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Groundwater dependence of coastal lagoons: The case of La Pletera salt marshes (NE Catalonia)

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ABSTRACT

Coastal wetlands are among the most productive ecosystems of the world, playing an important role in coastal defense and wildlife conservation. These ecosystems, however, are usually affected by human activities, which may cause a loss and degradation of their ecological status, a decline of their biodiversity, an alteration of their ecological functioning, and a limitation of their ecosystem services. La Pletera salt marshes (NE Spain) are located in a region mainly dominated by agriculture and tourism activities. Part of these wetlands and lagoons has been affected by an incomplete construction of an urban development and in this moment is the focus of a Life^{+} project, whose aim is to restore this protected area. Several studies have analyzed the role of hydrological regime in nutrients, phytoplankton and zooplankton in this area, however, the role of groundwater was never considered as a relevant factor in the lagoon dynamics, and its influence is still unknown. In this study, the hydrogeological dynamics in La Pletera salt marshes has been analyzed, as a basis to set sustainable management guidelines for this area. In order to determine their dependence on groundwater resources, monthly hydrochemical (with major ions and nutrients) and isotopic ($\delta^{18}O_{H2O}$ and δD) campaigns have been conducted, from November 2014 to October 2015. In particular, groundwater from six wells, surface water from two nearby streams and three permanent lagoons, and sea water was considered in these surveys. Taking into account the meteorological data and the water levels in the lagoons, the General Lake Model has been conducted to determine, not only evaporation and rainfall occurring in the lagoons, but also the total inflows and outflows. In addition, the Gonfiantini isotopic model, together with equilibrium chemical-speciation/mass transfer models, has been used to analyze the evaporation and the physicochemical processes affecting the lagoons. Results show that during the dry season groundwater inputs may account for 15–80% of the water in La Pletera lagoons. Besides, water salinity depends on two main processes: 1) mixing of fresh and sea water occurring within the lagoons or in the aquifer; and 2) evaporation. According to the obtained results, the goal of preserving La Pletera lagoons and their salinity conditions implies maintaining groundwater fluxes towards the ocean, and also the hydraulic connectivity of these lagoons with the aquifer.

1. Introduction

Coastal wetlands have been usually described as the confluence of inland and marine water, being among the most fluctuating and productive ecosystems of the world, and performing a wide range of ecosystem services of socio-economic value to coastal communities. These values include shoreline stabilization, sediment and nutrient retention, high primary and secondary production, fisheries resources, habitat and food resources for terrestrial, aquatic and marine fauna, coastal water quality buffering, biomass and biodiversity reservation, and recreation and tourism amenities (Mitsch and Gosselink, 1993, 2000; Kjerfve, 1994; Costanza et al., 1997; Gopal et al., 2000; Basset et al., 2006; Gedan et al., 2011; Beer and Joyce, 2013). These ecosystems play an important role in coastal defense and wildlife conservation. They can also act as

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sinks or sources of a wide range of substances, such as nutrients, organic matter, pollutants, etc. (Boorman, 1999; Costa et al., 2001, López-Flores et al., 2003; Salvadó et al. 2006).

Coastal lagoons have been classified in different groups depending on their connection to the sea. For instance, Bamber et al. (2001) and Beer and Joyce (2013) have distinguished different sub-types of lagoons according to their physiographic characteristics (isolated lagoons, percolation lagoons, silled lagoons, sluiced lagoons, and lagoonal inlets). Besides, Félix et al. (2015) have simplified their characterization, classifying them in open and closed lagoons, and considering the second group as those that have no connection or a short period of connection to the sea. Closed lagoons have been also termed as landlocked or enclosed lagoons, and have been described as a group of shallow and confined brackish-water systems, highly dependent on freshwater discharges, either from surface run-off or groundwater. Similarly, Kjerfve & Magill (1989) classify lagoons in leaky, restricted and chocked depending on their connection to the sea and to the freshwater circulation. Moreover, in the Mediterranean region there are some coastal aquatic ecosystems, which remain isolated most of the year from any type of surface connection to the sea and to the freshwater sources. These ecosystems, defined as confined coastal lagoons (Trobajo et al 2002), only connect during flooding events, such as sea storms or freshwater floods, but remain without surface inputs the rest of the year (Quintana et al., 1998a; Badosa et al., 2006).

