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4 1 THE IMPACT OF POPLAR TREE PLANTATIONS FOR BIOMASS PRODUCTION
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6 2 ON AN AQUIFER WATER BUDGET AND THE BASE FLOW OF A
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8 3 MEDITERRANEAN RIVER BASIN
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23 11 Abstract

24 12 Poplar plantations are used for biomass production in many countries. These plantations are
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26 13 often located in areas where the tree roots can reach the water table of shallow aquifers to
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28 14 reduce irrigation costs and increase evapotranspiration, mainly during the summer. This study
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30 15 aims to assess the effects of these plantations on an aquifer water budget and on the stream flow
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32 16 of a Mediterranean basin (Santa Coloma River, 321.3 km² NE Spain). A numerical flow model
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34 17 was constructed to simulate shallow aquifers and to simulate the stream-aquifer interaction for a
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36 18 period of 9 years. Once the model was calibrated, different land use scenarios, such as
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38 19 deciduous forests, dry farming and irrigated farming, were simulated for comparison. The mass
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40 20 balance shows that poplar extracts an average of 2.40 hm³ from the aquifer, i.e., approximately
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42 21 18% of the average recharge of the modelled area. This effect reduces the groundwater flow to
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44 22 the main stream and increases the infiltration from the stream to the aquifer. As a result, there is
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46 23 an average reduction in the main stream flow by 46% during the summer, when the lowest flow
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48 24 occurs and when the river is most sensitive. The results indicate that these impacts should be
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50 25 considered in basin management plans and in evaluating the benefits of this type of biomass
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52 26 production.
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59 28 Keywords
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29 Bioenergy, groundwater-surface water interaction, evapotranspiration, river flow

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31 1. Introduction

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

42 From an economic perspective, various parts of poplar trees can be used for different types of
43 marketable products. The woody parts can be chipped to produce particle boards, pulp and
44 bioenergy. Additionally, higher quality wood can be used for solid wood products, such as
45 pallets and veneer. During drought, leaves and small branches can be pruned from hybrid
46 poplars to create an inexpensive livestock feed (Fortier et al., 2010). Wood production remains
47 the main objective of growing poplars. In 2008, Spain produced 770.000 m³ of wood from
48 poplar plantations (Coaloa and Nervo, 2011). Furthermore, in many countries, poplar
49 plantations are used for phytoremediation and phytostabilisation of soils contaminated by
50 various pollutants, i.e., boron (Rees et al., 2013), cadmium (Marmioli et al., 2013), zinc (Van
51 Nevel et al., 2013), lead (Hu et al., 2013), nitrate and phosphate (Merseburger et al., 2011), as
52 well as TCE (Shang and Gordon, 2002). Depending on the treated pollutant, phytoremediation
53 using this type of tree could provide two major services: the rehabilitation and restoration of
54 contaminated soils and biomass production (Ciadamidaro et al., 2013).

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4 55 *Populus* spp. is excellent for the above-mentioned tasks because it grows quickly, providing raw
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6 56 material in relative short periods (Meiresonne et al., 1999). Depending on the desired end
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8 57 product and the local climatic conditions, hybrid poplars can be managed for rotation periods of
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10 58 2-5 years, 10-15 years and 25-40 years (Johansson and Karačić, 2011). Long rotation periods
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12 59 are used to produce pulpwood and timber, and Short Rotation Coppice (SRC) can produce
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14 60 biomass for energy (Sevigne et al., 2011). Biomass has received attention as a promising way to
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16 61 develop local and sustainable energy sources (Sevigne et al., 2011) that reduce the carbon
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18 62 emission rate (Rowe et al., 2009); thus, biomass is important in many industrial countries. For
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20 63 instance, Sweden obtains 14% of its energy from biomass, and it has plans to increase bioenergy
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22 64 production and use (Hall and Scrase, 2012). The high content of cellulose in poplars and
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24 65 willows indicates that these trees could also be a potential feedstock for bioethanol production
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26 66 (Rosso et al., 2013). Furthermore, because the poplar tree is a bountiful species in riparian
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28 67 forests, reusing riparian vegetation as biomass for energy production has economic and
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30 68 environmental benefits (Recchia et al., 2010). Although using biomass as an energy source
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32 69 results in a favourable balance between energy use and the environment, the fast-growing poplar
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34 70 trees consume more water than other crops (Petzold et al., 2010). Therefore, the water
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36 71 consumption required by poplars to avoid a kg of CO₂ release is 4.6 m³, and the per unit of
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38 72 energy obtained is 45 m³GJ⁻¹ (Sevigne et al., 2011).

