Conference Proceedings Paper

Using thermal modelling to characterize the groundwater discharge towards a permanent pond (Doñana National Park, Spain)

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Abstract: We have modeled groundwater inputs to Santa Olalla pond, the only permanent pond of Doñana Biological Reserve (Andalusia, Southern Spain) by means of the application of a thermal modelling methodology. During the study period (February-May 2017) a chain of thermistors obtained hourly temperature data from the surface water and the groundwater in the sediment below. In addition, water level in the pond and in the aquifer near the shores was also monitored at similar time rates. Results showed that a net groundwater discharge occurs heterogeneously through the pond's bed. The comparison of these outcomes with previous studies made in the pond, such as hydrological water balances, is coherent and strengthens the existing hydrological knowledge of this water body. Finally, it has been detected that the pond is strongly influenced by the alterations of the sand aquifer, even if such alterations are produced away from the pond and at high depths. The effects of groundwater extractions for urban supply of a nearby coastal resort are immediately affecting the evolution of the water level, although this effect is not necessarily translated to water level depletion.

Keywords: Heat flow, surface water-groundwater interaction, hydrological monitoring, Doñana National Park

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1.Introduction

The Doñana area is located only a few kilometers from the Atlantic Ocean, between Tinto River estuary, in the province of Huelva, and the Guadalquivir River mouth, in the province of Cádiz. Its total area is more than 3,000 km^2 , which covers as well part of the province of Seville. Inside the limits of the 543-km^2 Doñana National Park is the Doñana Biological Reserve (68 km^2), where numerous ponds are flooded during rainy periods [1]. The ponds interact with local groundwater flow systems and form in depressions, as a result of the intersection of the land surface with the water table. Depending on the time of year, the inundation of the pond and the water table position, different regional and/or local flow systems are formed [5].

Among these ponds is Santa Olalla. Its 25 ha area make it the largest pond in the area and the only pond with permanent hydroperiod. Its mean depth during the years 2015-2017 was 1.28 m.It has previously been the subject of hydrogeological research [5,7,9,11]. Santa Olalla is a groundwater flow-through pond located above a uncofined aquifer (part of Doñana aquifer) essentially formed by fine aeolian sands. The regional groundwater flow direction in the Doñana aquifer is south-western towards the Atlantic Ocean.

Groundwater discharge from the Doñana aquifer (3,600 km^2) is believed to maintain the hydroperiod of these ponds. From the last decades it has been subjected to differents pressures, especially due to crop irrigation and water consumption in the coastal resort "Matalascañas" [3], located only 3.8 km from Santa Olalla pond and less than 1 km from other died out ponds such as Charco del Toreo (Figure 1). In this type of ecosystem, the groundwater discharge/recharge is the most difficult component of the water balance to quantify. Therefore, in hydrogeological studies of lakes in particular and, in any hydrogeological research in general, different methodologies tend to be used to estimate the groundwater component and thereby be able to compare the results obtained with different methods.

Heat has been used as a tracer of ground-water flow movement by the early 1900s. Some years later, temperature patterns started to be exploited to study subsurface flow systems. They limitations such as data-acquisition and computational techniques, that have been successfully developed throughout the years [12]

The objective of this study is to estimate the groundwater discharge from the sand aquifer to Santa Olalla pond by analysing temperature data using a numerical water and heat transfer model. These results will be compared and discussed with flow rates calculated by more classical methodologies, such as water balances.

