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An analysis of groundwater drought in combination with meteorological droughts. Case study of the Gwda River catchment (northern Poland)

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Abstract
The article presents the research results aimed at determining the impact of meteorological droughts on groundwater droughts in the Gwda River catchment (northern Poland). The analysis was based on the Standardised Precipitation Index (SPI) and Standardised Groundwater Index (SGI) in various cumulation periods (1, 6, 12, 18, 24, 30 and 36 months) from 1986–2015. Monthly groundwater levels measured in wells and monthly sums of precipitation from meteorological stations in the vicinity of those wells were used to assess the relationships between droughts. During the study period from 1986–2015, three to 43 meteorological droughts and one to five groundwater droughts were identified. Meteorological droughts were most numerous for the shortest cumulation period (1 month), while droughts for the longer accumulation of 24 to 36 months were less numerous. The SPI and SGI indices were most strongly correlated over the annual cycle in the upper part of the catchment (between the Sępólno Wielkie station and well I-33_1). The correlation coefficient *r* was highest (0.69) between SPI-18 and SGI-1. Correlations were much lower in the middle of the catchment, where the maximum annual *r* coefficient was 0.39. There was no correlation between droughts in the lower catchment (*r*=0.14). The correlations presented for the Gwda catchment indicate that the relationship between droughts is not clear.

Keywords
Meteorological drought, hydrological drought, Standardised Precipitation Index (SPI), Standardised Groundwater Index (SGI), the Gwda River, Poland List the keywords covered in your paper.

Introduction

Drought is one of the most severe and extreme natural phenomena in terms of societal, environmental and economic impact. It is a natural threat that can be described as a temporary decrease in water availability over a significant period (Wossenyeleh et al., 2021). Droughts can be divided into four categories: meteorological, agricultural, hydrological (groundwater and surface water) and socio-economic (Wilhite & Glantz, 1985). This classification is based on drought impact propagating through the hydrological cycle. Meteorological drought is an absence or low level of precipitation over an extended period. Long-term precipitation deficits or heat waves can trigger agricultural droughts, which are generally defined as soil moisture deficits severe enough to negatively affect vegetation (van Hateren et al., 2021). Longer-term reduced supply from the earth's surface decreases groundwater levels, ultimately decreasing groundwater supply to rivers (Van Lanen & Peters, 2000; Lee et al., 2018; Kubiak-Wójcicka, 2021; Kubiak-Wójcicka et al., 2021c). Groundwater reacts slowly to meteorological drought, usually with a delay, and takes a long time to recharge (Chamanpira et al., 2014; Chao et al., 2017; Batalha et al., 2018). Hence, determining groundwater droughts requires that precipitation and its deficit be analysed over longer periods of time (Jamorska et al., 2019). An additional element that further lowers the groundwater level, worsening the hydrogeological droughts that result from natural conditions, is the increased consumption of groundwater for human activities (Wada et al., 2013; Wendt et al., 2020). For this type of human-induced drought, the concept of anthropogenic drought has been proposed (AghaKouczak et al., 2021; Ashraf et al., 2021).

Droughts have been studied in various areas and analysed from many perspectives. In recent decades, most studies have reported a general global trend toward more frequent and more severe meteorological droughts (Dai, 2011; Spinoni et al., 2014; Cammallieri et al., 2020; Chiang et al., 2021) or have predicted that such trends will result from future climate change (Lee et al., 2016; Hari et al., 2020; Khan et al., 2021). Although groundwater is an important source of water in the world, it is disregarded by many drought-related studies (Wilhite & Glantz, 1985; Talasken & Van Lanen, 2004; Verbeiren et al., 2013; Van Loon & Laaha, 2015; Papadopoulos et al., 2021).

As in other parts of the world, so too in Poland, extensive research on drought has been conducted (Kępińska-Kasprzak, 2015; Radzka, 2015; Łabędzki, 2016; Kuśmierek-Tomaszewska, 2018; Pińskwar et al., 2020; Kubiak-Wójcicka & Bąk, 2018; Przybylak et al., 2020), but little research has been done on groundwater droughts. Research on groundwater droughts began relatively recently, and not many results have been published (Farat et al., 1998; Kubicz & Bąk, 2018; Krogulec, 2018; Staśko & Buczyński, 2018; Kubicz et al., 2019; Jamorska et al., 2019). This was because the groundwater observation network was insufficient, and the period of observations was shorter than that for meteorological and hydrological observations. Groundwater is an important source of drinking water resources for human populations. In Poland, from 1999–2015, groundwater accounted for only 15.2% of total water abstraction (Kubiak-Wójcicka & Kielik, 2021), but groundwater abstraction has increased in recent years, accounting for 17.93% of extraction in 2018 (Kubiak-Wójcicka & Machula, 2020). Research by Przytuła and Razowska-Jaworek (2013) indicates that in the next 20 years, there may be areas where the balance of groundwater resources available for use will exhibit excessive depletion. Knowing the occurrence of drought is important because groundwater drought can have serious socio-economic and environmental impacts (Verbeiren et al., 2013).

This article aims to identify and assess groundwater droughts in connection with meteorological droughts and to determine the relationship between droughts in different cumulation periods. This goal was achieved using the index method, and the results were compared against the data in the literature. The work is also the latest in a series of articles (Kubiak-Wójcicka & Bąk, 2018; Kubiak-Wójcicka Kubiak-Wójcicka et al., 2021a, 2021b; Kubiak-Wójcicka & Juśkiewicz, 2020) providing an overview of droughts in Poland, ranging from meteorological drought, through hydrological and hydrogeological drought, and their interrelations.

Research area and data

The research area is in northern Poland and covers the Gwda River catchment (Fig. 1). The Gwda River is categorised as a fourth-order stream by the Polish hydrographic classification and flows into the Noteć River. The river is 139.95 km long. The Gwda catchment basin is a lakeland basin built of sands and glacial gravels with numerous undrained depressions and significant coverage of lakes and forests. Forest area accounts for 30% of the Gwda catchment's total area, while agricultural land accounts for 44.4%. Lakes cover 2.5% of the Gwda catchment (Kubiak-Wójcicka & Lewandowska, 2014). The Gwda catchment is an agricultural-forest-type catchment (Kubiak-Wójcicka et al., 2019).

The Gwda catchment was shaped during Poland's last glaciation and the Holocene. The area is highly spatially differentiated – from end-moraine plateaus exceeding 200 m a.s.l in the north of the catchment, through extensive moraine and outwash plains, troughs with lakes, to the depression of the Toruń-Eberswalde Ice-marginal Streamway of 50–55 m a.s.l in the south (Dąbrowski et al., 2013). In the Gwda catchment, waters usually occur to depths of approx. 150–190 m in the south and 300–350 m in the north within Cenozoic formations and at the top of Mesozoic formations, creating Quaternary, Palaeogene-Neogene and Lower Jurassic aquifers (Dąbrowski et al., 2013). The geological structure of the upper and lower parts of the Gwda catchment area is shown in Figures 2 and 3.

