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REPORT

Climatic and geologic controls on the piezometry of the Querença-Silves karst aquifer, Algarve (Portugal)

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Abstract Karst aquifers in semi-arid regions, like Querença-Silves (Portugal), are particularly vulnerable to climate variability. For the first time in this region, the temporal structure of a groundwater-level time series (1985–2010) was explored using the continuous wavelet transform. The investigation focused on a set of four piezometers, two at each side of the S. Marcos-Quarteira fault, to demonstrate how each of the two sectors of the aquifer respond to climate-induced patterns. Singular spectral analysis applied to an extended set of piezometers enabled identification of several quasi-periodic modes of variability, with periods of 6.5, 4.3, 3.2 and 2.6 years, which can be explained by low-frequency climate patterns. The geologic forcing accounts for ~15 % of the differential variability between the eastern and western sectors of the aquifer. The western sector displays spatially homogenous piezometric variations, large memory effects and low-pass filtering characteristics, which are consistent with relatively large and uniform values of water storage capacity and transmissivity properties. In this sector, the 6.5-year mode of variability accounts for ~70 % of the total variance of the groundwater levels. The eastern sector shows larger spatial and temporal heterogeneity, is more reactive to short-term variations, and is less influenced by the low-frequency components related to climate patterns.

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Introduction

The impact of climate variability on groundwater systems is central to the successful management and sustainability of water resources. The issue is even more important in semi-arid regions like the Algarve (Portugal), where climate models predict a progressive reduction in water availability during the 21st century, due to diminished precipitation and increased potential evapotranspiration (Santos and Miranda 2006). Strong changes in the seasonal distribution of precipitation, with a concentration of rainfall during the winter season and an increase in the frequency and intensity of droughts, in conjunction with warming, are expected to have a profound impact on water resources (Santos and Miranda 2006; Stigter et al. 2011). In fact, a reduction in aquifer recharge of ~25 % is expected towards the end of the century in Mediterranean semi-arid areas, as shown by Stigter et al. (2014) for case studies in south Portugal, Spain and Morocco. Nonetheless, there is still limited knowledge on the potential consequences of climate variability on aquifer levels. In the Algarve, climate scenarios have been included in previous studies that examined the influence of aquifer properties and the spatial and temporal distribution of recharge and abstraction on sustainable yields (Hugman et al. 2012; 2013; Stigter et al. 2014). Climate projections were translated into hypothetical distributions of recharge throughout the hydrological year (concentrated versus spread) which were then input to a numerical groundwater flow model to produce forecasts. The consideration of these influences is appropriate for operational decisions at seasonal to annual time scales, but neglects the long-term effects of climate variability.

Large-scale atmospheric and oceanic circulation patterns such as, for example, the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), are responsible for several quasi-periodic modes of variability, with time scales varying from several years to several decades, that are partially coincident with low frequency oscillations observed in hydrologic time series (Dettinger et al. 1998; Hanson et al. 2004; Dickinson et al. 2004; Gurdak et al. 2007; Holman et al. 2011; Tremblay et al. 2011; Kuss and Gurdak 2014). Previous studies on the influence of climatic patterns on water resources in Portugal have established a causal relationship between the NAO variability and the observed inter-annual variations of precipitation, river flow and surface water storage (Goodess and Jones 2002; Trigo et al. 2004; Jerez et al. 2013). Gámiz-Fortis et al. (2008) used singular spectral analysis to identify the main oscillatory components in the streamflow series of the Douro, Tagus and Guadiana rivers. To the authors' best knowledge, no similar studies have been published involving groundwater data from Portuguese aquifers. In fact, the links between groundwater levels and climate forcings remain largely unexplored in this region. This work presents the first analysis of piezometric levels in a karst aquifer in Portugal aiming to characterize the climate-induced variability.

Climate-induced variability is obviously affected by local geological conditions, particularly in karst aquifers like the Querença-Silves (QS), characterized by spatially heterogeneous geomorphologic and hydrogeologic properties (Monteiro et al. 2006; Hugman et al. 2012). The contribution of internal (geologic) forcings to the spatio-temporal variability of piezometric levels in karst aquifers has been previously quantified in the Upper Normandy, France (Slimani et al. 2009; El Janyani et al. 2012). As pointed out in those studies, a common feature of karst aquifers is the co-existence of a dual flow system, assisted by the fissured matrix (responsible for the capacitive function) and the conduit drainage network (responsible for the transmissivity function). In the QS aquifer, these properties have been mapped by inverse calibration of a finite element model (Monteiro et al. 2006; Hugman et al. 2012; 2013), but their contribution to the variability of the aquifer water table remains to be determined. The primary goal of this study is to quantify the relative contributions of climate and geology to the spatial and temporal variance of the groundwater levels in this aquifer. These contributions are identified and evaluated by applying wavelet transform methods and singular spectral analysis to the groundwater time series.

Hydrogeological setting

The QS aquifer system (Fig. 1a) is the largest (324 km^2) and most important groundwater reservoir in the Algarve region (south Portugal). This region has a temperate climate with dry summer (Csa Köppen classification), monthly average temperatures between 12 and 24 °C and a total annual rainfall of about 500 mm/year (1981–2010 climate normal). Most of the annual precipitation occurs during the 3-month winter season, while the summer months (June–August) are extremely dry, contributing to only 6 % of the annual precipitation (Miranda et al. 2002). As typically observed in southern Iberia, the precipitation in the study area is characterized by large values of inter-annual variability, with large disparities between wet and dry years (Santos and Miranda 2006).

The QS aquifer is formed mostly by Early and Middle Jurassic (Lias-Dogger) carbonate sedimentary rocks, which span from the Arade River estuary (to the west) to the village of Querença (to the east). It is limited to the north by the Triassic-Hettangian rocks and to the south by the Algibre thrust, a major thrust in the Algarve Basin separating the lower and upper Jurassic formations (Monteiro et al. 2006; 2007 and Terrinha 1998). The stratigraphy of the Lias-Dogger formation shows that the aquifer thickness increases from north to south, reaching average values of around 600 m (Manuppella et al. 1993). The most important fault in the QS aquifer is the S. Marcos-Quarteira fault (Fig. 1), which is a major regional structure inherited from the Variscan Orogeny. This NNW–SSE fault controlled the evolution of the Algarve basin during the Mesozoic, separating it into two blocks that evolved differently (Dias 2001). The fault also plays an important role on the regional groundwater circulation, as it apparently divides the QS aquifer into two compartments with distinct hydrogeological behaviour. The compartments can be identified from the spatial distribution of the piezometric isolines (Fig. 1a). The region to the east of the fault is characterized by closely spaced isolines, corresponding to relatively high (~15 %) hydraulic gradients (Almeida 1985), with an irregular contour pattern that is largely controlled by the topography. This pattern determines spatially varying groundwater flow directions, which are, on the whole, mainly directed towards the west. In contrast, the compartment to the west of the fault is characterized by small (~1.5 %) hydraulic gradients, smooth piezometric isolines and a predominant E–W flow direction. Given the evidence, the S. Marcos-Quarteira fault has been suggested to act as a low-permeability hydraulic barrier (Andrade 1989; Almeida et al. 2000).

