Pre-print of Hydrogeology Journal, http://dx.doi.org/10.1007/s10040-017-1665-2

Investigation of the climate-driven periodicity of shallow groundwater level fluctuations in a Central-Eastern European agricultural region

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Abstract

The distribution and amount of groundwater, a crucial source of Earth's drinking and irrigation water, is changing due to climate-change effects. Therefore, it is important to understand groundwater behavior in extreme scenarios, e.g. drought. Shallow groundwater (SGW) level fluctuation under natural conditions displays periodic behavior, i.e. seasonal variation. Thus, the study aims to investigate (i) the periodic behavior of the SGW level time series of an agriculturally important and drought-sensitive region in Central-Eastern Europe – the Carpathian Basin, in the north-eastern part of the Great Hungarian Plain, and (ii) its relationship to the European atmospheric pressure action centers. Data from 216 SGW wells were studied using wavelet spectrum analysis and wavelet coherence analyses for 1961-2010. Locally, a clear relationship exists between the absence of annual periodic behavior in the SGW level and the periodicity of droughts, as indicated by the self-calibrating Palmer Drought Severity Index and the Aridity Index.

During the non-periodic intervals, significant drops in groundwater levels (average 0.5 m) were recorded in 89% of the wells. This result links the meteorological variables to the periodic behavior of SGW, and consequently, drought. On a regional scale, Mediterranean cyclones from the Gulf of Genoa (northwest Italy) were found to be a driving factor in the 8-year periodic behavior of the SGW wells. The research documents an important link between SGW levels and local/regional climate variables or indices, thereby facilitating the necessary adaptation strategies on national and/or regional scales, as these must take into account the predictions of drought-related climatic conditions.

Keywords: climate change, groundwater periodicity, Hungary, PDSI, wavelet spectrum- and coherence analyses

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This article is part of the topical collection “Climate-change research by early-career hydrogeologists”

1. **Introduction**

It is a widely accepted fact that water is one of the most critical (UNESCO 2012) and threatened natural resources, and as such it is affected to a great extent by global and regional climate change (Aeschbach-Hertig and Gleeson 2012; Vörösmarty et al. 2000). In this sense groundwater is even more important because it represents, by volume, the second largest accessible fresh water supply, after frozen water (Aeschbach-Hertig and Gleeson 2012). In addition, groundwater is less vulnerable to droughts and anthropogenic contamination than surface water. It provides about 40% of the world’s water used for irrigation (Siebert et al. 2010), and a fair amount of the drinking water supply (Oki and Kanae 2006). Almost half of the world’s population depends on groundwater as a source of drinking water, while due to water stress, more than 2 billion people are exposed to a lack of potable freshwater and water for proper irrigation (Oki and Kanae 2006).

Although it is anticipated that in many regions climate change is set to increase the amount of renewable freshwater resources still, the probability of extreme events is also expected to increase (Oki and Kanae 2006), along with a general decrease in water levels. In certain regions, the groundwater-level decline is related to substantial aquifer dewatering (Hoque et al 2007; Ta'any et al 2009), while the increase in temperature due to climate change also has a significant driving effect on the decrease in shallow groundwater levels (Chen et al 2004). To complicate the picture further, in parallel with this overexploitation of water resources, water infiltration from anthropogenic sources may locally reverse the general decrease and cause an increase in shallow groundwater levels (Ta'any 2009). One indicator of the intermittent presence/intensity of these driving forces is the absence of natural periodic behavior (i.e. seasonal variation) in groundwater level fluctuations (Kovács et al. 2004). Taken together, these adverse scenarios directly affect both the natural environment (Sophocleous 2000) and the consumers of water, humans included. The effect on communities via drinking water is clear, but agriculture, and therefore those engaged in agriculture, may also be affected, since these phenomena increase the cost of pumping and/or the probability of wells drying up (Shah 2007). Adaptation to these unexpected changes is essential (Green et al. 2011).

