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Statistical analysis of groundwater drought on Dravsko-Ptujsko polje

Statistična analiza suše podzemne vode na primeru Dravsko-Ptujskega polja

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Abstract

Drought is a complex phenomenon and can be defined in many ways. It is a globally growing problem that occurs on a time scale ranging from months to years. There are several types of drought, but the least investigated is groundwater drought. Globally, research on it started relatively recently, in the last decade. In Slovenia, there are almost no data on groundwater drought. In this research, we focused on statistical analysis of groundwater level diagrams of individual groundwater stations, which can determine periods of groundwater drought. The first method used is based on ranking statistics defined by lower percentiles that indicate low groundwater level. Another approach was based on univariant Standardized Groundwater Index – SGI. As a case study, the unconfined Quaternary aquifer of Dravsko-Ptujsko polje was chosen. The results show that the groundwater deficits in the groundwater stations appear simultaneously but differ in intensity and duration of each drought period. The important conclusion is that the intensity of groundwater drought does not depend on the length of an event but more on thickness of the unsaturated aquifer zone. Also, groundwater stations located on the western rim below Pohorje Mountains have a higher amplitude of groundwater fluctuations than the others. The result of this are more intensive dry periods with longer duration. On the other hand, we have locations in the central and eastern part of the Dravsko-Ptujsko polje with more damped fluctuation, which leads to less intensive but more frequent groundwater drought events.

Izvleček

Suša je pojav, ki v svetovnem merilu predstavlja vedno večji problem. Poznamo več vrst suš, med katerimi je najslabše razumljena suša podzemne vode. Z raziskavami suše podzemne vode se je hidrogeologija začela intenzivneje ukvarjati šele v zadnjem desetletju. Za območje Slovenije skorajda nimamo podatkov o suši podzemne vode. V tej raziskavi smo se osredotočili na statistično analizo diagramov nihanja gladin podzemne vode v posamezni opazovalni vrtini, s katerimi lahko določimo sušna obdobja. Prva metoda temelji na vrstilni statistiki, določeni z najnižjo percentilno vrednostjo niza meritev obravnavane opazovalne vrtine. Druga metoda uporablja univariatni indeks podzemne vode – SGI. Za pilotno območje je bil izbran odprti kvartarni vodonosnik Dravsko-Ptujskega polja. Rezultati so pokazali, da se primanjkljaj podzemne vode pojavi na različnih mestih skoraj hkrati, a se razlikuje v intenziteti in trajanju posameznega sušnega pojava. Opazovalne vrtine, ki se nahajajo na zahodnem obrobju pod Pohorjem imajo višje amplitude nihanja podzemne vode kot vrtine v osrednjem delu Dravsko-Ptujskega polja, kar je pogojeno z večjo debelino nezasičene cone vodonosnika. To vpliva na bolj intenzivna sušna obdobja z daljšim trajanjem. Na drugi strani imajo opazovalne vrtine v osrednjem in vzhodnem delu Dravsko-Ptujskega polja bolj dušeno nihanje gladine podzemne vode, kar povzroči manj intenzivna, a bolj pogosta sušna obdobja.

Introduction

Even though Slovenia is a water-rich country, several drought events appeared in the recent past (in years 2003, 2012, 2013, 2017), which had substantial impact on national economy (Sušnik & Gregorič, 2017; Flis, 2017). By some climatic models, it is also predicted that in the future drought will be a more frequent event (Andjelov et al., 2016). The most important drought recognized in Slovenia is agricultural drought, which is usually explained as a meteorologically driven drought event. Not much is known about other droughts, among which groundwater drought can be very important. In everyday life, attention is usually paid to meteorological and agricultural drought, because their influence is immediate and visible to everybody. As well as in other regions around the world, in Slovenia, extensive research has been performed on drought and several results regarding drought are rising significantly, but there was not much effort put in the research of groundwater drought. Research on the latter started only recently and not so many results of it are published. Due to the role of groundwater in Slovenian economy, groundwater drought can have important consequences. From that point, the question how groundwater drought is influencing general water availability in water cycle and overall groundwater management can be raised.

In Slovenia, monitoring of groundwater quantitative status is well established (Andjelov et al., 2006). In some of the alluvial aquifers, the monitoring network is relatively dense and enables detection of local trends of decrease or increase of groundwater levels, which can be taken as indicators of groundwater storage change in the aquifer. Based on groundwater monitoring results and with the application of methodology for groundwater drought detection, it would be possible to optimize groundwater management in relation to extreme event appearance.

This paper aims to investigate available definitions of groundwater drought and possible indices from the literature. Based on the collected information, it was intended to define a drought indicator suitable for analysing the effects of drought in north-eastern Slovenia. In the second step, the intention was to compare meteorological and groundwater droughts. As a case study, the unconfined Quaternary aquifer of Dravsko-Ptujsko polje was chosen. The area was chosen due to the availability of relatively long and continuous set of groundwater measurements on 22 groundwater stations as well as due to the natural characteristics of the aquifer, which is well drained and its response to the underground water shortage is relatively rapid. The analysis performed was phenomenological; during the interpretation of the calculated indices, several questions arose in relation to groundwater level time depended trends. These questions remain to be open due to their complexity, which goes over the scope of the paper.

Methods

Groundwater drought definitions

There is no uniform and widely accepted definition of groundwater drought. Most of the available definitions rely on the fact that groundwater drought appears with a decrease of groundwater or piezometric level in the aquifer. This decline and consequent drought can be a consequence of natural or anthropogenic factors (Haas & Birk, 2017, Namdar Ghanbari & Bravo, 2011); therefore, we can have natural groundwater droughts and anthropogenically induced groundwater droughts.

One of the possible approaches to define groundwater drought is a statistical analysis of groundwater level fluctuation that is described as time series measured in individual groundwater stations, which is indicated through a decrease of groundwater or piezometric level. Two possible groups of measures can be applied; the first is based on ranking statistics of groundwater measurements, and the second is based on groundwater drought indices. Their application is similar to other indices applied in studies of meteorological and hydrological droughts (Dracup et al., 1980; Palmer, 1965; Vicente-Serrano et al., 2010; Brenčič, 2016). For both groups of measures, groundwater drought is defined when values are smaller than the critical measure.

The first method is ranking statistics, defined by percentiles when groundwater level in the aquifer falls below the critical value in a given period (Van Lanen & Peters, 2000). Critical value is defined as a selected percentile of all measurements and is usually based on socioeconomic or environmental aspects (Hisdal & Tallaksen, 2000). Studies of various drought aspects in Slovenia showed that, for a reliable drought estimate, at least 30-year series of continuous measurements are needed (Kobold et al., 2012). Three useful critical drought percentiles were defined: percentile P_{25} is a critical value when intensive monitoring of drought starts, percentile P_{10} is a critical value when the drought warning starts, and percentile P_5 represent onset of protection measures (Kobold et al., 2012). The same percentiles were used in our study.

The second method is based on groundwater drought indices, which are based on similar definitions as meteorological drought indices. In our study, we have applied Standardized Groundwater Index - SGI (Bloomfield & Marchant, 2013), which is based on groundwater level measurements. For representation of SGI, a proper selection of the time window is necessary. Its calculation depends on the available time series of groundwater measurements. For a sufficiently long measurement period where we want to determine the regional prevalence of drought (more than 30 years), it is more appropriate to use annual data of the selected parameter; while for a shorter period of time (less than 30 years), it is more appropriate to use the monthly values of the selected parameter, which give more precise local values (Mishra & Singh, 2010; Brenčič, 2017).

In our study, results of groundwater drought calculations were also compared with meteorological drought indices. As an indicator of meteorological drought, Standardized Precipitation Index – SPI was used (McKee et al., 1993). This is a univariate index where the only input parameter is precipitation. Its application is becoming more and more established, since it can quantify drought periods with a deficit or excess of precipitation at different time scales (Gregorič & Ceglar, 2017; Ceglar & Kajfež-Bogataj, 2008; Sušnik & Pogačar, 2010; Sušnik, 2014; Brenčič, 2016; Haas & Birk, 2017). It is based on the long-term average of the rainfall amount, which is often considered as a monthly value.

Statistical methods

Statistical analyses were carried out on public domain monitoring sites operated by the Agency for the Environment of RS (ARSO, 2018). Data were taken from 4 precipitation stations and from 22 groundwater stations (Fig. 1).