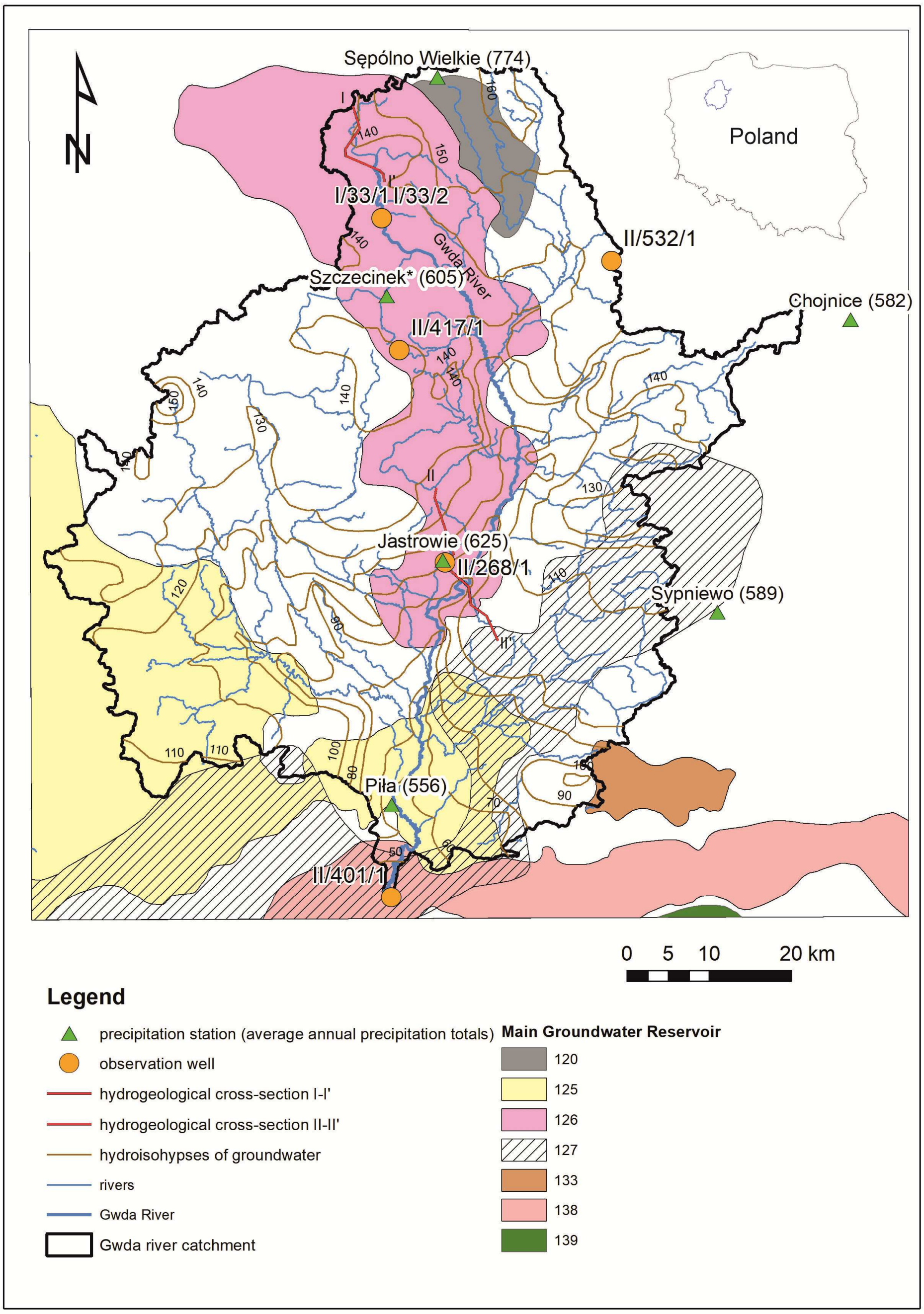


Fig. 1. Research area with Main Groundwater Reservoir (MGR): 120 –Bobolice intermoraine basin; 125 –Wałcz-Piła; 126 –Szczecinek basin; 127 –Złotów-Piła-Strzelce Krajeńskie basin; 133 –Młotkowo intermoraine basin; 138 –Toruń-Eberswalde buried valley; 139 – Smogulec-Margonin buried valley

The research employed average monthly sums of atmospheric precipitation and monthly average groundwater levels. Precipitation records were taken from seven meteorological stations belonging to the Institute of Meteorology and Water Management of the National Research Institute (IMWM-PIB). Daily sums of precipitation were used to calculate average monthly, annual and long-term sums of precipitation. Of the seven meteorological stations, four are in the Gwda catchment (Sępólno Wielkie, Szczecinek, Jastrowie and Piła), while three (Sypniewo, Wierzchowo and Chojnice) are in its immediate vicinity. The meteorological conditions in the upper Gwda catchment are illustrated by the data for the Sępólno Wielki, Szczecinek and Chojnice stations; the middle of the catchment is represented by Sypniewo, Jastrowie and Wierzchowo; and data for the lower (southern) catchment is from the Piła station (Fig. 1).

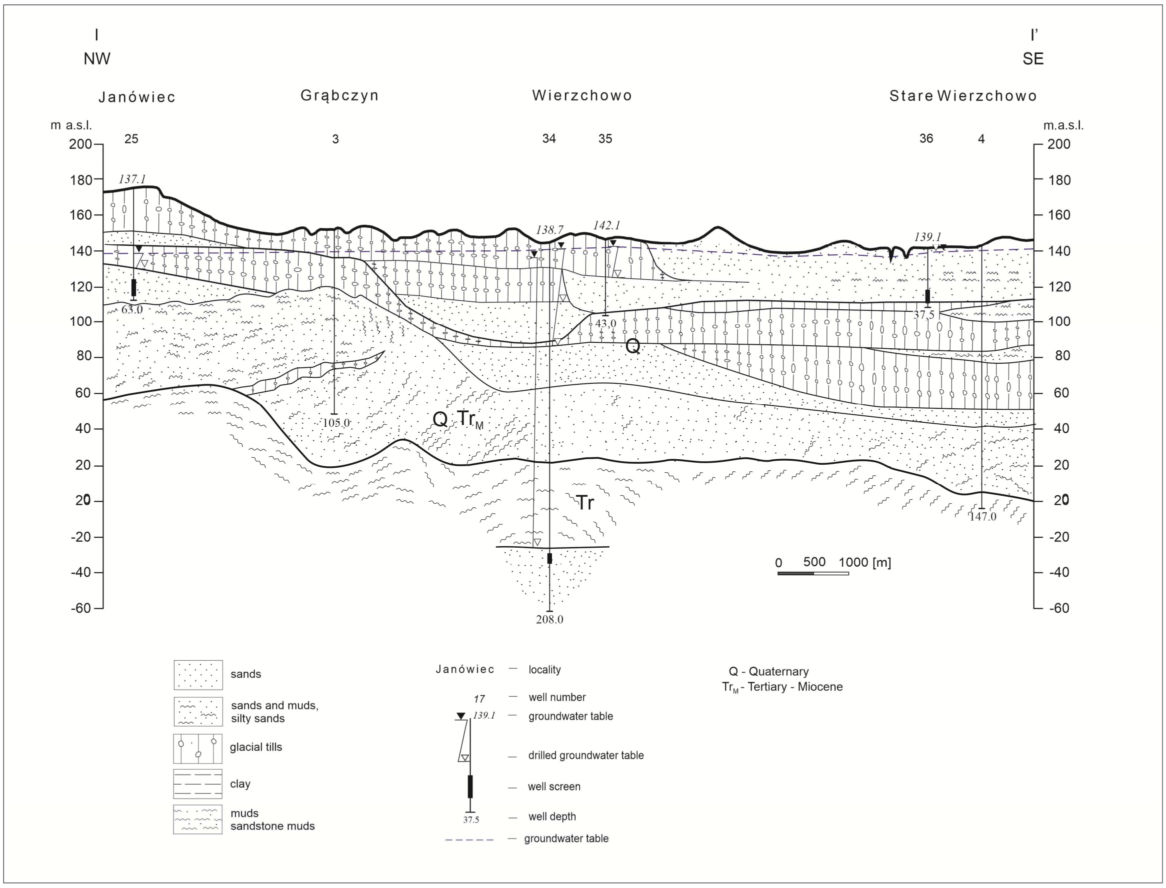


Fig. 2. Geological profile I-I' (based on Kreczko & Prussak, 2004).