The analysis of groundwater level patterns has a long history in academic literature. To take two recent examples, groundwater level patterns have been assessed on a global scale in terms of groundwater availability (Fan et al. 2013), and used in order to see the possible impacts of climate change as well (Green et al. 2011). Unfortunately, the available direct methods of measuring groundwater levels are more suited to regional analysis than to analysis on a global scale. Therefore, models developed for regional studies have to serve as stepping stones towards a broader understanding of the behavior of groundwater level fluctuations. These models concern (i) macro-regions with the assessment of phenomena in relation to global circulation models (Kuss and Gurdak 2014; Holman et al. 2011) and/or more localized climatic variables (Chen et al. 2004), and (ii) the derivation of models used in forecasting as well (Adamowski and Chan 2011; Mackay et al. 2015; Chen et al. 2002). From a practical point of view, a common characteristic of these macro-regional models is the use of state-of-the-art statistical tools, such as artificial neural networks, wavelet spectrum/coherence analyses, etc. In combination with a broader perspective, in the search for climatic driving factors of macro-regional or regional groundwater level fluctuations, these tools are both necessary and may be expected to lead to an enhanced understanding of annual and multi-annual scales of the groundwater level fluctuation prevailing in regional agricultural areas and their vulnerability.

The aim of the present study was, therefore, to investigate (i) the periodic behavior of the shallow groundwater level time series of an agriculturally important region in Central-Eastern Europe which is highly vulnerable to arid conditions; and (ii) its supposed relationship to the European atmospheric pressure action centers. If it is possible to draw a clear quantifiable connection between the periodic characteristics of the pressure action centers and the recurrence of drops in shallow groundwater levels in the study area, this work could contribute to management strategies that are used to prepare for future droughts on a broader spatial scale.

2. Materials and Methods

2.1. Site description

The study area is located in the north-eastern part of the Great Hungarian Plain within the Carpathian Basin in Central-Eastern Europe (47-48.2°N – 20.7-22.2°E; Fig. 1). The area is characterized by intense agricultural activity (Burgerné Gimes 2014) which has an important role for the whole Central-Eastern European region. Before the political and economic changes in the former Soviet satellite countries (1989-1990), Hungarian agriculture was booming, and it was the country's most successful economic sector. 60% of the investigated time span falls within that flourishing period. Hungarian agriculture in 1989-1990 produced 17% of the total Gross Domestic Product (GDP), providing work for about 22% of the total national labor force. Of the total amount of export products, 22% came from the agricultural sector. These proportions, however, fell significantly after 1990, reaching 3.3% (GDP), 4.7% (labor force), and 7% (exports), respectively by 2007 (Burgerné Gimes 2014).

The climate of the study area is continental with an annual mean temperature of 10.4 °C and 555 mm yr^{-1} mean precipitation (Fig. 2a) for the years 1961-2010. Regarding the annual distribution of precipitation, the maximum occurs in early summer (i.e. June); a second maximum can also be identified in late autumn, due to the impact of Mediterranean weather systems. The precipitation minimum occurs in winter (mostly February); however, the potential risk of drought generally appears in late summer because of higher summer temperatures (Fig. 2a). In the case of any one year, drought might occur in any month. For instance, in the years where drought was clearly recognized, such as years 1971-1974, arid conditions were present in spring and late summer (Fig. 2b), and for those years there was 63 mm less annual precipitation compared to the average for 1961-2010.

Although the area is not generally exposed to severe drought (Fig. 2), even a slight shortfall in precipitation (one or two consecutive arid years) can result in extensive dry conditions and a notable drop in shallow groundwater levels, as the soil is mainly sandy. In relation to this, about 60% of the area is characterized by downward seepage. Field experiments in the vicinity of the study area have proven that in more consolidated soils, even 60 mm of rain can be taken up by the soil without having a significant impact on the shallow groundwater levels within the span of two days (Varga Cs. Expert, Nitrogen Works Co. Ltd., personal communication, 2016). According to a recent study (Tóth 2012), one third of the area is exceptionally good for agricultural activity, though from another perspective, another third is highly sensitive to environmental changes in terms of their impact on potential agricultural production.