The settlement and structure of biological communities in enclosed lagoons are driven by freshwater inputs, which vary naturally or due to human pressures in their flow rates and biogeochemical characteristics. Changes in the water regime due to human activities have caused water quality degradation, lagoons and wetlands disappearance, or the establishment and expansion of invasive species (Crivelli, 1995; Oltra and Todolí, 2000; Pérez-Ruzafa et al., 2002; O'Connell, 2003; La Jeunesse and Elliott, 2004; Badosa et al., 2007). Furthermore, the level of impact in closed lagoons is also highly dependent on the morphological characteristics of each lagoon, and the result of the combination of both, freshwater inputs and morphological characteristics, determines the particular traits and biological role of these lagoons (Cancela da Fonseca et al., 2001; Basset et al., 2006; Cañedo-Argüelles and Rieradevall, 2010; Félix et al., 2015). Regarding confined wetlands, several studies have analyzed the role of hydrological regime in nutrients dynamics and in the aquatic biota. Sudden inputs during flooding events, and the lack of surface exchanges with the adjacent coastal waters during most of the year strongly determines nutrient dynamics and phytoplankton and zooplankton species composition in these habitats (Quintana et al., 1998a, 1998b; Brucet et al., 2005; Badosa et al., 2006; López-Flores et al., 2006, 2009; López-Flores et al., 2014). However, the role of groundwater has not always been considered as a relevant factor in the lagoon dynamics in ecological studies.

Nevertheless, the aquatic ecosystems dependence on groundwater is well known (Sear et al., 1999), and it has been studied using a wide range of methodologies, characterizing the spatial and temporal variability of surface water-groundwater interactions (Sophocleous, 2002; Kalbus et al., 2006; Martínez-Santos et al., 2010; Menció et al., 2014). For instance, in streams and rivers this relationship has been assessed using: direct measurements of water flux with seepage meters or similar devices (e.g., Kelly and Murdock, 2003); heat tracers or thermal studies based on temperature time series in both surface water and groundwater systems (e.g., Conant et al., 2004; Schmidt et al., 2006); methods based on Darcy's law, such as point measurements that investigate the hydraulic gradient established between groundwater level and stream stage, or potentiometric maps (e.g., Woessener, 2000; Brodie et al., 2007); mass balance methodologies or water budgets, based not only on streamflow measurements (e.g. Harvey and Wagner, 2000; Davie, 2002, Hannula et al., 2003), but also on hydrochemical and environmental tracers (e.g., Négrel et al., 2003; Pretty et al., 2006, Mas-Pla et al., 2013a; Mas-Pla et al., 2013b); and finally, analytical and numerical modeling techniques based on governing mathematical equations (e.g., Nyholm et al., 2002; Rodríguez et al., 2006; Mas-Pla et al., 2012). In the particular case of lagoons, the two main approaches that have been used to assess surface water-groundwater interactions are: heat, geochemical and isotopic tracers (e.g. Mudge et al., 2008; Santos et al., 2008; Shubert et al., 2011; Duque et al., 2016; Sadat-Noori et al., 2016), and modeling (e.g. De Pascalis et al., 2009; Martínez-Alvarez et al., 2011; Hipsey et al., 2014; Read et al., 2014; Yao et al., 2014). Several lake models have been developed for specific purposes, such as lake level, water thermal processes, ice dynamics, or nutrient and quality management. Among these models, the General Lake Model (GLM) has been developed to combine fluxes of mass and energy with a Lagrangian layer structure that adapts to changes in vertical gradients, including energy budget algorithms with mixing schemes (Hipsey et al., 2014). However, most of the studies conducted using this GLM have been specifically used to conduct temperature simulations in lake profiles (e.g. Read et al., 2014; Yao et al., 2014).

La Pletera salt marshes are located in the north of the mouth of the Ter River (NE Spain; Fig. 1), in a region mainly dominated by agriculture and tourism activities. They are composed of several coastal lagoons and wetlands that were affected by the incomplete construction of an urban development in 1987. This area has been the focus of a Life^{+} project (http://lifepletera.com/es/life-pletera/), whose aim is to restore this protected area and to recover its ecological functionality. It has been described as a confined Mediterranean coastal ecosystem due to its isolation from the sea and from continental fresh waters (Trobajo et al 2002; Badosa et al., 2006; López-Flores et al., 2006). Although surface water inputs in this area are well characterized, it is still not well known if groundwater circulation plays a significant role in the hydrological balance of the lagoon.

In this paper, we analyzed the hydrogeological behavior of La Pletera salt marshes, as a representative example of confined coastal lagoons. Our aim was to determine their dependence on groundwater resources to find out if water circulation in such confined lagoons is mainly determined by sudden surface inputs or, on the other hand, it is mainly driven by groundwater circulation. To know the hydrological dynamics is essential in order to set sustainable management guidelines for these specific types of ecosystems. In order to assess the main objective of this project the GLM has been used to analyze, not only the energy fluxes in the lagoon, but also the water mass fluxes, together with geochemical and isotopic modelling. Therefore, this study presents a comprehensive approach of the distinct characterization methods to determine surface water-groundwater interactions in lagoons.

2. Study area

La Pletera salt marshes are located in the Baix Empordà tectonic basin (NE Spain; Fig. 1). This basin was formed during the distensive period of the Alpine orogenesis and is delimited by the Montgrí Range at the north, characterized by Mesozoic limestone formations, and by the Gavarres Range at the south, composed of igneous and metamorphic rocks of Paleozoic age. The basement of this tectonic graben presents Paleozoic and Paleogene sedimentary materials, which were severely affected by the distensive period of the Alpine orogenesis (Mas-Pla and Vilanova, 2001; Montaner, 2010).