The aquifer water balance has been thoroughly studied by several authors (e.g. Almeida 1985; Almeida et al. 2000; Vieira and Monteiro 2003). The most recent studies obtained a detailed spatial distribution of recharge and estimated that the average annual recharge is 45 % (100 hm^3 year^{-1}) of the rainfall (Oliveira et al. 2008; 2011). As a result of several monitoring and modelling studies, mainly carried out at the University of Algarve, the groundwater flow pattern of the QS is reasonably well known (e.g. Monteiro et al. 2003; Vieira and Monteiro 2003). Groundwater abstraction in the region

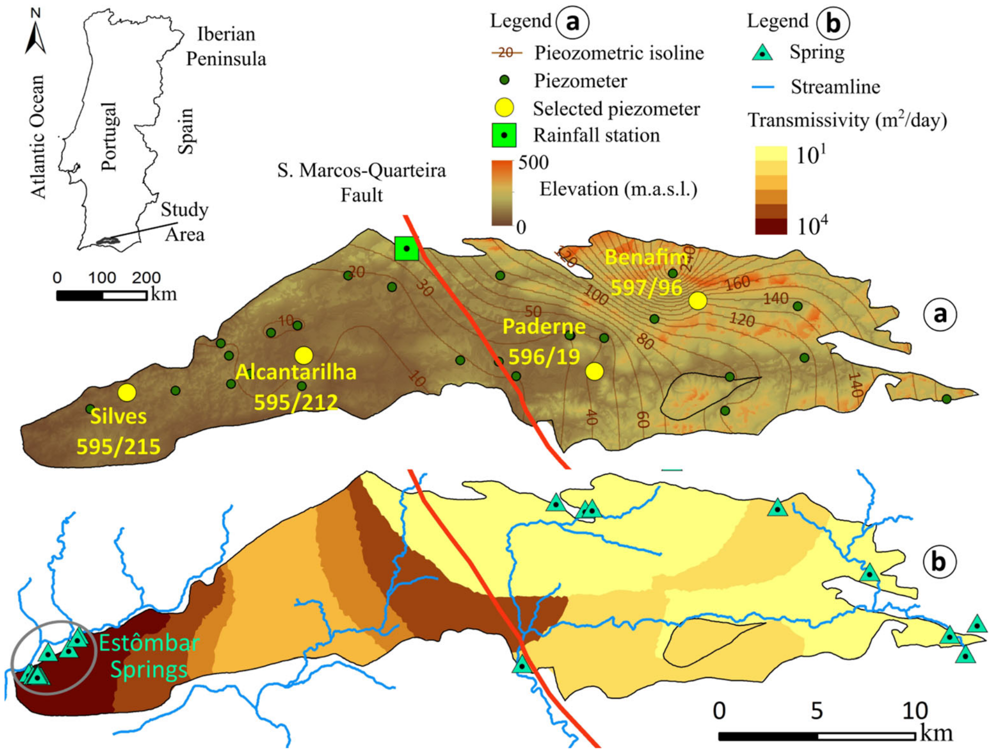

Fig. 1 Location of the Querença-Silves aquifer and the S. Marcos-Quarteira fault (*red line*) which divides the aquifer into two sectors. **a** Location of the four piezometers selected for analysis and the terrain elevation. The average piezometric isolines are computed from the average hydraulic head observed at the total 28 piezometers using the krigging linear method of interpolation. **b** Location of the Estômbar springs, among others, the stream network and the equivalent transmissivity distribution of the aquifer as calculated by Hugman et al. (2012)

has strongly decreased since the 1990s, due to the implementation of a multi-municipal system of urban water supply based on dams. However, the historical piezometric records obtained by the available monitoring system do not display any important changes in the regional flow pattern, as inferred from the spatial distribution and temporal evolution of the observed hydraulic heads, which suggests that, in this aquifer, the impact of anthropogenic processes on groundwater level fluctuations has not been significant. The numerical groundwater flow model presented by Monteiro et al. (2006) was the first to focus on the calibration of the hydraulic parameters, in particular of the transmissivity (corresponding to an equivalent porous media of a karst system). Stigter et al. (2009) performed simulations of hypothetical extraction scenarios in order to optimize a regional groundwater/surface-water integrated supply system, in which the distribution of the irrigation wells was refined according to their location. Attempts to synthesize the hydraulic behavior of the QS aquifer lead to the definition of 23 transmissivity zones (Fig. 1b) estimated by inverse modelling (Hugman et al. 2012; 2013). For each one of these zones, a reasonable fitting of field data is obtained using a single value of transmissivity. The discharge occurs mainly through a small number of large springs, called the Estômbar springs, located at the border of the aquifer with the Arade River (Fig. 1b).

The different hydrogeological behavior in the east and west side of the S. Marcos-Quarteira fault becomes evident when the hydraulic head variations are plotted as a function of longitudinal distance (Fig. 2), considering all the 28 piezometers in the area. The hydraulic head variations are not only larger as they are much more heterogeneous in the eastern sector of the aquifer. These observations provide a qualitative measure of the spatial variability of the system which is indeed much larger in the compartment to the east of the S. Marcos-Quarteira fault.

Data and methods

Time series data

In order to assess the climate forcing, the groundwater level records need to be long enough to capture inter-annual and inter-decadal fluctuations. The QS aquifer has few long-term records that fulfil this requirement, with 1984 being the starting year of the most complete (up to 2013) datasets. The piezometer selection criteria was primarily based on the length and completeness of the water level records, and only secondly determined by their spatial location: two piezometers lie on the west side of the Quarteira fault (Alcantarilha and Silves) and other two on the east side (Benafim and Paderne). The locations are meant to represent the two kinds of hydrogeological conditions found in the QS aquifer. The monthly groundwater level time series span from January 1985 to December 2010 (26 years long) and were obtained from the Portuguese National System for Water Resources Information SNIRH site (Sistema Nacional de Informação de Recursos Hídricos (SNIRH 2015). Although outside the

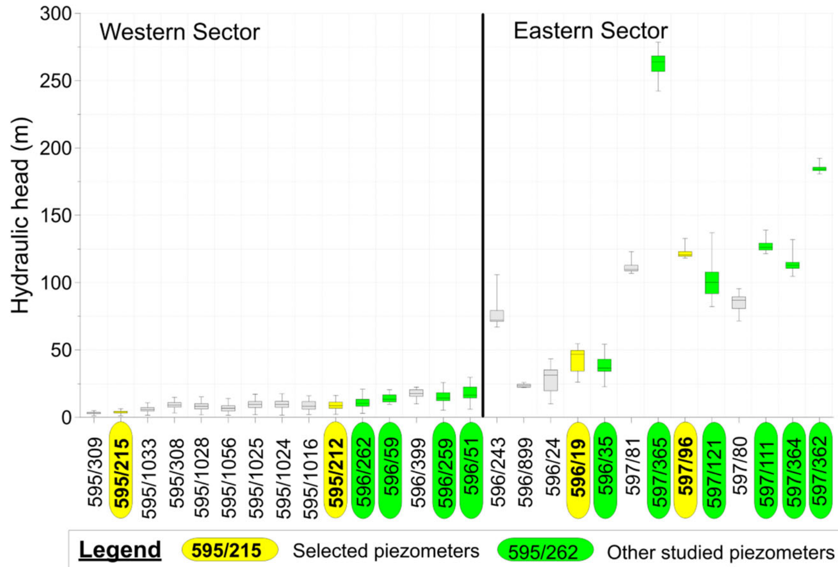

Fig. 2 Box and whisker plot of the available piezometric level (m a.s.l.) data between 1985 and 2010. The 28 piezometers on the *x-axis* are arranged according to their longitudinal distance to the westernmost observation point (Estômbar spring). The *black vertical thick line* represents the location of the S. Marcos-Quarteira fault. The edges of the boxes are the 25th and 75th percentiles, and the whiskers extend to the minimum and maximum observed groundwater levels