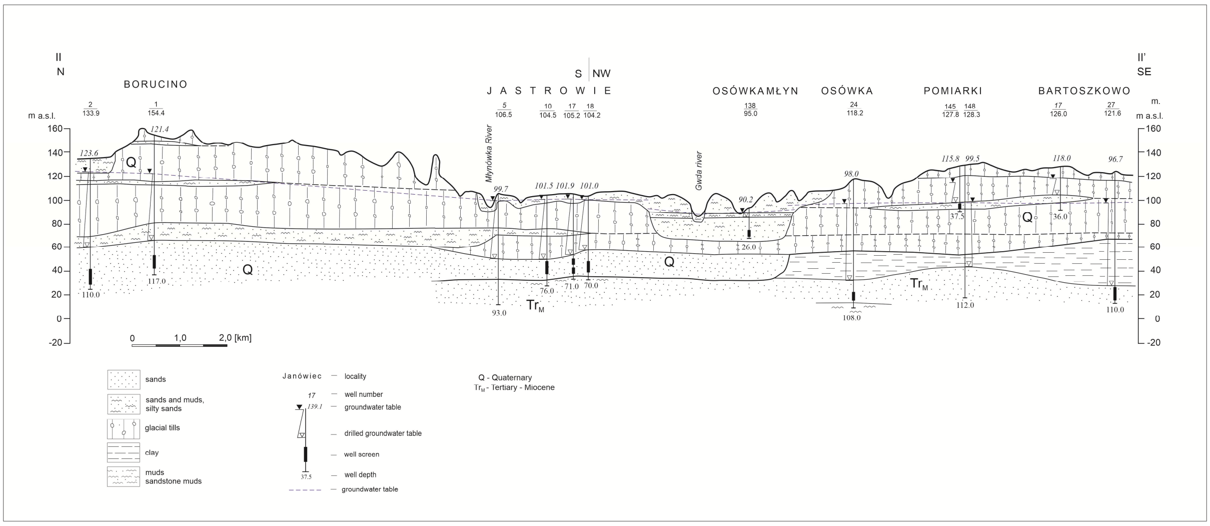


Fig. 3. Geological profile II-II' (based on Krawiec, 2004)

Observations of groundwater levels are taken from six observation stations belonging to the National Research Institute of the National Geological Institute (PGI-NRI). Groundwater levels are measured every seven days at monitoring points (piezometers) (Table 1), and these are used to calculate monthly averages. Most of the monitoring points represent the Quaternary level, of which three piezometers measure a confined groundwater level and two measure a water table. The water level monitoring point of the Neogene level No. I/33/1 lies in the north of the catchment, between Lake Wierzchowo and Lake Wielimie.

The shared study period for precipitation and groundwater level observations is 1981–2015, except for the data for the precipitation station in Szczecinek, which covers the period 1981–2009. Monthly data were used to calculate SPI and SGI values for a 30-year study period (1986–2015). The number of meteorological and hydrogeological stations and the adopted study period were determined by the availability of a continuous dataset for such a long period, i.e. 1981–2015. The 30-year observation period covering both parameters allows for sufficient documentation to detect hydrological changes and is in line with the recommendation of many authors (Kundzewicz & Robson, 2004; Bloomfield et al., 2015; Kubiak-Wójcicka et al., 2021c).

Methods and materials

The study is divided into three parts, analysing: meteorological droughts, groundwater droughts, and the correlation between them. Droughts were identified by the index method, which allows the same methodology to be used to calculate values of meteorological and hydrogeological drought and to determine drought parameters, and the same classification of drought intensity to be adopted. The drought index was used to analyse drought propagation – from meteorological drought to groundwater drought.

First, meteorological drought was analysed using precipitation data. The Standardised Precipitation Index (SPI; McKee et al., 1993) was used as the indicator of meteorological drought. This is a one-dimensional index whose only input parameter is precipitation. Its use is increasingly popular because it can measure periods of drought with a deficit or excess of precipitation (Thomas et al., 2017; Bąk & Kubiak-Wójcicka, 2016, 2017; Kubiak-Wójcicka, 2020). The SPI value is based on a probability distribution of long-term precipitation over various time scales. In this study, the SPI is calculated for each month, from January to December. Long-term precipitation is fitted to a probability distribution that, in turn, is converted to a normal distribution such that the average SPI for a location and desired period is zero. SPI values represent the deviation from the median expressed in standard deviations. To calculate the SPI, the distribution of the transformed variable f(P) is tested for compliance with the normal distribution using Pearson's $\chi 2$ goodness-of-fit test (Łabędzki, 2016). Positive SPI values indicate periods with above-average precipitation for a given period, while negative SPI values indicate periods of below-average precipitation.

The Standardised Groundwater Index (SGI) proposed by Bloomfield and Marchant (2013) was selected as the groundwater drought indicator. The SGI is calculated from water level measurements (Haas & Brink, 2017; Uddameri et al., 2019). The groundwater level is a highly seasonal continuous variable, so a lognormal function transformation was used to calculate the SGI based on monthly groundwater level data (Guo et al., 2021). Monthly groundwater observations were grouped for each calendar month, and within each group, the observations were ranked and assigned an SGI value based on the inverse norm of the cumulative data distribution (Bloomfield & Marchant, 2013).

It is essential to select an appropriate time window to present the SGI. Its calculation depends on the available time series of groundwater measurements. When we want to determine regional drought incidence for a particularly long measurement period (over 30 years), it is more appropriate to use annual data for the selected parameter; conversely, for a shorter period (less than 30 years), it is more appropriate to use monthly values, which give more precise local values (Mishra & Singh, 2010).

To calculate SPI and SGI values for different timescales (n months), cumulative precipitation values or groundwater levels must be obtained for each month and for n months. Different time series were analysed, i.e. 1, 6, 12, 18, 24, 30 and 36 months. Index values represent the deviation from the median expressed in standard deviations. The proposed approach is based on assessing water resources under different hydroclimatic conditions and determining different intensity classes. Positive SPI values indicate above-median precipitation, and negative values indicate below-median precipitation. Therefore, moderate drought occurs when the indicator falls to −1.0 or less (Table 1). An occurrence ends when the SPI or SGI value becomes positive. The drought intensity categories are determined based on SPI and SGI values, as shown in Table 1.

Tab. 1. Classification scale for SPI and SGI values

SPI, SGI value	Category
0.0 > SPI, SGI > -1.0	Normal
-1.0 ≥ SPI, SGI > -1.5	Moderately dry
-1.5 ≥ SPI, SGI > -2.0	Severely dry
SPI, SGI ≤ -2.0	Extremely dry

The relationships between the indices of groundwater droughts and meteorological droughts are presented based on the Pearson correlation coefficient. The higher the r coefficient value, the more dependent the groundwater level is on precipitation. It was also checked whether correlation coefficient values changed as time delays in groundwater drought relative to meteorological drought were factored in.

Three meteorological stations and three groundwater stations were considered for the correlation between meteorological droughts and groundwater droughts. The choice of groundwater stations was dictated by their location in the northern, central and southern parts of the catchment and by data continuity. The relationship between meteorological droughts and groundwater droughts was calculated for a piezometer and its closest meteorological station. The relationship between droughts in the upper catchment was calculated for piezometer

I/33/1 and the Sępolno Wielkie meteorological station. For the middle catchment, data were taken from piezometer II/268/1 and the Jastrowie meteorological station. The lower Gwda catchment was represented by piezometer II/401/1 and the Piła meteorological station.

Results

Precipitation and groundwater fluctuations, 1986–2015

In the study period, the average annual sums of precipitation within the Gwda river catchment ranged from 779.5 mm at the Sępolno Wielkie station (northern catchment) to 565.8 mm at the Piła station (southern catchment). The decreasing sums of precipitation from north to south are related to a decline in the terrain and to the south's lying in the rain shadow of the morainic plateaus (Figure 4). Precipitation in the study period was highest in 1998 (Szczecinek), 2007 (Sępólno Wielkie, Jastrowie, Chojnice), 2010 (Sypniewo, Wierzchowo) and 2012 (Piła). Precipitation was lowest in 1992 (Wierzchowo, Jastrowie), 1989 (Chojnice), 2003 (Sępólno Wielkie, Szczecinek) and 2015 (Piła, Sypniewo).

