determine the relationship between long-term meteorological drought and groundwater drought in the area of Wielkopolska and Kujawy. This goal was realized by indicator-based method and the results are explained by additional references to literature concerning the characteristics of precipitation and geological measurements in the studied locations. The knowledge gained will explain the response of groundwater to shortages of rainfall and may be useful in managing the intake of water during meteorological drought.

Materials and Methods

Study Sites and Data

Precipitation conditions in Kujawy and Wielkopolska were determined on the basis of monthly sums of precipitation P (mm) in a multi-year period (1981-2015) from the station belonging to the Institute of Meteorology and Water Management at the National Research Institute (IMGW-PIB) in Poznan, and the station belonging to the Institute of Technology and Life Sciences (ITP) in Bydgoszcz. Groundwater levels were measured at four piezometric wells belonging to the observational research of Polish Geological Institute–National Research Institute (PGI-PIB). In Kujawy, measuring points were located in Solec Kujawski and Jagodowo near Bydgoszcz, in Wielkopolska Lowland in Stęszew and Czachurki near Poznan (Fig. 1). For analysis and calculation, average monthly values of the position of the groundwater level H (m) were used.

Although measurements of water level in Jagodowo and Solec Kujawski started at the turn of 1976 and 1977, due to periodic shortages of the analysis of sequences of measurements reported in multi-years, we used 1992-2015 and 1980-2015. In the case of Stęszew and Czachurki, the measuring period covered the years 1980-2015.

The measurement points are located on the Polish Lowland. The point in Solec Kujawski is located within the Toruń Basin, in Jagodowo, in Wysoczyzna Świecka, an upland, and in Stęszew it is located on the Poznan

Fig. 1. Location of piezometric wells and meteorological stations.

Lakeland Area and Gniezno in Czachurki Lakeland [45-47]. In terms of hydrogeological measuring, the stations in Stęszew and Czachurki are located in the basin of the Warta River, in the lowland subregion, and in Solec Kujawski and Jagodowo located in the basin of the lower Vistula River in the lakeland subregion [48].

Measured aquifers occurred in deposits of quaternary, in sands, and sand with gravel [49]. Water surfaces at all points have changed periodically, which was caused by the water flows and hydrometeorological factors [49-51]. In particular places according to geological data different thicknesses of aquifer were found: Stęszew (II/406/1) 3.8 m, Czachurki (I/428/4) 7.7 m, Solec Kujawski (II/185/1) 13 m, and Jagodno (I/257/4) about 68 m. Three observation points are located in the area of main groundwater basins (MGBs). The exception was in Solec Kujawski. In addition, the location of water intakes may have an impact on the position of the groundwater levels in these points. This factor should be taken into account in the case of the observation in Czachurki. The monitoring point I/428/4 in Czachurki is located in the influence zone of two underground water intakes for Poznan and Gniezno. Collective information on measuring points is presented in Table 1.

Table 1. Summary of analyzed information about the monitoring points (source: own study).

Point number	II/185/1	I/257/4	II/406/1	I/428/4
Site	Solec Kujawski	Jagodowo	Stęszew	Czachurki
Stratygraphy	Quaternary	Quaternary	Quaternary	Quaternary
Lithology	Sands	Sands	Sands and gravels	Sands and gravels
Start of records	1985	1992	1980	1980
End of records	2015	2015	2015	2015
Mean annual precipitation (mm), meteorological stations	513 Bydgoszcz		526 Poznań	
Groundwater level (m a.s.l.)	Min	41.6	76.3	85.9
	Max	41.7	78	87.5
	Mean	42.4	77.2	86.4
Well depth relative to soil surface (m)	14	71.5	8.1	8.5
Water table met during drilling (m)	1.0	2.72	4.72	0.8
Average hydraulic conductivity of aquifer ($m \cdot s^{-1}$)	$3 \cdot 10^{-4} \div 1 \cdot 10^{-4}$	$3 \cdot 10^{-4} \div 1 \cdot 10^{-4}$	$3 \cdot 10^{-4} \div 1 \cdot 10^{-4}$	$3 \cdot 10^{-4} \div 1 \cdot 10^{-4}$
Surface features	Soils comprising loose sand and loamy sand	Soils comprising loamy loose sand	Soils comprising glacial tills and sands overlying loam or silt	Soils comprising loose sand
Major groundwater basin (MGB)	-	140	144	144

Research Method

This paper uses an indicator-based method that allows for adopting the same methodology of calculating values of the meteorological and hydrogeological drought, determining the parameters of drought, and adopting the same classification of drought intensity [52-53]. SPI is quoted widely in the literature for meteorological drought [11, 26, 28, 38, 43, 54-64]. Despite the objections of some authors who drew attention to the possible restriction of the use of this indicator [41], it is recommended by the World Meteorological Organization (WMO) to monitor the operating risk of drought [65].