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42 73 Because of their high water consumption, poplar plantations have important water needs. For
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44 74 this reason, many poplar plantations are located in areas with a shallow groundwater table
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46 75 (Allen et al., 1999; Guidi et al., 2008; Meiresonne et al., 1999; Petzold et al., 2010; Pistocchi,
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48 76 2009; Wilske et al., 2009; Zhang et al., 1999). After one year of growth, during all rotation
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50 77 periods, poplars can obtain water directly from the aquifer (Fu et al., 2013; Quinn et al., 2001;
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52 78 Wilske et al., 2009). This phenomenon produces direct groundwater evapotranspiration,
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54 79 increases the discharge from the aquifer, and modifies the hydrological cycle in areas where
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56 80 these plantations are located. This practice is common in arid and semiarid areas (Loheide et al.,
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58 81 2005; Pistocchi, 2009; Wilske et al., 2009), such as in Mediterranean countries, because the
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4 82 irrigation-related growing costs are significantly reduced. Nevertheless, many shallow aquifers
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6 83 are located in alluvial planes where important river-aquifer interactions occur (Krause et al.,
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8 84 2007; Langhoff et al., 2006; Mas-Pla et al., 2012; Parkin et al., 2007); the groundwater
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10 85 discharge to these rivers helps maintain the environmental water flow (Krause et al., 2007;
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12 86 Markovic et al., 2013; Parkin et al., 2007). The increase in aquifer evapotranspiration, i.e.,
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14 87 aquifer discharge, due to poplar plantations could have the same effect as groundwater
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16 88 pumping, whose impact in river base flows and related ecosystems has already been
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18 89 demonstrated (Wilske et al., 2009; Yin-Phan et al., 2014; Zhang et al., 1999).

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21 90 Following the Water Framework Directive (WFD) (200/60/CE), it is important to study the
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23 91 potential effect of poplar plantations on rivers basins to define an appropriate regulation of
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25 92 pressure and impacts imposed by the various water users; the aim would be to maintain the
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27 93 healthy ecological status of river basins. Although some papers explore the link between
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29 94 *Populus* spp. biomass production and water consumption (Rowe et al., 2009; Sevigne et al.,
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31 95 2011) or its environmental impact (Rowe et al., 2009), the impact of poplar plantations on river
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33 96 base flows is not as well known. Thus, in this paper, we characterise and quantify the impact
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35 97 *Populus* plantations on the aquifer water balance and the base flow of a Mediterranean stream
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37 98 by means of numerical modelling. As a paradigmatic example, a numerical flow model
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39 99 considering groundwater and river/aquifer interaction was constructed to simulate the Santa
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41 100 Coloma basin (Catalonia, NE Spain), where 3% of the land cover is poplar plantations, 27% of
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43 101 which are located near the main stream.

44 45 46 47 102 **2. Study site**

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50 103 The Santa Coloma basin is located in NE Catalonia (NE Spain) in the range-and-basin area of
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52 104 La Selva. Santa Coloma de Farners is the most significant village, with more than 12,600
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54 105 habitants. The other towns within the study area are Sils, Riudarenes and Caldes de Malavella,
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56 106 with a total population of 12,717. This zone is characterised by intense agriculture and farming
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58 107 activities, along with a growing industrial sector and urban development. Additionally, poplar
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4 108 trees are used for paper production and the energy industry. This area has a Mediterranean
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6 109 climate characterised by an annual rainfall between 700 and 900 mm and an average
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8 110 temperature between 12.8 and 29.3°C during the study period. The river basin area is 321.3 km²,
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10 111 with a total length of 21 km. Low stream flow occurs during summer, with almost no flow at
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12 112 some locations during the driest years.

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15 113 Geologically, the range area is formed by igneous and metamorphic hard rocks, while the basin
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17 114 Neogene sedimentary infilling is constituted by alternating silts, arkosic sands, gravels and
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19 115 conglomerates with low clay content (Fig. 2). The Selva basin has been hydrogeologically
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21 116 characterised in detail in previous studies (Folch and Mas-Pla, 2008; Folch et al., 2011; Folch,
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23 117 2011; Menció et al., 2010; Puig et al., 2013). In the Santa Coloma basin area, groundwater is
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25 118 stored under unconfined conditions in deep sedimentary formations. A multi-layered aquifer
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27 119 system under confined or leaky conditions can reach a total thickness of more than 200 m. The
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29 120 shallow aquifer is formed by the surface Neogene sedimentary materials and the alluvial
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31 121 quaternary deposits associated with the drainage network. The most important alluvial
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33 122 formation in the area is related to the main Santa Coloma stream from Santa Coloma de Farners
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35 123 to Riudarenes, with a maximum thickness between 15 and 20 metres (Figs. 1 and 2). Apart from
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37 124 river-aquifer interactions, the groundwater flow in the sedimentary formations is also influenced
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39 125 by upward flows along the main regional faults (Folch et al., 2010; Folch and Mas-Pla, 2008;
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41 126 Folch et al., 2011; Folch, 2011; Menció et al., 2010).