main scope of this report, the relation between precipitation and groundwater level is succinctly explored using one rainfall station (Messines). Monthly precipitation data for this station were also obtained from the SNIRH site, but the available data only spans from January 1985 to December 2009.

Time series analysis

The groundwater time series were investigated using several analytical techniques in order to characterize the temporal structure and the periodic components of their signal. The applied methods were: (1) computation of autocorrelation functions, (2) simple spectral analysis, (3) continuous wavelet transform and (4) singular spectral analysis. Each technique has its own purpose and advantages and their combination provides a more robust estimate of the statistical properties of the aquifer regarding its groundwater level variability. Typical pre-processing steps such as searching for outliers, interpolation for estimating missing values, detrending and normalization by standard deviations were carried out before the analysis.

1. Autocorrelation functions represent the linear dependence of an event on the subsequent values of the time series, and thereby are usually computed to quantify the memory effect. The auto-correlogram is the plot of the correlation of a time series with itself after being shifted by increasingly larger time intervals (lags). The time lag corresponding to an autocorrelation coefficient of 0.2 is referred to as the memory effect (Mangin 1984). Although some authors argue that the memory effect should be inferred from the slope (rate of decrease) of the auto-correlogram (Massei et al. 2006), rather than from a single value such as 0.2, the two approaches applied to the QS dataset lead to identical conclusions.
2. Simple spectral analysis is classically used to obtain the energy spectrum, a plot of the variance of a time series as a function of wavenumber or frequency. It is calculated from the Fourier transform of the autocorrelation function normally using a windowing function to reduce spectral leakage. One of the advantages of simple Fourier spectral analysis is that it allows to visualize the global statistics of the time series in terms of scale invariants regimes (e.g. Mandelbrot 1982; Lovejoy and Schertzer 2013). Multifractal behavior can be identified when the log-log plot of the energy spectrum can be broken in more than one interval (range of frequencies), each interval being fitted by a straight line with a different slope (power law exponent). There is a growing body of evidence showing that groundwater levels may show scale-invariant, or fractal, behavior over a wide range of time scales (e.g. Zhang and Schilling 2004; Little and Bloomfield 2010; Liang and Zhang 2013). Given the time scale of this study it seems appropriate to investigate if there is one scaling regime in the low frequencies, representing the response to long-term climate variations, and another on the high frequencies, representing the short-term response to the meteorological conditions.
3. A comprehensive review of the applications of the wavelet transform in hydrology time series has recently been made by Sang (2013). This study uses the continuous wavelet transform (CWT) in order to further explore the temporal structure of the groundwater level records. In contrast with classical Fourier analysis, which implicitly assumes that the underlying physical processes are stationary, the CWT is suited to the analysis of signals that have temporal variations in both amplitude and frequency.

Its main advantage over classical spectral methods is that it is able to reveal the time evolution of the dominant modes of variability, being as such specially tailored for the detection of localized or intermittent events. The CWT is defined as the convolution of the signal with a scaled and translated version of the wavelet function (Daubechies 1990). The method is implemented using the Morlet wavelet and the algorithm described in Torrence and Compo (1998). In the case of the Morlet wavelet, the scale and the equivalent Fourier period are practically identical, so the two terms are used synonymously. The wavelet spectrum, defined as the absolute value squared of the wavelet transform, is constructed to display the distribution of the variance of the time series at each scale, as a function of time. A clear picture of the net changes in variance over the whole recording period is provided by the global wavelet spectrum, which is a time average of the wavelet spectrum.

4. The singular spectral analysis (SSA) is a form of principal component analysis that is used to detect periodic signals and extract the dominant frequencies in short and noisy time series. Following the methods outlined by Dettinger et al. (1995) and Hanson et al. (2004), this technique is applied to decompose the detrended and normalized groundwater level records into principal components (eigenvalues) that represent the projection of the original time series onto empirical orthogonal functions (eigenvectors). The calculations are carried out by diagonalizing a lagged covariance matrix (Vautard et al. 1992; Ghil et al. 2002). The main advantage of SSA is that it allows the reconstruction of the original record using a linear combination of the most statistically significant oscillations. Hanson et al. (2004) showed that the variability in most hydrological time series can be described in terms of the first 10 reconstructed components (RCs). In this study the chi-square significant test is applied to isolate the most significant reconstructed components of the variability modes, and then compute their relative contribution to the total variance of the time series.

The relation between groundwater level and monthly precipitation in the QS area is examined using both linear regression, with a two-tailed significant t test at the 95 % confidence level, and lag correlation analysis. First, the monthly precipitation times series needs to be transformed into cumulative departures, detrended and normalized using the methods described by Hanson et al. (2004). The lag correlation analysis, which gives the correlation coefficient as a function of the lag between the two time series, allows identifying the lag of maximum correlation between the causal process (precipitation) and the system response (groundwater level).

Results

The four raw piezometric time series are displayed in Fig. 3 and their main statistical parameters are summarized in Table 1. All piezometers show annual fluctuation superimposed on multi-year periods of high and low groundwater level stands. On the long-term (over 26 years), all piezometers show slight negative tendencies on the mean groundwater level, the most significant (−0.018 m/month) being found in Alcantarilha and Paderne. This long-term trend is in agreement with an important, but not statistically significant, decrease in the regional average total precipitation observed in Portugal in the period 1976–2007 (De Lima et al. 2014). The most striking observation is the clearly distinct oscillatory pattern in the western and eastern sectors of the aquifer. Alcantarilha and Silves, in the western sector, present similar regular fluctuations with smoother piezometric variations, while Benafim and Paderne, in the eastern sector, display relatively heterogeneous and sharp head variations, with fast rise and recession events. The eastern compartment of the QS aquifer is thus characterized by a relatively higher temporal and spatial variability than its western counterpart.

Figure 4a shows the raw monthly precipitation data recorded at the Messines rainfall station, which lies exactly in between the two sectors. After transforming the raw precipitation data into monthly cumulative departures (Cdep) the linear regression analysis between Cdep and the groundwater level time series (truncated for the 1985–2009 period) was performed for each one of the four selected piezometers. The obtained linear regression coefficients vary between 0.6 and 0.75 revealing that, despite the local geological complexities and other potential perturbing factors, there is a strong positive correlation between the groundwater levels and the rainfall in the two sectors of the aquifer. The results of the lag correlation analysis indicate that the time lag of maximum correlation is 1 month in both sectors (Fig. 4b).