A standardized rate of the groundwater-level SGI (standardized groundwater level index) was chosen as a hydrological drought index used in this paper. It is calculated based on the measuring of ground water level H [41, 44]. SGI is a rate equivalent to the rate of SWI, which was proposed by Bhuiyan [39] and is also used to monitor groundwater shortages.

The values of indicators are the standardized deviations of precipitation and groundwater levels from the median value in the multi-year studied period. In Kujawy and Wielkopolska it has practically been verified earlier by Łabędzki [54]. The good fit to a normal distribution of strings of homogenous precipitation was obtained by transforming function $f(P) = \sqrt[3]{x}$ [54]. As a hydrological factor, which is also recommended in the literature, a two-parameter logarithmic function ln was adopted [66-67]. Compatibility of the transformed variable distribution f (P) with the normal distribution should be examined using, e.g., Pearson's chi-squared test or the Kolmogorov-Smirnov test. The positive test result enables further calculation of the values SPI and CGI according to the equation:

$$Z = \frac{f(X) - \hat{\mu}}{\hat{\delta}} \quad [1]$$

…where Z is choosen index (*SPI, SWI*), P is precipitation [mm], H is water level [m], $f(X)$ is transformer sums of precipitation or water level, $\hat{\mu}$ is mean of normalized X, and $\hat{\delta}$ is standard deviation of normalized X.

According to McKee [68], it has been assumed that in times of drought all the values of SPI and SGI are negative, while at least in one month, these values are lower than or equal to -1.0. The interruption of drought occurs when the value of the indices increases to zero. For the indices whose values satisfy the condition X<-1.0, a joint assessment by three classes of intensive drought was adopted [37]. Thresholds of -1.0 are responsible for moderate drought, -1.5 for severe drought, and -2.0 for extreme drought.

Studies of meteorological and hydrological droughts were carried out in time scales of 6, 12, 24, and 48 months. An important aim of our work was to determine the relationships between the two droughts based on the correlation coefficients r between SPI and SGI [52, 62] and the relationship between SPI and the monthly average of the groundwater level H. The small value of r is not indicative of a total lack of relationship between