42 43 44 45 127 **3. Methodology**

46 47 48 128 **3.1 Aquifer evapotranspiration by poplar trees**

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51 129 Evapotranspiration (ET) is an important factor in the water and energy balance, particularly in
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53 130 zones with shallow groundwater, plantations and riparian areas, where poplar trees are common.
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55 131 Evapotranspiration in riparian forests can be a major component of the annual water budget in
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57 132 arid and semiarid catchments. For example, the ET in the forested extent of the riparian
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59 133 vegetation along the Middle Rio Grande in New Mexico represents 20-30% of the total
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4 134 estimated water depletion of this river reach (Dahm et al., 2002). However, there are few studies
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6 135 that directly quantify ET from the aquifer (water table) in Mediterranean areas.
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9 136 It is difficult to quantify the direct ET from groundwater due its temporal and spatial variability.
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11 137 To calculate this parameter, several methods have been used with disparate results.
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13 138 Groundwater evapotranspiration can be estimated using daily fluctuations of the groundwater
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15 139 level, well hydrographs or streams records. These methods are cheaper than monitoring ET with
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17 140 lysimeters (Yin et al., 2013). Three common mathematical equations can be used to calculate
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19 141 ET from an aquifer. The most traditional equation is the White method (White, 1932), which
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21 142 has been improved over the years to yield the Hays (2003) (Hays, 2003) and Loheide methods
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23 143 (Loheide et al., 2005). These three methods rely on different algorithms and different data
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25 144 sources to calculate the variable groundwater flow; thus, they produce different ET rates, as
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27 145 shown by Yin et al. (2013).
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31 146 Using direct field measurements, such as lysimeters, to calculate the ET rate provides values
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33 147 that are frequently not regionally representative (Guidi et al., 2008; Pistocchi, 2009). Another
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35 148 common field method to quantify aquifer evapotranspiration (Dahm et al., 2002; Steinwand and
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37 149 Harrington, 2006; Wilske et al., 2009) is the eddy covariance technique, in which the vertical air
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39 150 movement characterises the energy fluxes above the canopy; the calculation is converted to a
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41 151 rate of ET expressed as a quantity per unit of time. However, this method requires expensive
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43 152 equipment and only provides a local estimate of evapotranspiration. ET can also be calculated
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45 153 by sap flow rates that are strongly related to transpiration; the aquifer transpiration by an
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47 154 individual tree can be estimated and scaled to the stand level (Allen et al., 1999; Boronina et al.,
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49 155 2005; Meiresonne et al., 1999; Petzold et al., 2010; Zhang et al., 1999). Additionally, ET can be
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51 156 simulated by water balance modelling. This type of method consists of different modules where
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53 157 the one-dimensional water transport in the soil is described and the actual transpiration is the
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55 158 integral of the root water uptake over the profile soil. As with all models, the input data are from
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58 159 a meteorological station, and soil hydraulic properties and other field parameters are required
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60 160 (Meiresonne et al., 1999).
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4 161 Although there are several methods for calculating ET from an aquifer, the ET results and the
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6 162 scale at which they are estimated vary. Furthermore, most of these estimation techniques are
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8 163 applied to establish the groundwater evapotranspiration rate in riparian areas (Ajami et al.,
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10 164 2012; Boronina et al., 2005; Butturini et al., 2002; Chen, 2007; Pistocchi, 2009; Tabacchi et al.,
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12 165 2000; Yin et al., 2013; Yin-Phan et al., 2014), and only a few studies focus on the
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14 166 evapotranspiration from poplar or willow plantations.

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17 167 One study compares two methods (sap flow and WAVE water balance modelling) for a poplar
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19 168 plantation in Flanders (Belgium) and finds similar results (Meiresonne et al., 1999). This work
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21 169 was conducted in an area with similar conditions to those found in the SCR basin: the climate
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23 170 conditions (annual precipitation of approximately 750 mm and an average temperature of 9°C),
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25 171 type of trees (*Populus* spp.), average tree age (average 15 years in both cases), tree spacing (7 x
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27 172 7.5 m), type of soil and shallow water table (<5 m). Although the average temperatures in
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29 173 summer and throughout the year are lower in Flanders (maximum of 21.6°C, minimum of
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31 174 12.8°C) and are not equally distributed compared with our study area (maximum of 29.3°C,
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33 175 minimum of 13.5°C), the ET values found in this study provide a minimum estimate of the
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35 176 expected ET we could find in the Santa Coloma basin.

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39 177 The study by Meiresonne et al. (1999) quantified the transpiration of a fast-growing 13-year-old
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41 178 monoclonal poplar during summer when direct ET from groundwater occurs. The study period
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43 179 was from August to September with a total poplar transpiration of 320 mm; the average
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45 180 minimum value was 2 mm/day, and the average maximum value was 4 mm/day. The days with
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47 181 maximum ET coincided with days with no precipitation, while the low ET rates were associated
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49 182 with rain events. These results are comparable with the study of Zhan et al. (1999) for different
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51 183 climatic conditions and younger trees, where the maximum ET was 3.6 mm/day and the
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53 184 minimum was 2.7 mm/day. These ET values were obtained by sap flow, leaf area,
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55 185 environmental condition and stomatal conductance measurements in the study area. In our
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57 186 work, the ET from the aquifer was estimated based on the rain events from June to September.

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4 187 During other months of the study period, the direct ET from the aquifer is negligible, but the
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6 188 total ET is non-negligible.
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9 189 The aquifer ET values of the above-mentioned study are in the range of the groundwater
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11 190 evapotranspiration found in riparian forests with the same climatic conditions in the Furiosos
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13 191 stream, which is 20 kilometres away from the modelled area (Sabater and Bernal, 2011).
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15 192 Although riparian forests, unlike poplar plantations, are natural ecosystems, poplars are still
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17 193 abundant. Sabater and Bernal (2011) showed that the actual evapotranspiration from riparian
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19 194 forests during the vegetative period (April-October) is between 2 and 5 mm/day.
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21 22 195 **3.2 Modelling approach** 23 24

25 196 The presented model is based on a previous model from the Catalan Water Agency (ACA,
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27 197 November 2009). The goal is to define an appropriate mass balance to assess the available water
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29 198 resources for enforcing the WFD. The finite difference numerical model Modflow (McDonal
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31 199 and Harbaugh, 1988) and the graphical interface Visual Modflow Pro 4.3 were used.
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33 200 The model integrated the shallow Neogene materials, the alluvial formations, and the related
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35 201 river/drain systems (Fig. 2). Granitic rocks of the Guillerries range area and the effect of upward
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37 202 vertical flow from regional faults were included in the model as boundary conditions (Fig. 3).
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39 203 The initial modelling approach is explained in Folch et al. (2010) for the period of 2003-2009.

