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The impact of poplar tree plantations for biomass production on the aquifer water budget and base flow in a Mediterranean basin

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HIGHLIGHTS

• Biomass production impacts must be considered for evaluating water resources planning

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ABSTRACT

Poplar plantations are used for biomass production in many countries. These plantations are often located in areas where the tree roots can reach the water table of shallow aquifers to reduce irrigation costs and increase evapotranspiration, mainly during the summer. This study aims to assess the effects of these plantations on an aquifer water budget and on the stream flow of a Mediterranean basin (Santa Coloma River, 321.3 km^2 NE Spain). A numerical flow model was constructed to simulate shallow aquifers and to simulate the stream–aquifer interaction for a period of 9 years. Once the model was calibrated, different land use scenarios, such as deciduous forests, dry farming and irrigated farming, were simulated for comparison. The mass balance shows that poplar extracts an average of 2.40 hm^3 from the aquifer, i.e., approximately 18% of the average recharge of the modelled area. This effect reduces the groundwater flow to the main stream and increases the infiltration from the stream to the aquifer. As a result, there is an average reduction in the main stream flow by 46% during the summer, when the lowest flow occurs and when the river is most sensitive. The results indicate that these impacts should be considered in basin management plans and in evaluating the benefits of this type of biomass production.

1. Introduction

To survive, humans must use natural resources, such as wood, sustainably in the long-term (Christersson, 2010). In Europe, wood resources, which are considered a prerequisite for building a prosperous society, are becoming scarce. The energy crises between 1973 and 1976 stimulated an intensive search for fast-growing tree species, such as poplars and willows. Poplar (*Populus* spp.) is well known for its large biomass production, its ability to adapt to different environments, its ability to integrate and synergise with agriculture and its high energy potential (Coaloa and Nervo, 2011). European countries such as Italy, France, Belgium, Spain, Hungary, and Serbia have a long tradition of poplar cultivation. Plantations are usually established on fertile sites, such as riparian areas (Johansson and Karačić, 2011); poplars account for 4% of the total plantations in Europe.

From an economic perspective, various parts of poplar trees can be used for different types of marketable products. The woody parts can be chipped to produce particle boards, pulp and bioenergy. Additionally, higher quality pieces can be used for solid wood products, such as pallets and veneer. During drought, leaves and small branches can be pruned from hybrid poplars to create an inexpensive livestock feed (Fortier et al., 2010). Wood production remains the main objective of growing poplars. In 2008, Spain produced 770,000 m^3 of wood from poplar plantations (Coaloa and Nervo, 2011). Furthermore, in many countries, poplar plantations are used for phytoremediation and phytostabilisation of soils contaminated by various pollutants, i.e., boron (Rees et al., 2013), cadmium (Marmiroli et al., 2013), zinc (Van Nevel et al., 2013), lead (Hu et al., 2013), nitrate and phosphate (Merseburger et al., 2011), as well as TCE (Shang and Gordon, 2002). Depending on the treated pollutant, phytoremediation using this type of tree could provide two major services: the rehabilitation and restoration of contaminated soils and biomass production (Ciadamidaro et al., 2013).

Populus spp. is excellent for the above-mentioned tasks because it grows quickly, providing raw material in relatively short periods (Meiresonne et al., 1999). Depending on the desired end product and

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the local climatic conditions, hybrid poplars can be managed for rotation periods of 2–5 years, 10–15 years and 25–40 years (Johansson and Karačić, 2011). Long rotation periods are used to produce pulpwood and timber, and Short Rotation Coppice (SRC) can produce biomass for energy (Sevigne et al., 2011). Biomass has received attention as a promising way to develop local and sustainable energy sources (Sevigne et al., 2011) that reduce the carbon emission rate (Rowe et al., 2009); thus, biomass becomes important in many industrial countries. For instance, Sweden obtains 14% of its energy from biomass, and it has plans to increase bioenergy production and use (Hall and Scrase, 2012). The high content of cellulose in poplars and willows indicates that these trees could also be a potential feedstock for bioethanol production (Rosso et al., 2013). Furthermore, because the poplar tree is a bountiful species in riparian forests, reusing riparian vegetation as biomass for energy production has economic and environmental benefits (Recchia et al., 2010). Although using biomass as an energy source results in a favourable balance between energy use and environment, the fast-growing poplar trees consume more water than other crops (Petzold et al., 2010). Therefore, the water consumption required by poplars to avoid a kg of CO_2 release is 4.6 m^3, and the per unit of energy obtained is 45 m^3GJ^{-1} (Sevigne et al., 2011).

As these kinds of trees have important water needs, many poplar plantations are located in areas with a shallow water table (Allen et al., 1999; Meiresonne et al., 1999; Zhang et al., 1999; Guidi et al., 2008; Pistocchi, 2009; Wilske et al., 2009; Petzold et al., 2010). After one year of growth, during all rotation periods, poplars can obtain water directly from the aquifer (Quinn et al., 2001; Wilske et al., 2009; Fu et al., 2013). This phenomenon produces direct groundwater evapotranspiration, increases the discharge from the aquifer, and therefore modifies the hydrological cycle in areas where these plantations are located. This practice is common in arid and semiarid areas (Loheide et al., 2005; Pistocchi, 2009; Wilske et al., 2009), such as in Mediterranean countries, because the irrigation-related growing costs are significantly reduced. Nevertheless, many shallow aquifers are located in alluvial planes where important river–aquifer interactions occur (Langhoff et al., 2006; Krause et al., 2007; Parkin et al., 2007; Mas-Pla et al., 2012). For instance, groundwater discharge to these rivers helps maintain the environmental water flow (Krause et al., 2007; Parkin et al., 2007; Markovic et al., 2013) and provide diverse eco services. The increase in aquifer evapotranspiration, i.e., aquifer discharge, due to poplar plantations could have the same effect as groundwater pumping, whose impact in river base flow and related ecosystems has already been demonstrated (Zhang et al., 1999; Wilske et al., 2009; Yin-Phan et al., 2014).