The daily groundwater level data were calculated to average monthly values, for which the continuity and density at individual groundwater station were analysed. Some of them were omitted due to inadequate measurements or were corrected with linear interpolation. Since the time series of the available data sets among the groundwater stations are not the same, we have chosen four different time intervals that cover the different measuring ranges. Groundwater level data were analysed with frequency distribution parameters where we described the properties of the data with respect to shape, position, and dispersion.

With time series diagrams, we detected anomalous groundwater level trends that can influence stationarity required for frequency analysis. Such stations were omitted from further analysis. Data were also analysed on a normal prob-

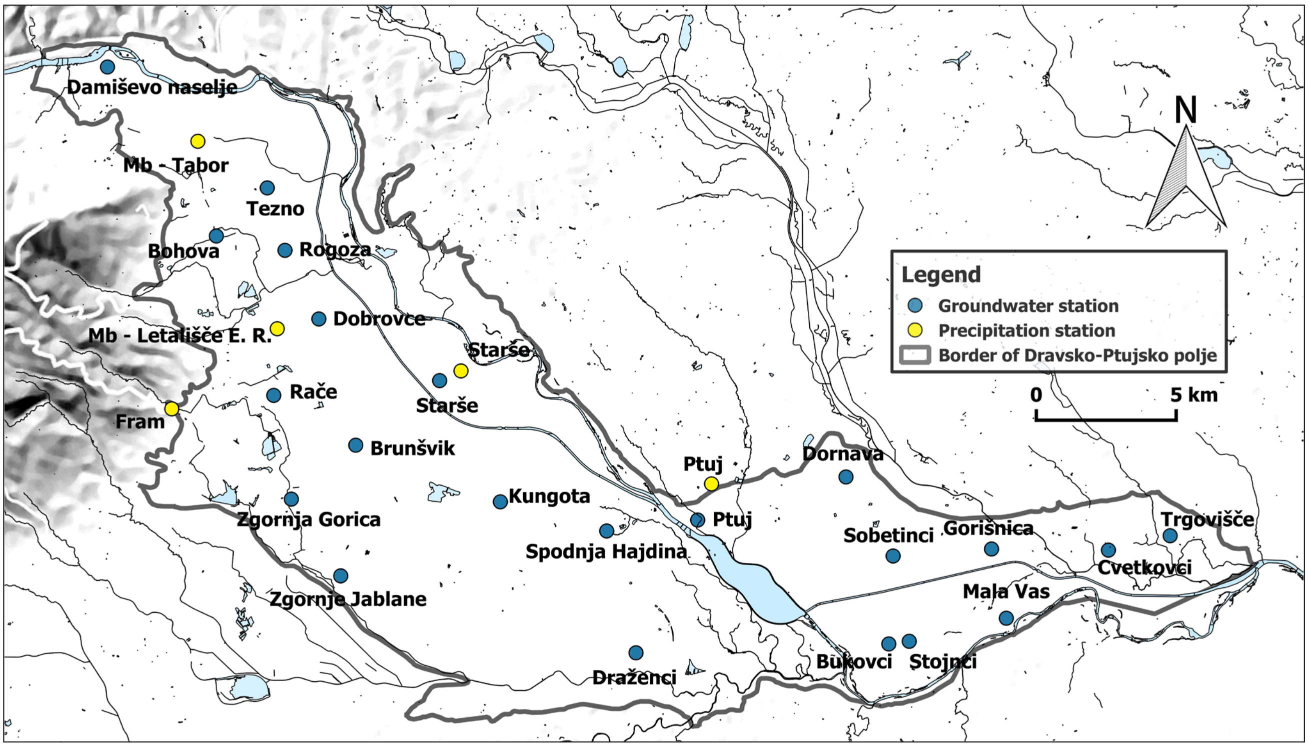


Fig. 1. Dravsko-Ptujsko polje groundwater and precipitation station locations (cartographic basis Geodetska uprava Republike Slovenije, DPK750, 2017).

ability plot where the extreme values (i.e. floods, droughts) are clearly visible, since the deviations of the lowest and highest values of the actual measurement curve are clearly separated from the theoretical curve.

For further calculations, we checked the probability distribution of groundwater levels. We used the Kolmogorov-Smirnov test, which is a non-parametric test for continuous probability distributions. It is based on the deviation of the distance between the distribution function and the comparative distribution function, which is then compared with the tabulated critical value (McKillup & Darby Dvar, 2010).

We also checked the measurements of the theoretical distribution with the Anderson-Darling test, which is suitable for testing continuous data and is based on a comparison of the empirical and theoretical distribution function (Stephens, 1974). It is a modification of the Kolmogorov-Smirnov test and gives more weight to the tails. The equation of Anderson-Darling test is defined as:

$$AD = -n - \frac{1}{n}\sum_{i=1}^{n}\{(2i-1)\ln F(X_i) + (2n+1-2i) \ln(1 - F(X_{n-i+1}))\} \quad (1)$$

n sample size

$F(X_i)$ cumulative distribution function for the specified theoretical distribution

i the i[th] rank when the data is sorted in ascending order

Ranking statistics of percentiles

The first method used for the analysis of groundwater drought was based on ranking statistics of percentiles, using the lowest 10 % of the measurements of an individual groundwater station – P_{10}. They were presented on a duration curve (Fig. 2), which shows the percentage of time in which the groundwater level was lower or equal to a certain limit value (Searcy, 1959). The values of the groundwater level were arranged in a descending order from 1 to n and the percentage was ascribed according to the equation:

$$P(\%) = \left(\frac{M}{n}\right) * 100 \quad (2)$$

P possibility that value exceed or is equal to a certain % of the time

M ranked value of n data

n number of all data

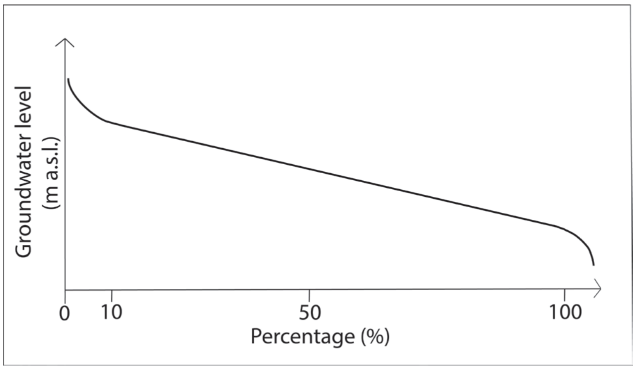


Fig. 2. Schematic representation of groundwater level duration curve.

The critical limit value P_{10} was used for the calculation of groundwater deficit D. The method for calculating D is based on the following equation (Peters et al., 2005 & 2006) (Fig. 3):

$$D = \int_{t_0}^{t_x} [P_{10} - x_i]dt \quad (3)$$

t_0 start of the drought (day)

t_x end of the drought (day)

X_i data on interval between t_0 and t_x

P_{10} threshold level value of observed data (m)

The second method used for analysis of groundwater drought was based on index calculations. We applied the concept of the SGI calculation (Bloomfield & Marchant, 2013), which has the same logic as the SPI calculation (McKee et al., 1993).

Calculation of standardized precipitation index – SPI

SPI is a univariate index where the only input is precipitation data. The index represents the number of standard deviations of precipitation from the long-term average in the observed period. This applies only to normally (Gaussian) distributed precipitation, but this is not usually their characteristic. Therefore, the appropriate theoretical distribution must be first determined. The first step is to determine the probability density that describes the past series of precipitation. This gives us a probability distribution of a continuous random variable for the selected time range of data. The range can be given for a different set of precipitation, for example, SPI1 (one month) and SPI3 (three months). The next step is to calculate the distribution function for the selected sum of precipitation that is normalized. The values obtained represent SPI (Table 1). The distribution, where the mean value is 0 and the standard deviation 1, is called the standardized Gaussian distribution (McKee et al., 1993).