40 204 In summary, this model is constituted by a finite difference grid with four horizontal layers,
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42 205 each with a constant thickness of 10 m and 48.408 active cells. A major refinement was
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44 206 conducted along the main alluvial formations with cell widths between 40 and 120 m. Distinct
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46 207 types of boundary conditions are used (Fig. 3). Constant flow cells are located in the upper
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48 208 reaches of the alluvial formations to represent the groundwater flow from the upper part of the
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50 209 reaches not included in the model domain. A general head boundary is intended to represent the
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52 210 contribution of the fault zones to the nearby alluvial formation, as well as the fluxes from the
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54 211 weathered granite. Constant head is defined at the lower reach of the alluvial formation. A river
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56 212 boundary condition is applied to the SCR main stream, while drainage boundary conditions are
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selected for all natural and ancient man-made drains located along the basin in which water only flows during periods of rain. A no-flow boundary is defined for the Neogene materials in the northern hydrographic limit of the SCR basin (Fig. 2).

The recharge rate was estimated independently based on the soil mass balance by considering several parameters, such as land use based on a land cover map of Catalonia (2005-2007) (for interpretation of the references in this map, the reader is referred to the web version of this figure), retention capacity, wilting point, soil depth, field capacity and the runoff threshold ~~among others~~. Groundwater exploitation by different water users has also been included by considering agriculture, cattle stock, industrial extraction and water supply. To simulate returns from waste water treatment plants, injection wells were included in the cell near the stream (modelled as a river and/or a drain) where the facility was located. Irrigation returns were also included in the soil mass balance using the GARCO 1.0 program of the Catalan Water Agency. Finally, hydraulic parameters were obtained from previous studies and were adjusted through calibration processes; a final set of 20 hydraulic conductivity zones was obtained (Fig. 4).

The model used for this exercise is an updated version with improved hydrogeological features compared with the previous model:

- 1) A better characterisation of the groundwater flow from the granite formations based on hydrochemical, piezometric and stream flow data (ACA, October 2010a). Thus, a new general head boundary condition has been included in the model domain (GHB2, Fig. 3).
- 2) An improved definition of hydraulic conductivity and storage coefficient values of the alluvial formation related to the Santa Coloma main stream based on a long-term pumping test (ACA, December 2010b).
- 3) Direct groundwater evapotranspiration produced by poplar plantations has also been included as extraction wells in the model. Thus, pumping wells have been added in those cells to represent areas with poplar plantations. In each cell, a pumping rate equivalent to the groundwater evapotranspired by the trees within the cell area has been assigned. Poplar plantations are considered twice in the basin water balance: 1) in

the soil water balance to define the infiltration rate and 2) as extraction wells to simulate the direct evapotranspiration from the aquifer during summer (Fig. 5). All new features included in the simulation provide a modelling result that is more indicative of the observed values, with a more realistic water budget of the Santa Coloma basin. Furthermore, additional years are included: 9 years under transient conditions between 2003 and 2011, with a significant range in precipitation (between 366 and 410 mm per year). For calibration, between 2 and 100 observation wells from several field campaigns (February, July and December 2003; May and October 2004; February, May and October 2005; May 2006 December 2008, May 2009, September 2009, April 2010) and one monthly monitoring point for the main alluvial formation were used. The initial hydraulic heads were defined according to the result of a previous steady-state simulation, which included all terms affecting the water balance. Once the model was calibrated, it was run for different land uses to study the effects of poplars on the base stream flow and on the basin water balance. Three distinct plantations were simulated with the following land cover types: 1) deciduous forest, 2) dry farming and 3) irrigated crops.

4. Results and discussion

4.1 Numerical flow model

4.1.1 Calibration and fitting

After including the new hydrological and hydrogeological information in the initial model (Folch et al. 2010), a posterior model calibration was conducted. During this process, different conductivity zones were formed based on the geological formations (Fig. 4) in Table 1. In the cells that represent two geological formations, an intermediate hydraulic conductivity between the formations was assigned. In the Santa Coloma alluvial formation, two terraces were differentiated according to ACA (2010b) to define the essential river-aquifer interaction. The first terrace (closest to the stream) has a K value of 175 m/day, and the more distant terrace has