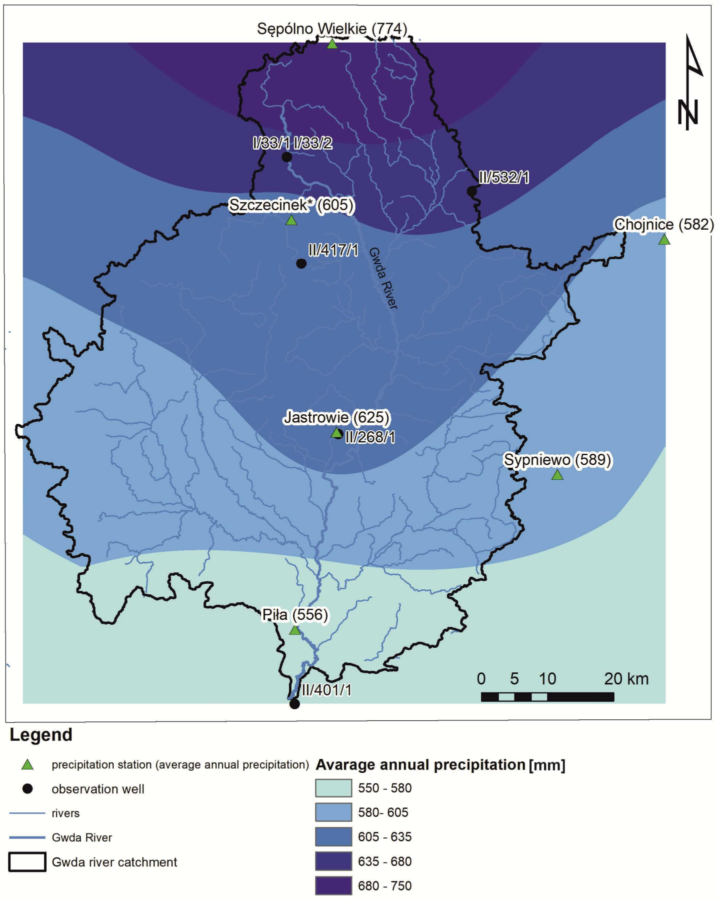


Fig. 4. Average sums of precipitations in the Gwda catchment in years 1986-2015

Observations of groundwater fluctuations within the Gwda River catchment were carried out at six piezometers. Most of the observations are made within the Quaternary layer, with wells ranging in depth from 22.8 to 48.5 m b.g.l. (Table 2). In one case (Spore), it is a Neogene layer that is observed, and the well depth is 197 m. The water level is a confined groundwater level at four piezometers (Spore, Jastrowie, Rzeczenica) and a water table at two (Ujście, Turowo).

Tab. 2. Characteristics of measuring wells

Well No.	Town/City (voivodeship)	Age of layer	Ordinate of piezometer [m a.s.l.]	Type of water level	Depth of well [m]	Ordinate of aquifer [m a.s.l.]	Average annual amplitude in water level depth [m]	Long-term amplitude [m]
I/33/1	Spore (West Pomerania)	Ng/M	138.63	Confined	197.0	137.86	0.27	0.85
I/33/2	Spore (West Pomerania)	Q	138.80	Confined	42.0	137.60	0.27	0.79
II/268/1	Jastrowie (Greater Poland)	Q	105.56	Confined	48.5	101.86	0.37	2.30
II/401/1	Ujście (Greater Poland)	Q	62.21	Water table	30.0	49.20	0.59	2.30
II/417/1	Turowo (West Pomerania)	Q	158.96	Water table	24.0	153.00	0.58	2.12
II/532/1	*Rzeczenica (Pomerania)*	*Q*	*150.00*	*Confined*	*22.8*	*144.50*	*1.16*	*3.99*

Despite relating to aquifers of different ages and depths, the water levels in the I/33/1 and I/33/2 wells follow very similar courses. Well I/33/1 is 197 m deep and records data from a Neogene layer, while well I/33/2 is 42 m deep and records the waters of a Quaternary layer (Fig. 5). This situation may indicate the presence of hydrogeological windows between aquifers. Additionally, the average annual amplitudes for the I/33/1 well in the Neogene layer and the I/33/2 well in the Quaternary layer are the same, at 0.27 m, with a long-term amplitude of 0.8 m. This situation is confirmed by the research results of Kotowski and Najman (2015) in this area. They showed the existence of a strong hydraulic connection between aquifers and significant importance for the groundwater circulation system of deeply incised river and lake valleys as well as deep erosional channels and palaeovalleys, which significantly facilitate water infiltration into deeper aquifers (Jamorska et al., 2019).

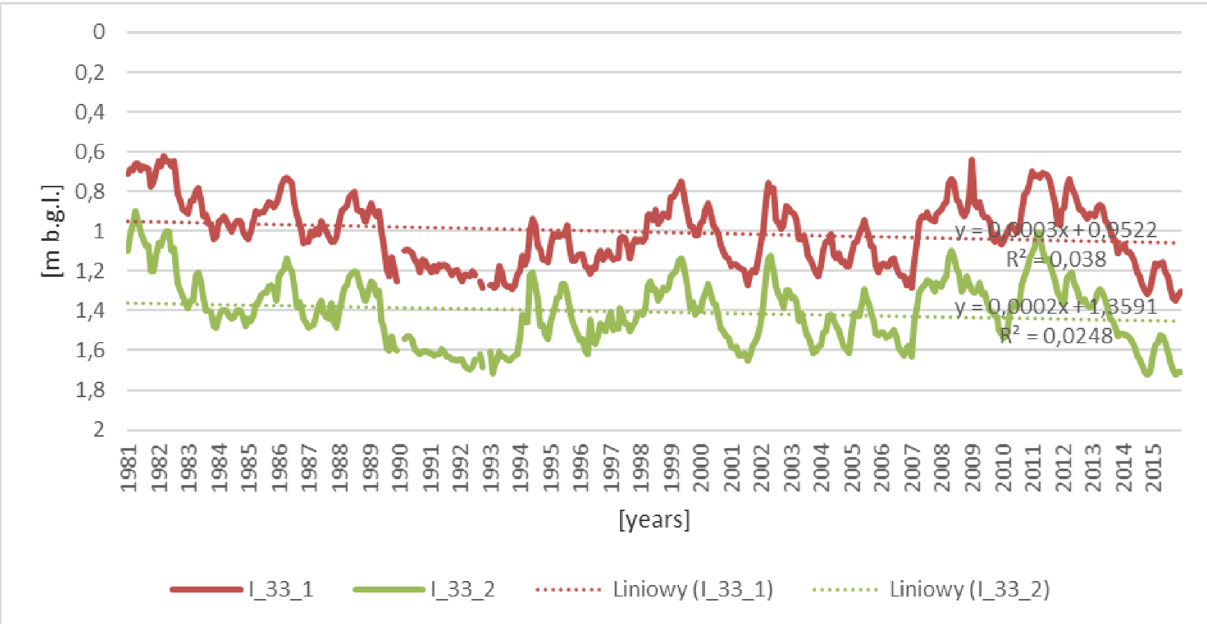


Fig. 5. Groundwater levels in Neogene (I/33/1) and Quaternary (I/33/2) layers in the study period

Both piezometers, as well as the II/268/1 and II/417/1 wells, lie within the Szczecinek Reservoir (No. 126) of Poland's "main groundwater reservoir" [GZWP]. In the Cenozoic sediments of this water body, three main usable aquifers have been distinguished that are also major usable layers. These are: the first usable Quaternary layer (a near-surface, upper interclay level), the second usable Quaternary layer (lower interclay level) and the third usable Quaternary–Neogene layer (Quaternary subclay bottom layer, Miocene layer, subordinate Oligocene). The most abundant aquifer in GZWP no. 126 is the third usable Quaternary–Neogene layer

(Quaternary subclay "bottom" layer, Miocene and subordinate Oligocene layer). The top of the sandy series of this horizon occurs at various depths in the range of 50–120 m b.g.l. The reservoir GZWP No. 126 is mainly charged by the infiltration of atmospheric precipitation within the reservoir. The area of GZWP No. 126 is mostly agricultural land. Medium and large-scale agriculture focussing on crop and livestock farming dominates here. Forest complexes (mainly associated with river valleys and outwash areas) occupy 35% of the GZWP area (Mikołajków and Sadurski, 2017).

The analysis of average monthly groundwater layers shows that the depth of the water level followed similar courses at all piezometers in the study period (Fig. 6). Fluctuations were greatest in well II/532/1 (confined aquifer) in the north-east of the catchment. Despite the wide fluctuations, the overall shape of the water level depth curve at this piezometer indicates a similar groundwater response to that observed in the other wells (Jamorska et al., 2019).

