Unraveling the Hydrological Behavior of a Coastal Pond in Doñana National Park (Southwest Spain)

by Ana Fernández-Ayuso¹, Héctor Aguilera², Carolina Guardiola-Albert², Miguel Rodríguez-Rodríguez³, Javier Heredia², and Nuria Naranjo-Fernández²

Abstract

Time series analysis methods have been used to detect behavioral patterns in a set of nine time series. These series contained information in a 3-h time step about meteorological, hydrological and tidal data of a sand dune pond area located in Doñana National Park in the southwest of Spain. The methods used, such as wavelet analysis and additive seasonal decomposition, had never been applied before in the types of ecosystems studied. These approaches have improved the current knowledge of the conceptual model of the Santa Olalla pond system, the only system with a permanent hydroperiod located in this protected area. In addition, complex surface water-groundwater interactions, not visible through descriptive methods, have been distinguished to have a strong seasonal component. Finally, we evaluated the effect of pumping activity in a nearby coastal resort on the water supply of the Santa Olalla pond system. Although direct damage to this sand dune pond has not yet been identified, special attention must be paid in order to maintain groundwater inputs that are integral to maintaining its current status.

Introduction

Doñana National Park (DNP) is well known for the richness of its ecosystems. It is frequently mentioned that the DNP wetlands are the largest in Western Europe (Dimitriou et al. 2017; Green et al. 2017). Due to this condition, the Doñana area is protected as a Natural World Heritage Site, Biosphere Reserve and Ramsar Site. Nevertheless, since 1970, several studies have warned about the impact of groundwater withdrawal in the DNP. This withdrawal has stemmed from both crop irrigation (60-90 hm³/year) and the need to satisfy the water demand for urban supply (c. 3 hm³/year) in a touristic coastal resort, Matalascañas (Suso and Llamas 1993; Serrano and Serrano 1996; Dimitriou et al. 2017). These studies reveal that the maintenance of piezometric levels in the aquifer is at risk. Furthermore, due to the existence of groundwater-dependent ecosystems, the DNP has become a more vulnerable area for the consequences of climate change (Guardiola-Albert and Jackson 2011; Scheffer et al. 2015; Green et al. 2017). Piezometric levels are generally found at a very shallow depth, and during rainy years more than 3000 temporary ponds are created in the area. Some of these temporary ponds are located on very permeable aeolian sands which formerly constituted active dunes. Our case study is focused on the Santa Olalla sand dune pond, the only pond in the DNP with a permanent hydroperiod. Santa Olalla is located 3.7 km away from Matalascañas. This resort uses groundwater from the unconfined unit of the aquifer. This unconfined unit lies within an important recharge area of the aquifer.
Some authors have claimed that intensive groundwater extractions in the coastal resort have caused the drying out of the Brezo and Charco del Toro ponds (Figure 1a), the two closest ponds to the pumping area, just 0.7 km from Matalascañas (Serrano and Serrano 1996; Muñoz-Reinoso 2001; Rebollo et al. 2008; Serrano and Zunzunegui 2008; Dimitriou et al. 2017). Additionally, the hydroperiod and maximum flooded surface area of other ponds have been reduced (Díaz-Paniagua and Aragonés 2015; Dimitriou et al. 2017). Due to this situation, some studies have been carried out with the purpose of establishing whether the Santa Olalla pond is being adversely affected in a similar manner (Sacks et al. 1992; Lozano et al. 2002; Fernández-Ayuso et al. 2018). The results of these studies have revealed the complexity of establishing a hydrological conceptual model of Santa Olalla.

Mathematical methods applying time series analysis are increasingly being used to improve the understanding of surface water/groundwater interactions (Kaplan et al. 2010; Aguilera et al. 2013; Acworth et al. 2015; Chiaudani et al. 2017; Oh et al. 2017; Haaf and Barthel 2018; Trásy et al. 2018). Acworth et al. (2015) successfully used Fourier analysis on daily and sub-daily scales to identify responses to evapotranspiration in hydraulic head fluctuations. Rebollo et al. (2008) applied correlation and spectral analysis to daily time series of surface water and groundwater levels in the sand dune ponds located in the DNP in the period 2001-2007. Their results evidenced the impact of groundwater pumping on the dynamics of the ponds. Four of these monitoring points were the same ones that we have analyzed. Similarly, the time-frequency analysis of rainfall, river level and groundwater level by Chiaudani et al. (2017), combined with hydrogeological knowledge, revealed the conceptual hydrodynamic model of an alluvial aquifer in central Italy.