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4 266 a value of 90 m/day (ACA, December 2010b). Similarly, the specific storage (S_s) is 0.01 m^{-1} for
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6 267 the terrace closest to the stream and 0.001 m^{-1} for the terrace farthest from the stream.
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9 268 The transient simulation reproduces the temporal evolution of natural and human influences on
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11 269 the hydrogeological system and estimates the flow exchange between the stream and the
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13 270 aquifer. Simulated and observed heads must be compared to demonstrate the goodness-of-fit of
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15 271 the model. The results show that approximately 70% of the simulated head data for May 2009,
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17 272 the campaign with many observation wells, exhibits a good correlation with the observations (R
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19 273 of 0.98 and a standard error of the estimate of $\pm 0.41 \text{ m}$). The maximum difference between the
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21 274 observed and simulated heads is 14.5 m, and the minimum difference is 0.009 m, with an
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23 275 average of $0.34 \pm 0.41 \text{ m}$ for the entire modelled domain (Fig. 7). The largest discrepancies are
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25 276 found in the Neogene sedimentary formations due to the multi-layered character of the aquifer
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27 277 (Folch et al., 2010).
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31 278 In the main alluvial formation, following the main stream, the correlation coefficient (R)
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33 279 between the simulated and observed head is 0.99. The difference between the observed and
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35 280 simulated heads is lower than the entire modelled domain ($0.3 \pm 0.36 \text{ m}$). The observed
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37 281 hydraulic head evolution and the only piezometer with monthly information in the study area
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39 282 (Fig. 8) were available during 2003-2007. The maximum difference between the observed and
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41 283 simulated hydraulic head during the summer is less than 0.4 m. However, annually, the best fit
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43 284 occurred for the 2007-2011 period. This improvement between the observed and modelled data
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45 285 is attributed to the hydrogeomorphological changes observed in the main stream. A change has
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47 286 occurred in the river morphology, from a braided (high flow and high sediment supply) to a
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49 287 single-thread channel (flow predominance) (Fig. 6). This observed change could induce flushing
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51 288 of fine material in the main channel to increase the hydraulic conductivity (Nowinski et al.,
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53 289 2011), i.e., increasing the river conductance.
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57 290 Although this geomorphological change could be produced by different factors (land use
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59 291 change, climatology, etc.), it is mainly attributed to the construction of a motorway in the
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headwaters of the main stream in 1998, as shown by Batalla and Sala (1996) in a nearby stream. Because no data are available, a single value for the river conductance was used for the calibration; the value had the best fit after 2007 during the driest years (Fig. 8).

The model improved the fit between the observed and simulated heads in the main alluvial formation compared with the initial version presented in Folch et al. (2010). Although new hydrogeological features are considered in this updated version, the improved modelling results are mainly attributed to the consideration of direct groundwater ET of poplar plantations, which represents 27% of the land use in this area (Fig. 1). Therefore, the results that include aquifer water extraction by poplars are superior.

The model also shows a good correlation with the total stream discharge during the low-flow periods (summer) (Fig. 9), when the stream flow is mainly controlled by groundwater discharge, as observed at the basin gauge station downstream of the modelled area (Fig. 2). Groundwater discharged in the stream network was calculated by summing the groundwater discharge along the drains (*Drain*) and the main stream (*Stream gain*) and by diminishing the stream water infiltrating the aquifer (*Stream loss*) (Table 2). The rise and fall of the Santa Coloma river flow show that in some months, the main stream is nearly dry due to the low-flow of the summer. Because of the lack of quality data, the period of comparison is only 2003 to 2007, despite the improved adjustment with the observed head in the wells after 2008.

4.1.2 Water Budget

The main water inputs to the system are rainfall recharge, groundwater flow from the granite formations (*General head boundary* in Modflow terminology), water from the upper reaches not drawn in the simulated area (represented as *constant flux* in the model), returns from waste water treatment plants that are represented as injection wells (*Wells in*) and stream contributions from the main stream during water loss (*River leakage in*). The outputs of the system are the groundwater discharge to the adjacent river basin (*constant head*), the exploitation via wells

317 (*GW extraction*) and the outflow from the aquifer to the drains (*Drains out*) and to the main
318 stream when losses occur (*River leakage out*) (Table 2).

319 The largest input in the water balance is recharge. With an average value of 13.2 hm³ over the
320 modelled period, recharge represents 60% of the total input in the aquifer. This value changes
321 over the study period because it depends on climate variations. The dry years (e.g., 2007) the
322 recharge is up to 88% lower than that in the wet years (2003 and 2011).

323 Groundwater from granite formations provides a total volume of 1.43 hm³ every year, which is
324 approximately 7% of the total inputs of the system. This input flow represents a significant
325 percentage (60%) of the direct evapotranspiration of the poplar plantations located in the
326 alluvial aquifer near this tectonic contact. Therefore, the flow of the fault zone is an important
327 element that plays a significant role in the water balance. The returns from waste water
328 treatment plants represent an average of 4.42 hm³. This term also varies with the recharge term
329 because the treated waste water is lower during drought periods than during other years.

330 The main outputs of the system are produced by extraction via pumping wells, drains and poplar
331 plantations. Approximately 20% of the output is from exploitation wells for agriculture,
332 industry and domestic water supplies (4.10 hm³). Furthermore, the drains are responsible for a
333 significant loss of groundwater resources (9.3 hm³), approximately 70% of the total recharge.
334 This percentage represents the effective action of such historical drains on wetlands, except in
335 summer when the loss of groundwater is zero because the recharge is small and the water table
336 is low. Groundwater transpiration produced by poplar plantations (4.10 hm³) represents
337 approximately 12% of the total output of the system and 18% of the total rainfall recharge of the
338 modelled period. Groundwater transpiration is an important term to consider in the water budget
339 as it is relatively constant over time compared with the variability in the recharge term.