A decrease in SGW level was observed in the study area, leading to an increase in irrigation water demand thus a further decrease in SGW levels; a similar finding was reported for the Danube-Tisza interfluve (southern Hungary) in a study by Szalai (2011). In the study area reported here, the water for irrigation was first taken from the shallow strata (~15 m), then as the groundwater levels dropped and the amount of available water decreased, deeper strata were tapped (~40 m). The result was a depletion of the subsurface water reservoir. This resource shortage, however, was hard to monitor because the amount of water used by the farmers can only be tracked by the voluntary declarations of the farmers, and no inspections were yet conducted to record the situation.

It is important to note that, on the "sensitivity of environmental areas" scale, this area is categorized as "highly sensitive" with respect to water protection and its natural environment when compared with the country as a whole (Harsányi et al. 2013). In order to assess the phenomena driving the arid conditions and climate in the study area, not only local weather conditions were considered, but all of the key atmospheric pressure action centers affecting the weather of the Carpathian Basin (as defined by Péczely, 1961) were taken into account: the Genoa Low (off the coast of northwest Italy), the Icelandic Low, the Azores High, and the Eastern European High (for details see **Section** *'Meteorological data').*

2.2. **Shallow groundwater monitoring wells**

Due to the long history of agriculture in the area, the study had at its disposal the water-level time series data of a dense and highly developed network of shallow groundwater monitoring wells, giving a high degree of spatio-temporal coverage. Thus, 216 shallow groundwater level monitoring wells, part of the Hungarian National sampling network, could be analyzed for the period 1960-2010 (Fig. 1). The number of available wells increased continuously over time with a random presence of missing data; the period with the greatest number of data gaps was the late 1970s.

The sampling frequency also varied over time as well as in space, e.g. in the 1960s the sampling frequency was 3 days, while in 1970-1990 it was weekly, and post-1990 digital recording increased the frequency to every 4 hours. By the beginning of the 2000s the dataset could be categorized in three classes: 1-week, 3-day, and 4-hour data. The preprocessing steps of the data are discussed in **Section** *'Statistical tools used'***.**

2.3. **Meteorological data**

The meteorological data were acquired from the CarpatClim (Climate of the Carpathian Region) online database (Spinoni et al. 2015) for the study area with a 0.1° horizontal resolution and for the time interval 1961-2010. Specifically, mean air temperature, precipitation, cloud cover, global radiation, relative humidity, and potential evaporation were included as the independent meteorological parameters, as were the following indices: the standardized precipitation (SPI), standardized precipitation-evapotranspiration (SPEI), self-calibrating Palmer Drought Severity (scPDSI) and aridity (AI). However, of the mentioned indices, only the scPDSI and the AI proved capable of showing an interpretable relationship with the periodic behavior of the shallow groundwater levels in the area (for details see **Section '***Wavelet Spectrum analysis'*). Therefore, the computational background to just the scPDSI and AI will be presented in the following paragraphs.

The scPDSI is derived from monthly precipitation, temperature and soil moisture data, taking the local climate into consideration (Wells et al. 2004). Negative and positive values indicate dry and wet conditions, respectively, with greater values implying drier/wetter climatic conditions. The AI is the ratio of monthly precipitation and potential evapotranspiration; it basically indicates dry and wet periods (Mihic et al. 2013).

Information concerning large-scale meteorological patterns and events, i.e. pressure data driving the European large-scale weather phenomena affecting the Carpathian Basin (including the study area), is represented from the gridded reanalysis pressure fields of the European Centre for Medium-Range Weather Forecasts ERA-20C database (Hersbach et al. 2015; Poli et al. 2016), which covers the entire 20th century and the first decade of the 21st century. The Gulf of Genoa, the Icelandic Low and the Eastern European High are the key action centers which influence the weather of the Carpathian Basin to the greatest degree. The average monthly sea-level pressure at the representing grid points was downloaded from the online database of ECMWF.