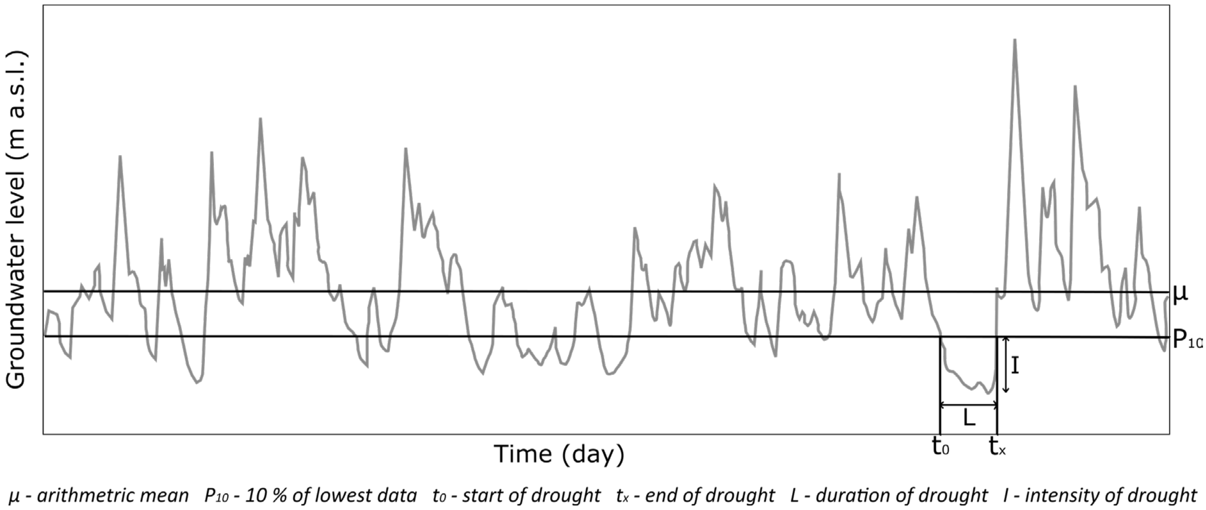


Fig. 3. Groundwater level fluctuations with drought parameters for groundwater station Gorišnica (1990–2016).

The most common theoretical distribution used is the gamma distribution that needs to be modified, because it is not defined at a value of 0 but occurs often due to the absence of precipitation. Then the cumulative value is transformed into a Gaussian distribution (Thom, 1966; McKee et al., 1993). The gamma distribution of a given variable is defined as follows:

$$g_x(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (4)$$

$\alpha > 0$	shape parameter
$\beta > 0$	scale parameter
$x > 0$	precipitation amount
$\Gamma(\alpha)= \int_0^{\infty} y^{\alpha-1} e^{-y} dy$	gamma function

Table 1. SPI and SGI categories (after McKee et al., 1993).

SPI values	Drought category	SGI values	Drought category
≥ 2.00	Extremely wet		
1.50 to 1.99	Very wet	Above 0	No drought
1.00 to 1.49	Moderately wet	–1.00 to 0	Minimal drought
–0.99 to 0.99	Near normal	–1.50 to –1.00	Moderate drought
–1.49 to –1.00	Moderately dry	–2.00 to –1.50	Severe drought
–1.99 to –1.50	Severely dry	< –2.00	Extreme drought
≤ –2.00	Extremely dry		

The parameters α and β should be defined so that they match the precipitation distribution for each time series and station separately. The process was described in more detail by McKee et al. (1993), who determined the calculation of the parameter estimates by the maximum probability method. The equations are as follows:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (5)$$

$$\hat{\beta} = \frac{\overline{x}}{\hat{\alpha}} \quad (6)$$

$$A = ln\overline{x} - \frac{\sum lnx}{n} \quad (7)$$

With the obtained parameters $\hat{\alpha}$, $\hat{\beta}$, and A, we were able to find the distribution function. Since the gamma distribution is not defined at x=0, the equation is modified and defined as the following:

$$H(x) = q + (1 - q)G(x) \quad (8)$$

q	probability with no precipitation (x=0); $q = m/n$
m	number of precipitation periods
n	number of observations

The final step is to transform the theoretical distribution into a standardized Gaussian variable with an average of 0 and a standard deviation of 1.

For a quicker calculation of SPI, a computer program was used. The program is available on the website of US National Drought Management Centre (2015).

Calculation of standardized groundwater index – SGI

Standardised Groundwater Index - SGI (Bloomfield & Marchant, 2013; Draksler et al., 2017) represents the number of standard deviations of the groundwater level deviating from the long-term average for the selected interval. SGI is based on the same principle as SPI, but there are two major differences. The first is that, for the groundwater level as an input variable, it is unnecessary to separate the parameter into predefined time periods. The second difference is in choosing the correct fit and distribution of raw data, since SGI seldom fits the gamma distribution, as is typical for SPI (Bloomfield & Marchant, 2013). If the parameter is unevenly distributed, we use non-parametric methods. In this case, each calculated monthly measurement of groundwater level gets a value that is determined on a basis of rank within the entire set of measurements. The obtained values are then determined by the inverse normal cumulative distribution. If measurements are already evenly distributed, parametric methods may be used following the procedure described for the SPI calculation. The results are SGI values within the range from +2 to –2 (Table 1).

In our case, we selected a Gaussian distribution for transformation, because we get the best fit depending on theoretical distribution. We randomly transformed the variable with the following equation (Bloomfield et al., 2015; Draksler et al., 2017; Chu, 2018):

$$z = \frac{x - \mu}{\sigma} \tag{9}$$

x	random variable
μ	arithmetic mean of data in observed time interval
σ	standard deviation of data in observed time interval

Calculation of the probability of a continuous, normally distributed variable was performed using the following equation (Bryc, 1995):

$$p_i = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{10}$$

To use the inverse normal cumulative distribution function, each value of the probability p_i is converted from *1/(2n) to 1 – 1/(2n)*.

The relation between SPI and SGI for groundwater stations were analysed with Pearson's correlation coefficient (Rodgers & Nicewander, 1988):

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{11}$$

$\overline{x}$	average value of observations for x
ȳ	average value of observations for ȳ
n	number of observations
x_i, y_i	observed values with index i

Results

Groundwater stations and time intervals

After reviewing the calculated monthly groundwater measurements on 22 groundwater stations, the availability and consistency of the data were checked. At some groundwater stations, the data sets are not long enough, they do not coincide with other stations, or they do not fit to the theoretical distribution (possible reasons are indicated for each selected time interval separately). Because of that, some stations were omitted (Table 3). Where the set of missing monthly values for individual groundwater station was shorter than 6 months (station Brunšvik, Kungota, Zgornje Jablane, Spodnja Hajdina), they were replaced by linear interpolation based on the comparison with neighbouring stations. Stations used in the analysis are presented in Table 2 and Figure 4.

To compare results of calculations, the time intervals between different stations must overlap. Based on the data overlapping, four time intervals were defined (Table 2).

1. 1956–2000: The period enables to detect older dry periods, but for this period, only two stations are suitable for the analysis. During this period, boundary conditions of Dravsko-Ptujsko polje aquifer has changed, which gave a disadvantage to the analysis and caused substantial changes in time-dependent trends and groundwater level fluctuations.

2. 1982–2012: Due to a 30-year time range, this is the most suitable interval. Six stations are suitable, which allows general analysis of drought spatial distribution. Unfortunately, in this time interval, no station is available in the west and south part of the observed area. During the interval changes in the aquifer, boundary conditions were present.

3. 1991–2011: The advantage of the time interval is a relatively large number of 12 groundwater stations, distributed throughout the entire area. Fluctuations of groundwater levels at the stations do not have a distinct trend, which improves the quality of drought analysis. The disadvantage of the interval is a short period that covers only 20 years, which is not entirely appropriate for the analysis of SGI. According to the basic methodology, the calculation requires at least a 30-year dataset (Bloomfield & Marchant, 2013).

4. 1990–2016: The interval was chosen to analyse recent dry periods. The interval is not entirely appropriate, as it has a length of 26 years. The number of relevant stations is 12, which is providing reasonable spatial representation. The disadvantages of the period are bigger changes in groundwater levels that happened from 2012 at several observation stations.

Table 2. Groundwater stations used in the analysis.