Time series decomposition is another approach used to characterize hydrological patterns (Machiwal and Jha 2006; Von Asmuth et al. 2008; Peterson and Western 2014; Wang et al. 2015; Chiaudani et al. 2017; Haaf and Barthel 2018). Concerning this method, there is a new flexible additive model developed by Facebook (Prophet) that considers non-periodic changes in trends as well as customizable seasonal periodic components in a Bayesian framework as easily interpretable parameters (Taylor and Letham 2018a). This model’s applicability to hydrometeorological data has already been highlighted by some authors such as Papacharalampous et al. (2018).

Wavelet analysis for hydrologic time series analysis has been widely applied since the 1990s, with increasing popularity in recent years (Sang 2013). A wavelet transform is able to work with non-stationary time series...
and detect when significant periods are presented through time (Sleziak et al. 2015). One of the applications of wavelet analysis is multi-temporal scale analysis. This method can be applied to hydrologic series to reveal complex hydrological processes and their variability (Torrence and Compo 1998; Labat 2005; Sang 2013). Oh et al. (2017) combined dynamic factor analysis with wavelet analysis to identify and quantitatively evaluate complex latent factors controlling groundwater level fluctuations in a riverside alluvial aquifer. These latent factors included the influence of precipitation and direct runoff, seasonal surface water-groundwater interaction, temporal and seasonal agricultural pumping, and regional and local recharge cycles. Therefore, wavelet analysis on fine time scales may reveal relevant information that can characterize surface water-groundwater interactions and hydrogeological functioning of fast response systems including coastal ponds in sandy environments.

In this paper, sub-daily hydrometeorological time series (i.e., surface water and groundwater levels, precipitation and sea tide series) are characterized on different temporal scales for the period June 2016 to January 2018. The selected methodology is based on three core factors. These factors are the descriptive and quantitative time series analysis, comparison of seasonal components extracted with an additive model (Prophet), and time-frequency wavelet analysis of non-stationary short-term periodicities. The main objectives of the present study are to: (i) apply a new combination of time series analysis methods to detect behavioral patterns in surface and groundwater hydrographs, (ii) update the hydrogeological conceptual model of the Santa Olalla coastal pond system, and (iii) identify the effect of nearby groundwater pumping on the hydrological system.

Materials and Methods

Study Site

The Doñana area (37°N, 6°W) spreads along more than 1000 km² in three provinces of southwestern Spain. This area has a sub-humid Mediterranean climate. Rainfall is distributed on a seasonal basis. Mean precipitation registered in the last 30 years was around 550 mm, most of it taking place during the wet season (October-April). However, interannual variability exists, and during some years the major rainfall occurs in autumn, while in others it occurs in winter or spring (Díaz-Paniagua et al. 2015).

The Almonte-Marismas aquifer system (3409 km²) represents the main groundwater resource in the Doñana area. Broadly, Almonte-Marismas is considered as a multilayer alluvial aquifer constituted of silts, sands and gravels of fluvial-deltaic and marine origin (Salvany and Custodio 1995). Santa Olalla and other sand dune ponds are located on unconfined aeolian sands that contain an irregular presence of alluvial clays and marls. The status of the complete Almonte-Doñana system is classified as “pre-alert” by the latest report of the Guadalquivir River Basin Authority (2018). However, some of the groundwater bodies that constitute the aquifer, including both the coastal area and other areas affected by groundwater pumping for crop irrigation, are in the “alert” category.

The Santa Olalla pond (25 ha) is part of the Dulce-Santa Olalla-Pajas pond system, in which Dulce is a semi-permanent pond. Santa Olalla is a permanent pond and Las Pajas is a seasonal water body. These ponds are located in depressions in the fringe between stabilized and mobile dunes (Figure 1a) and are hydrogeologically connected (Sacks et al. 1992). During some extremely rainy years, this system can become connected as a single pond network (Díaz-Paniagua et al. 2015). The groundwater flow in the Santa Olalla pond generally moves from the northwest (Dulce area) to the southeast (Pajas area), although some authors have suggested that there are certain differences in the flux direction between the dry and the wet seasons (Sacks et al. 1992; Lozano et al. 2002). Sacks et al., in their study carried out in 1992 based on a solute transport model, stated that in the middle of the wet season (December), the groundwater flux was discharged towards the pond from the southern shore. At the end of the dry season (September), the groundwater flux direction was similar, although groundwater was also discharged from the aquifer through the pond bed as flow patterns were mainly influenced by a deeper flow.