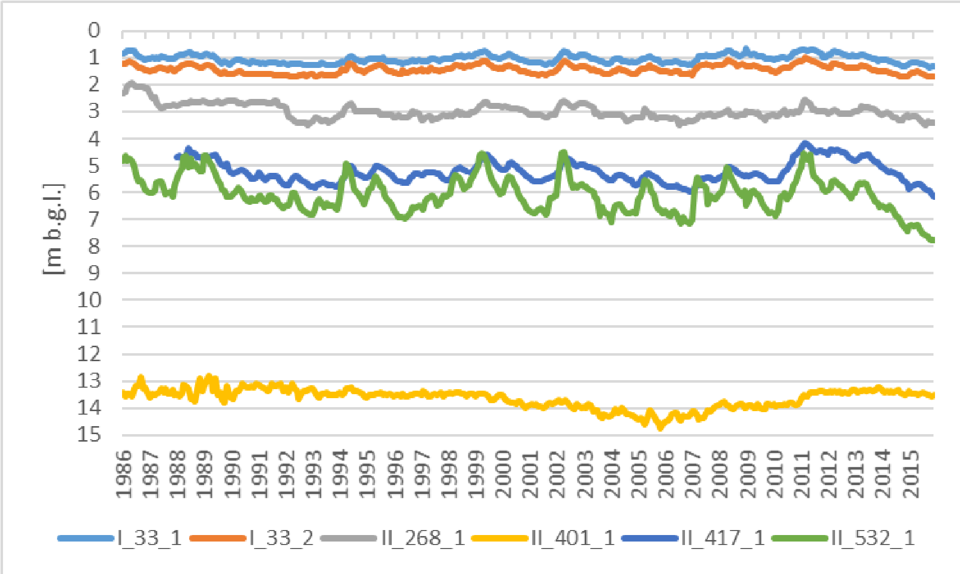


Fig. 6. Fluctuations in groundwater level, 1986–2015 (based on PIG data)

Meteorological and groundwater droughts

In the 1986–2015 study period, meteorological droughts and groundwater droughts were identified. Depending on the cumulation period adopted, the range of SPI and SGI index values differed for different stations. Table 3 presents meteorological drought parameters, while Table 4 presents groundwater drought parameters for the research period.

Tab. 3. Meteorological drought parameters in different cumulation periods

	SPI-1	SPI-6	SPI-12	SPI-18	SPI-24	SPI-30	SPI-36
Sępólno Wielkie							
Min. index value	-2.96	-2.44	-2.70	-2.26	-2.55	-2.45	-2.46
Number of droughts	43	17	11	8	6	5	7
Duration of drought	101	131	156	160	137	137	152
Drought magnitude	-110.49	-136.04	-130.63	-139.11	-133.84	-128.80	-132.67
Jastrowie							
Min. index value	-2.81	-2.91	-2.61	-2.50	-2.73	-2.78	-2.46
Number of droughts	42	13	8	6	5	4	3
Duration of drought	107	121	133	135	147	144	135
Drought magnitude	-107.33	-127.24	-124.75	-133.59	-138.39	-141.18	-140.11
Piła							
Min. index value	-3.08	-2.79	-2.72	-2.47	-2.64	-2.64	-2.29
Number of droughts	38	10	7	6	4	4	5
Duration of drought	98	119	137	121	148	153	151
Drought magnitude	-107.55	-121.18	-131.23	-127.82	-132.65	-135.95	-135.75

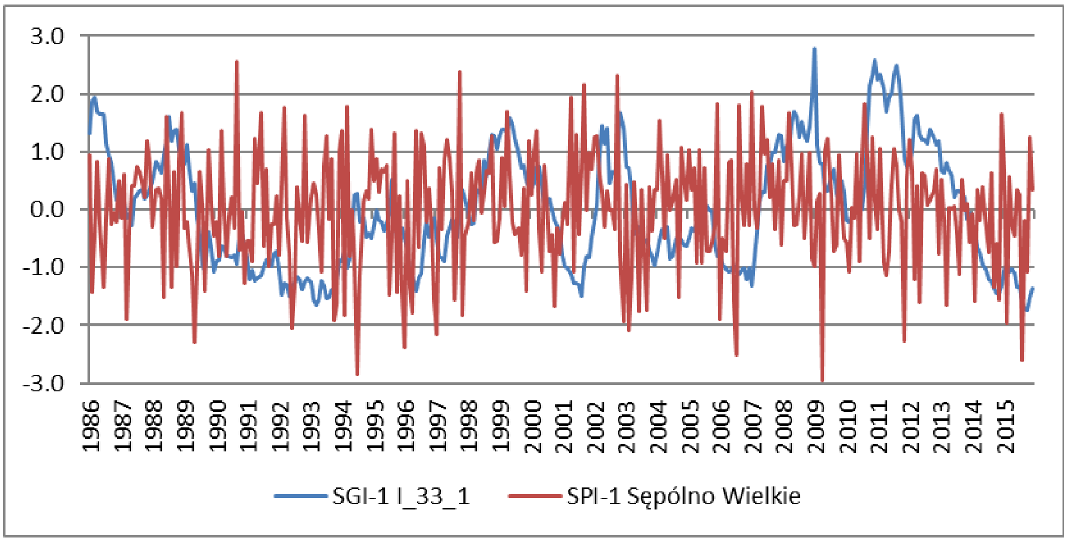
For meteorological drought analysed at three meteorological stations, SPI values ranged from −2.26 to −2.96 at the Sępólno Wielkie station, from −2.46 to −2.91 at the Jastrowie station and from −2.29 to −3.09 at the Piła station. Extreme meteorological droughts occurred in 1992–1996, 2003, 2011 and in 2014–2015, depending on the adopted cumulation periods. The droughts were strongest in short cumulation periods (of 1 and 6 months), while the intensity of droughts decreased in longer cumulation periods (of 12 to 36 months). Total drought duration ranged from 98 months (Jastrowie) to 160 months (Sępólno Wielkie) in the study period. Single drought duration lasted from 1 to 6 months in a 1-month cumulation period, whereas single drought duration ranged from 22 to 52 months for a longer cumulation period. For longer cumulation periods, the number of droughts in the study period falls, and the single drought duration rises. For SPI-1, from 38 to 43 droughts were recorded during the study period, whereas for SPI-18 and longer cumulation periods, the number of meteorological droughts ranged from three to eight.

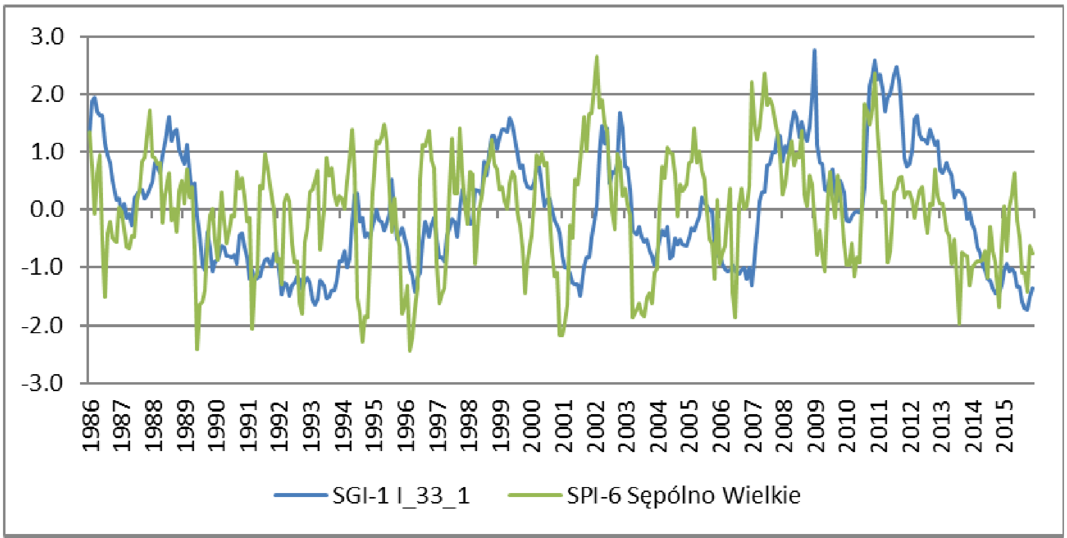
Tab. 4. Groundwater drought parameters in various cumulation periods