2.4. **Statistical tools used**

As a first step, the data were preprocessed if the gap between any two data was smaller than one month; the time series was interpolated by a cubic spline and resampled to 14 days to ensure equal spacing without missing data, because this is one of the most basic requirements of periodicity analyses methods. However, if the gap was longer than a month, then the time series was split, and sections at least 10-yrs long were obtained. It is well-known that any interpolation will cause spectral bias and result in a “reddened” interpolated time series (Schulz and Stattegger 1997). The frequency band of the investigations (annual period) is not, however, one in which spectral bias due to the current interpolation is to be expected. From the 57 time-series that are longer than 30 yrs, using 20-yr low-pass filtering, the long-term trend was removed.

In the study, wavelet spectrum analysis (WSA) was used to assess the periodic behavior of the shallow groundwater levels. The basis for WSA is the continuous wavelet transform ($W_n(s)$), which could be defined as the convolution of the data X_n with a scaled and translated version of the wavelet function ψ (Torrence and Compo, 1998; Eqn (1)), which is localized in both frequency and time with a zero mean (Grinsted et al. 2004).

$$W_n^X(s) = \sqrt{\frac{\Delta t}{s}} \sum_{n'=1}^{N} X_{n'} \Psi^* \left[(n' - n) \frac{\Delta t}{s} \right] \qquad (1)$$

Whereby the asterisk (*) represents the complex conjugate, *s* represents the wavelet scale, Δt is the uniform time steps, and *n* is the localized time index. The Morlet mother wavelet (Morlet et al. 1982) is the source function used to generate daughter wavelets by transforming them (Kovács et al. 2010a). The Morlet mother wavelet was chosen because, with respect to other functions (wavelet and e.g. sine), it describes the shape of hydrological signals quite well, while providing a good balance between time and frequency localization (e.g. Gaucherel, 2002; Labat, 2005; Kang and Lin, 2007). The aim of the wavelet transformation is multiple dissociation by decomposing the data in the scaling space, thus making it possible to reveal its self-similarity structure (Hatvani 2014); for an example of the output of WSA see Fig. 3.

WSA provides the basis for wavelet transform coherence analysis (WTC). WTC is able to indicate the areas with a common power of the two variables in the time-frequency space (Torrence and Webster 1999). This was particularly important when the relationship of the periodic behavior of the SGW wells and the climate data was assessed on a regional scale (see **Section** *'Regional driving factors'*)

A close resemblance can be observed between the WTC and the traditional correlation coefficient. Thus, the WTC can be interpreted as the localized squared correlation coefficient in the time-scale plane (Grinsted et al. 2004). However, the fact that WTC indicates a strong common periodic behavior does not directly mean that the assessed two time series will correlate as well to the same degree, because the periodic components must be present in both to show coherence in the WTC output (Kern et al. 2016). Because wavelets are not completely localized in time, WTC produces edge artifacts, thus the introduction of a cone of influence (COI) is suggested in which edge effects cannot be ignored (Torrence and Compo 1998).

In the course of the evaluation, only those signals were taken into account which were significant (α=0.95) and the “phase information” could be interpreted (i.e. the signals were in-phase, in antiphase, or the phase difference could be related to natural phenomena; for details see Rösch and Schmidtbauer 2014a). Moreover, spectral constraints were established by combining WTC and band filtering, thus, the signal-to-noise ratio was successfully improved in certain cases by extracting “focus” bands with a rectangular window.

2.5. **Software used**

R statistical environment (R_Core_Team 2008) was used to perform the calculations – specifically, the WSA was done with the analyze.wavelet function – while the WTCs were generated with the analyze.coherency function of the Wavelet-comp package (Rösch and Schmidbauer 2014b) and the frequency filtering was done using the astrochron package (Meyers 2014). In addition, Surfer 11, QGIS 2.8, Excel 2016 and CorelDRAW X6 were used in the preparation of the paper.