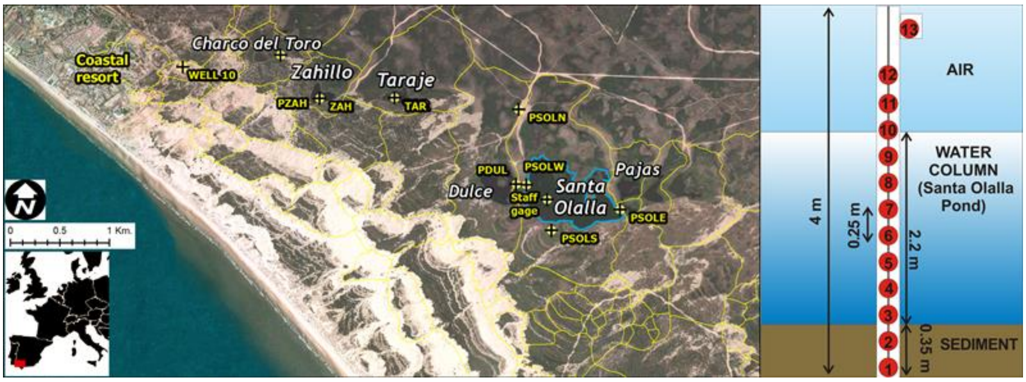

Figure 1. (**A**)The location of Dulce-Santa Olalla-Pajas, Charco del Toro, Zahillo and Taraje ponds are shown. Sensors installed in the ponds, nearby piezometers and Well 10 are shown in yellow. The Coastal resort is seen on the west. (**B**) Schematic diagram of the temperature sensor installation. For the purpose of this study only Sensors 1 to 6 have been used.

2. Methodology

A chain of twelve autologging temperature sensors (Maxim, iButtons DS1922L-F5), with a separation of 25 cm among them, were installed inside a PVC tube in Santa Olalla pond. The measurement period was three months, from February 14 to May 15, 2017. The deepest sensor was installed at 35 cm depth, below the bottom. They were programed to record temperature data hourly with a resolution of 0.0625°C. Software 1D-Temp-Pro [4] was used for the analysis of one-dimensional vertical temperature profiles which numerically solves the flow and heat-transport equations, availables in [2] This software was employed to interpretate the data and estimate a discharge flux using the parameters shown in Table 1.

Table 1. Physical properties used in the model 1D Temp PRO.

Modeling conditions 1D Temp PRO V.2	
Porosity Φ_s	0.35 (m^3/m^3)
Thermal conductivity (full saturation)λ_e	2 W/(m°C)
Sediment heat capacity Cs	$2{\cdot}10^6$ J/(m^3°C)
Dispersivity α	0.01 m

Water balances were used as complementary research methods to interpolate the flow rates estimated by the thermistors. For the water balance in Santa Olalla pond, data were collected from three hourly measurements by a pressure transducer installed in the staff gage which define the change in the storage (ΔS). Further data needed for the water balance were: evaporation rate (E), which was estimated by Penman equation, daily precipitation data (P), collected by nearby meteorological stations, and basin discharge (BD), that was considered to be groundwater discharge, due to the high permeability of the aeolian sands.