	SGI-1	SGI-6	SGI-12	SGI-18	SGI-24	SGI-30	SGI-36
				I_33_1			
Min. index value	-1.74	-1.60	-1.58	-1.68	-1.84	-1.84	-1.91
Number of droughts	5	4	4	4	3	3	3
Duration of drought	147	164	189	188	166	162	192
Drought magnitude	-133.36	-137.08	-153.36	-155.07	-145.66	-145.71	-151.01
				II_268_1			
Min. index value	-1.59	-1.46	-1.55	-1.64	-1.70	-1.32*	-
Number of droughts	4	5	5	5	4	2*	-
Duration of drought	185	189	185	189	188	172*	-
Drought magnitude	-123.93	-129.10	-132.76	-135.43	-138.27	-125.00*	-
				II_401_1			
Min. index value	-2.65	-2.51	-2.29	-2.23	-2.18	-2.16	-2.11
Number of droughts	1	1	1	1	1	1	1
Duration of drought	131	132	135	134	135	136	136
Drought magnitude	-146.34	-151.70	-153.72	-154.17	-154.24	-154.15	-154.01

Groundwater drought parameters are presented in Table 4. SGI values ranged from −1.32 to −2.65. The lowest SGI values for the longer cumulation periods occurred at station I_33_1 in the 24, 30 and 36-month cumulation periods and at station II_268_1 in the 24-month period. Low SGI values were recorded in short cumulation periods (1 and 6 months), being −2.65 and −2.51, respectively. Extreme groundwater droughts were recorded in the years 1992–94, 2005–07 and 2015. A total of one to five groundwater droughts were recorded, with a total duration ranging from 131 to 192 months. The II_401_1 station in the lower Gwda catchment is notable for having the fewest groundwater droughts, the shortest total duration of all droughts and the lowest SGI values as compared to the data from the other piezometers in the upper and central part of the catchment.

Individual groundwater droughts were much longer lasting, lower in intensity and fewer in number than meteorological droughts. The course of droughts is presented in the example of the Sępólno Wielkie meteorological station and the I_33_1 piezometer (Fig. 7). The groundwater reacted much more slowly than did the course of meteorological droughts. The drop in the water level was often delayed. The course of the SPI fluctuates significantly (especially in short cumulation periods) compared to groundwater droughts. The groundwater droughts identified in the Gwda River catchment occurred all over Poland. According to Tarka and Staśko (2010), changes in groundwater levels were greatest in the early 1990s, manifesting as a decrease in groundwater levels in shallow and deep levels alike. In deep waters, this sometimes came after a two-to-three-year delay. Extremely low states referred to as "hydrogeological low waters" were found in 1992–94 in deeper, large aquifers. Moreover, an extensive drought was found in the shallow layers from 2003–05 (Tarka and Staśko, 2010).

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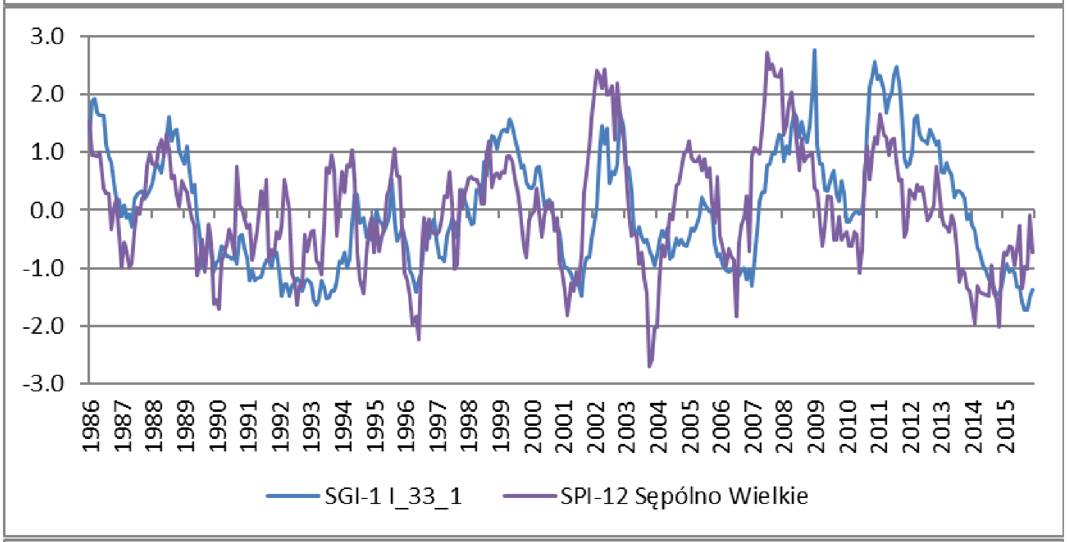
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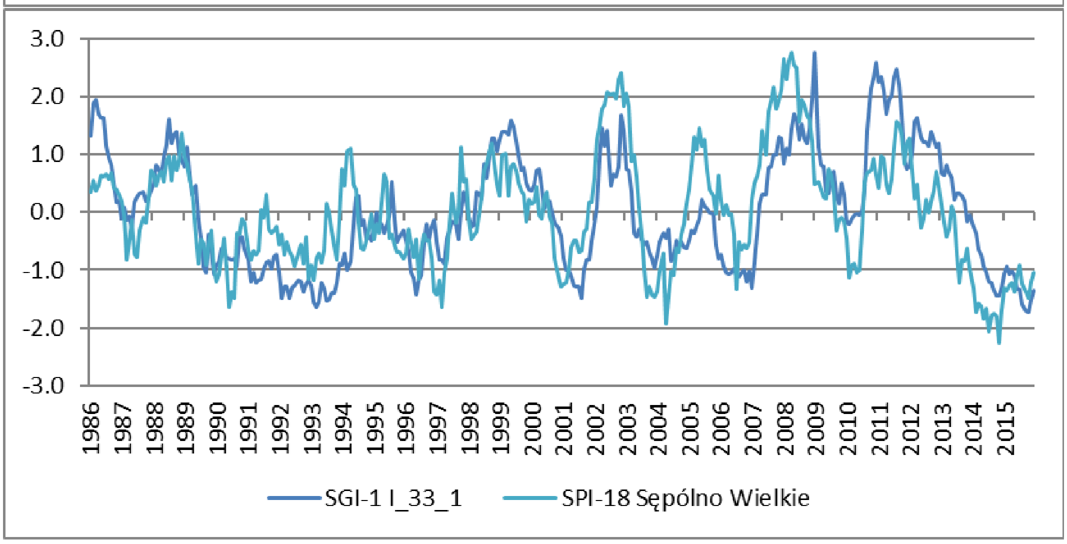
1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
SGI-1 I_33_1
SPI-12 Sępólno Wielkie


3.0
2.0
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1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
SGI-1 I_33_1
SPI-18 Sępólno Wielkie