Name of the borehole	Location	GKX [m]	GKY [m]	Measuring period	Selected period			
					1. 1956–2000	2. 1982–2012	3. 1991–2011	4. 1990–2016
0890	Bohova	151899	550523	1990–2016			X	X
1710, Bru-1/11	Brunšvik	144522	555551	1956–2016	X			
2401, 2411, 2412, Ku-2/09	Kungota	142561	560725	1990–2016			X	X
1250, Rač-1/11	Rače	146264	552615	1990–2016			X	X
2830, SHaj-2/14	Spodnja Hajdina	141564	564525	1981–2016		X	X	X
2120, Sta-1/11	Starše	146842	558519	1981–2016		X	X	X
1631	Zgornja Gorica	142587	553273	1990–2016			X	X
1600	Zgornje Jablane	139878	555058	1956–2016	X	X	X	X
0721	Tezno	153620	552320	1969–2016		X	X	X
0370, Do-2/09	Dornava	143579	573033	1981–2016		X	X	X
0152	Gorišnica	141084	578251	1990–2016			X	X
0283, Sob-1/14	Sobetinci	140792	574746	1990–2016			X	X
0060	Trgovišče	141641	584612	1990–2016		X	X	X

Table 3. Groundwater stations that were omitted from the analysis.

Name of the borehole	Location	GKX [m]	GKY [m]	Measuring period
0290	Damiševo naselje	157858	546607	1979–1989
1030	Dobrovce	148990	554200	1956–2016
3040, Lp-01	Draženci	137248	565618	1981–2016
Rog-1/11	Rogoza	151413	552973	2012–2016
Buk-1/14	Bukovci	137666	574631	2015–2016
0531, 0721	Ptuj	141989	567766	1982–2016
0051, 0230	Cvetkovci	141100	582420	1960–1981
0210, 0211	Mala Vas	138633	578811	1965–1984
0280	Sobetinci	140792	574746	1954–1983
0240	Stojnci	137770	575360	1981–2015

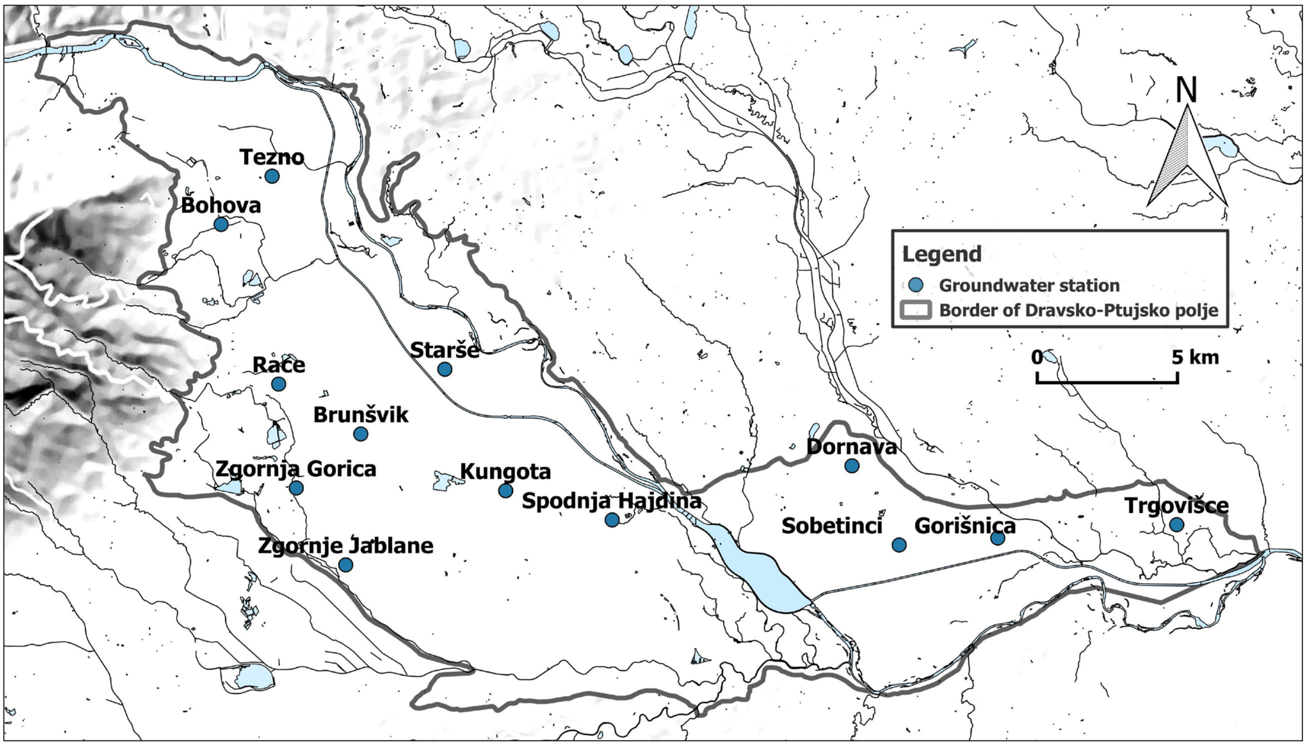


Fig. 4. Dravsko-Ptujsko polje groundwater station locations that were used in analysis (cartographic basis Geodetska uprava Republike Slovenije, DPK750, 2017).

Trend analysis

In most cases, the measurements are continuous and distributed as unimodal distributions. For groundwater stations where the data deviate from the unimodal distribution, it is typical that they have a large amplitude of fluctuations (e.g. Rače and Starše station), or the aquifer reacts rapidly to the periods of recharge, which results in high deviations from the average values of the groundwater level (e.g. the Sobetinci station). Therefore, models of unimodal distributions cannot be approved by the testing with Kolmogorov-Smirnov and Anderson-Darling tests. Such behaviour can be observed on stations Rače (Fig. 5a), Spodnja Hajdina (Fig. 5b), Zgornje Jablane, Starše, Trgovišče, and Sobetinci.

At such stations, further processing of data was not performed. Even though this is a real condition in the aquifer, it is a result of influences on the aquifer, which cannot be defined without detailed analysis. A significant linear trend in groundwater levels influences time appearance of drought events through time. For further analysis, different time intervals were selected, such that groundwater levels were not deviating from long-term average.

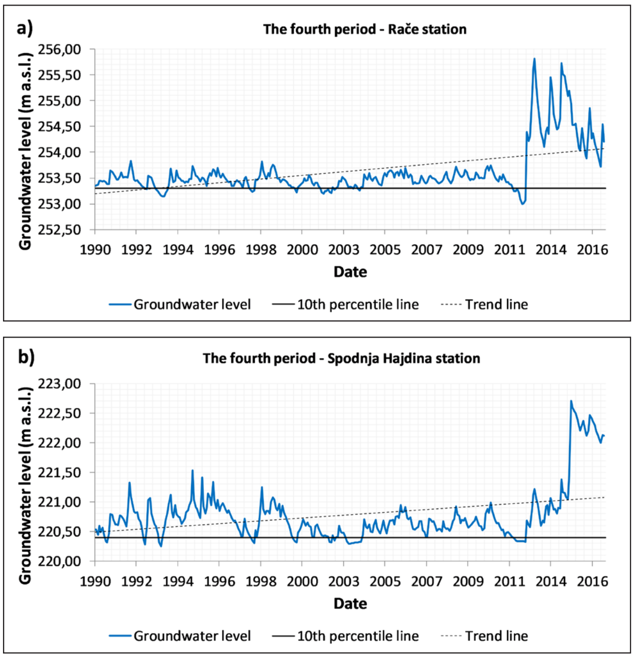


Fig. 5. a) Fluctuation of groundwater for the Rače station (fourth interval, between years 1990 and 2016). b) Fluctuation of groundwater for the Spodnja Hajdina station (fourth interval between years 1990 and 2016).

Time intervals analysis

In the continuation, each time interval is presented in detail. In the tables (Tables 4–7) are data for individual groundwater station: the range of groundwater level fluctuations, number of drought periods, trend of groundwater level fluctuations, maximum intensity *I*, maximum deficit *D* of the dry period defined as lowest 10 % percentile – P_{10}, and minimum and maximum drought duration.

The **first interval** (Table 4) represents measurements from year 1956 to year 2000. The Brunšvik station has stronger intensities *I* of the dry periods than the Zgornje Jablane station, which is probably due to a higher amplitude of groundwater level fluctuation. Same can be said for the size of the deficit *D* of drought periods, which is greater at the Brunšvik station. We assumed that this is a consequence of a thicker aquifer, which, in addition to rainfall, is also supplied by Pohorje streams. Since groundwater is located at a depth of 10 to 15 m, it takes longer to experience drought, which in turn means that it is more intense and long-lasting. The Zgornje Jablane station is in the more southwestern part of the Dravsko polje, where the aquifer is limited by the Holocene clay sediments of Pohorje streams. We can still define the fluctuation as large (depending on the range of amplitudes of other groundwater stations in the Dravsko-Ptujsko polje), but due to the low groundwater depth (1–5 m), the drought is recovered with short-term precipitation. This is confirmed by the fact that we noticed many shorter dry periods (2–3 months) in this area.