Matalascañas is a coastal resort that belongs to the Almonte municipality, which was built in the 1970s (Figure 1a). Its population of no more than 3000 inhabitants during the low season increases exponentially during the summer, when it reaches more than 100,000 occupants. In light of this situation, water demand drastically increases from mid-June to the beginning of September. This water demand is solely satisfied by groundwater resources. Its withdrawal comes through five pumping wells bordering the DNP. Some of the wells are used to withdraw water during the whole year, while others only work during the weekends or the summer season. The groundwater abstraction rights are limited to 2.75 hm³/year, although some authors have pointed out that actual consumption is higher (Dimitriou et al. 2017).

Time Series Data

Hourly precipitation data during the period 06/24/2016-01/15/2018 were obtained from the “Almonte-Doñana” meteorological station (MS) of the Spanish Meteorological Agency (AEMET). Total rainfall during the hydrological year 2016-2017 was 531 mm, which is similar to the long-term average. Time series of groundwater level (GW) at different monitoring points were obtained from two different sources: data for GW-1 and GW-4 (see Figure 1a) come from the Spanish Geological Survey (IGME), and series from GW-2, GW-3 and PW were collected by Pablo de Olavide University. Specific characteristics of the sensors and time steps are detailed in Table 1. Data for PW and GW-1d were only available from 05/17/2017 and 02/09/2017, respectively. The PW sensor was installed in a pumping well at 30 m depth. During the pumping period, the water table
drops below the depth of the sensor, so there are no measurements below 5 m asl. Data from GW-4 were used to compare water table levels in piezometers with the same depth as GW-1, but closer to the coastal resort.

Santa Olalla pond surface water levels (SW) were recorded with a Diver® water level logger (see Table 1) installed in the deepest area of the pond. On-site measurements from a staff gauge were used to correct the data.

Finally, tidal oscillations (SL) were obtained from the “Bonanza 2” tide gauge station (36.80°N, 6.34°W), which is located 24 km southeast of the Santa Olalla pond, at the mouth of the Guadalquivir River (Figure 1b). This station belongs to the Spanish State Ports Authority.

**Methods**

The relatively short period analyzed (approximately 1.5 years) does not allow for a robust time series analysis of precipitation data due to its high variability. Therefore, precipitation was only used as Supporting Information. The analysis of hydrological time series characterization was divided into three consecutive steps: (i) visual and descriptive analysis through time series plots and boxplots; (ii) time series decomposition into relevant periodic seasonal components; (iii) continuous wavelet analysis of high-frequency components in the time-frequency domain. The methods used for the last two steps are described as follows:

(ii) Time series decomposition: distinction of the seasonal (periodic) components of the time series was performed with the Prophet model (Taylor and Letham 2018a). If $y(t)$ is the observed time series, Prophet uses an additive model, where linear growth trends ($g(t)$) are fitted with periodic seasonalties ($s(t)$), plus a normal random error term ($\varepsilon(t)$):

$$y(t) = g(t) + s(t) + \varepsilon(t)$$  \hspace{1cm} (1)

We used the implementation of Prophet in the R package Prophet (Taylor and Letham 2018b). Prophet models linear growth using a simple piecewise constant function. $S$ changepoints at times $s_j, j = 1, \ldots, S$ (dates where the growth rate is allowed to change) are modeled using a vector of rate adjustments $\delta \in \mathbb{R}^S$, where $\delta_j$ is the change in rate at time $s_j$. Prophet puts a sparse prior $\delta_j \sim \text{Laplace}(0, \tau)$ on the magnitudes of the rate changes. The parameter $\tau$ controls the flexibility of the model to choose potential changepoints at which the rate is likely to change. Large values will make the trend more flexible and will allow many changepoints. By default, Prophet specifies 25 potential changepoints which are uniformly placed in the first 80% of the time series. After some trials with different values, we found this setup to be suitable to represent the relatively regular hydrological time series.

Seasonal components are fitted using a partial Fourier sum on the corresponding periodicity (e.g., 365.25 days for yearly component, 7 days for weekly component, etc.) with coefficients estimated from a normal smoothing prior distribution $\beta \sim N(0, \sigma^2)$. The number of cosine-sine terms in the partial sum determines how quickly the seasonality can change, and the smoothing prior parameter ($\sigma^2$) controls the strength of the seasonal component. We considered daily, weekly and yearly components for each series.

The **Prophet** developers set default values for the parameters that are appropriate for most forecasting problems (Taylor and Letham 2018a): $\tau = 0.05, \sigma^2 = 10, 10$ Fourier terms for the yearly periodic component, three Fourier terms for weekly periodic component and four Fourier terms for daily periodic component. These values proved to be suitable for our data.