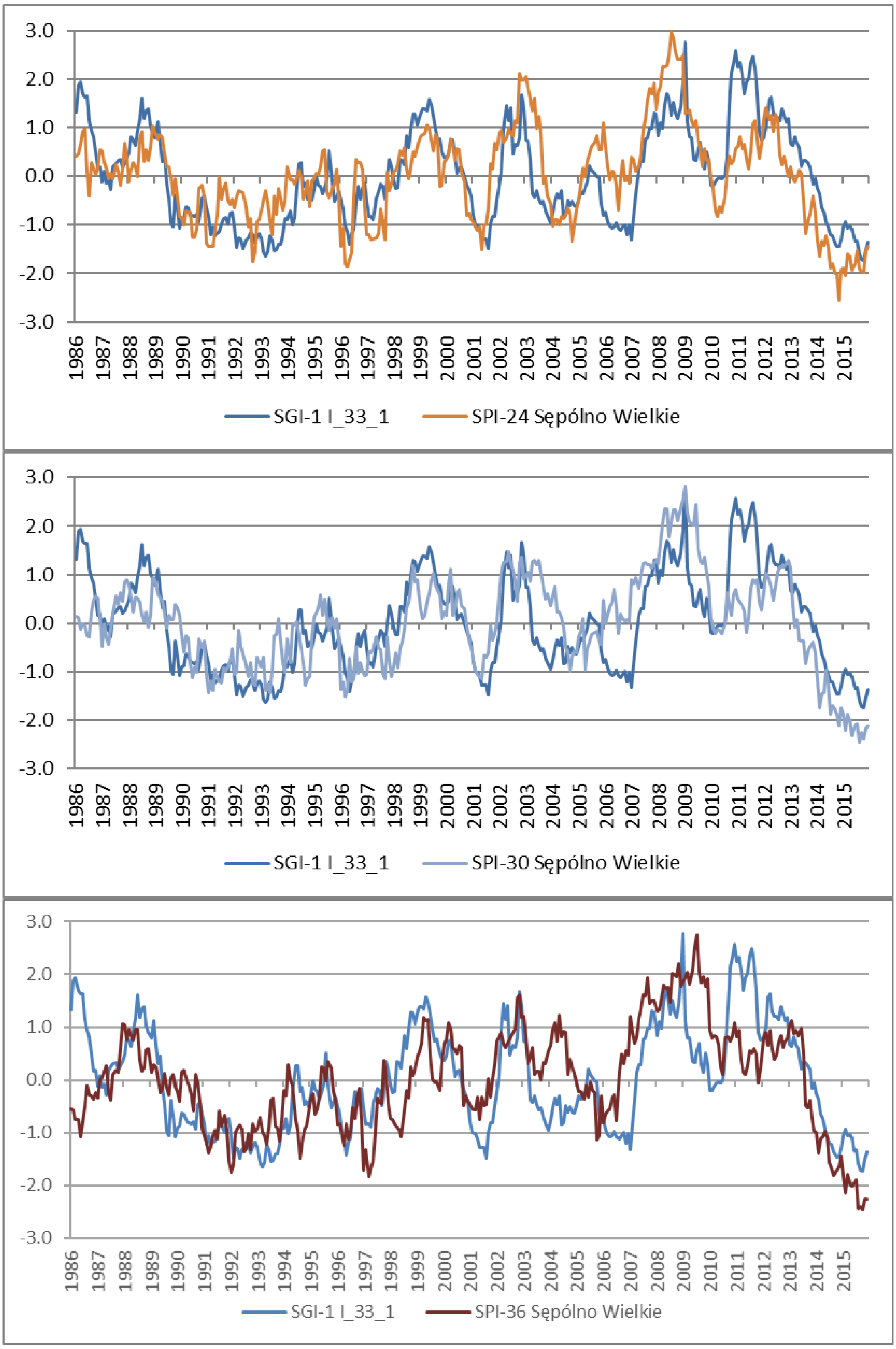

Fig. 7. Course of SGI and SPI values at the Sępólno Wielkie station in various timescales, 1986–2015

Correlations between meteorological and groundwater droughts

In the study period of 1986–2015, dry years are interrupted by wet years. The course of groundwater drought expressed by the SGI index fluctuated less widely than the course of the SPI index. The fluctuation and variability of the SPI and SGI series undoubtedly show consistent patterns over the period studied. However, the degree of consistency changes over time. The study assumed that the impact of precipitation on the water level might be delayed by several months (from 1 to 36 months). Therefore, the course of precipitation was crosscorrelated with water level depth. The results for the three stations showed these relations to be diverse. The best relations were recorded in the upper Gwda catchment between piezometer I_33_1 and the Sępólno Wielkie meteorological station (Fig. 8).

The annual correlation coefficient (r) between these two indices, i.e. SPI at Sępólno Wielkie and SGI for the I-33_1 piezometer, ranged from 0.02 to 0.69. The highest annual correlations between these indicators were recorded for SGI-1 and SPI-12 (0.59), SPI-18 (0.69), SPI-24 (0.65), SPI-30 (0.67) and SPI-36 (0.63). According to Minea et al. (2022), a correlation coefficient of *r*~0.45–0.68 indicates a close relationship between meteorological and hydrological drought. Research conducted by Leelaruban et al. (2017) has shown that SPI-24 correlates best with the groundwater level during drought (correlation coefficient is 0.6 or more).

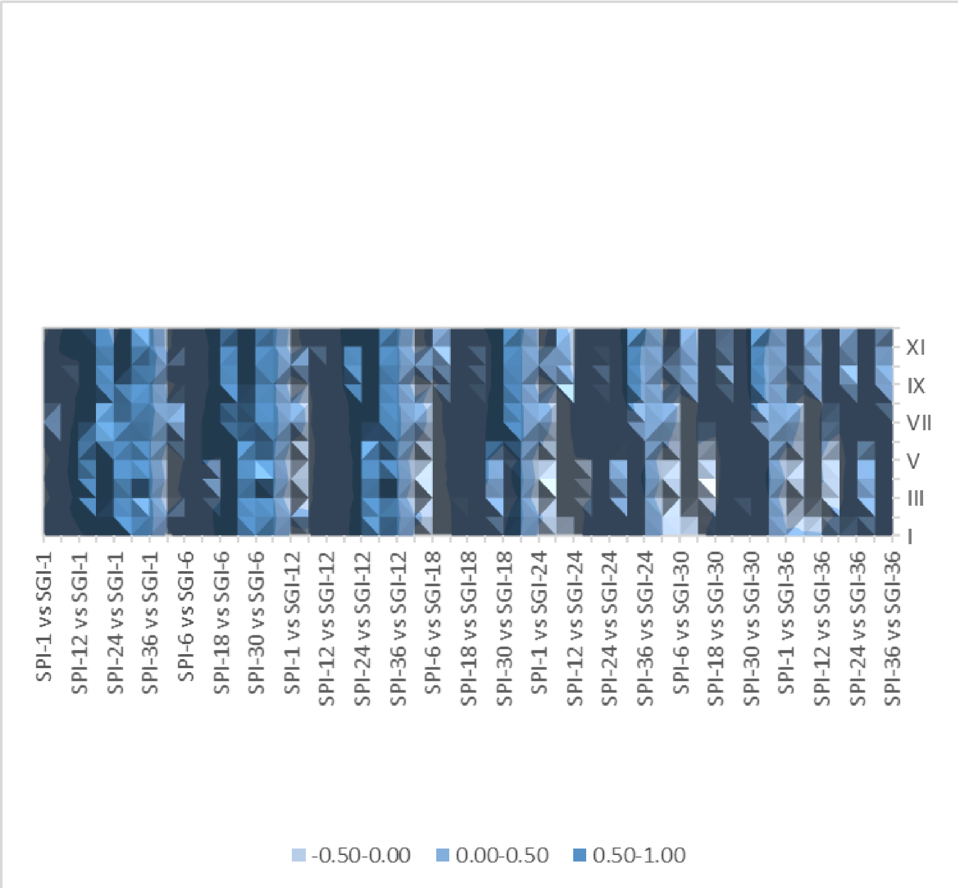

Fig. 8. Correlation coefficient r between meteorological droughts in Sępólno Wielkie and groundwater droughts at the I_33_1 station

The correlations in the remaining measurement points in the middle and lower parts of the Gwda catchment were much lower. The highest annual correlation coefficients between SPI for Jastrowie meteorological station and piezometer II_268_1 were 0.39 (Fig. 9).