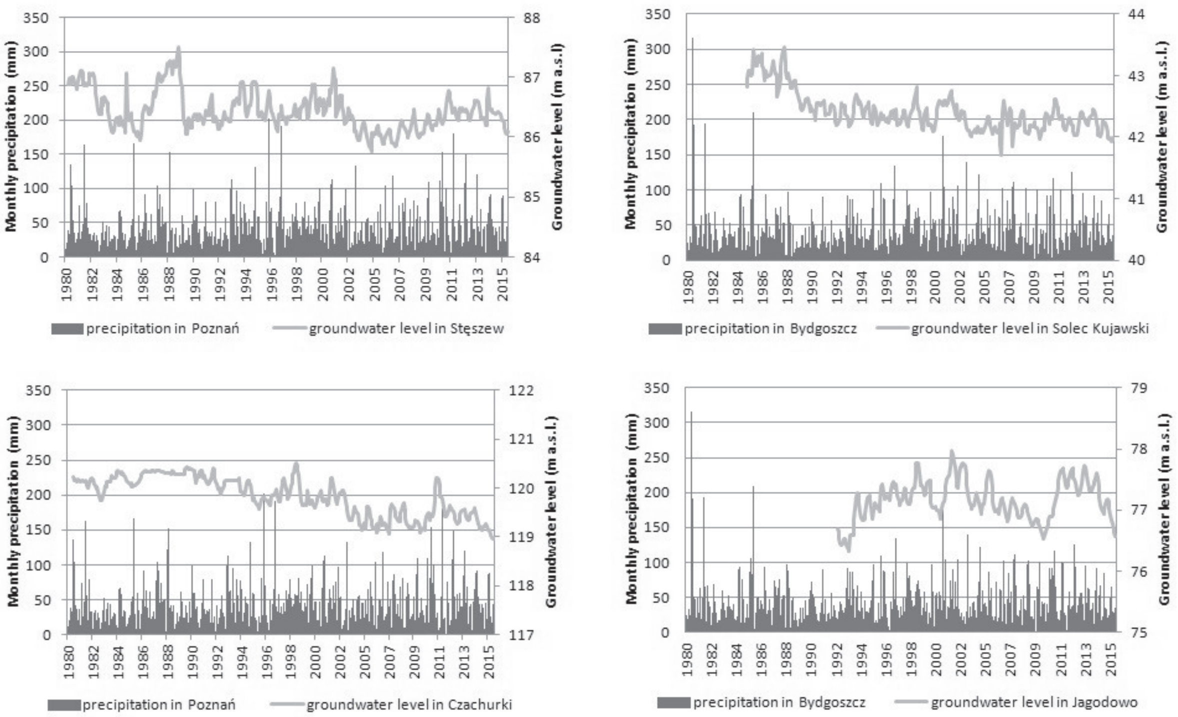

Fig. 2. Monthly sums of precipitation P (mm) corresponding with mean monthly groundwater level H (m) for the study sites (source: own study).

droughts, but it indicates a much larger share of other external factors that weaken these relationships. Greater values are evidence of the increased rainfall infiltration capability by the aquifer. The appropriate classification of assessment depending on the value of r was presented by Bachmair et al. [69]. Additionally, it was checked how the value of the correlation coefficients were changed taking into account the time shift of meteorological drought in relation to groundwater drought, and a reaction of water levels and the mutual relationships of the two types of drought [70].

Table 2. Correlation coefficients r between monthly SPI and monthly average groundwater table H (m) (source: own study).

Site	*r*			
	SPI-6	SPI-12	SPI-24	SPI-48
Solec Kujawski	0.22*	0.25*	0.16*	-0.16*
Jagodno	-0.02	0.04	-0.02	-0.00
Czachurki	-0.02	-0.10*	-0.20*	-0.32*
Stęszew	0.26*	0.35*	0.41*	0.24*

*statistical significance at the 0.05 level

Results and Discussion

The variability of mean monthly values of the ground water table H and simultaneous precipitation P is shown in Fig. 2.

In the analyzed multi-year period in Poznan (8 years) and in Bydgoszcz (16 years) we observed annual rainfall lower than the long-term average. Furthermore, a number of a few months` sequences of significantly lower rainfall than the long-term average were noted. In Poznan there were 11 and in Bydgoszcz 13 of such periods of rainfall deficiency. The longest periods with a series of dry months occurred in both towns in the multi-year period from 1982 to 1985 and in 2015. In other years, e.g., 1989, 1992, 2004, 2006, 2008, and 2015 we found a series of at least four-month periods of reduced rainfall. Reaction levels of groundwater to the shortage of rainfall were analyzed at measuring points. Lowering the water level frequently appeared with a delay, e.g., in Stęszew in response to the drought in the period from 1982 to 1986 it was observed between 1985 and 1986. In Jagodno the drought occurred in 2006 and 2008, and its effects appeared in 2009 and 2010. Examples of simultaneous courses of meteorological and hydrological drought were determined on the basis of SPI and SGI (Fig. 3). Values of the correlation between coefficient SPI and groundwater level H are shown in Table 2. In most cases, these relationships were statistically significant at the 0.05 level.

The best relationships were found in Stęszew (SPI-24 vs. H, r = 0.41) and Czachurki (SPI-48 vs. H, r = -0.32). The results indicate the fact that these relationships were determined by the properties of the surface layer, which delayed the flow of rain to the water-bearing system. It was found that in more concise soils in Stęszew this delay was longer than in light soils in Solec Kujawski. However, in Jagodno due to the thickness of the aquifer (over 71 m), there was no effect of precipitation conditions on water level. Demonstrated lack of association between