The east–west split in hydrogeological behavior of the QS aquifer is confirmed in quantitative terms in several ways. A first quantitative estimate of the timescale of the natural attenuation, or filtering properties of the aquifer, is provided by the autocorrelograms (Fig. 5). The so-called memory effect obtained using this method is 15–16 months in the western sector (Alcantarilha and Silves) and 11–13 months in the eastern sector (Benafim and Paderne). The longer memory effect that characterizes Alcantarilha and Silves is consistent with the smoother variations of the hydraulic head observed in Fig. 3. Longer memory effects, which denote high inertia to changes and low-pass filtering properties, often reflect thick surficial formations (longer times of recharge) or significant amounts of water storage/volume in the karst network. In the QS aquifer, the longer memory effects in the western compartment are

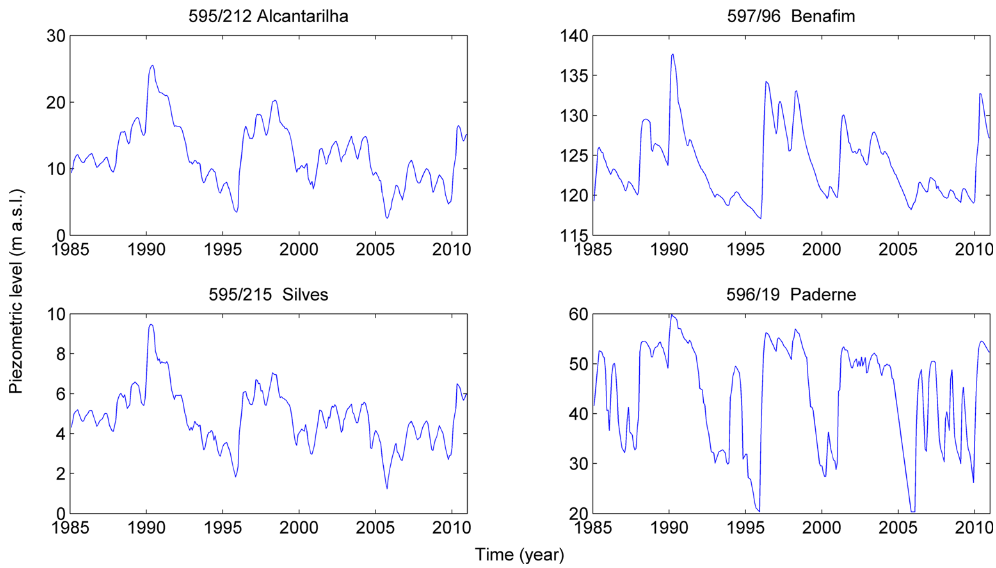

Fig. 3 Monthly groundwater levels at four piezometers from the two main sectors of the Querença-Silves aquifer: *Alcantarilha* and *Silves* (western sector) and *Benafim* and *Paderne* (eastern sector)

mainly attributed to larger water storage capacities that have been recognized in this sector in previous studies (e.g. Hugman et al. 2012).

The simple spectral analysis of the four piezometric records (Fig. 6) reveals relatively consistent peak frequencies corresponding to cycles of 1, 4.3 and 6.5 years. In the eastern sector there is also a peak at 2.5 years, which is not observed in the west. The peaks in the spectrum indicate that a significant amount of the variance of the groundwater level record is contained in these frequencies. The sharpest peak is associated with the annual precipitation cycle (1/12 month frequency). The multi-annual periodicities are related to low-frequency climate signals and will also emerge from the continuous wavelet transform and singular spectrum analysis methods. Their association with large-scale climate teleconnections patterns have already been recognized in other Mediterranean aquifers (e.g. Andreo et al. 2006; Massei et al. 2007; Luque-Espinar et al. 2008; Slimani et al. 2009) and will be analyzed in more detail in the next section.

Figure 6 also enables the definition of scaling regimes by fitting the energy power spectra with an empirical power law with exponents β. In Alcantarilha and Silves, the spectral slope remains unchanged on both sides of the annual peak, that is, there is only one scaling regime, with β=2.4–2.6. In general, the lower the magnitude of the spectral exponent, the higher the variability in the data. As the magnitude of the β exponent is similar in these two piezometers, these results quantitatively demonstrate that a similar amount of variability is present in Alcantarilha and Silves. In contrast, in Benafim it is possible to detect two scaling regimes, with the break occurring at the 1/12 month frequency. In this case, it is possible to separate the short-term response to intermittent meteorological conditions from the low frequency response to multi-annual climate variations. The scaling behavior of Paderne is not clear. It is similar to Benafim in the long-term range, but in the short-term, like the two piezometers in the western sector, it lacks a distinctive response to high-frequency variations. The difference between the energy power spectra of Benafim and Paderne, despite being in the same sector, reflects the compartmentalized structure of this part of the Aquifer. Benafim, at relatively high elevation—182 m above sea level (m a.s.l.)—is an upstream site, whereas Paderne (44 m a.s.l.) is close to a spring outlet that defines one of the downstream boundaries of the groundwater basin. The eastern sector is indeed subdivided into a large number of more or less independent units, which result from limitations on flow paths

Table 1 Summary of hydrologic and statistical parameters of the data (1985–2010)

Piezometer	Topographic elevation (m a.s.l.)	Mean piezometric level (m)	Range of water-level fluctuations (m)	Memory effect (months)	Scaling exponent (β)
Alcantarilha (595/212)	47.02	12.16	2.50–25.55	16	2.6
Silves (595/215)	63.76	4.82	1.22–9.46	15	2.4
Benafim (597/96)	182.52	123.91	117.04–137.69	13	1.7 and 3.8
Paderne (596/19)	75.34	43.83	20.34–59.94	11	1.8 and 2.1