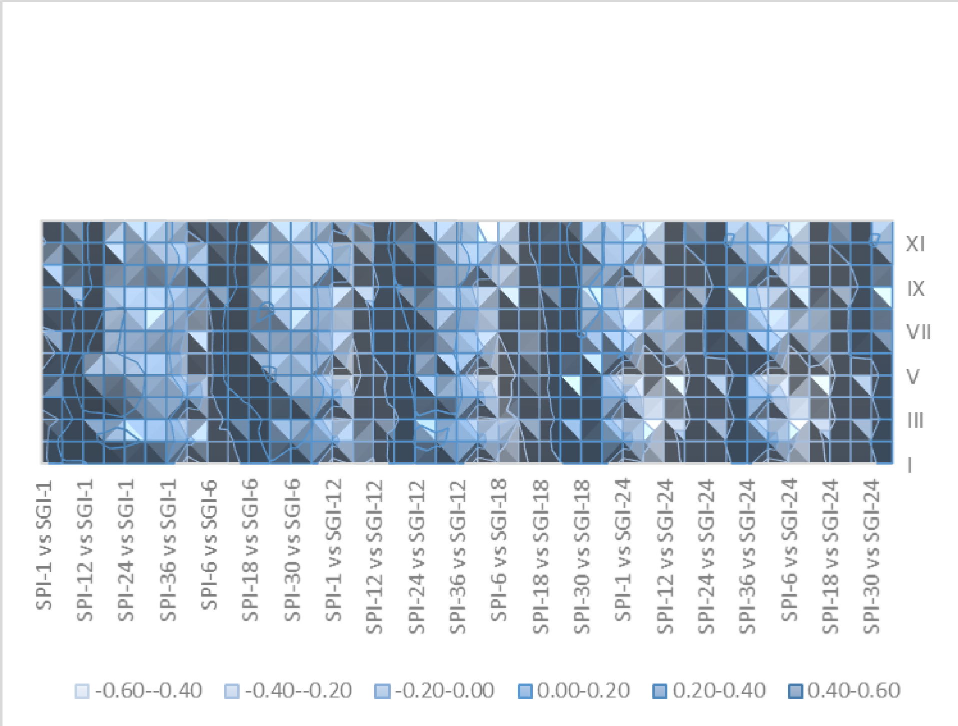

Fig. 9. Correlation coefficient r between meteorological droughts in Jastrowie and groundwater droughts at the II_268_1 station

Even lower annual correlation coefficients were obtained between the SPI for Piła and the SGI indices for the II_401_1 piezometer. Their highest correlation was 0.14 (Fig. 10). Analysis of water table depth in this well revealed precipitation to have no significant impact, despite the aquifer being unconfined. This 30-m-deep well is in a valley area (the Toruń–Eberswalde ice-marginal streamway) close to the Gwda catchment. The well's location in a drainage area means that the more-than-30-metre-thick aquifer is charged mainly by the inflow of water from interclay horizons. For this reason, this region's typically low sums of precipitation (averaging c.550 mm), which are comparable to evaporation levels, result in no visible reaction in the water level at the I/401/1 well.

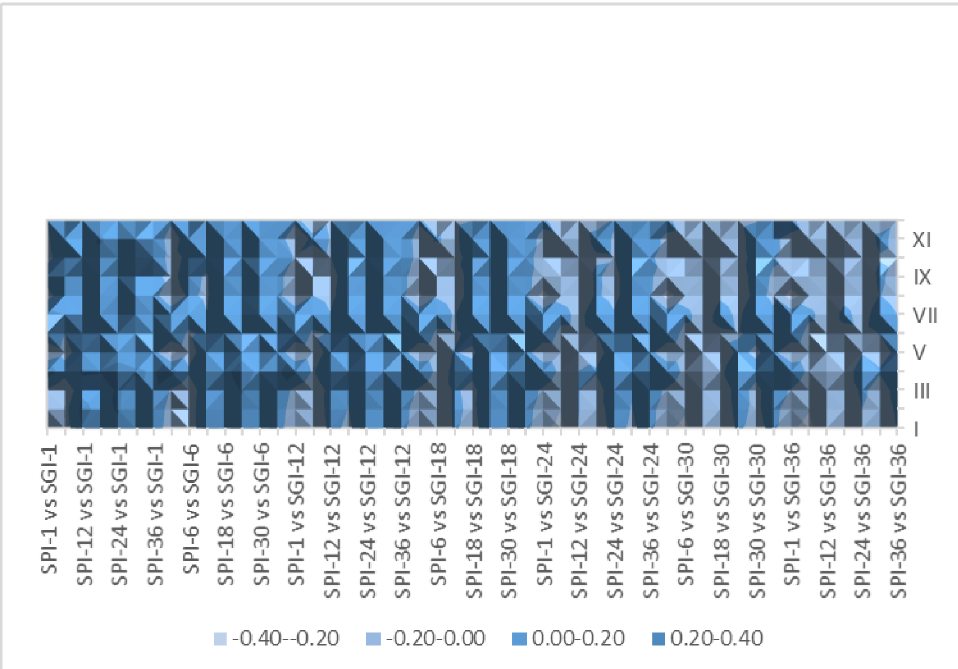

Fig. 10. Correlation coefficient r between meteorological droughts in Piła and groundwater droughts at the II_401_1 station

The correlations obtained between meteorological droughts and groundwater droughts indicate significant relationships between precipitation and groundwater level only in the upper catchment of the Gwda River. In the middle and lower Gwda catchment, the relationships between meteorological droughts and groundwater droughts are weak (low correlation coefficient *r*). The low value of the r coefficient, especially in the lower Gwda catchment, indicates that precipitation conditions, i.e. low sums of precipitation, had little effect on the course of groundwater droughts.

Discussion

The speed of the water level's response to precipitation depends on many factors, including geological structure, evaporation volume and human activity, meaning that these fluctuations occur significantly later than the changes in precipitation that cause them. Studies on the effect of meteorological droughts on groundwater droughts have been conducted in regions of Poland with diverse geological structures, including by Zdralewicz and Lejcuś (2008), Tarka and Staśko (2010) and Kowalczyk et al. (2015), and the results of these studies have been inconclusive. Furthermore, research by Kowalczyk (2019) showed that the upward and downward trends in drought numbers were entirely uncorrelated among different aquifers; this proves the great natural variability of individual aquifers' susceptibility to drought. Depending on local hydrogeological conditions, the duration of low water can be either longer or shorter in deeper aquifers than in the topmost aquifer, and the direction of changes is in many cases, not uniform between successive levels. A study by Adinek and Brencic (2019) in karst areas of Slovenia showed that groundwater drought depends on the unsaturated and saturated thickness of the aquifer. Other researchers have concluded similarly, pointing out that, for deeper water levels, droughts were more delayed and more severe, and where the unsaturated zone was less thick, the response to meteorological influences was faster. Research by Bloomfield and Marchant (2013) in England indicated that groundwater droughts calculated using the SGI index correlated most strongly in SPI cumulation periods of 6–28 months. By contrast, research by Li and Rodell (2014) in the US indicated that the relationship between SGI and SPI generally correlated more closely in 12- and 24-month periods than in shorter timeframes but varied with climatic conditions. The correlation between GWI and SPI generally decreases for deeper water levels, which in turn depends both on substrate depth (the CLSM parameter) and on annual average precipitation. In the catchments of Iberian rivers, research by Lorenzo-Lacruz et al. (2013b) showed the greatest correlation indices between droughts in the periods of 3 and 12 months. The utility of SPI in characterising groundwater drought on a local and regional scale was examined by Kumar et al. (2016) using observations from more than 2,000 groundwater wells in geologically diverse areas in Germany and the Netherlands. The cumulation periods that yielded the maximum correlation varied greatly between locations (ranging from 3 to 36 months). This study of the Gwda River catchment showed that the water level response to precipitation to be delayed by about 18 months, in the range of 18- to 36-month cumulation periods. However, this result was not uniform across the whole catchment, nor for all aquifers. The correlation was lowest in wells in the middle and south of the catchment, where the water table is unconfined. According to Kubicz and Bąk (2016), a low *r*-value indicates much greater participation of other external factors that lessen the water level's response to precipitation. Higher r values are evidence of greater capacity for precipitation to infiltrate aquifers.

Conclusions

In this study, SPI and SGI indices were used to determine meteorological drought and groundwater drought. The analysis of the course of meteorological droughts and groundwater droughts in the Gwda catchment revealed that groundwater drought develops and spreads slowly. The analysis of groundwater drought showed that groundwater drought events were fewer than meteorological droughts. Hence, not all meteorological drought events led to groundwater droughts. The results confirmed other authors' conclusions that there is no linear relationship between meteorological drought conditions and groundwater drought. The correlations we have presented for the Gwda catchment indicate that the relationship between droughts is not clear. There are strong correlations between droughts in the upper Gwda River, indicating a delay in groundwater response to precipitation in cumulation periods of between 18 and 36 months.

The relatively low correlation coefficients between the SPI and SGI indices in the central and lower parts of the Gwda catchment show that groundwater drought is influenced by other factors independent of precipitation. These may include geological structure, human activity and total evaporation.

Based on this work and the results of other authors, a hydrogeological drought would better be monitored by conducting more observations of groundwater levels in various aquifers – including deep aquifers, which often constitute exploited layers.

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