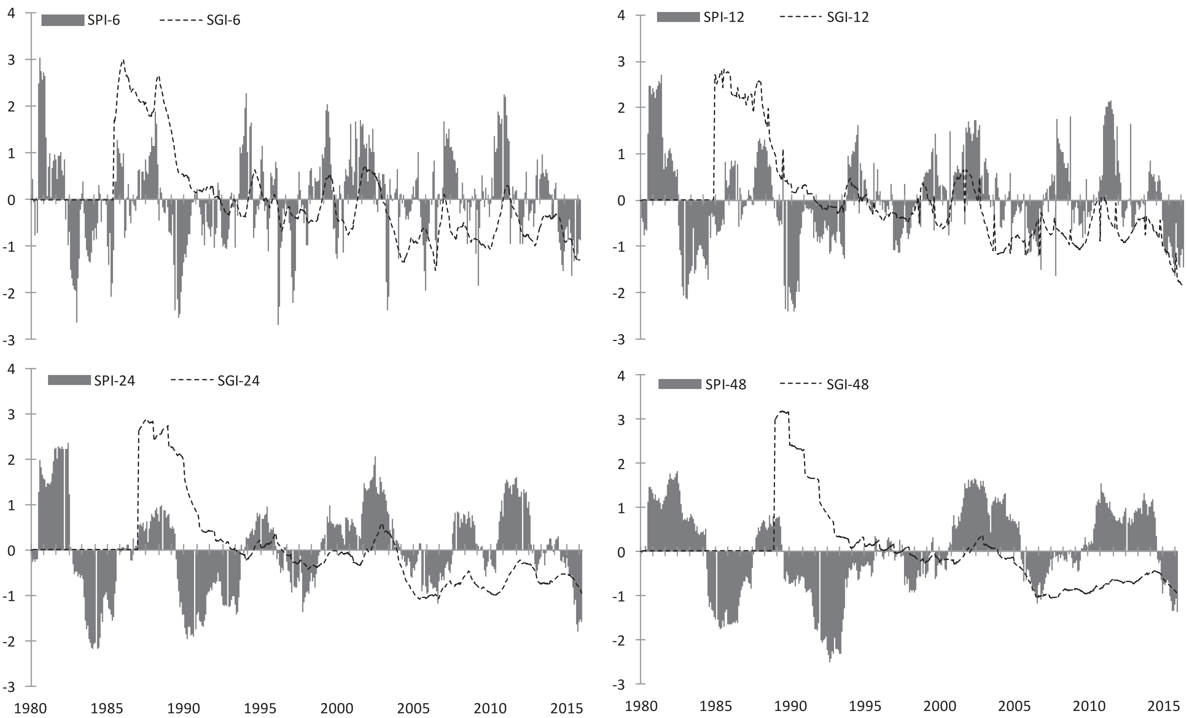

Fig. 3. Example plots of SPI and SGI in different time series for Bydgoszcz and Solec Kujawski (source: own study).

Table 3. Correlation coefficients between SPI and groundwater H in different scales of time delay (source: own study).

SPI	Site	Time delay (months)										
		1	2	3	4	5	6	9	12	18	24	48
SPI-12	Solec Kujawski	0.25*	0.22*	0.19*	0.17*	0.16*	0.12*	-0.12*	-0.25*	-0.38*	-0.38*	-0.42*
SPI-48	Czachurki	-0.30*	-0.30*	-0.30*	-0.31*	-0.31*	-0.31*	-0.31*	-0.31*	-0.30*	-0.28*	-0.37*
SPI-24	Stęszew	0.45*	0.45*	0.45*	0.44*	0.42*	0.40*	0.32 *	0.25 *	0.09	-0.15*	-0.50*

* Statistical significance at the 0.05 level

SPI and H in this location was the reason why further research in Jagodno has been discontinued. The negative relationship between the indicators SPI-12, SPI -24, and SPI -48 and the mean level of the groundwater table H was observed in Czachurki. The absolute values of these correlation coefficients were increased with the length of accumulating time. The probable cause of the reverse relationships, especially in increased periods of rainfall deficiency, was the water consumption for Poznan and Gniezno from MGBs.

The study assuming that the impact of rainfall on the water table may appear with a delay of some months, of from 1 to 48. The results obtained in Stęszew, Czachurki, and Solec Kujawski have shown that these relationships were varied (Table 3). In the case of Stęszew it showed that if the interactions were to occur they would be the strongest in months 1-6 or 48, whereas in Czachurki their relationships were reversed and they would be almost constant. Interesting results were obtained in Solec Kujawski, where a positive and at the same time a weakening relationship occurred during months 1-6. Delay would cause a reversal of these relationships, the value of the correlation coefficient would be negative, and the absolute value of the calculated correlation coefficients increase.

The next stage of the study was assessing the relationships between SGI and SPI for different periods of time (Table 4). In this part of the analysis the results of previous analyses were taken into account. The best correlated SPI with groundwater level H (Table 3) were correlated with SGI (Table 4).

The best relationship between SPI-24 and SGI-6 was found in Stęszew, the SPI-48 and the SGI-48 in Czachurki and SPI-12 and SGI-48 in Solec Kujawski (Table 5). The relatively low value of the relationships between SPI and SGI points to the fact that the existence of hydrological drought is affected by other factors independent of rainfall. These include the physical properties of the terrain, the hydraulic properties of the aquifer [72-73], and anthropogenic factors [74].