340 Therefore, changes in the water storage in the aquifer (*In-Out*, Table 2) supply the amount of
341 water needed for the plantations in the driest years (low recharge), as seen in 2006, 2007 and
342 2009. The aquifer works as a buffer to reduce the impacts of these types of plantations on the

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4 343 overall components of the water budget, specifically on the stream flow during the driest
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6 344 months. However, this buffer capacity can be considerably lower if the dry period lasts more
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8 345 than one year because the water table level would be lower and less groundwater discharge
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10 346 would reach the streams.

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13 347 The flow exchange between the main stream course and the alluvial aquifer is not constant over
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15 348 the year or along the stream because the stream flow is subject to various influences, such as
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17 349 treated waste water in tributaries, well extraction and transpiration from poplar plantations.
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19 350 Thus, the main stream can undergo a simultaneous gain and loss. This dual behaviour is shown
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21 351 in the potentiometric map from the numerical flow model: the upper part of the river tends to
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23 352 gain water, while the middle of the river tends to lose water. The dual “gaining/losing”
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25 353 characteristic of the stream influences the stream base flow by reducing it when losses occur
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27 354 and by increasing it when gains occur (Fig. 10).

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31 355 There is also an intra-annual variation in the relation between the stream and the aquifer. During
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33 356 summer, the aquifer flow contributions to the river are reduced in the stretch of stream gaining
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35 357 water, while the infiltration from the stream to the aquifer increases in stream section losing
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37 358 water. An important reduction in the stream base flow is observed during this period (Fig. 10).
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39 359 This dual dynamic water flux between the aquifer and the stream has been observed in
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41 360 Mediterranean riparian zones where the riparian vegetation induces infiltration from the river to
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43 361 the aquifer and reduces the flow from the aquifer to the river (Medici et al., 2008; Mencia et al.,
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45 362 2014).

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48 363 Lastly, geomorphological changes in the main stream and resulting change in the stream-aquifer
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50 364 interaction are observed. After 2007, *stream loss* tends to increase simultaneously with a
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52 365 decrease in the groundwater discharged to the main stream (*stream gain*) (Table 2). It is difficult
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54 366 to quantify the observed change due to the complexities of the aquifer water balance because it
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56 367 depends on the yearly inputs and outputs of the system and on the changes in storage related to
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59 368 the previous year’s water budget. However, regarding the monthly gain and loss behaviour (Fig.

10), the main difference is not observed in summer. Nevertheless, this behaviour affects the water budget of the aquifer system.

4.2 Comparing the effects of poplar plantations with other land cover types in terms of the mass balance and related river-aquifer interaction

Once the model was calibrated, to compare the effects of poplars with other land uses, the area occupied by poplar plantations was simulated with other land cover: deciduous forest, dry farming and irrigated farming. Consequently, the infiltration rate changed according to the soil balance with the new land cover. Groundwater extraction (direct evapotranspiration) for those areas occupied by poplars was modified and adapted to these new scenarios. In the case of irrigated farming, groundwater extraction was simulated according to the pumping rates in the irrigation areas of the basin; groundwater extraction was removed for deciduous forest and dry farming.

As mentioned, the effect of direct groundwater evapotranspiration by poplar plantations corresponds to approximately 18% of the average recharge. Although it depends on precipitation (Meiresonne et al., 1999) over the entire modelled period, the direct poplar ET is between 2.31 and 2.52 hm³/year, even with important changes in precipitation/recharge (2007 vs. 2003). In this sense, for the driest years (e.g., 2007), the direct evapotranspiration from the aquifer was almost equal to the aquifer recharge. Poplars affect the entire mass balance and thus influence the relation between the main stream and the main inputs and outputs from the aquifer (Table 3). The main influence of the three plantation types is manifested in the stream flow by reducing the discharge of the aquifer into the drains (*Drain*) and into the main stream (*stream gain*) and by increasing the infiltration of the stream water to the aquifer (*stream loss*). All these changes produce an annual 1.03 to 2.09 hm³/year decrease in the groundwater discharged in the basin streams/drains compared with the deciduous forest (Table 3).

As mentioned, the results shown in Table 3 suggest that the water stored in the aquifer acts as a buffer capacity. However, when the lowest recharge occurs (2007 and 2009, Table 2), the buffer

capacity will also decrease. This phenomenon is observed in the years with the lowest recharge and/or dry summers (2007 and 2009, Table 2), in which the impact of poplar plantations is prolonged compared with the deciduous forest (see gain and/or loss behaviour evolution in Figure 11). In 2007, the flow reduction occurs from May 2007 to January 2008; in 2009, the impact is prolonged 8 months, from June 2009 to January 2010 (Fig. 11). Therefore, when dry years occur consecutive, this buffer capacity is progressively reduced. In contrast, in the years with high recharges, the groundwater recharge to the river is recovered at the end of summer, allowing the aquifer to act as a buffer the following year.