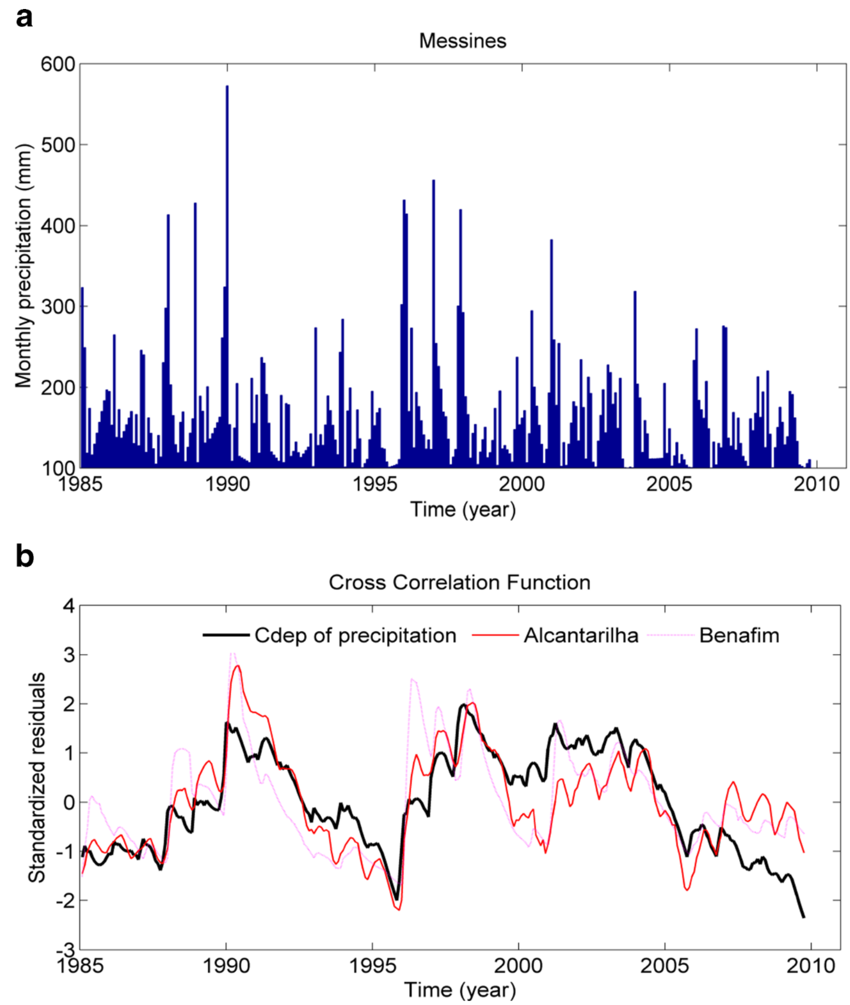

Fig. 4 Relation between precipitation and groundwater levels. **a** The monthly precipitation at the Messines rainfall station. **b** The monthly values of normalized residuals of cumulative departure of precipitation and the normalized residuals of groundwater level at Alcantarilha and Benafim lagged 1 month

generated by stratigraphic and lithologic factors and a less developed karst when compared with the western sector.

The normalized wavelet power spectra of the groundwater levels, computed using the continuous wavelet transform method, are displayed in Fig. 7. Each diagram depicts the temporal distribution of the power (variance) of the time series as a function of period, over the 26 years of analysis, in a color scale that goes from blue (minimum) to brown (maximum). The 5 % significant levels, computed using a chi-square test against a red noise spectrum as the null hypothesis, are displayed as white contours. Also shown is the cone of influence (black parabolic lines) which delimits the regions where

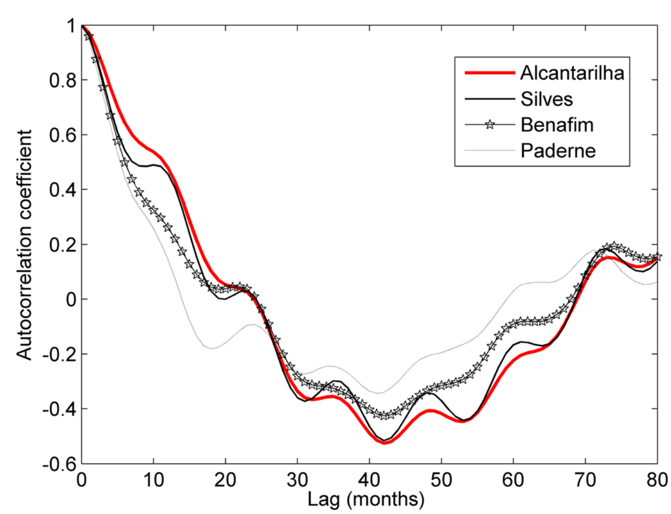

Fig. 5 Autocorrelation functions of the four piezometric time-series (total window of 312 months and lag step of 1 month) truncated in the 0–80 lag range

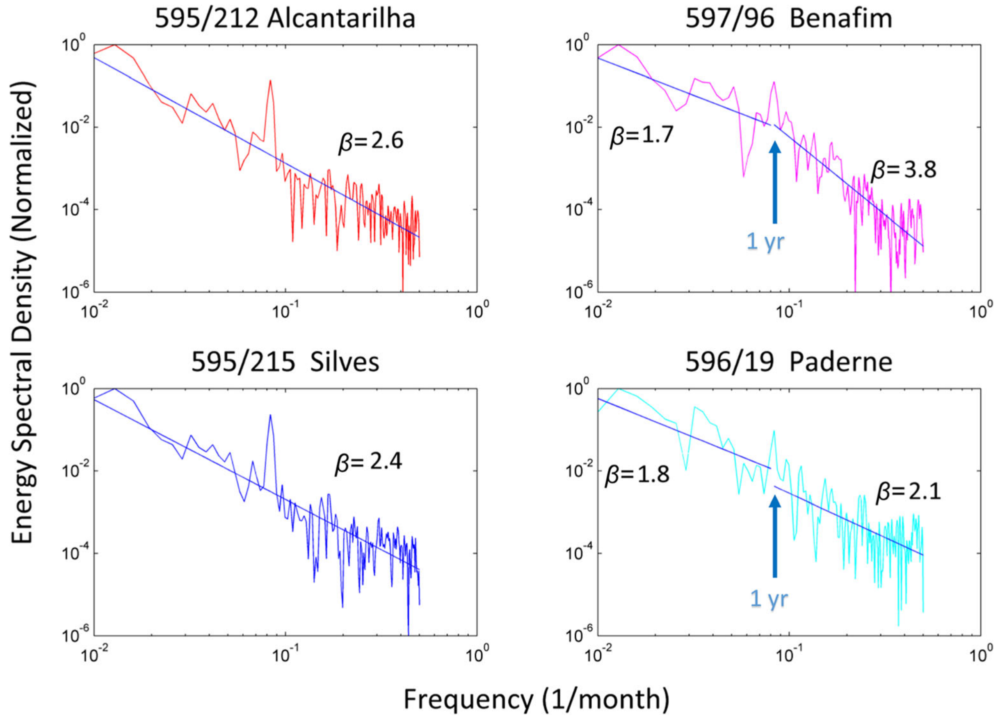

Fig. 6 Energy (power) spectra of the four groundwater level records in a log-log plot. The slopes of the lines, computed from linear regression, correspond to estimates of the empirical β exponents defining scaling regimes

the edge effects, due to zero padding, make the results less reliable. The comparison of the four spectra immediately exposes the east–west division of the aquifer. The most remarkable difference between the two sectors occurs in the 2–4-year band. These modes of variability are intermittently quite important in the east, the most extreme example being