(iii) Wavelet analysis: time-frequency analysis was performed through continuous wavelet analysis using the R package WaveletComp (Roesch and Schmidbauer 2018). For a detailed discussion on wavelet analysis, reference is made to Torrence and Compo (1998) and Labat (2005). WaveletComp analyzes the frequency structure of univariate and bivariate time series using the complex-valued Morlet wavelet transform:

$$\varphi(t) = \pi^{-1/4} e^{\text{tot} - t^2/2}$$  \hspace{1cm} (2)

<table>
<thead>
<tr>
<th>Point</th>
<th>X UTM ETRS89 30 N</th>
<th>Y UTM ETRS89 30 N</th>
<th>Altitude (m asl)</th>
<th>Depth (m)</th>
<th>Measurement Frequency (h)</th>
<th>Sensor (Brand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>193,540</td>
<td>4,099,220</td>
<td>5</td>
<td>—</td>
<td>3</td>
<td>Baro Diver</td>
</tr>
<tr>
<td>SW</td>
<td>190,338</td>
<td>4,098,040</td>
<td>3.4</td>
<td>—</td>
<td>3</td>
<td>Mini Diver CTD</td>
</tr>
<tr>
<td>GW-1d</td>
<td>190,019</td>
<td>4,098,532</td>
<td>6.9</td>
<td>72</td>
<td>1</td>
<td>OTT Mini Orpheus</td>
</tr>
<tr>
<td>GW-1m</td>
<td>190,018</td>
<td>4,098,535</td>
<td>6.8</td>
<td>30</td>
<td>1</td>
<td>OTT Mini Orpheus</td>
</tr>
<tr>
<td>GW-2m</td>
<td>190,055</td>
<td>4,098,288</td>
<td>5.8</td>
<td>17</td>
<td>3</td>
<td>Mini Diver</td>
</tr>
<tr>
<td>GW-3s</td>
<td>190,336</td>
<td>4,097,910</td>
<td>5.9</td>
<td>2.7</td>
<td>3</td>
<td>Mini Diver</td>
</tr>
<tr>
<td>GW-4m</td>
<td>187,212</td>
<td>4,100,197</td>
<td>19.5</td>
<td>45</td>
<td>3</td>
<td>OTT Thalímedes</td>
</tr>
<tr>
<td>GW-4m</td>
<td>187,212</td>
<td>4,100,197</td>
<td>19.9</td>
<td>22</td>
<td>3</td>
<td>OTT Thalímedes</td>
</tr>
<tr>
<td>GW-4d</td>
<td>187,208</td>
<td>4,100,186</td>
<td>20.4</td>
<td>100</td>
<td>3</td>
<td>OTT Mini Orpheus</td>
</tr>
<tr>
<td>PW</td>
<td>183,625</td>
<td>4,102,119</td>
<td>17.45</td>
<td>180</td>
<td>1</td>
<td>Level Scout</td>
</tr>
</tbody>
</table>
where $\psi(t)$ is the mother Morlet wavelet function, $t$ is time and $\omega$ is the angular frequency, which is set to 6 rad $t^{-1}$. This wavelet is widely used for hydrometeorological data (Andreo et al. 2006; Fengqi and Lijuan 2015; Schulte et al. 2016). It leads to a continuous, complex-valued wavelet transform of the time series, and is therefore an information-preserving tool that can be applied to select any time and frequency resolution parameters. The transform can be separated into its real part and its imaginary part, thus providing information on both local amplitude and the instantaneous phase of any periodic process across time. The Morlet wavelet transform of a time series $y_t$ is defined as the convolution of the time series, with versions of the mother wavelet translated in time by $h$ and scaled in frequency by $m$ using a fast Fourier transform:

$$\text{Wave}(h, m) = \sum_t y_t \frac{1}{\sqrt{m}} \phi^*(t - h/m)$$

(3)

The symbol “$^*$” denotes the complex conjugate. The square of the modulus of the wavelet transform can be interpreted as time-frequency (or time-period) wavelet energy density, and is called the wavelet power spectrum:

$$\text{Power}(h, m) = \frac{1}{m} |\text{Wave}(h, m)|^2$$

(4)

The proportionality factor $1/m$, introduced by Liu et al. (2007), is used to reduce bias in high-frequency phenomena. In the WaveletComp package, the wavelet power spectrum is visualized with an image plot in the time-period domain. For the purpose of testing the null hypothesis of “no periodicity,” the significance is assessed against a white noise process fitted to the data (Roesch and Schmidbauer 2018).