The precipitation pattern observed over dry summers and/or over long periods with low precipitation is similar to the future patterns expected in the Mediterranean, as shown in other studies (Founda and Giannakopoulos, 2009; Mas-Pla et al., 2012; Pal et al., 2004). Therefore, the impact of poplar plantations on the aquifer and on the stream base flow is expected to increase in future decades. Aquifer properties play an important role in determining which geological formations with a high porosity/storage capacity in shallow aquifers will have high buffer capacities.

To understand the effects of poplar plantations, the stream-aquifer interaction (i.e., the gain and loss behaviour) was studied in more detail in the Santa Coloma main stream. This area is the best characterised by the model (ACA, December 2010b; ACA, October 2010a), and it contains the highest density of poplar plantations, i.e., 27% of the main alluvial aquifer surface linked with the main stream is occupied by poplar plantations (Fig. 1).

Then, to compare the total effect of poplar plantations on the stream base flow, considering the changes produced in the stretches with water gain and loss, with other scenarios with different land uses, we apply the following equation:

$$\% Total Effect = \left(\left(\frac{SG_{poplar} - SG_{scenario}}{SG_{poplar}} \right) - \left(\frac{SL_{poplar} - SL_{scenario}}{SL_{poplar}} \right) \right) * 100 \quad (1)$$

where the total effect is the reduction or increase (percentage) in the main stream flow due to different scenarios compared with poplar plantations; SG_{poplar} (Stream gain) is the flow to the aquifer in the scenario with poplar plantations (hm^3/month); $SG_{scenario}$ is the same flow but with the results of the model with another scenario (deciduous forest, irrigation or dry crops) (hm^3/month); SL_{poplar} (Stream loss) is the infiltration of the main stream to the aquifer with poplar; and $SL_{scenario}$ represents the same flow but with the results of the other scenarios mentioned (hm^3/month).

During the summer (June-September), when the stream flow is controlled by stream-aquifer interactions, a 46% reduced stream flow is observed compared with a deciduous forest scenario; this values reaches 55% in the driest years. For the same months, the minimum reduction of the flow is approximately 33% in 2004. In the case of dry crops, the main stream flow annually increases an average of 33% (maximum of 42%). These differences indicate that the areas that are currently inhabited by poplar plantations would be occupied by deciduous forests or dry crops, and there would be an increase of at least 30% in the stream flow during the summer (Fig. 11).

Annually, the scenario with irrigated crops is more damaging than the current situation with poplars, with an average annual groundwater flow reduction of 0.01 hm^3 to the river. However, during summer months (June-September), irrigated crops would reduce the stream flow by 5% more, on average, than poplar plantations (Fig. 12) because groundwater extracted for agriculture occurs from spring until the end of August, whereas plantations mainly extract water from June to September. Furthermore, during spring, the main stream is greatly influenced by surface runoff, limiting the impact of these extractions.

5. Conclusions.

The impact of poplar plantations on an aquifer water budget and on the stream base flow of the Santa Coloma basin was quantified by means of a numerical flow model. Poplar plantations account for 30% of the aquifer withdrawal and approximately 18% of the total aquifer recharge.

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4 445 Furthermore, because direct groundwater evapotranspiration mainly occurs during summer
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6 446 (June to September), when the stream flow is lowest, there is a flow reduction of 46% compared
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8 447 with a natural forest. Thus, poplar tree plantations significantly modify the natural flow
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10 448 conditions of Mediterranean streams during the months with the lowest flow.

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13 449 During dry years, water stored in the aquifer acts as a buffer by limiting the effect of the poplars
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15 450 on the stream flow. However, under multi-year droughts, a more critical impact is expected.
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17 451 Furthermore, despite the presented case, geomorphological changes observed in the main stream
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19 452 do not appear to have an important influence on the flow. The presented result show that the
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21 453 impact of poplar plantations on the aquifer water balance and on the stream flow should be
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23 454 considered in conjunction with other variables that affect the system (e.g., surface and
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25 455 groundwater extraction and other land use changes).

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28 456 Comparing poplar plantations with other land uses, the least influential scenario is dry farming
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30 457 or a deciduous forest. Furthermore, the scenario with irrigated farming would be similar to that
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32 458 with poplar plantations because the Santa Coloma stream flow would decrease by a similar
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34 459 volume during the summer. However, in the scenarios with irrigated farming, the river flow is
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36 460 also impacted at the end of spring when the input of surface water to the river system is high.

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40 461 Nevertheless, the impacts of these plantations on river/streams and related ecosystems should
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42 462 not be considered equivalent to the effects of riparian forests in the same hydrogeological
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44 463 settings. Although both land uses produce an increase in evapotranspiration-regulating nutrients
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46 464 and/or filtrating pollutants (Butturini et al., 2003; Flewelling et al., 2014; Hanson et al., 1994;
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48 465 Sabater et al., 2003), riparian forests also promote habitat diversity and sediment retention,
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50 466 among others ecosystem services (García-Arias et al., 2014).

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52 467 In contrast to the direct groundwater extraction by poplar plantations, wells used for irrigation
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54 468 are controlled by water agencies. The owners of these wells pay a specific rate for water
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56 469 consumption. Thus, water withdrawal produced by poplar plantations is not controlled or
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59 470 included in basin water management plans. Because of their impact on the water budget and on
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the river base flow during the summer, legislation should be reviewed to include these types of plantations in basin water management plans; further, these plantations may even be considered water users by local/national water agencies.