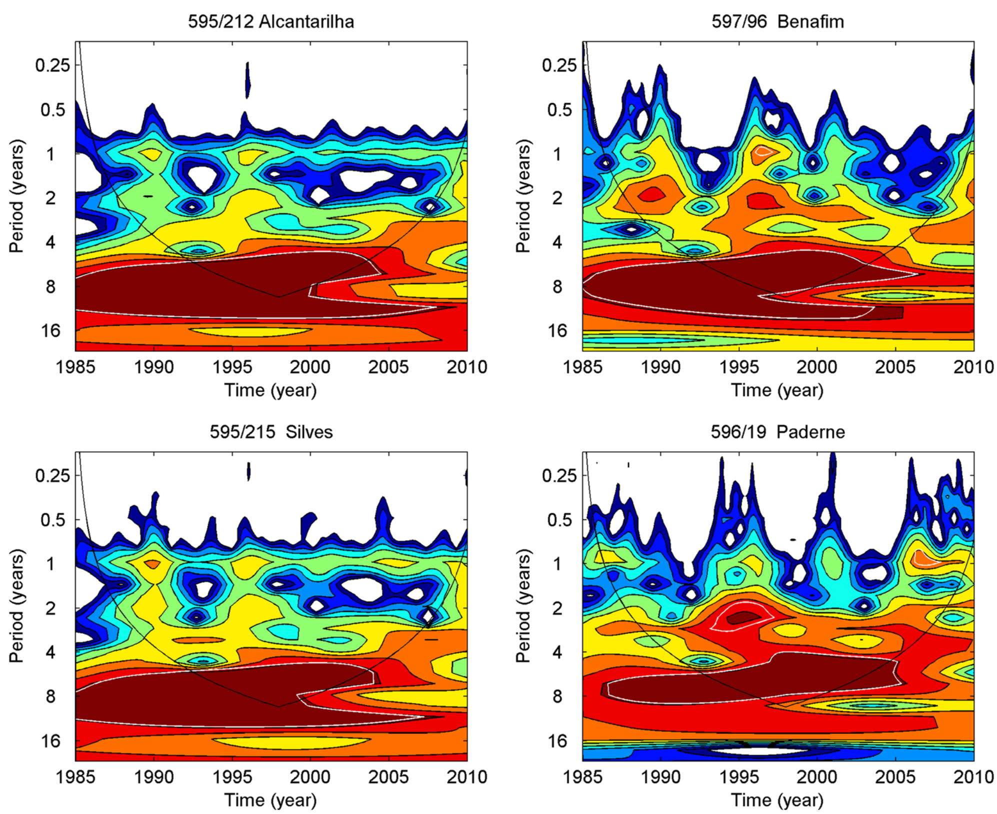

Fig. 7 Local wavelet power spectrum of the four time-series computed using a Morlet wavelet and normalized by $1/\sigma^2$. The *white* contours enclose regions of greater than 95 % confidence levels. The *black lines* delimit the cone of influence, where zero padding has reduced the variance

the peak at ~2.5 years located in Paderne and centered on 1996. The presence of these modes of variability in the east, but not in the west, is discussed in the next section.

Despite the local differences, the most important aspect that emerges from Fig. 7 is the power concentration in the 5–13-year band, within the 95 % confidence interval, present at all sites. The 5–13-year variance can be mainly attributed the North Atlantic Oscillation (NAO) which is the dominant mode of atmospheric variability at mid-latitudes in the North Atlantic. The spectrum of the winter (December–March) NAO index, is indeed characterized by a slightly enhanced power in the 6–10 year band, particularly on the last quarter of the 20th century (Hurrell and Van Loon 1997; Hurrell et al. 2003). At smaller scales, with less amounts of energy, one can observe several scattered peaks at periods of 1 year. The strongest patches occur in 1990, 1996 and 2000, which were anomalously wet years (Miranda et al. 2002). It is also interesting to note the strong attenuation of power, or lack of variance, in the 1–2-year band centered on 2004, but extending for almost a decade in the western sector. This anomaly is attributed to the outstanding drought that affected the Iberian Peninsula in 2004–2005 (García-Herrera et al. 2007).

Figure 8 displays the time-averaged wavelet spectrum over the whole period (26 years) of record, the so-called global wavelet spectrum, computed using the method described in Torrence and Compo (1998). When averaged over time only two variability modes have enough persistence and amplitude to remain statistically significant. The first and more conspicuous has a period of 6.5 years. The second, with a period of 11–13 years, is also statistically significant at the 5 % level at three (Alcantarilha, Silves and Benafim) of the four sites.

The relative contribution of the 6.5-year mode of variability to the total variance of the time series, along with other leading modes, has been computed using the singular spectral method. The SSA was applied on the lagged-covariance matrix based on the Vautard et al. (1992) algorithm, using an $M = 60$ month window length, which is approximately 1/5 of the time series length, as recommended by Ghil et al. (2002). The oscillatory modes derived from the SSA corresponding to the first six empirical orthogonal functions (EOFs), are listed in Table 2 for Alcantarilha and Benafim. These are enough to represent the western and eastern sector of the aquifer, respectively, since the EOFs of Silves and Paderne (not shown) are the same. EOFs 1 and 2, as well as EOFs 5 and 6 in Alcantarilha, and EOF 4 and 5 in Benafim, are in quadrature. The most robust result is the persistence of the first EOF pair, corresponding to the 6.5 years periodicity, over the whole aquifer. The other leading scales of variability correspond to a set of oscillations with associated periods of 4.3 years (EOF 3), 3.2 years (EOF 4) and 1 year (EOFs 5–6) in Alcantarilha, and 13 years (EOF 3), 2.6 years (EOFs 4–5) and 2 years (EOF 6) in Benafim. Overall, these results are in agreement with those found using the simple spectral analysis and the continuous wavelet transform. The amount of variance attributed to the 6.5-year mode of variability (EOFs 1–2) is approximately 70 % in the western sector (73 % in Alcantarilha and 68 % and Silves). In the eastern sector, the same components explain approximately 55 % of the total variance (59 % in Benafim and 52 % in Paderne). The contribution of the annual cycle component to the total variance is approximately 7 % in both sectors (EOFs 8–9 in Benafim, not shown).

The reconstruction of a set of significant components, the reconstructed components (RCs), is carried out by linearly combining the EOFs and the principal components. The RCs have the property of capturing the phase of the time series and can be superimposed with the original data on the same timescale. Here, only the most important EOF pairs in each one of the piezometers are used: 1–2 and 5–6 in Alcantarilha, and 1–2 and 4–5 in Benafim, (Fig. 9). In the terminology of Ghil et al. (2002) each of these two RCs form the robust skeleton of the Lorenz attractor (Lorenz 1963). The composite of selected RCs contain 80 and 70 % of the total variance of the groundwater level record, in Alcantarilha and Benafim, respectively. The low frequency components (RCs 1–2 and RCs 4–5) show substantial amplitude modulation. The amplitude of the 6.5 years oscillation progressively decreases towards the end of the recording period (after year 2000). The amplitude of the 2.6 years component, in Benafim, is much more irregular but also slightly decreases after year 2000. This result is consistent with the wavelet power spectra (Fig. 7) which clearly shows that the power concentration in the 5–13-year band is much weaker in the 21st century than before. Although this band is inside the cone of influence after year 2005, the SSA analysis confirms that these low frequency periodic oscillations have been losing strength in recent years. These results also demonstrate the complementarity of the SSA and continuous wavelet transform methods.