Calculation of SGI (Fig. 6) shows that the dry periods in the past did not appear as often as in the period from 1980 to 2000. Severe droughts indicated by a value of –1.5 and less have been occurring almost every year since 1975. The calculated SGI that shows periods of severe drought coincide with the drought periods defined by P_{10}.

The **second interval** (Table 5) represents measurements from year 1982 to year 2012. We can see that the intensities *I* of the dry periods of the Dornava, Tezno, and Starše stations are stronger. For the Trgovišče and Spodnja Hajdina, the

Table 4. Descriptive statistics for the first interval between years 1956 and 2000.

Station	Max. GW level fluctuation (m)	Number of drought periods	Trend of GW fluctuation	Max. *I* of dry period (m)	Max. *D* of dry period	Duration (day)	
						Min.	Max.
Brunšvik	5.93	10	decrease	0.69	151	28	275
Zg. Jablane	3.97	17	decrease	0.34	56	31	214

GW – groundwater

drought intensity values do not exceed 0.23 m. In all cases, with time we observe an increase in the intensity of dry periods. The exception is the Spodnja Hajdina station. The size of the deficit *D* of drought periods between the groundwater stations appears quite evenly, and the difference between the deficits in individual stations is noticed. Dornava, Tezno, and Starše have a larger deficit. Dornava and Tezno are located on the margins of the field where the deficit depends on the amplitude of the fluctuations of groundwater levels. The recharge is also influenced by nearby streams. At the Starše station, located in the middle of the Dravsko polje, the size of the deficit and the intensity is a consequence of greater aquifer thickness.

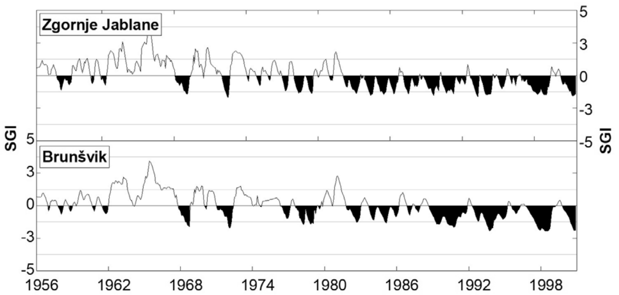


Fig. 6. SGI graph of first interval of measurements between years 1956 and 2000.

SGI was calculated (Fig. 7) at all groundwater stations except for the Zgornje Jablane, since for the second interval, the empirical distribution has not proper fit to the theoretical Gaussian distribution. For other stations, SGI showed three larger periods of severe drought when SGI values were below –1.5. For the first time, such an extreme event occurs in the year 1993 at all stations, except in the Starše station. The second larger period is between 2000 and 2003. The exceptions are the Spodnja Hajdina and Trgovišče stations, where the dry periods are shorter with the rapidly changing SGI. This reflects a thinner unsaturated area at the observed station. The third larger period occurs in December 2011 and persists to the end of 2012. It is a period that is common to all stations where the intensity rises equally. The SGI values at Trgovišče, Dornava and Starše exceed –2.0, which is characterized by extreme drought.

All stations in the Dravsko polje have common drought periods since 2000. The most likely reason for this is a permanent trend of decreasing groundwater level. Exceptions are Trgovišče and Dornava, where the trend of groundwater level is not detected.

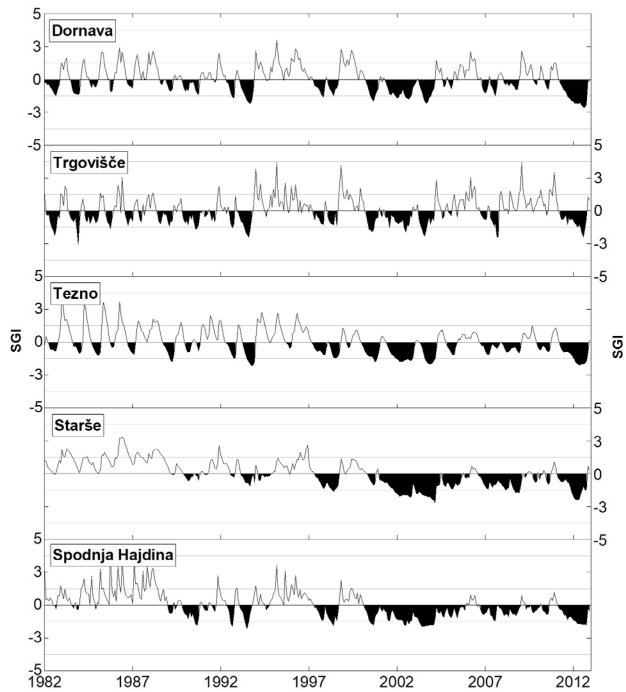


Fig. 7. SGI graph of second interval of measurements between years 1982 and 2012.

The **third interval** (Table 6) represents measurements from year 1991 to year 2011. We noticed that between the dry periods, Tezno, Bohovo, Starše, and Kungota stations have higher intensities *I*. These are areas with higher amplitudes of groundwater fluctuations, which also affects the size of the drought intensity. Rače, Zgornja Gorica, and Trgovišče stations are characterized by a small amplitude that is reflected in the lower intensity of dry periods. The size of the deficit *D* increases with time at most groundwater stations.

Table 5. Descriptive statistics for the second interval between years 1982 and 2012.

Station	Max. GW level fluctuation (m)	Number of drought periods	Trend of GW fluctuation	Max. *I* of dry period (m)	Max. *D* of dry period	Duration (day)	
						Min.	Max.
Sp. Hajdina	1.47	10	decrease	0.16	39	31	334
Starše	2.26	5	decrease	0.39	81	30	365
Tezno	3.62	7	decrease	0.34	83	31	334
Dornava	2.16	16	decrease	0.53	98	31	245
Trgovišče	1.04	15	decrease	0.23	26	28	183

GW – groundwater

Table 6. Descriptive statistics for the third interval between years 1991 and 2011.

Station	Max. GW level fluctuation (m)	Number of drought periods	Trend of GW fluctuation	Max. *I* of dry period (m)	Max. *D* of dry period	Duration (day)	
						Min.	Max.
Bohova	5.44	5	not present	0.74	135	61	273
Kungota	3.13	2	not present	0.48	336	61	702
Rače	0.69	6	not present	0.16	38	61	355
Sp. Hajdina	1.28	6	decrease	0.15	34	61	304
Starše	1.97	4	decrease	0.34	104	59	334
Zg. Gorica	1.24	12	not present	0.16	31	28	304
Zg. Jablane	1.90	9	decrease	0.15	18	31	153
Tezno	2.55	4	decrease	0.33	61	61	334
Dornava	2.07	8	not present	0.23	41	61	184
Gorišnica	1.69	8	decrease	0.23	28	31	184
Trgovišče	0.95	8	not present	0.15	23	30	153

GW – groundwater

Table 7. Descriptive statistics for the fourth interval between years 1990 and 2016.

Station	Max. GW level fluctuation (m)	Number of drought periods	Trend of GW fluctuation	Max. *I* of dry period (m)	Max. *D* of dry period	Duration (day)	
						Min.	Max.
Bohova	5.44	6	not present	0.70	128	61	304
Kungota	4.17	3	increase	0.63	479	31	758
Zg. Gorica	1.24	21	not present	0.22	47	28	304
Tezno	2.55	5	decrease	0.32	87	61	334
Dornava	2.80	9	not present	0.34	124	30	365
Gorišnica	2.28	7	not present	0.22	88	61	396

The calculation of SGI (Fig. 8) for the third interval of measurements was possible at all stations except for Sobetinci, because it has an asymmetric distribution of data; therefore, fitting it to Gaussian distribution was not possible. Otherwise, SGI shows two major periods with severe drought, meaning that SGI is lower than –1.5. First, it occurs at the end of year 1993 and lasts until spring 1994. Exceptions are the Starše and Kungota stations where drought occurs, but they were less intensive. The second period occurs between years 2001 and 2004. It starts at the end of summer 2001, but the aquifer does not recover due to lack of precipitation until spring 2003. At that time, there was a decrease in intensity at all locations, but it then starts rising until January 2004. This period is particularly persistent around Starše and Kungota stations. SGI between 2003 and 2004 at all stations exceeds –2.0, indicating extreme drought (Table 1). At Kungota station, this value persisted for two years.