In order to analyze non-stationary periodic components of the series in the time-frequency domain, and complement the previous analysis of seasonal components, continuous wavelet analysis was performed on the differenced data (i.e. $x_t - x_{t-1}$, $t = 2, \ldots, n$), where $n$ is the length of the series. This allows comparison of water level lags among monitoring points, and the ability to focus on the higher-frequency components of the series.

**Results and Discussion**

**Descriptive Analysis**

The nine hydrological time series shown in Figure 2a-2c are strongly influenced by the seasonality effect. A summary of the statistics in the dataset can be seen in Table 2. All the water tables and water levels decreased during the summer, when very few precipitation events occurred. However, at the end of June, even sharper water table drops occurred in the deepest piezometers close to the resort (i.e., GW-4 m2 and GW-4d). Figure 2a shows the time series of the sensor

![Figure 2](image-url). (a) Water table evolution in PW. (b) Water table evolution in GW-4 m2, GW-4 m1 and GW-4d. (c) Water level evolution in the Santa Olalla pond (SW) and water table evolution in four piezometers (GW-2 m, GW-3 s, GW-1d, and GW-1 m) located close to the pond. (d) Precipitation (P) events during the study period. Sensor locations are shown in Figure 1.
PW (Figure 1a). Pumping effects are clear in GW-4 piezometers (e.g., 1 m of water table depletion in GW-4d sensor in June 2017). A 2-week window of PW and GW-4d time series from 10/13/2017 to 10/30/2017 is shown in Figure 3. The maximum piezometric levels were reached at the end of the weekdays, while at the beginning of the weekend, the groundwater level decreased by up to 30 cm. A time lag between the pumping and the effect on the GW-4d levels can also be seen.

Precipitation events in October 2016 and November 2017 represented the end of the decreasing water level trends of the summer. The range of GW-4 sensors during the year was around 2 m (Table 2). This variation is caused by a growth in the volume of tourists in the coastal resort that creates an increase in the water demand. The water level in the pond (SW) was below the water table in the surrounding area during almost the complete study period (Figure 2c). Nonetheless, during the dry season of 2017 (March-October), SW was above the shallow groundwater table near the pond (i.e., GW-3 s). The fact that this circumstance only occurs in certain years illustrates the complexity of the hydrological functioning in the Santa Olalla pond. Lozano et al. (2002), through hydrogeochemical and isotopic analyses, also detected recharge from the pond to the aquifer on the southern side of the shore in May 2000. Analogous complexity between groundwater and interdunal wetlands was studied by Doss (1993) and Winter (1999) in dune terrain settings located in Indiana and Nebraska. In such studies, Doss and Winter detected how some water bodies changed from flow-through to groundwater recharge. These changes were caused by the interchange of recharge and evapotranspiration in the perimeter of the wetlands.

Water table evolution in the deep and medium-depth piezometers, located in the northwestern part of the pond (i.e. GW-2 m, GW-1 m and GW-1d), showed analogous behavior. GW-2 m, however, had an overflow. In March 2017, there was an overflow in GW-2 m because the water table reached a hole in the pipe.

The boxplots of the distribution of water levels by month in Figure 4 show a similar variation in SW and the shallow level of GW-3 s from January to June (months 1 to 6). There was increased variability in SW compared to GW-3 s from July to October (months 7 to 10) due to evaporation. However, in November and December, distributions were similar again.

The monthly distribution of groundwater levels at medium depths in the northwestern part of the pond (i.e., GW-2 m and GW-1 m) is similar. GW-1d shows smaller variations, likely due to the buffer effect of the regional flux at deeper levels. However, these observations should be interpreted carefully as this point has less than a year of available data (February 2017 to January 2018).

The deeper piezometers GW-4 m2 and GW-4d near the coastal resort show wide yearly variations, and a sharp decrease in the water tables starting in June (month 6 in Figure 4) triggered by the intensification of pumping activity. Groundwater levels then recovered in fall and winter, due to greater precipitation in December and January. The shallowest point near the resort GW-4 m1 shows an almost constant distribution of groundwater levels across the year (only a slight decrease in the summer). Apparently, this piezometer is not affected by pumping activity. This would be due to the presence of fine alluvial materials of low permeability in the first 22 m below the surface and also because groundwater in the resort is pumped at greater depth (Figure 1).