Additional research is needed to conceptualise the costs and benefits of this type of non-natural plantation for biomass production, specifically, the associated economic benefits and the effects on the water budget (i.e., stream flow) at various scales (local, basin or national level).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://www.creaf.uab.es/eng/index.htm>.2014.11.01.

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Figure captions

Fig. 1. Aerial view indicating the main villages, the modelled area limits and the poplar plantation locations.

Fig. 2. Geological map with groundwater contour lines for the shallow sedimentary aquifers (Neogene and quaternary) of the Santa Coloma River basin (Field survey May 2009).

Fig. 3. Modelled domain with different parameters.

Fig. 4. Modelled domain with 20 hydraulic conductivity zones defined using outcrops, boreholes and pumping tests data.

Fig. 5. Scheme of total evapotranspiration from poplars, where ETR_T is the total evapotranspiration, $ETRs$ is the evapotranspiration produced during water infiltration and ETR_{gw} is the groundwater directly evapotranspired from the aquifer.

Fig. 6. Hydrogeomorphological changes in the main stream of the Santa Coloma over time.

Fig. 7. Observed versus simulated hydraulic head data in May 2009.

Fig. 8. Observed and simulated evolution of the hydraulic head as measured by a piezometer ACA/S-11 in the SCR alluvial aquifer.

686 Fig. 9. Santa Coloma stream flow and total model output from the aquifer to the stream (total
687 output of drain + river boundary conditions).

688 Fig. 10. Trend in hm^3/month for *River leakage in* (contributions of the river to the aquifer) and
689 *River leakage out* (contributions of the aquifer to the river) during the study period.

690 Fig. 11. Stream flow loss and gain for the study period based on poplar plantations and
691 deciduous forests.

692 Fig. 12. Percentage change in the river base flow (*River leakage in + out*) with poplar
693 plantations compared with other land uses.

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1 Table 1. Obtained hydraulic conductivities for the entire model domain.

2

Geological formations	Conductivity (K) in <i>m/day</i>	Specific storage (<i>S_s</i>) in <i>m⁻¹</i>
Alluvial formations (four zones)	Between 20 and 175	0.001
Neogene	Around 0.25	0.002
Alluvial and Neogene	100	0.008
Granitic material (weathered)	0.20	0.03
Granitic material (non- weathered)	0.02	0.0001
Volcanic formations	Between 0.03 and 0.10	0.001

3

1 Table 1. Mass balance results in hm³/year for the transient simulation.

2

Real terminology	Modflow terminology	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
Recharge	Recharge In	22.90	19.19	15.47	8.84	2.58	10.06	6.18	11.78	21.95	13.21±2.37
Contributions											
through fault zones	GHB In	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43±0.00
Stream losing	River Leakage In	2.45	2.23	2.45	2.49	2.72	2.69	2.65	2.57	2.50	2.53±0.05
Inflow from upper reaches	Constant flow	0.12	0.11	0.09	0.06	0.00	0.07	0.05	0.07	0.14	0.07±0.01
Returns from waste water	Wells In	5.62	5.58	4.56	3.65	2.72	4.24	3.34	3.62	5.73	3.73±0.37
Total Inflow	Total inputs	32.52	28.54	23.99	16.47	9.45	18.49	13.64	19.46	31.75	21.59±2.71
Stream gaining	River Leakage Out	4.60	5.59	4.29	4.15	2.73	2.92	3.04	3.39	4.97	3.96±0.33
Drains	Drains Out	10.16	12.75	10.50	10.75	7.61	7.60	7.92	7.54	8.89	9.30±0.61
GW extraction	Wells Out	3.88	3.47	3.93	4.37	4.32	3.81	5.02	4.07	4.01	4.10±0.15
GW Transpiration	Poplar extraction	2.47	2.31	2.25	2.50	2.38	2.38	2.52	2.30	2.46	2.40±0.03
GW discharge to the next river	Constant Head Out	0.87	0.89	0.85	0.82	0.78	0.81	0.80	0.83	0.87	0.83±0.01

basin

Total outflow	Total outputs	21.98	25.00	21.82	22.58	17.82	17.52	19.29	18.12	21.20	20.59±0.85
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Storage	In-Out	10.54	3.53	2.17	-6.11	-8.37	0.97	-5.65	1.34	10.55	1.00±2.28
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4

1 Table 3. Differences in the main terms of the simulated water budget using poplar plantations
2 compared with using deciduous forests. Negative values indicate a decrease in the contributions
3 and positive values indicate an increase in the inputs induced by plantations.

4

Real terminology	Modflow terminology	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
GW Transpiration	Poplar extraction	2.47	2.31	2.25	2.50	2.38	2.38	2.52	2.30	2.46	2.40
Stream loosing	River Leakage In	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.08	0.09	0.08
Stream gaining	River Leakage Out	-0.38	-0.43	-0.44	-0.47	-0.47	-0.48	-0.50	-0.49	-0.53	-0.46
Drains	Drains Out	-0.59	-1.00	-1.13	-1.25	-1.25	-1.31	-1.37	-1.41	-1.47	-1.20
GW discharge to the next river basin	Constant Head Out	-0.04	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Storage	In-Out	-1.39	-0.76	-0.57	-0.79	-0.57	0.20	-1.19	-0.29	-0.35	-0.63

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