3. **Results**

The first step was to construct a dataset consisting of the time series of the 216 shallow groundwater wells. Then, with WSA, their periodic behaviors were assessed. Consequently, the time periods were extracted in which most of the wells indicated the absence of annual periodic behavior. This pattern was compared with the local climate data and assessed statistically – using wavelet coherence analysis – with the regional climate data (Fig. 4).

3.1. **Annual periodicity**

3.1.1. **Wavelet Spectrum analysis**

As indicated by WSA, clear peaks can be observed in a number of wells with missing annual periodicity (Fig. 5a). The absence of the annual periodicity was not observed in all the wells at the same time. There were four distinct time intervals in which the one-year period was missing in more than 50% of the wells and four additional ones if this boundary is lowered to 25% of the total number of available wells. The most characteristic interval when the annual periodicity was absent peaked in 1974, when more than 90% of the wells did not show annual periodicity. From this point on, the gaps in annual periodicity decreased regarding both the number of wells involved and the duration of the time periods. If the number of wells in which annual periodicity was absent reached 25% of the total number available at that particular time, this was considered a *1-yr absence peak*, where the term “1-yr” refers to the absence of the annual periodicity. The five 1-yr absence peaks sub-divided the full time interval into 11 sections, where periodic and non-periodic time intervals follow each other in tandem (Fig. 5a). If the peaks are assessed using WSA, a significant 8-yr return cycle can be determined (Fig. 5b).

WSA was systematically conducted on all the meteorological parameters that were available and could possibly have been driving the periodic behavior of the shallow groundwater levels. However, either there was no absence of annual periodicity in the meteorological parameters’ time series in the investigated time at all (e.g. mean air temperature, global radiation, cloud cover, relative humidity, potential evaporation), or the period with no annual periodicity (e.g. precipitation, SPI, SPEI) did not overlap the periods with no periodicity in the shallow groundwater wells.

Since groundwater level depends both on the available water income (i.e. precipitation) and water loss (i.e. evaporation), which is also highly affected by temperature, complex climatic indices are more efficient in reflecting the statistical behavior of SGW level time series. Therefore, the AI (Fig. 6a) and the scPDSI (Fig. 6b) were selected from the available meteorological variables.

The results of the AI with respect to annual periodicity show a similar behavior to the groundwater level in the SGW wells, namely, the 1-yr absence peaks of AI were mostly in line with the gaps of annual periodicity in the SGW wells (Fig. 6a).

Because in the derivation of the scPDSI, a 7-8-month average of potential evapotranspiration values is used (Wells et al. 2004), WSA was not able to locate the annual periodicity. However, as expected, the visual comparison between the 1-yr absence peaks and the negative peaks in the scPDSI time series concurred in almost all cases (Fig. 6b). The most characteristic concurrence can clearly be identified in 1974, when the scPDSI is below -4, indicating an extreme drought. The negative scPDI peaks before 1966 and after 2008 (Fig. 6b) were not reflected in the 1-yr absence peaks because of the edge effects causing high uncertainty (Torrence and Compo, 1998) in the wavelet spectra of the SGWs.

4. Discussion

4.1. Local driving factors

The absence of annual periodicity in the SGW wells is also known to have occurred in other areas of Hungary since the mid-2000s (Kovács et al. 2004, Szalai 2011). However, detailed investigation of the study area only began around 2010 (Kovács et al. 2010b). The absence of periodic behavior determined in these studies was significant with regard to the annual, 5-yr, and 11-yr period bands. It should be noted, however, that the methodology used by Kovács et al. 2004 was (i) only capable of determining whether the absence occurred or not, and (ii) was not able to localize the phenomena in time, unlike in the present study using WSA.