Following the Water Framework Directive (WFD) (2000/60/CE) it is important to study the potential effect of poplar plantations on rivers basins to define an appropriate regulation of pressure and impacts imposed by the various water users. The aim would be to maintain the healthy ecological status of river basins. Although some papers explore the link between *Populus* spp. biomass production and water consumption (Rowe et al., 2009; Sevigne et al., 2011) or its environmental impact (Rowe et al., 2009), the impact of poplar plantations on river base flows is not as well known. Thus, in this paper, we characterise and quantify the impact of *Populus* plantations on the aquifer water balance and the base flow in a Mediterranean basin by means of numerical modelling. As a paradigmatic example, a numerical flow model considering groundwater and river/aquifer interaction was constructed to simulate the Santa Coloma basin (Catalonia, NE Spain), where 3% of the land cover is poplar plantations, 27% of which are located near the main stream in the alluvial plain.

2. Study site

The Santa Coloma basin is located in NE Catalonia (NE Spain) in the range-and-basin area of La Selva (Fig. 1). Santa Coloma de Farners is the most significant village, with more than 12,600 habitants. The other towns within the study area are Sils, Riudarenes and Caldes de Malavella, with a total population of 12,717. This zone is characterised by intense agriculture and farming activities, along with a growing industrial sector and urban development. Additionally, poplar trees are used for paper production and the energy industry. This area has a Mediterranean climate characterised by an annual rainfall between 700 and 900 mm and an average temperature between 12.8 and 29.3 °C during the study period. The river basin has an area of 321.3 km^2, with a total length of 21 km for the main water course. Low stream flow occurs during summer, with almost no flow at some locations during the driest years.

Geologically, the range area is formed by igneous and metamorphic hard rocks, while the basin Neogene sedimentary infilling is constituted by alternating silts, arkosic sands, gravels and conglomerates with low clay content (Fig. 2). The Selva basin has been hydrogeologically characterised in detail by previous studies (Folch and Mas-Pla, 2008; Menció et al., 2010; Folch et al., 2011; Puig et al., 2013). In the Santa Coloma basin area, groundwater is stored under unconfined conditions in deep sedimentary formations. A multi-layered aquifer system under confined or leaky conditions can reach a total thickness of more than 200 m. The shallow aquifer is formed by the surface Neogene sedimentary materials and the alluvial quaternary deposits associated with the drainage network. The most important alluvial formation in the area is related to the main Santa Coloma stream from Santa Coloma de Farners to Riudarenes, with a maximum thickness between 15 and 20 m (Figs. 1 and 2). Apart from river–aquifer interactions, groundwater flow in the sedimentary formations is also influenced by upward flows along the main regional faults. This flow interaction is similar to shallow groundwater discharging into the rivers. In this case, regional groundwater flow discharges to shallow aquifer systems along the main faults. This influence by regional groundwater flow system in the area has been confirmed by means of numerical flow modelling (Folch and Mas-Pla, 2008), the basin water balance (Menció et al., 2010) and hydrochemical and isotopical data (Folch et al., 2011).

3. Methodology

3.1. Aquifer evapotranspiration by poplar trees

Evapotranspiration (ET) is an important factor in the water and energy balance, particularly in zones with shallow groundwater, plantations and riparian areas, where poplar trees are common. Evapotranspiration in riparian forests can be a major component of the annual water budget in arid and semiarid catchments. For example, the ET in the forested extent of the riparian vegetation along the Middle Rio Grande in New Mexico represents 20–30% of the total estimated water depletion of this river reach (Dahm et al., 2002). However, there are few studies that directly quantify ET from the aquifer (water table) in Mediterranean areas.

It is difficult to quantify the direct ET from groundwater due to its temporal and spatial variability. To calculate this parameter, several methods have been used with disparate results. Groundwater evapotranspiration can be estimated using daily fluctuations of the groundwater level, well hydrographs or streams records. These methods are cheaper than monitoring ET with lysimeters (Yin et al., 2013). Three common mathematical equations can be used to calculate ET from an aquifer. The most traditional equation is the method of White (1932), which has been improved over the years to yield the methods of Hays and Loheide (Loheide et al., 2005). These three methods rely on different algorithms and different data sources to calculate the variable groundwater flow; thus, they produce different ET rates, as shown by Yin et al. (2013).

Using direct field measurements, such as lysimeters, to calculate the ET rate provides values that are frequently not regionally representative (Guidi et al., 2008; Pistocchi, 2009). Another common field method to quantify aquifer evapotranspiration (Dahm et al., 2002; Steinwand and Harrington, 2006; Wilske et al., 2009) is the eddy covariance technique, in which the vertical air movement characterises the energy