Discussion

Climate forcing

The North Atlantic Oscillation (NAO) is the main large-scale phenomenon controlling winter precipitation over the western Iberian Peninsula (Hurrell and Van Loon 1997; Trigo et al. 2002). Its impact on river flow regimes, with obvious consequences for all water resources in the region, has been thoroughly assessed in recent years (e.g. Trigo et al. 2004; Gámiz-Fortis et al. 2008; Lorenzo-Lacruz et al. 2011; Jerez et al. 2013). A singular spectral analysis carried out to isolate the main oscillatory components of the streamflow series of the main Iberian Peninsula international rivers (Douro, Tejo, and Guadiana) revealed modulated amplitude oscillations with associated periods in the bands 2–3, 4–5, and 6–8 years (Gámiz-Fortis et al. 2008). The winter Guadiana series (south

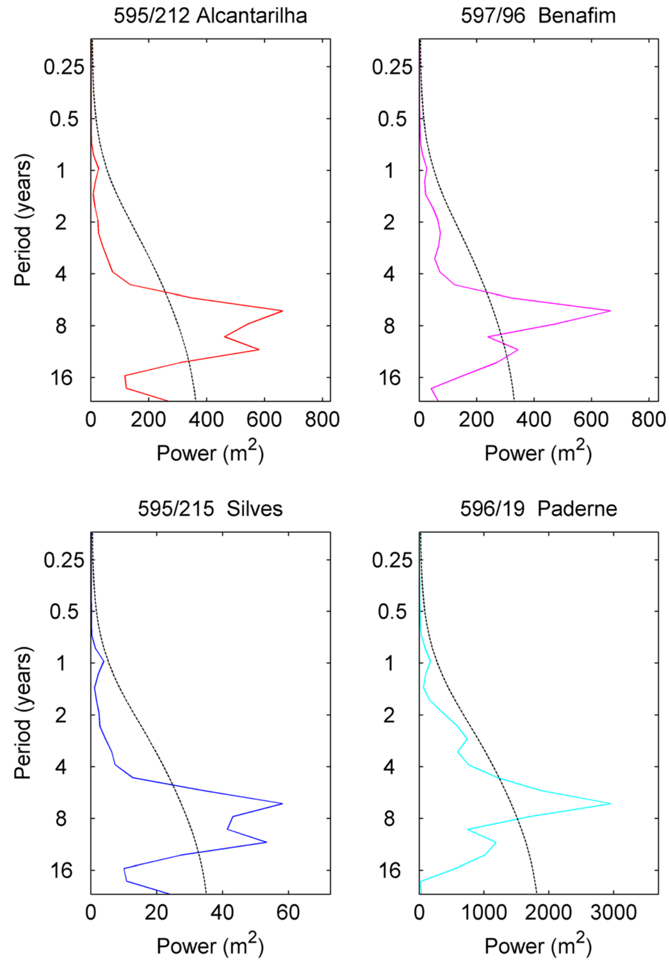

Fig. 8 Global (or time averaged) wavelet spectrum of the groundwater level records (*solid line*) as a function of period. The *dashed line* is the 5 % significance level, assuming a corresponding *red* noise process. The power amplitude (σ^2) is proportional to the amplitude of the hydraulic head variations in each piezometer

Portugal), in particular, was found to be represented by a model containing a decadal variability with a set of oscillations with associated periods of 2, 4.5, 6.5, and 3.4 years, which are remarkably similar to the periods found during this study in the QS aquifer. However, caution is required in analyzing these results as the relation between the NAO and the surface climate has been shown to be non-stationary (Vicente-Serrano and López-Moreno 2008).

The NAO index, on the other hand, can be broken down into some modulated amplitude oscillations with periods around 4.8, 7.7, and 2.4 years, along with nonlinear trends (Gámiz-Fortis 2002). When trying to match the NAO index and the streamflow main modes of variability in Iberia, previous studies found common oscillations at 7.7 and 4.8 years, but suggested that the overall relationship between the NAO and streamflow is complex and nonstationary (Gámiz-Fortis et al. 2008). The complexity was attributed to the role played by other climate variables such as temperature and wind, which have a direct effect on evapotranspiration but are not so clearly related to the NAO. Moreover, it has been recognized that the average monthly and seasonal precipitation in the Iberian Peninsula, although mainly influenced by the NAO, also depends on other teleconnections such as the Scandinavian and Eastern Atlantic patterns (Trigo et al. 2008; Espírito Santo et al. 2013).

Groundwater levels have a more complex relation to precipitation than river flow. For example, models of time-varying climate controls on groundwater recharge have shown that groundwater responds more strongly to the comparatively slow trends associated with low frequency climate fluctuations than to isolated climate extremes (Dickinson et al. 2004; Dettinger and Earman 2007). The relationship between

Table 2 Comparative results of the SSA in the western/eastern sectors of the aquifer

EOF	(595/212) Alcantarilha (west)		(597/96) Benafim (east)	
	Period (years)	Variability (%)	Period (years)	Variability (%)
1	6.5	43	6.5	34
2	6.5	30	6.5	25
3	4.3	8	13	7
4	3.2	5	2.6	6
5	12	4	2.6	6
6	12	3	2	5

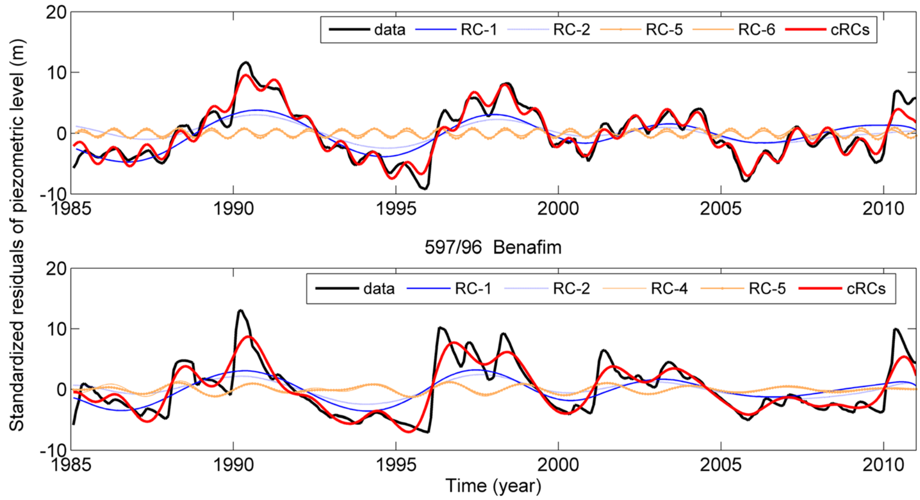

Fig. 9 Partial reconstruction of the groundwater level records in Alcantarilha, based on EOFs 1–2 (6.5-year cycle) and EOFs 5–6 (1-year cycle) and Benafim, based on EOFs 1–2 and EOFs 4–5 (2.6-year cycle). The *black line* is the original data and the *red line* is the composite of the reconstructed components (*cRCs*)

