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The impact of climate change, human interference, scale and modeling uncertainties on the estimation of aquifer properties and river flow components

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SUMMARY

Within the period 1978–2006, climate change and human interferences produced noticeable impacts on the hydrology of a small watershed, known as the Beça River basin. Climate change was characterized by a persistent raise in temperature (+0.78 °C decade^{-1}) and a drop in the annual rainfall (−300 mm decade^{-1}). Human interferences included the construction of a dam for electric power generation, in 1998, and since then the transference of Beça River flows from the dam lake to the adjacent Tâmega River. The impacts on catchment hydrology comprised a decline of aquifer hydraulic conductivity and effective porosity, by approximately one order of magnitude, related to a water table lowering of about 17 m within the bedrock aquifer composed of weathered and fractured Hercynian granites and Paleozoic metassediments and of saprolite layers derived therefrom. Aquifer property estimates were compared across spatial scales, namely the Beça River and the nested sub-basins scale. Sub-basin aquifers are more porous and permeable than the basin aquifer because corresponding hydraulic circuits are shallower. Comparisons were also made between aquifer properties derived from measured and simulated stream flows, which revealed effects of modeling uncertainties on the results. River flows also suffered a substantial decrease in the course of climate change and human interference, especially the overland flows (4/5 decrease) and the base flows (2/3 decrease). The inter flows were less affected (1/3 decrease) because they were partly fed with water from the aquifer storage, which in turn underwent depletion. The hydrologic changes in the Beça River basin anticipate important impacts on the local use of natural water. In this context, the aforementioned water table lowering may have caused limited access to shallow groundwater for activities such as crop irrigation from dug wells, whereas the severe decline in overland flows and base flows had certainly reduced the availability of surface water for the refilling of dam lakes and of groundwater for the supply of public and private boreholes.

1. Introduction

The impacts on hydrology caused by climate change in the 20th century have been reported in many watershed studies around the globe, and in some cases were also anticipated for the future. For example, in the St. Lawrence fluvial corridor between Montreal and Quebec City (Canada), Boyer et al. (2010) reported an increase in winter flows and decrease in spring flows caused by a shift in winter precipitation from snow to rain (early freshet) in the course of a temperature increase occurring within the second half of the 20th century. Based on climate change scenarios set up for the 21th century, which predicted an amplification of winter flows, they also anticipated impacts on the hydrology and ecology of St. Lawrence tributaries, namely an enhancement of river channel erosion and an alteration of stream conditions for winter spawning fish species. Similar studies were carried out in Ireland by Steele-Dunne et al. (2008), in the Loess Plateau of China by Zhang and Liu (2005) and in the Spencer Creek watershed (Southern Ontario,

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Canada) by Grillakis et al. (2011), although more focused on the risks of flooding and soil erosion induced by a rise in winter flows, enhanced by an increase in the frequency of extreme precipitation events, all caused by a predicted rise in the mean annual temperature during the present century. A number of other studies relating future changes in temperature and precipitation to the magnitude and timing of hydrologic events could be cited, for example the ones by Merritt et al. (2006), Westmacott and Burn (1997) and Yu et al. (2002), among others.

In a different line of thought, some studies analyze the impacts of climate change and indirect human interferences (e.g., land use change) on the water balance components of catchments or lakes, and sporadically on water quality. For example, Li et al. (2009) quantified the impacts of past land use changes and climate variability on surface runoff, soil water contents and evapotranspiration in the Heihe catchment of the Loess Plateau of China, while Tomer and Schilling (2009) attributed to climate and land use changes the increase in baseflow and in the ratio surplus precipitation/unsatisfied evaporative demand, in catchments of the US Midwest. Impacts of climate change on the hydrology of lakes Gallocanta (Spain), Chaohu (China) and Ziway (Ethiopia) were discussed by Kuhn et al. (2011), Chen et al. (2013) and Legesse et al. (2003), respectively, whereas Tu (2009) analyzed the combined impact of climate and land use changes on stream flow and water quality in eastern Massachusetts (USA). Following the route of simulating future distributions of water balance components, some authors centered the discussion on the economical and social implications of changing the surface water compartment, namely as regards the management of hydropower generation, the public supply of water from dam reservoirs, etc. (Bozkurt and Sen, 2013; Matondo et al., 2004b). A review on the impact analysis of climate change as regards water resources management has been presented by Nan et al. (2011). Some other studies pursuing the objective of diagnosing or simulating the impacts on the hydrological cycle induced by past or future climate changes include the cases of Andersen et al. (2006), Kienzle et al. (2012), Serrat-Capdevila et al. (2007), Tshimanga and Hughes (2012), and references therein.