The smallest fluctuations, between years 2001 and 2004, occurs in stations Zgornja Gorica, Rače, Trgovišče, and Gorišnica. This is due to the small thickness of the unsaturated area and consequentially the fast response to the recharge.

The **fourth interval** (Table 7) represents measurements from year 1990 to year 2016. The highest drought intensity *I* is noticeable at the Kungota, Bohova, Tezno, and Dornava stations. As mentioned before, this is due to the higher amplitude of the groundwater level fluctuation. The highest drought intensity was recorded at the Kungota station with 0.64 m. The low drought intensity is typical for the Zgornja Gorica station where intensity does not exceed 0.20 m. There is also a positive linear trend in the increasing intensity of dry periods. The same applies to the size of the deficit *D* of dry periods P_{10}.

In this period, empirical distributions of many stations are highly asymmetric and consequently do not fit to Gaussian distribution. We have applied transformation to transfer these distributions closer to theoretical, but again Kolmogorov-Smirnov and Anderson-Darling tests were not significant. These data were not analysed.

Three periods are typical for SGI smaller than –1.5 (Fig. 9). The first is the year 1993, visible at all stations. The smallest deficit of dry period is present at the Kungota station. The second is the period between 2000 and 2004. There is a slight increase in the groundwater level in 2001 and 2003 throughout all locations, alleviating the intensity of the dry season. The exception again is the Kungota station, this time due to SGI with

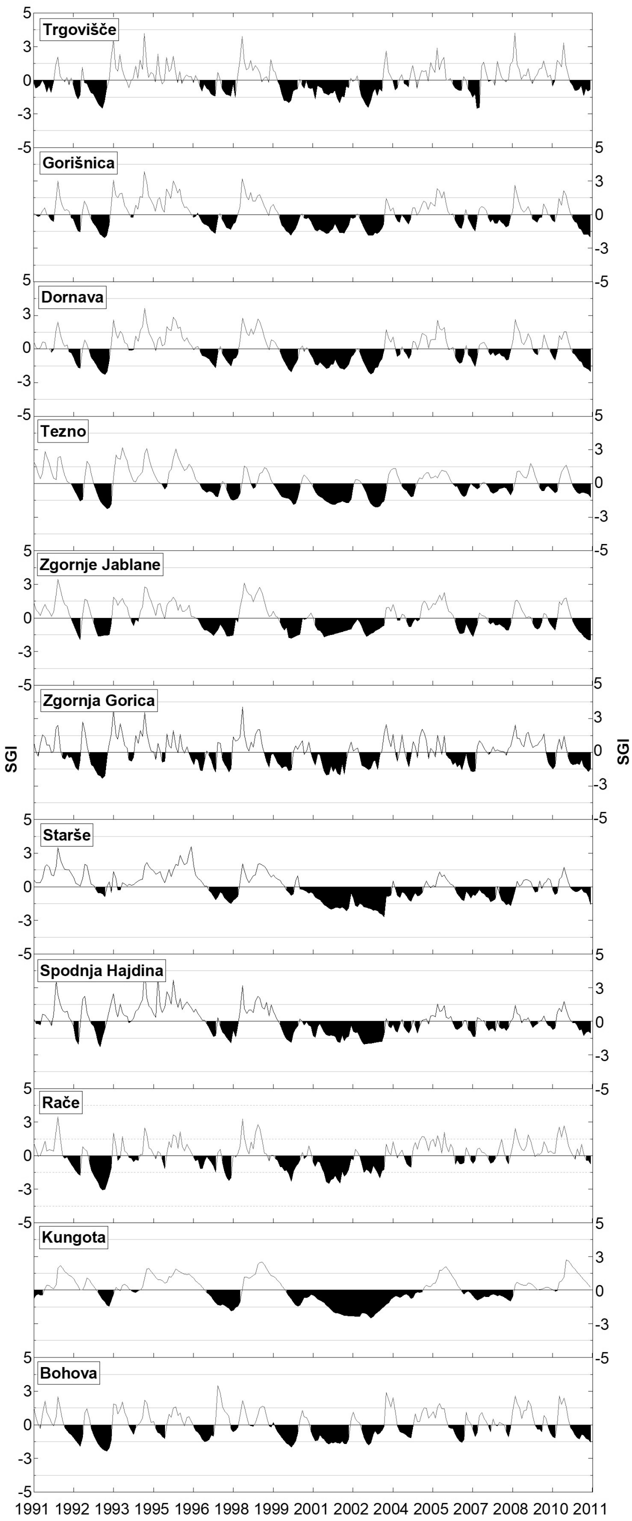


Fig. 8. SGI graph of third interval of measurements between years 1991 and 2011.

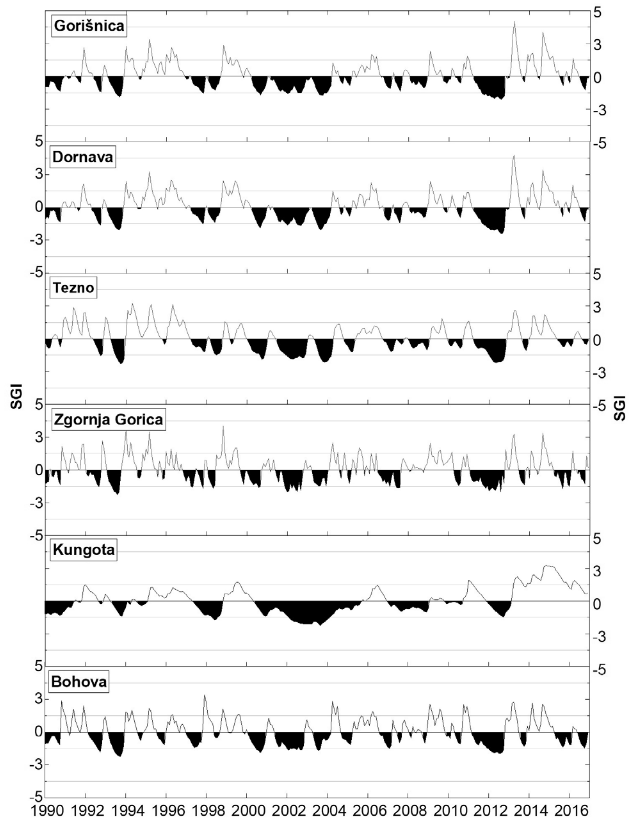


Fig. 9. SGI graph of fourth interval of measurements between years 1990 and 2016.

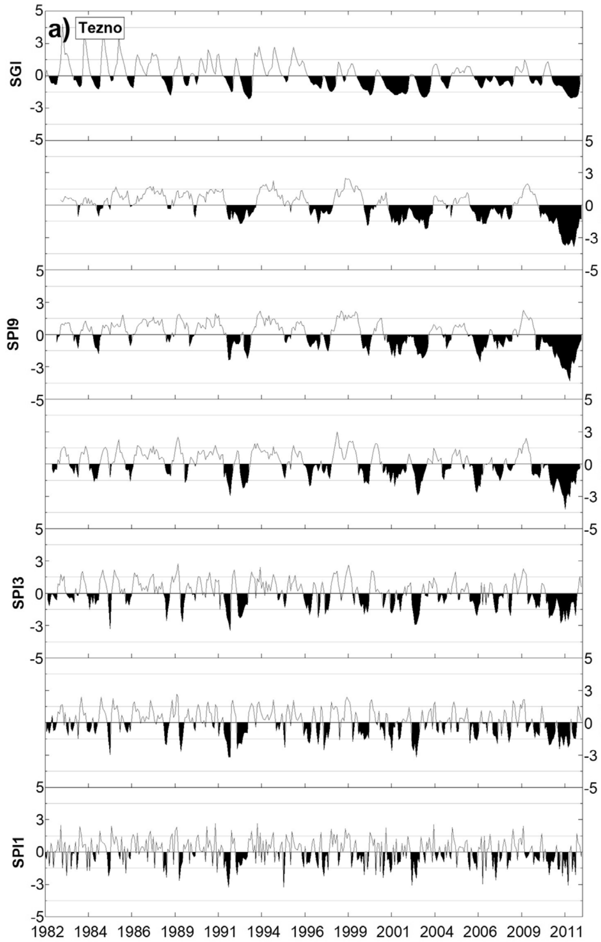
less than –2.0. Where groundwater is shallow, the curve is very irregular indicating a rapid response of the aquifer to the recharge. The third period started in summer 2011 and persisted until autumn 2013. The deficit is visible throughout all groundwater stations. The most variable in the period is index at the Zgornja Gorica station.