### Additive Decomposition

The Prophet additive model performed well for both SW and GW level time series in terms of goodness-of-fit and error measurements (Table 3). Most models show values of $R^2$ higher than 0.8 and an RMSE lower than 0.1 m asl. GW-1 points show the worst performance, but the representation still captures the main time series patterns. The fit plots in Figure 5 and in the Appendix S1 reflect the adaptability of Prophet to different time series patterns. The oscillations in the fit line in GW-4 m2 reveal the strong weekly periodic component (Figure 5b).

### Yearly Component

Despite the fact that the hydrological time series are shorter than 2 years, the yearly component allows for clear visualization and comparison of the different patterns

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**Table 2**

Summary Statistics for Each of the Time Series:

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Max</th>
<th>Min</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>5.26</td>
<td>5.19</td>
<td>0.36</td>
<td>5.89</td>
<td>4.66</td>
<td>1.23</td>
</tr>
<tr>
<td>GW-2 m</td>
<td>5.95</td>
<td>5.89</td>
<td>0.33</td>
<td>6.48</td>
<td>5.46</td>
<td>1.02</td>
</tr>
<tr>
<td>GW-3 s</td>
<td>5.32</td>
<td>5.23</td>
<td>0.30</td>
<td>5.90</td>
<td>4.95</td>
<td>0.95</td>
</tr>
<tr>
<td>GW-1d</td>
<td>6.23</td>
<td>6.18</td>
<td>0.34</td>
<td>6.78</td>
<td>5.81</td>
<td>0.97</td>
</tr>
<tr>
<td>GW-1 m</td>
<td>6.03</td>
<td>5.99</td>
<td>0.34</td>
<td>6.60</td>
<td>5.54</td>
<td>1.06</td>
</tr>
<tr>
<td>GW-4 m2</td>
<td>11.49</td>
<td>11.45</td>
<td>0.45</td>
<td>12.12</td>
<td>10.46</td>
<td>1.66</td>
</tr>
<tr>
<td>GW-4 m1</td>
<td>12.78</td>
<td>12.75</td>
<td>0.31</td>
<td>13.13</td>
<td>12.26</td>
<td>0.87</td>
</tr>
<tr>
<td>GW-4d</td>
<td>11.89</td>
<td>11.91</td>
<td>0.59</td>
<td>12.75</td>
<td>10.29</td>
<td>2.46</td>
</tr>
<tr>
<td>PW</td>
<td>1.94</td>
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<td>4.25</td>
<td>5.29</td>
<td>−11.23</td>
<td>16.52</td>
</tr>
<tr>
<td>P</td>
<td>0.17</td>
<td>0.00</td>
<td>1.51</td>
<td>48.80</td>
<td>0.00</td>
<td>48.80</td>
</tr>
<tr>
<td>SL</td>
<td>1.76</td>
<td>1.72</td>
<td>0.71</td>
<td>3.46</td>
<td>0.31</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Note(s): Series are expressed in meters above sea level. P (precipitation) is quantified in mm.
Figure 4. Boxplot diagrams of the monthly distribution of water levels in the Santa Olalla pond (SW) and in the groundwater (GW) monitoring points arranged by distance to the pond. Groundwater levels in GW4 piezometers have been rescaled by subtracting 6 units from the actual measurements. Month 1 corresponds to January, 2 to February, etc.

Table 3

<table>
<thead>
<tr>
<th></th>
<th>SW</th>
<th>GW-2 m</th>
<th>GW-3 s</th>
<th>GW-1d</th>
<th>GW-1 m</th>
<th>GW-4 m2</th>
<th>GW-4 m1</th>
<th>GW-4d</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.996</td>
<td>0.803</td>
<td>0.891</td>
<td>0.627</td>
<td>0.752</td>
<td>0.987</td>
<td>0.997</td>
<td>0.985</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.022</td>
<td>0.022</td>
<td>0.141</td>
<td>0.847</td>
<td>0.736</td>
<td>0.045</td>
<td>0.013</td>
<td>0.068</td>
</tr>
</tbody>
</table>

observed in the data (Figure 6). Moreover, the plots support the applicability of Prophet to analyze interannual seasonal patterns from a methodological point of view. There are similar groundwater level yearly patterns in all points near the pond and in the water level of the pond itself (i.e., SW, GW-1 m, GW-1d, and GW-3 s). The yearly component in the deeper GW-4 points shows a sharp drawdown in the summer, accounting for the pumping influence.