The presence or absence of periodic behavior in the SGW levels is in and of itself not informative enough to prepare for future droughts and/or the impact of climate change without knowledge concerning local and regional driving factors. A relationship between standardized precipitation indices and groundwater drought return periods (Kwak et al. 2013), as well as groundwater drought in general, has been uncovered previously (Bloomfield and Marchant 2013; Khan et al. 2008; Kumar et al. 2016; Raziei et al. 2009). Although numerous indices have been examined in the present study, whether or not these are linked to SGW periodicity, their relationships were not present or at best inconclusive. As seen in **Section** *'Wavelet Spectrum analysis'* the most comprehensive link between local meteorological conditions and the periodic behavior of SGW was found using scPDSI and AI. As far as can be ascertained from the literature, the relationship between the periodic behavior of (i) SGW level and (ii) scPDSI and AI as measures of drought, has not been thoroughly investigated before, especially not with a special focus on the absence of periodic behavior. Only a couple of studies exist on this topic, e.g. Edossa et al. (2015), who investigated the question of whether a relationship exists between the periodic behavior of SGW level fluctuations and scPDSI in Africa, or Chen et al. (2002), who determined 7-8 and 13-14 yr periods in the hydrographs, but did not link them to local or regional phenomena.

In the study area here, the connection between drought indicated by scPDSI and AI, and the periodic behavior of SGW levels manifested itself directly in the water levels of the wells. Based on the results, if periodic behavior of the water levels in the wells changes and/or is lacking, it is to be expected that recharge from precipitation will have decrease as well, since it was found that during the 1-yr absence peak periods (Fig. 5a), the average water levels of the wells were indeed lower than that which was to be found between them. This was true in 9 out of the 11 periodic and non-periodic time intervals. During the five 1-yr absence peaks, the average shallow groundwater level was 100.63 m, and 101.18 m between them, indicating a 55 cm difference for all the wells available during the period spanning 1961-2010. This phenomenon can be investigated more closely for each well separately and visualized for the study area using kriging (Cressie 1990, Oliver and Webster 2014) (Fig. 7). For 89% of the wells available, it was true that on average the water levels were lower during the 1-yr absence peaks than the average water levels between them. The average water-level depth in the wells from the topography, i.e. ground surface (Fig. 7a; 1961-2010), was compared to the average difference of water levels between the 1-yr absence peaks (Fig. 5a) and the periodic years for each well separately (Fig. 7b). It became clear that the difference between the water levels of the periodic and the non-periodic intervals was greatest (i.e. the drop in water level was the greatest) in those areas where the water levels measured from the topography were already generally deeper (the north-northeastern part of the study area). These areas overlap with the agriculturally more exploited regions in the study area (Harsányi 2013), which seem to be most vulnerable in this way. The drops in water levels between the periodic time intervals and the 1-yr absence peaks decrease the height of capillary saturation in the non-periodic time intervals, calling for adaptation in terms of species- and crop-yield expectations. Meanwhile, the difference was the smallest in the western part of the study area, where the water levels were, in general, higher (Fig. 7a).

The areas with high SGW levels were the discharge areas (Székely 2003), while the ones where drought – based on this study – has the greatest effect are the recharge areas (Székely 2003). Thus, the link between the non-periodic time intervals and drought (low SGW levels) may be related to the vulnerability of the recharge areas in the northeast (Fig. 7b).

According to Wilhite (1997) “drought is a normal, recurrent feature of climate that may occur everywhere even though its characteristics and impacts vary significantly from region to region”.

To reveal the reasons or driving factors behind the substantial changes in local climatological conditions, the investigation of the possible teleconnections between SGW periodicity and the pressure action centers influencing the area would appear to be necessary.