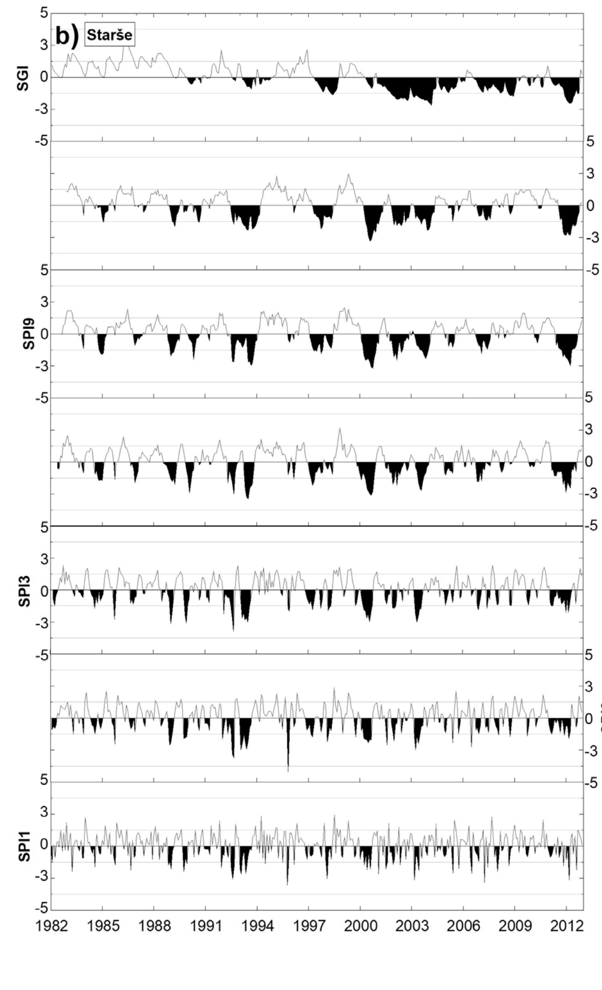
Comparison of meteorological drought with groundwater drought

Depending on the meteorological drought, the groundwater drought occurs with a lag, the length of which depends on the thickness of the unsaturated zone, porosity and transmissivity. Since hydrogeological systems differ one from another, the influence of the coincidence of these types of drought varies. We have chosen six different time scales for calculating SPI: SPI1, SPI2, SPI3, SPI6, SPI9 and SPI12.

To compare meteorological and groundwater drought, SPI was calculated for three meteorological stations positioned on the Dravsko-Ptujsko polje: precipitation stations Tezno, Starše and Zgornje Jablane. The time interval between year 1982 and year 2012 was chosen, despite the decreasing groundwater level trend. The results are shown in the figure (Fig. 10).

On shorter time scales, the SPI variability is greater than on longer time scales. The reason is representation of seasonal, short-term droughts. Based on the SPI and SGI graphs, we concluded that the Zgornje Jablane station does not show any delay in terms of the meteorological drought (Fig. 10c). Both droughts appear simultaneously, which is particularly noticeable in years 2002 and 2012. SPI12 for year 2002 is –1.54 in January, while in the same month the SGI value is –1.35.





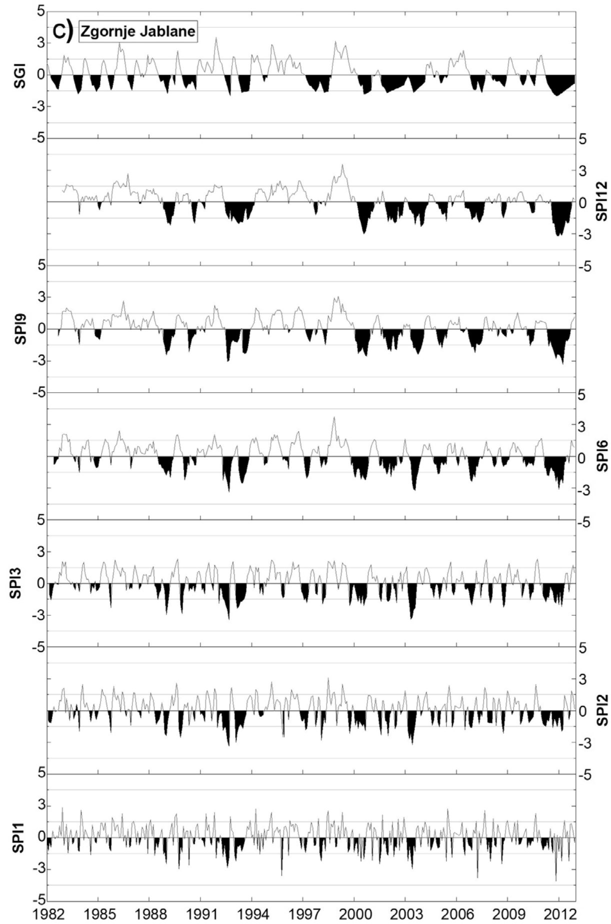


Fig. 10. Comparison of SPI and SGI between a) precipitation station Maribor Tabor and groundwater station Tezno from 1982–2012, b) precipitation station Starše and groundwater station Starše from 1982–2012 and c) between precipitation station Fram and groundwater station Zgornje Jablane from 1982–2012.

At the Tezno station, there is a delay in the appearance of groundwater drought (Fig. 10a). These differences are most noticeable in years 1993 and 2012, when groundwater drought occurs with an average half-year lag. For the year 2012, SPI12 has the lowest value in January when it exceeds –3.0, while SGI is the lowest in May with a value of –1.63. The situation is similar for the year 1993.

The meteorological drought at the precipitation station Starše (Fig. 10b) does not coincide with the groundwater drought observed at the groundwater station Starše. The shift between the lowest SPI and SGI value is greater than near Tezno. In August 2000 when the SPI12 reached the lowest value of –2.77 and when later negative values persist until the next summer, negative SGIs have started slowly but have been steadily decreasing since the end of 2000 until they reach the lowest value of –1.72 in August 2002. The amount of precipitation then increased, which led to an increase of both indices; the trend reverses again when the SPI12 persists with the negative values throughout 2003. SGI reaches the lowest value of –2.19 only in March 2004. A delayed response of groundwater to recharge is apparent.

Drought periods occurrence map

Despite the short range of measurements, we showed the third interval of measurements (1991–2011), where the density of the stations on the western and southern parts of the Dravsko-Ptujsko polje are more dense (Fig. 11). The period from July 2002 to April 2003 is characterized by extreme drought. We can observe that the SGI values vary by month and location.

For July 2002 (Fig. 11a), drought periods with an index of –1.5 and more are present. The drought was spread over the entire Dravsko-Ptujsko polje. The lowest SGI value is in the north-western part of the area, while in the western part (near Zgornje Jablane) the values were not lower than –1.0. The reason for this is a recharge from the Pohorje streams on the western part of the area. In October 2002 (Fig. 11b), the SGI values decreased in the central part of the area (still above –1.6), and then values are diminishing towards the east. And the dry period significantly diminishes around Zgornje Jablane and Trgovišče. In January 2003 (Fig. 11c), the groundwater deficit is only present in the central part of the area (near Kungota). In the east and northwest, SGI rises above 0.0, indicating a period without groundwater drought. In April 2003 (Fig. 11d), the dry period in the central part of the area is still present. The SGI around Kungota is around –1.6, which shows a severe drought. There is no drought in the north-west of the area. Again, the reason is in the aquifer recharge from the Pohorje streams. There is a deficit to the east, where SGI is between 0.0 and –0.7.

Discussion

The presented analysis of groundwater drought can be divided into three parts. The first part consisting on the ranking statistics of groundwater fluctuations and the second part on the calculation of Standardized Groundwater Index – SGI. The third part represents a comparison between Standardized Precipitation Index – SPI and Standardized Gorunwater Index – SGI.