Weekly Component

Figure 7 shows the weekly component of groundwater levels in GW-4 piezometers. They were the only ones having a significant weekly pattern. In the deepest piezometers (GW-4d and GW-4 m2), weekly variation ranges were found to be an order of magnitude higher than in the shallower GW-4 m1 (0.02 vs. 0.0025 m). This data illustrates the greater effect of the weekly component in the deepest piezometers. A decreasing tendency in piezometric levels can be observed during the weekend when the influx of people at the coastal resort increases (Figure 3). The piezometric levels then recover during the weekdays. These conclusions corroborate the findings of Rebollo et al. (2008).

Daily Component

The amplitude of the daily components in the pond (SW) and the shallow groundwater levels closest to the pond (GW-3 s) exhibit the evaporation processes most common to the pond itself (Figure 8). The bimodal daily pattern in GW-1 m could be attributed to the tidal effect as will be discussed in the next section. In the case of GW-2 m, the tidal variations are not so clear. In GW-4, an alteration of the tidal signal can be seen, which could be produced by the different time offset expected between groundwater pumping and low and high tidal signals. Furthermore, most of the possible absorption of the tidal signal occurs during the night, when the water withdrawal intensity is higher.

Wavelet Analysis

The wavelet power spectrum and time-averaged power spectrum of the differenced univariate series in Figure 9a and 9b show significant daily periodicity in the pond (SW) and in shallow groundwater close to the pond (GW-3 s) due to evaporation processes. The daily component was particularly strong during the summer and dissipated in both autumn 2016 and winter 2017, as shown by the gaps with non-significant areas (no red) and the low power levels in the wavelet spectrums of SW and GW-3 s (Figure 9a and Appendix S2).
Figure 5. Time series reconstructed by Prophet (blue line) for GW-3 s (a) and GW-4 m2 points (b). Black points are actual measurements.

Figure 6. Yearly component of the additive model in SW, GW-3 s, GW-1 m, GW-1d, GW-4 m2, and GW-4d time series.

On the other hand, all the wavelet power in the medium groundwater levels located in the northwestern part of the pond (GW-1 m and GW-2 m) was concentrated on the semidiurnal periodic component during the whole period studied. This is shown by both the significant red power levels and the black line depicting the ridge of the maximum power levels around the 0.5-day period in Figure 9c. Furthermore, the semidiurnal periodicity of these series had the highest average power levels of all the points. Similarly, as inferred from the component analysis, these results depict tidal oscillations as the main controlling factor of piezometric variations at these points. The amplitude of the semidiurnal tides in this area of the Atlantic Ocean is relatively constant at approximately 2.5 m. These types of tides are characterized by high tides and low tides alternating every 12.5 h (Appendix S2).

Figure 7. Weekly component of the additive model in GW-4 water table time series.

Figure 8. Daily component of the additive model in SW, GW-3 s, GW-2 m, GW-1 m, GW-4 m2, and GW-4d time series.

There are a couple of small gaps in the dataset between May and July 2017. The semidiurnal control on GW-2 m (Figure 9c), however, is seen more clearly than it was through the daily component (Figure 8). The gap in semidiurnal periodicity in GW-2 m during February and March 2017 is attributed to the interference caused by the water outflow through the piezometer. Wavelet power spectrums for GW-1d and GW-1 m are not shown because they are very similar to that of GW-2 m. Therefore, homogeneous hydrodynamic behavior in depth can be inferred in the area where these piezometers are located (Figures 1 and 9).

The behavior of GW-4 piezometers, located near the tourist area, is a function of depth and lithology. The deeper GW-4 m2 and GW-4d show relatively constant semidiurnal periodicity which is linked to tidal oscillations and weekly and half-weekly (i.e., weekend) components during the summer related to pumping activity (Figure 9c). GW-4d has almost identical patterns of time-frequency variation, and the plots have been omitted. The average wavelet power of the shallower GW-4 m1 shows the same components, but they are weaker in terms of power levels and irregularly distributed in time. This irregularly distributed time is as if there was a dampened response to the dynamics at the deeper aquifer levels (Figure 9c). At the same time, the average power plots in Figure 9c indicate a slight seasonal effect at periods longer than 1 month that decreases in depth from GW-4 m1 towards GW-4 m2. This would be related to the slower recharge processes through finer, less permeable materials (Figure 1c) and to the groundwater flow through a higher-scale regional flux system, registered by
Figure 9. Wavelet power spectrum and wavelet power averages of surface water level in the Santa Olalla pond (SW), groundwater level in GW monitoring points (see Figure 1). The power levels in the spectrum are the square root of actual power values in order to accentuate the contrast of the image. In the image plots of wavelet power spectrum, the color scale represents the quantiles of the distribution of wavelet power levels; the area within the white lines represents high power at the 0.1 significance level with respect to the null hypothesis of white noise processes; black lines depict power ridges (maximum levels). In the plots of wavelet power averages, the red dots represent periods where the average of the wavelet power spectrum is significant at the 0.05 level.