A third line of research within the topic of climate change and concomitant impacts on hydrology is focused on modeling aspects, namely on General Circulation Models (GCM) together with greenhouse gas emission scenarios to generate future climate data, on downscaling techniques and uncertainty analysis, or on the coupling between GCM and watershed models, occasionally lumped with ecological models, to predict the implications of climate change for the global or regional hydrologic cycle, environmental quality or freshwater biodiversity. In this category of studies one can include those carried out by Chen et al. (2011), Grillakis et al. (2011), Jiang et al. (2007), Luo et al. (2013), Matondo et al. (2004a), Mauser and Bach (2009), Menzel and Bürger (2002), Tisseuil et al. (2012), Tripathi et al. (2006), Xu et al. (2013), among others.

In compliment to climate change and indirect human interferences, hydrologic processes can be impacted by direct human interferences, such as water withdrawals and return flows which can affect the base flow recession process (Thomas et al., 2013; Wang and Cai, 2009, 2010), or the construction of dams which can affect the river flow regime depending on whether the dam lake is impounding, releasing or diverting water (Gao et al., 2013; Guo et al., 2012; Zhao et al., 2012). Alternate impounding and releasing of water from dam lakes may also affect river channel morphology and riverine ecosystems (Dai and Liu, 2013; Marston et al., 2005; Petts and Gurnell, 2005; Yuan et al., 2012; Zahar et al., 2008).

Despite the large number and diversity of studies addressing the role of climate change and human interference on hydrology, there are some topics which remain poorly understood. One of these topics is the impact of climate change on groundwater reservoirs, especially on their hydraulic properties and in relation to scale (river basin and nested sub-basins). The relation between climate variables and the groundwater compartments is considered more complicated than with the surface water compartment, because groundwater residence times can range from days to tens of thousands of years, which is likely to delay and disperse the effects of climate change, and challenge efforts to immediately detect responses in the aquifers (Chen et al., 2004; Holman, 2006; IPCC, 2007). In a recent paper, Green et al. (2011) reviewed the consequences of climate change on the subsurface hydrologic cycle, namely on recharge, base flow discharge, flow and storage, but the impacts on hydraulic properties of aquifers were not properly attended. The study by Laroque et al. (1998) is probably one of a few that tackled this problem. In that study, it was shown how persistent and severe dry periods have altered the transmissivity of a regional karst aquifer in France. Another topic claiming for discussion is the influence that diversion of water from dam lakes to adjacent watersheds may have on the results of aquifer property estimation by recession flow analysis. The main purpose of this paper is to reveal how prolonged periods of drought can change the hydraulic conductivity and effective porosity of a fractured and weathered rock aquifer. In this context, the analysis will cover the river basin scale representing the regional (deeper) flow circuit and the nested sub-basins scale representing the more local (shallower) circuits. Additionally, one will report how the continuous decrease in precipitation over three decades and diversion of dam lake water after 1998 influenced the calculation of aquifer properties by recession flow analysis and affected the magnitude and spatial distribution of river flow components in the studied watershed.

2. Study area

2.1. The Beça River basin

The studied region comprises the hydrographic basin of Beça River, which covers an area of approximately 345 km^2. The main watercourse of Beça River basin is 55.2 km long, being a left-margin tributary of the Tâmega River, which in turn is a left-margin tributary of the Douro River, the most important watercourse in north Iberia. The Beça River basin is located in the Trás-os-Montes and Alto Douro province, north of Portugal, between the latitudes 41°31′38.53″N–41°49′00.36″N and longitudes 7°37′10.84″W–7°55′04.87″W (Fig. 1). It occupies the leeward side of Barroso Mountains where altitudes vary in the interval 190–1270 m above sea level and average hillside inclinations reach 11.7 ± 7.6°.

The geology of Beça River basin is characterized by Silurian black schists and quartzites, which were intruded by Hercynian granites and fractured by small-scale replicates of regional NNE–SSW fragile faults and NW–SE shear zones. Land use and occupation is dominated by semi-natural areas (45%), agricultural areas (32%) and forests (23%). In the upstream and middle sectors of the basin, occupation is characterized by shrubs, where the relief is craggy, and by dry farming areas, pastures and natural grasslands in the valleys surrounding the local villages. The downstream sector is used for wood production, being occupied by large and continuous spots of *Pinus pinaster* forests (Caetano et al., 2009). Above the altitude of 700 meters the Beça River is relatively straight following the N–S direction. The riverbed is rocky and the margins generally do not accumulate sediments. Below that altitude and especially downstream the confluence with the right-margin tributaries, the river tends to meander and develop lateral channel sinuosity-driven hyporheic zones. In these zones, riparian vegetation is well-preserved, being dominated by *Fraxinus angustifolia*, *Alnus glutinosa*, *Salix atrocinera* and *Betula pubescens*.