In the area of Dravsko-Ptujsko polje, based on the ranking statistics, we have identified one- to three-month periods of groundwater deficit, which most often occur in autumn or winter. We conclude that this is a consequence of the delayed impact of the meteorological drought that occurs in the summer. When short-term summer drought periods occur, they often have greater intensity than short-term winter drought periods.

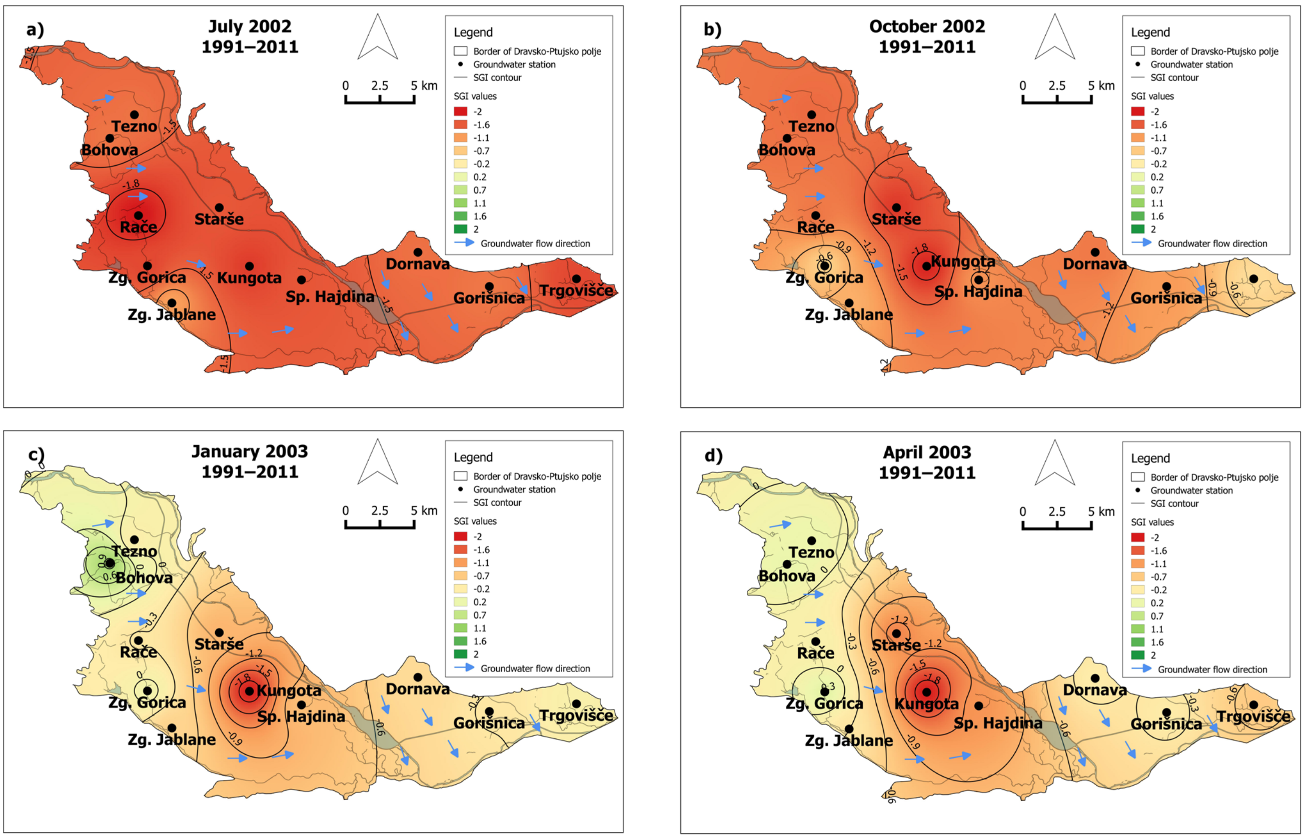


Fig. 11. Maps of dry periods for the third interval (1991–2011). SGI is shown for a) July 2002, b) October 2002, c) January 2003 and d) April 2003.

In the western part of the Dravsko-Ptujsko polje, the amplitude of groundwater level fluctuations is up to 5 m high (Brunšvik station), while in the eastern part it does not exceed 1 m (Trgovišče station). This has also effects on the duration and intensity of dry periods. In the north-western part, the Brunšvik and Tezno stations have the longest and most intense dry periods. In the southeast, the Sobetinci, Gorišnica, and Trgovišče stations have several shorter dry periods, characterized by a low intensity that does not increase with the length of the event. Many one- to three-month dry periods occur in the south-eastern part of the field in summer, as a response to the meteorological drought is almost immediate. The reason is the small thickness of the unsaturated zone. Groundwater is at the depth of 5 m; therefore, the rare longer periods of drought are not the result of the delayed impact of the aquifer but the persistence of meteorological droughts. During the analysis of different time intervals, we indicated a decreasing trend of groundwater level, which affects the variety of drought intensity and size of deficit. Due to the decreasing trend in recent time, many dry periods have occurred.

Dry periods do not occur evenly but depend on local changes in the aquifer. Sometimes, we detect very monotonous drought periods, sometimes drought periods are locally distributed. Therefore, the analysis of groundwater deficits should consider local hydrogeological and geological characteristics of individual aquifers. This is confirmed by the fact that uniform definitions of groundwater drought cannot be given. Each region under consideration has a different variation of the variables.

Based on the SGI calculations, the worst long-lasting droughts usually begin in winter, when the aquifer does not recover after the previous summer drought. Since the amount of recharge is insufficient in the springtime, along with the onset of the next summer, the intensity of drought increases and causes an even greater shortage of groundwater. An example of severe droughts in years 2003 and 2012 is seen at all stations on the Dravsko-Ptujsko polje.

A visual comparison between SGI and percentile P_{10} calculations found that the drought periods determined by both methods coincide. The comparison of the dry period's size is characteristic between the value of P_{10} and the SGI category, which indicates the occurrence of severe drought with values less than or equal to –1.5. This confirms the suitability of both methods for analysing groundwater drought.

From the comparison of SGI and SPI, we have discovered that locations with a higher groundwater level amplitude, where the duration and intensity of drought periods are higher, also have a greater lag in terms of the occurrence of meteorological droughts. At the Tezno station, the lag for the period from 2002 to 2003 is six months. Stations with a smaller amplitude that are typical for the eastern part of the Dravsko-Ptujsko polje reflect the shallow groundwater level. It also follows that relation between groundwater drought and meteorological drought is influenced by the thickness of vadose zone. Where the unsaturated zone is thicker, it takes longer time for meteorological drought to reach groundwater (e.g. Tezno and Starše). If it occurs, the intensity of the dry season is stronger, which means that it takes longer time for the aquifer to recover.

Conclusions

Groundwater drought is a phenomenon that must be investigated in more details in the future. Several theoretical improvements are needed in the future; among them is the redefinition of groundwater drought, which cannot be solely based on the groundwater level fluctuation analysis, but it must include also amount of water stored in the aquifer. Our analyses have shown that for Dravsko-Ptujsko polje, methods for groundwater drought analyses can be applied as they are already presented in the current scientific literature. Drawbacks of the methods applied are only indirectly indicated. At present, the conclusions of the case study are as follows:

- Groundwater drought develops slowly in time and space.
- The occurrence of groundwater drought depends on the thickness of the unsaturated and saturated aquifer zone.
- Where the depth to groundwater level is greater, droughts occur with a longer delay and greater intensity and where the thickness of unsaturated zone is small, the response to meteorological influences is faster.
- Standardized Groundwater Index – SGI is a more suitable index than percentile values of groundwater level; it integrates more information about groundwater fluctuations than percentile values.

As other types of drought, also groundwater drought is a complex event. From that point of view, it is important to consider different types of indices. We have illustrated applicability comparison of meteorological drought indices with groundwater drought indices. Beside the application of indices, it is also important to consider aquifer's dynamics.

One of the drawbacks of our analysis is the lack of longer groundwater level time series and spurious spatial distribution of stations. At present, the spatial distribution of groundwater monitoring stations in Dravsko-Ptujsko polje has improved, and it is recommended to repeat our calculations in due time. It is also important to focus more on the aquifer boundary conditions that have changed several time during the course of time on Dravsko-Ptujsko polje. Also, some statistical theoretical questions in relation to groundwater level data treatment remains to be opened among them are important questions connected to the fitting of theoretical distributions in relation to extreme values.

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