the deeper sensors GW-4 m2 and GW-4d. Overall, the disturbed time-frequency spectrum at GW-4 m2 results from the combined effect of surface hydrometeorological processes and influencing dynamics from the deeper levels. Here, the strength of wavelet analysis for hydrogeological characterization that cannot be unraveled solely through hydrograph inspection and descriptive statistics is evidenced. These manifested differences detected between GW-4 piezometers and piezometers in the Santa Olalla area show that the unconfined aquifer near Santa Olalla is not affected by pumping activity in the coastal resort.

All water level monitoring points, except for the pumping-influenced deeper levels in GW-4, show higher wavelet power in periodicities up to 2 weeks, coinciding with rainfall events which occurred in October and November 2016 (Figure 2). These are the red/orange areas in Figure 9a and 9b, which are not seen in Figure 9c. These findings show quantitative evidence of relatively fast groundwater responses in the system, as argued by other authors (Sacks et al. 1992; Lozano et al. 2002).

Enhancement of the Conceptual Model of the Santa Olalla Pond

The results provide new insights into the conceptual hydrogeological model of the Santa Olalla pond. The main findings in the hydrogeological time series analysis are as follows:

• (i) Surface water in the pond (SW) and shallow aquifer (GW-3 s) showed similar behavior (Figures 6–8), including a significant daily periodic oscillation during late spring and summer (Figure 9a and 9b); (ii) groundwater in the area surrounding the pond (GW-2 m, GW-1 m, and GW-1d) at medium and deep locations (17 to 72 m) had similar seasonal components (Figure 6) and a constant semidiurnal periodicity linked to tidal
Groundwater pumping in Matalascañas does not seem to affect groundwater dynamics in the area surrounding the Santa Olalla pond. These results support the current conceptual hydrogeological flux model of the aquifer in Doñana. Due to the fact that the Santa Olalla pond is located in an area where deep groundwater fluxes discharge, it has water throughout the year (Sacks et al. 1992; Lozano et al. 2002; Díaz-Paniagua and Aragonés 2015). The primary output from the pond is through evaporation processes. Furthermore, it has been verified that during dry seasons, Santa Olalla may recharge water to the aquifer through the southern shore (GW-3 s).

Conclusions

Nine hydrometeorological time series from groundwater levels, surface water level, rainfall and sea tides in the Santa Olalla permanent pond area within the DNP have been analyzed. The main contribution of the methodological approach through time series decomposition and wavelet analysis is the disaggregation of overlapping hydrodynamic effects (e.g., evaporation, tides, recharge, pumping, etc.) that cannot be separated by visual inspection of hydrographs and descriptive statistics. Moreover, continuous wavelet analysis allowed for a more concise estimation of dominant temporal scales in the hydrogeological system and assessment of the differences between dry and wet conditions. Shallow groundwater level oscillations in the aquifer near the pond influence the surface water level oscillations in the Santa Olalla pond. Sea tides influence groundwater levels in all medium and deep piezometers. Lastly, a pumping impact has been detected in piezometers close to the coastal resort, but not in the Santa Olalla area. The connection of the Santa Olalla pond with both deep groundwater flux and local flux has been distinguished. In light of the results, it must be highlighted that, although hydrological effects caused by pumping have not yet been identified in the Santa Olalla pond area, in order to guarantee its preservation, special care must be taken to maintain groundwater levels in the Almonte-Marismas aquifer. The outcomes and methods presented in this case study can improve the current knowledge of the processes occurring in surface water-groundwater interactions in similar contexts.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally not peer reviewed.

Appendix S1. Fit of the Prophet model in all the time series analyzed. The blue line is the time series reconstructed by Prophet. The black points represent actual measurements.

Appendix S2. Wavelet power spectrum and wavelet power averages of groundwater level GW-3 s and tidal oscillations SL (see Figure 1). The power levels in the spectrum are the square root of actual power values in order to accentuate the contrast of the image. In the image plots of wavelet power spectrum, the color scale represents the quantiles of the distribution of wavelet power levels; the area within the white lines represents high power at the 0.1 significance level with respect to the null hypothesis of white noise processes; black lines depict power ridges (maximum levels). In the plots of wavelet power averages, the red dots represent periods where the average of the wavelet power spectrum is significant at the 0.05 level.

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