$$BD = E - P + \Delta S$$

3. Results

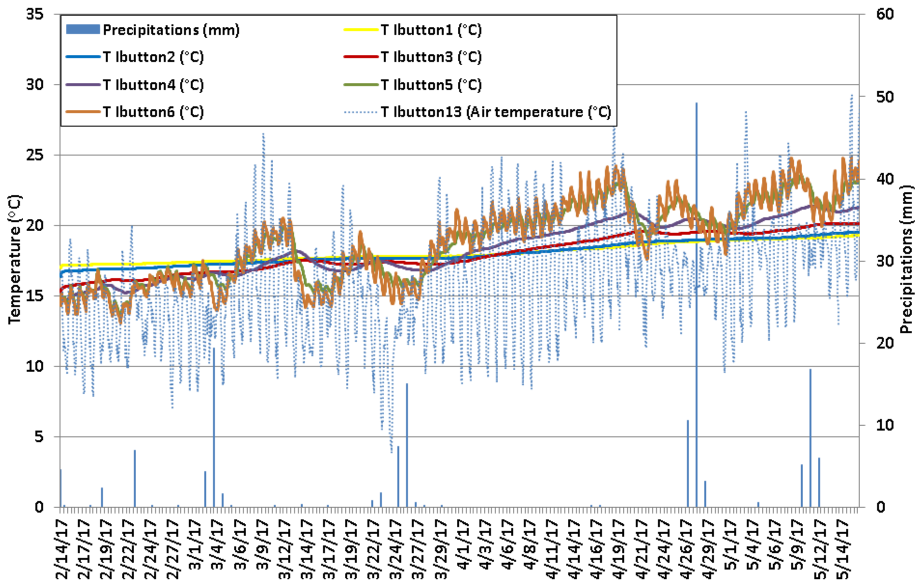

Figure 2. Temperature measured by iButton (IB) sensors 1 to 6 and 13 (air temperature), and rainfall events during the study period. IB1 and IB2 were installed at 0.35 m and 0.1 m respectively below the pond bottom. IB3, IB4, IB5 and IB6 at 0.15 m, 0.4 m, 0.65 and 0.9 m above the pond bottom.

Figure 2 shows the temperature time series measured by the most representative sensors. It can be clearly seen that temperature recorded by IB1 and IB2, installed 0.35 m and 0.1 m respectively below the pond bottom, show almost no daily oscilations. It fluctuates during the study period no more than two degrees (Table 2). IB3 and IB4, installed 0.15 and 0.4 m over the bottom illustrate a higher dependence on air temperature. The fluctuation range was 5°C (from 15.5 to 20.5 °C). No daily temperature fluctuations were observed. Finally, IB5 and IB6, at 0.65 and 0.9 m over the bottom pond, do record daily temperature oscilations. The temperature ranged during the study period from 13.1°C to 24.9°C. The water level in SOL at the beginning of the study period was 1.6 m and at the end of it 1.7 m.

Table 2. Maximum, minimum, mean and median values of ibuttons 1 to 6.

	Ibutton 1	Ibutton 2	Ibutton 3	Ibutton 4	Ibutton 5	Ibutton 6
MAX (°C)	19.3	19.5	20.1	21.4	23.6	24.9
MIN (°C)	17.0	16.4	15.3	14.5	13.4	13.1
MEAN (°C)	18.1	18.0	18	18.3	18.9	18.9
MEDIAN (°C)	17.9	17.8	17.6	18.1	19.2	19.2

Figure 3 shows temperature data used in the modelling. IB3 was used to set the boundary condition at the sediment-water interface and IB1 to set the lower boundary conditioin in the sediment. Model paramaters including groundwater flow velocity were adjusted to achieve the best match between the observed temperature measured by IB2 and the simulated temperature at the same depth. Finally, bottom conditions were stablished by thermistor 2. Temperature at the sediment-water interface fluctuated between 15.3°C and 20.1°C.

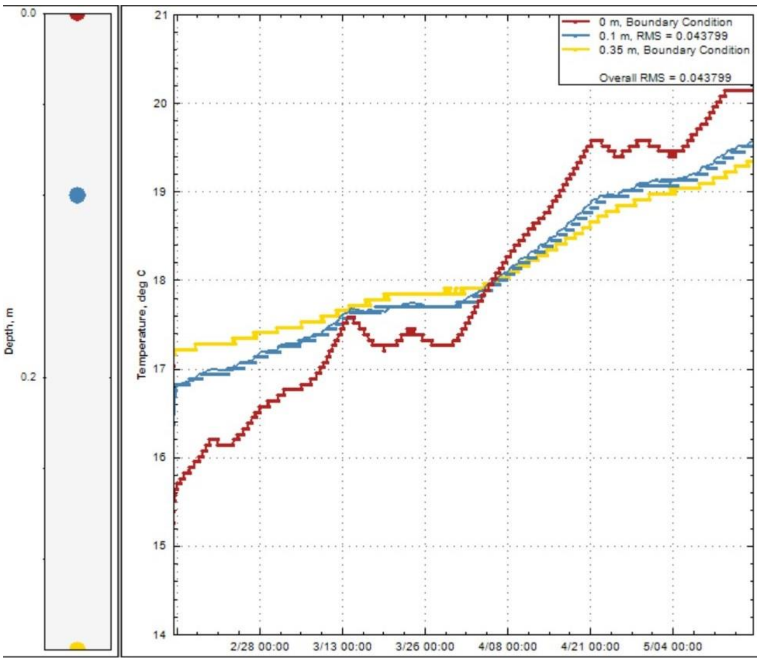

Figure 3. Results from the thermistors finally used in the model. Boundary conditions were stablished by thermistor 1 (at 35 cm below the bottom) and thermistor 3 (at 15 cm above the bottom*). * The bottom of the pond is not a hard surface, as it is formed by undefined layer, mixture of water, silt and clay.