groundwater level fluctuations and low frequency (inter-annual to multi-decadal) atmospheric circulation systems has been intensively investigated in recent years (e.g. Gurdak et al. 2009; Holman et al. 2011; Tremblay et al. 2011; Kuss and Gurdak 2014). In the south of the Iberian Peninsula, periodicities of 2.5 and 5 years were reported in a study that focused on the relation between rainfall, temperature and outflow of a karst spring from the Sierra de las Cabras carbonate aquifer, near Gibraltar (Andreo et al. 2006). Spectral methods applied to a set of 53 piezometer time series from the Vega de Granada alluvial aquifer, along with rainfall, temperature and river flow data, also identified cycles of 8–11 and 3.2 years (Luque-Espinar et al. 2008). In both cases, the authors argued for a clear correlation between the NAO index and the low frequency hydraulic head variations. Another study in a karst aquifer, this time in the Upper Normandy (France), detected the same frequencies, 2–3 and 6–7 years, in piezometric levels (Slimani et al. 2009). The results from this study, especially the wavelet power spectra (Fig. 7), are remarkably similar to the results of Slimani et al. (2009), most likely because this study analyzed a similar time span (in the Slimani et al. case, 1985–2005). The evidence thus suggests that the 3.2, 4.3, 6.5, and 2.6-year oscillations identified in the QS aquifer are driven by natural recharge rates associated with the NAO climate cycle. The full demonstration of this relation is nonetheless outside the scope of this study.

Geologic forcing

Once the climate forcing has been identified, the question now is to determine the extent to which the geologic factors filter the climate-induced oscillations in the groundwater levels. This section aims to explain the distinct behavior of the piezometers in the face of a common climatic input, focusing on the differences between the eastern and western sector of the aquifer. According to the results, the most important differences between the two sectors are: (1) in the western sector the groundwater level response is spatially homogenous, the memory effects are larger, the high-frequency content is filtered out and there is only one scaling regime, meaning there is no distinctive response to short-term variations; (2) in the eastern sector there is greater spatial variability in hydraulic head variations, and there is, at least in some piezometers, two scaling regimes, implying that there is a noticeable response to short-term meteorological conditions. There is also a 2.6-year mode of variability in the eastern sector, probably related to the frequency of depressions and frontal systems affecting western Iberia in connection with the NAO, which was not detected in the western sector.

All these observations are consistent with the regional flow pattern model developed for the QS aquifer (Monteiro et al. 2006; 2007; Stigter et al. 2010; Hugman et al. 2012; 2013). The spatial distribution of the porous-karst media equivalent transmissivity in the aquifer has been obtained in previous studies using inverse calibration of finite element model predictions against piezometric and discharge data (Hugman et al. 2012), and considering both autogenic and allogenic recharge (Salvador et al. 2012). In the western sector, the models show a regular distribution of high transmissivity values, indicative of a well-developed karst conduit network that supports high rates of water flow. The main region of water storage, with relatively large storage coefficients, also occurs in the western sector of the aquifer (Hugman et al. 2012). Together, these two properties (high transmissivity and large storage capacity) make the western sector more resilient to short-term climate-induced variations. In contrast, the eastern sector of the aquifer is characterized by comparatively less efficient water storage and water transport, owing to the less-developed and discontinuous nature of the karst conduit network. This explains why the eastern sector is less sensitive to the long-term climate oscillations and more reactive to the short-term meteorological conditions. Thus, it becomes apparent that the 2.6-year periodic oscillations, which are probably related to stormy episodes, have not enough

Table 3 Main mode of variability and contribution to the total variance (VAR) for an extended set of piezometers. Measure of geological variability relative to the Alcantarilha record. The analysis in the five piezometers presented in italic is restricted to the 1996–2010 interval and to the eastern sector

	Piezometer	Time (year range)	Period (years)	VAR	Difference with Alcantarilha 595/212
Western sector	595/215 Silves	1985–2010	6.5	68 %	5 %
	596/262	1988–2010	6.5	69 %	3 %
	596/259	1985–2010	6.5	73 %	0 %
	596/51	1985–2010	6.5	72 %	1 %
	596/59	1985–2010	6.5	76 %	3 %
Eastern sector	596/19 Paderne	1985–2010	6.5	52 %	21 %
	597/96 Benafim	1985–2010	6.5	59 %	14 %
	597/111	1987–2010	6.5	58 %	14 %
	597/362[a]	1996–2010	5	17 %	41 %
	597/364[a]	1996–2010	5	25 %	33 %
	597/365[a]	1996–2010	5	24 %	34 %
	596/35[a]	1996–2010	5	37 %	21 %
	597/121[a]	1996–2010	5	30 %	28 %

amplitude to affect the western sector (with large volumes of stored water) but are sufficient to impact the relatively depleted eastern sector of the aquifer.

A quantitative measure of internal variability due to geological filtering can be obtained by comparing the contribution of the different modes of variability to the total variance of the groundwater levels (Table 2). For instance, comparing Alcantarilha and Benafim, there a difference of 14 % in the contribution of the 6.5-year mode of variability. The difference in the 2.6-year mode contribution is also of that order of magnitude (12 %). In order to further assess the spatial distribution of the geological filtering, the SSA analysis was extended to another 10 piezometers in this aquifer (Table 3). Only five of them have records in the time span analyzed so far (1985–2010) and, in this subset, the 6.5-year periodic component is also significant. The difference in variability with respect to the Alcantarilha piezometer, taken as the reference and considering the same time interval, emphasizes the uniformity of the response in the western sector. It also confirms the existence of a systematic difference of 15–20 % that can be attributed to geological filtering between the eastern and western sectors of the aquifer. The analysis in the remaining five piezometers (at the bottom of the column) is restricted to the 1996–2010 interval and to the eastern sector. In this time interval the SSA indicates a shorter periodic component (5 years) and an even larger spatial variability due to geologic factors.[a]Restricted to the 1996–2010 interval and to the eastern sector

Conclusions

The analysis of groundwater time series from the Querença-Silves aquifer, using simple spectral analysis, continuous wavelet transform and singular spectral analysis, revealed the presence of consistent inter-annual periodicities. The main mode of variability having enough persistence and amplitude to remain statistically significant over the analyzed time interval (1985–2010) corresponds to a period of 6.5 years. Other leading modes of variability correspond to oscillatory components with periods of 4.3, 3.2 and 2.6 years. A similar set of oscillations has been found in the surface flow of the Guadiana River time series in previous studies, suggesting that they have a common climatic origin related to the North Atlantic Oscillation. The differences in the temporal variability of hydraulic head variations are interpreted as a result of geologic forcing. The time series exhibit two distinctive types of modulation of the climate signals, showing that the aquifer is effectively divided in two distinct sectors by the S. Marcos-Quarteira fault. The region to the west of the fault is characterized by spatially homogenous periodic oscillations, larger memory effects and only one scaling regime. These properties are attributed to a better developed and connected flow network, which in conjunction with a greater water storage capacity, make this part of the aquifer more resilient to short-term variations. The region to the east of the fault is more reactive to high frequency variations and shows a greater spatial and temporal variability in groundwater levels. The results are consistent with previous estimates of hydrogeologic properties (transmissivity and storage capacity) in the region. The 6.5-year mode of variability contains ~70 % (55 %) of the total variance of the groundwater level in the western (eastern) sector of the aquifer. The geologic forcings then account for ~15 % of the differential response among the two sectors.

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