4.2. Regional driving factors – pressure action center in the Gulf of Genoa

A complex analysis should include the large-scale factors which influence the climate of the Carpathian Basin. The large scale weather patterns are dominated by pressure action centers on a European continental scale (e.g. Barnston and Livezey, 1987). The main high pressure action centers are located over Eastern Europe and near the Azores. Anticyclones often form over these regions and result in calm weather conditions in their vicinity; however, they do not move as fast as the midlatitude cyclones with low central pressure which result in substantial changes in local weather conditions due to their frontal zones (e.g. Barry and Carleton, 2001). Low pressure action centers are located near Iceland (aka the Icelandic Low) and in the Gulf of Genoa (Mediterranean cyclones form here and approach the Hungarian study area). Although Mediterranean mid-latitude cyclones are generally weaker (i.e. the central low pressure of the cyclone is generally less low, and the cyclone size is smaller), with shorter lifetimes than the cyclones originating from the Icelandic Low (Bartholy et al. 2006), their local effects on the weather phenomena and climatic events of the Carpathian Basin are quite strong (e.g. Alpert et al. 1990), resulting in intense precipitation and wet conditions in the target area of this study. This stronger relationship is partially explained by (i) the shorter distance from the Gulf of Genoa to the study area compared to the longer distance between the Icelandic Low and the study area, and (ii) the general patterns of cyclone tracks within the southern part of Europe, which includes the Carpathian Basin too, while the tracks of the Icelandic cyclone centers are usually north of the study area (Kelemen et al. 2015; van Bebber 1891).

Thus, the relationship between the pressure center of the Gulf of Genoa and the study area was proven to be most persistent and strongest out of the three pressure centers studied. The 8-yr return period of the 1-yr absence peaks was compared with the spatial average pressure of the Gulf of Genoa with WTC (Fig. 8a). To enhance the signal-to-noise ratio, the periods under 7 years were removed from the spectrum of both time series, thus, the 8-yr common period was revealed to be present to a significant degree, with the highest power between 1975 and 1995 (Fig. 8a), and in-phase (Fig. 8b) throughout the whole investigated period. This means that when 1-yr absence peaks occurred, the regional air pressure in the Gulf of Genoa reached its maxima, thus, the corresponding occurrences of cyclogenesis in the region were substantially less frequent than usual. This relationship can be explained by the fact that the occurrence of fewer cyclones results in less precipitation and drier conditions along the cyclone paths, including this study area. Climatic conditions are reflected in SGW wells, which can hence be considered as a good indicator of local climatic change. Those large-scale climatic processes projected well by global climate models (for which quite high confidence has already been built) enable the prediction of finer-scale regional/local phenomena. These physically-based predictions should be considered as key input information to develop appropriate adaptation and mitigation strategies on regional/local scales. Due to the agricultural role of the study area, such strategies are especially important in reducing the vulnerability of local economies.

In the past century-long period, only slight changes can be detected as a synoptic-scale atmospheric impact of global climate change (Bartholy et al. 2009). Nevertheless, this century may result in greater changes of cyclone activity and cyclone tracks. Projected future cyclone climatology over Europe is analyzed by Muskulus and Jacob (2005) using a single climate model and one specific scenario. Their results suggest more Mediterranean cyclones overall, but fewer strong cyclones. The resulting precipitation is highly dependent on the strength of the cyclone; the stronger the cyclone (i.e. the lower the central air pressure), the greater the amount of precipitation along the cyclone track. However, a comprehensive assessment of future conditions would require several climate models and different scenarios.

5. Conclusions

With the complex hydrogeological/meteorological model developed in this study, non-periodic time intervals were found in the shallow groundwater levels (in 216 wells) of an agriculturally important study area in Central-Eastern Europe. These statistical behaviors were then proven to have a clear pattern of coincidence with drought indices (scPDSI and AI). The time intervals with the annual periods missing in at least 25% of the available shallow groundwater wells were (i) therefore linked to drought conditions, (ii) proven to have significantly lower water levels mostly in the recharge areas of the studied sector, and (iii) linked to the maxima of the regional air pressures in the Gulf of Genoa. In this sense, the study found an evident but as-yet undocumented link between the (non)-periodic behavior of SGW levels and drought indices, and also for the first time described a relationship between SGW periodicity and regional circulation patterns. Thus, on the basis of the available climate model projections, estimated changes in the large-scale circulation patterns provide key useful information concerning local climatic changes, including possible changes in drought frequency, duration, and severity. Since drought-related characteristics and their future changes strongly affect local agricultural production, necessary adaptation strategies on either national or regional levels should take into account the predictions of drought-related climatic conditions. If plant or crop species to be cultivated in a specific region are selected according to the modified climatic conditions, many potential local problems induced by global warming can be avoided.