From the parameters shown in Table 1 and the temperature evolution with the boundary conditions established in Figure 3, the outcome of the modeling is a net groundwater flux of -0,6 m/d. Negative values indicates upward groundwater flow from the aquifer through the bottom of the pond.

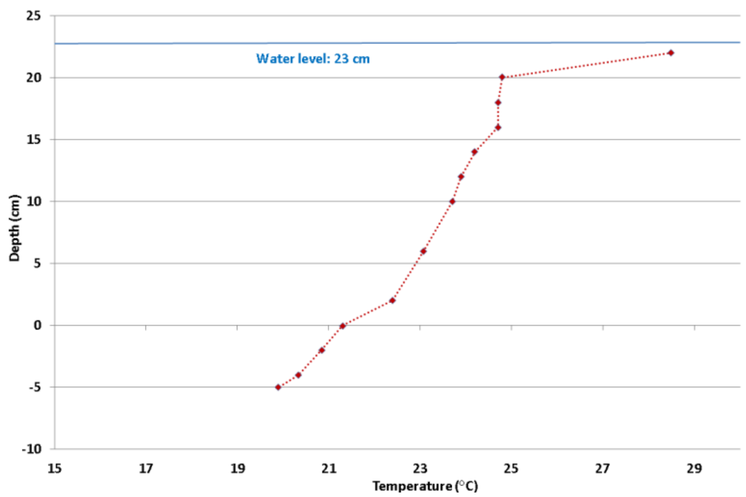

Figure 4. Temperature profile in the western shoreline of Santa Olalla pond on May 8th, 2017.

Figure 4 shows the vertical profile of manually measured temperature in the west shoreline of Santa Olalla pond. Altogether, a difference of 8.6°C was recorded from the pond surface to the bottom, being the groundwater 8.6 °C cooler than the surface water.

4.Discussion

Groundwater discharge in Santa Olalla pond has been studied previously by several authors [7,8,9,11]. The volume of groundwater discharged estimated was 0.36 x 10^3 m^3/year with the water balance equation.

The steady temperature values registered by the thermistors beneath the bottom are in accordance with temperature of the groundwater, which is constant. Anyhow, the discharge result given by the thermal method (0.6 m/d) seems to be an overestimation of the actual groundwater discharge produced in Santa Olalla pond. The specific groundwater flux calculated by the water balance was 0.005 m/d. This fact reveals that aquifer discharges to this water body heterogeneously: the center of the pond, where the temperature sensors were installed, seems to be one of the areas where more water is discharged, taking into account the results provided by the thermal modeling and not only the northern and perimetral area, as other authors suggested [11]. The center of the pond is also its deepest area.

As it is common in many wetlands [10], horizontal flow was suspected, so the vertical temperature profile in the western shoreline of Santa Olalla pond served as a proof of the existence of groundwater discharge also in the perimeter of the pond.