Table 4. Correlation coefficients r in selected periods of time between SPI and SGI (source: own study).

SPI	site	*r*			
		SGI-6	SGI-12	SGI-24	SGI-48
SPI-12	Solec Kujawski	0.13*	0.20*	-0.26*	-0.36*
SPI-48	Czachurki	-0.27*	-0.29*	-0.31*	-0.36*
SPI-24	Stęszew	0.51*	0.44*	-0.11*	-0.45*

* Statistical significance at the 0.05 level

The above relationships were also examined, assuming that the effects of SPI on SGI may increase with the delay in the selected months from 1 to 48. The results obtained in Stęszew, Czachurki, and Solec Kujawskim showed SPI delay vs. SGI only in Czachurki (Table 5). The highest correlation coefficient was observed for four months of delay. The observation in this place suggested that a delay longer than four months caused weaker relationships. The delay between meteorological and groundwater drought in Stęszew caused a decrease in the absolute value correlation coefficients in months 1-18, and a slight increase in 24- and 48- months. The results obtained in Solec Kujawski indicated no connections between SPI and delay time in most cases.

Obtained results confirm findings of other authors, e.g., Bloomfield and Marchant [39] and van Loon [1], who signaled the lack of a linear relationship between meteorological drought and groundwater drought because usually both droughts are delayed. Research by Khan et al. [71] suggested that relationships between SPI and the level of groundwater H depend primarily on location in the hydrodynamic system, rainfall shortages, and groundwater exploitation accounting for economic purposes, in this case for irrigation of fields. Similar conclusions can be found in the work by Bhuiyan et al. and other works [39]. Research conducted in Iran by Mohammadi Ghaleni and Ebrahimi [44] and Chamanpira et al. [70] showed that after two years of meteorological drought, groundwater resources significantly decreased, and a shift of both droughts on average was 12 months. As a reason for the delayed reaction of hydrological drought to meteorological drought, authors pointed out the properties of a geological formation, which in this case resulted in prolongation of infiltration of rainwater into the water-bearing system. It should be recalled that the level of groundwater is formed by a number of factors, including the physical properties of the terrain, the hydraulic properties of the aquifer, and changing weather conditions [72-73]. Whittemore [74] also noted that the anthropogenic impact, e.g., large consumption of water, could weaken the relationship between the level of groundwater and climate variables.

Table 5. Correlation coefficients between SPI and SGI in selected time scales (in different scale delay) (source: own study).

r	Site	Time delay (months)										
		1	2	3	4	5	6	9	12	18	24	48
SPI-12 vs. SGI-12	Solec Kujawski	0.02	-0.01	-0.03	-0.06	-0.08	-0.10	-0.14*	-0.16*	-0.13*	-0.06	-0.02
SPI-48 vs. SGI-48	Czachurki	-0.30*	-0.33*	-0.33*	-0.38*	-0.33*	-0.32*	-0.32*	-0.31*	-0.31*	-0.29*	-0.23*
SPI-24 vs. SGI-6	Stęszew	0.48*	0.47*	0.44*	0.42*	0.39*	0.36*	0.27*	0.18*	-0.06	-0.21*	0.55*

*Statistical significance at the 0.05 level

Conclusions

Understanding the impact of long-term meteorological drought on changes in groundwater level and on the course of groundwater drought is a significant problem, especially in these regions where limited water resources are used for consumption and economic purposes. This problem is less frequently presented in the literature than the results of research regarding the relationships between meteorological drought and hydrological drought of surface waters. One of the reasons for this approach is the fact that water for the above-mentioned purposes is mainly taken from rivers and lakes, and in these places the changes of water resources caused by insufficient amount of precipitation are observed at the earliest. In arid agricultural regions, such as Wielkopolska and Kujawy regions, we observed an increase of the number of sprinklers that require the supply of water for agricultural production. In most cases it is groundwater. Water consumers, including farmers, are not always aware that after a long-time meteorological drought, there is a risk of delay, and groundwater drought and water consumption may be limited.

Important factors that should always be considered in researching the relationship between both droughts are the long-term local precipitation statistics and historical changes, the type and properties of the layer located directly above the aquifer, and the anthropogenic factors that influence these relationships. We must also remember that the environment is not a permanent element and that it can change as a result of the activities of nature and people.

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