Acknowledgements

The authors would like to thank the data providers: CARPATCLIM Database © European Commission – JRC, 2013; ECMWF and the Water Directorates of the region. In addition, we are grateful for the support of the MTA "Lendület" program (LP2012-27/2012), the János Bolyai Research Scholarship of the Hungarian Academy of Sciences and the "Agrárklíma2" Project (VKSZ_12-1-2013-0034). This is contribution No. 52 of 2ka Palæoclimate Research Group. The authors appreciate the contributions of the Early Career Hydrogeologists' Network (ECHN) of the International Association of Hydrogeologists (IAH) and the journal editorial team and reviewers.

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FIGURE CAPTIONS:

Fig. 1. The location of the study area in Central-Eastern Europe – the Carpathian Basin, in the north-eastern part of the Great Hungarian Plain (the relief map is based on Horváth et al. 2006). The parameters used in the study are the gridpoints of the ERA20C database representing the pressure center in the Gulf of Genoa (*red crosses*, upper-left map), the shallow groundwater observation wells (*red dots*, lower-right grid-map) and the gridpoints of the CarpatClim database, representing the meteorological data (*grey crosses*, lower-right grid-map). [Codes for countries adjacent to the study areas -- FR: France, CH: Switzerland, AT: Austria, SI: Slovenia, HR: Croatia, RS: Serbia, RO: Romania, UA: Ukraine, SK:Slovakia]

Fig. 2 Walter-Lieth diagrams for **a** 1961-2010 (annual mean temperature 10.4 °C and precipitation 555 mm yr^{-1}) and **b** 1971-1974 (annual mean temperature of 10.4 °C and precipitation 492 mm yr^{-1}). Both cases represent the whole study area

Fig. 3 An example of the WSA output, with: **a** the water levels of a SGW well (*blue dots*); **b** the 20-yr low-passed 14-day resampled time series of the same well**;** and **c** its power spectrum density graph. The 5% significance level against red noise is shown as a *thick black contour*. The *black shaded areas* mark the cone of influence (COI). The *black dashed horizontal line* indicates where the annual periodicity could be found (e.g. Jan 1961 – May 1970; Nov 1976 – Oct 1981)

Fig. 4 Flowchart describing the steps of the analyses. WTC refers to wavelet transform coherence and WSA to wavelet spectrum analysis

Fig. 5 **a** Summary figure for the number of wells where the annual periodicity was missing, indicating the 1-yr absence peaks, where 100% equals the total number of wells available in that particular year. **b** WSA result of the 1-yr absence peaks, where the *dashed line* indicates their 8-yr return period

Fig. 6 **a** Summarized WSA result for the AI, in which the *horizontal lines* represent a given grid point's time series, and **b** scPDSI time series compared to the 1-yr absence peaks. The *red ellipses* indicate the concurrence of the 1-yr absence peaks and the minima of the scPDSI. If a given line in **a** is red, the annual periodicity was present; if it is grey the annual periodicity was not present in the grid point's time series.

Fig. 7 Isoline maps of **a** average water depths from ground surface, and **b** average difference in water levels between the 1-yr absence peaks and the periodic years for each well separately for 1960-2010, measured in meters. The maps were derived using ordinary point kriging with the isotropic variogram models **a**: Co=0.001; Co+C=1.986; a=14400 m and **b**: Co=0.0052; Co+C=0.0494; a=5600 m (for details see Oliver and Webster 2014)

Fig. 8. The WTC graphs of the 1-yr absence peaks and the monthly average air pressure in **a** the Gulf of Genoa and **b** phase difference. *Horizontal black dashed line* indicates the 8-yr periodicity.