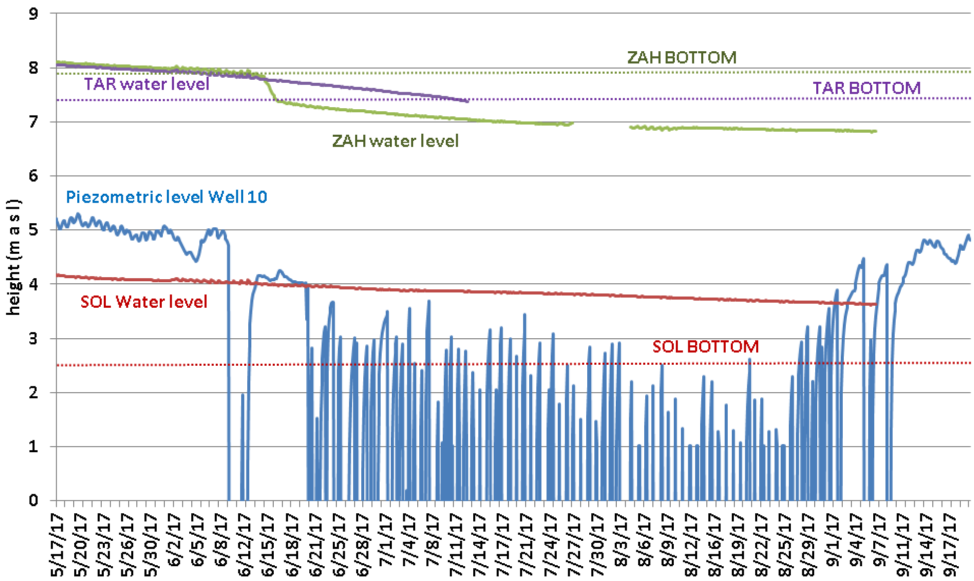

Figure 5. Piezometric level evolution in Well 10 and water table evolution in TAR (Taraje Pond), PZAH (Piezometer Zahillo pond) and SOL (Santa Olalla pond).

As it can be seen in Figure 5, there is a negative trend for the water levels in Well 10, located in the coastal resort, as well as in the study ponds Taraje, Zahíllo and Santa Olalla ponds during the study period. The distance among the pumping area and the ponds is 2.1 km, 1.3 km and 3.8 km respectively. Taraje pond at the beginning of the study period was 0.75 m deep and dried out on July 13, 2017. It can be noticed oscilations of some centimeters on the water level recorded by the pressure transducer from 1st to the 13th of June. These oscilations can also be seen during the same time period in the other studied ponds and coincided with a decay on the piezometric level in Well 10.

On the other hand, Zahillo pond water depth was 0.35 m in the middle of May and dried out the 14th of June. Finally, Santa Olalla pond, at the beginning of the studied period the staff gage indicated a water depth of 2.31 m. At the beginning of September the staff gage registered a water depth of 1.60 cm.

Furthermore, the piezometric head in Well 10 dropped 0.40 m from the beginning of the study period to the end of it. The groundwater abstraction rights for urban water supply at the coastal resort are capped at 2.75 millions m^3 per year, although some authors state that real consumption is higher [3]. This water is pumped by five wells located in the coastal resort. Some of them only a few meters from Doñana Biological Reserve.

5. Conclusions

The results given by the thermal method (specific discharge -0.6 m/d) constitute a further advance in the knowledge of the hydrogeological functioning of Santa Olalla pond, and more specifically, it constitutes an evidence about the existence of areas within the pond with high groundwater discharge. Discrete areas of groundwater discharge in a wetland are often critical for quantifying wetland dynamics [4]. Nevertheless, the study period needs to be increased in order to compare long-term data series along with different methodologies, to accurately appreciate surface water - groundwater interactions. Furthermore, the installation of another chain of temperature sensors at the west shoreline could clarify if the groundwater discharged from the shoreline is significant with regard to the groundwater discharged from the center of Santa Olalla pond.

There is evidence of groundwater relation among the pumping area at the coastal resort and the ponds situated at Doñana Biological Reserve, as piezometric level depletions on the former are sometimes translated into centimetric level oscillations in the ponds.

Further studies need to be done to specify the hydrological functioning of crucial water bodies such as Santa Olalla pond, since the existence of many biological communities depend on them.

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Author Contributions: M. Rodriguez-Rodriguez and A. Fernandez Ayuso designed and performed the experiments; M. Rodriguez-Rodriguez, A. Fernandez Ayuso, F. Moral-Martos and M. Hayashi analyzed the data; A. Fernandez-Ayuso wrote a first draft of the manuscript and all authors participated in the final writing.

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