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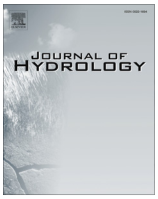

Simulating the hydrological response of a closed catchment-lake system to recent climate and land-use changes in semi-arid Mediterranean environment

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SUMMARY

Lake water levels are sensitive sentinels of changes in the climate and landscape of the broader lake catchment. This means that lakes can be useful for quantifying the effects of these changes on the water yield of a catchment. This study presents a water balance model of a closed catchment-lake system in the semi-arid Mediterranean climate over the last 85 years, with the objective to understand the influence of precipitation change and the conversion from Mediterranean maquis to pasture. Deforestation alters the balance between evapotranspiration and canopy interception, and causes the rapid decay of soil hydrological properties, thus changing the mechanisms of runoff generation. The overall impact of these changes on the water yield has been evaluated for the catchment of the lake. A physically based rainfall–runoff model, combined with the energy budget method for estimating lake evaporation, were used for the lake water balance model. The calibration was carried out with the continuous measurements taken during the period 2008–2013. The reliability was evaluated with the historical lake levels between 1929 and 2008. Simulation errors were small despite the high sensitivity of the water balance model to precipitation, which in the historical period was that of a non-local station. The simulation results show that the balance was influenced by a combination of climate and land-use changes. The 23% decrease in precipitation observed in the last 50-years has resulted in a 72% decrease in average streamflow. The contemporaneous deforestation in 18% of the catchment area resulted in a 13% decrease in streamflow. The main mechanism of runoff generation under the maquis cover was saturated subsurface-flow. At hillslope scale this can eliminate the surface runoff, giving the impression that the water yield is lower than that of deforested hillslopes. However, at the basin scale the effect can also be reversed. The reduction in soil hydraulic conductivity and porosity in deforested and altered soils produces higher soil moisture and perched water-table, which means that there are higher evaporation and percolation losses. As simulated by the hydrological model, these higher losses compensate for the greater throughfall. Thus deforestation gives rise to lower water yield in this semi-arid Mediterranean environment.

1. Introduction

The water level in lakes acts as a sensitive sentinel of changes in climate and landscape in their broader catchment (Adrian et al., 2009; Williamson et al., 2009a,b). This means that lakes are important sources of data, where we can explore the influence of changes in vegetation and precipitation on water resources. The United Nation Convention to Combat Desertification (UNCCD, 1994) recognized that the two main drivers of land degradation in semiarid environments were changes in climate and land-use. These drivers may cause an ecosystem to shift to a "desertified" state. This results in the services provided by the ecosystem being lost and also poses serious threats to sustainable systems. In order to combat desertification, it is of fundamental importance to quantify the extent to which a region's degradation is caused by either climate change or human activities (Wang et al., 2012; D'Odorico et al., 2013). Several authors have analyzed precipitation variability and trends in the Mediterranean area in the twentieth century. Xoplaki et al. (2004) found that precipitation reached a maximum in the 1960s, and declined afterwards. Giorgi (2002), Mariotti (2010) and Barkhordarian et al. (2013) also found similar precipitation trends for the Mediterranean area, and others authors found the same results in regional station-based studies in the Western and Central Mediterranean (e.g. Esteban-Parra et al., 1998; Buffoni et al., 1999; Tomozeiu et al., 2002). Global and regional

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model simulations have also been used by many authors (e.g. Gibelin and Déqué, 2003; Giorgi, 2006; Gao et al., 2006; Giorgi and Lionello, 2008), and these indicate that the Mediterranean area is a primary "Hot-Spot" for climate global change.

Many human activities overlapped this period of climate change. These include deforestation, cultivation of steep slopes, fires and overgrazing. Such human impact was especially drastic in the second half of the last century with the increased mechanization of agriculture. This triggered off soil erosion and led to severe land degradation (Cantón et al., 2011). Several studies throughout the world (e.g. Celik, 2005; Gonzalez-Sosa et al., 2010; Agnese et al., 2011) have demonstrated that forest cover preserves the high hydraulic conductivity and porosity of the soil, through the presence of macropores adjacent to the stem and roots, and soil fauna activity. As a result, deforestation is generally associated with the rapid decay of the hydrological properties of the soil (De Moraes et al., 2006; Germer et al., 2010; Alaoui et al., 2011). This affects the soil moisture dynamics and the runoff generation processes (Niedda and Pirastru, 2013b). The conversion of the land cover from perennial scrubs and forest to annual crops is typically associated with a decrease in canopy interception, an increase in groundwater recharge and the rise of shallow water-tables (Wang et al., 2012). Because the water-table is closer to the surface, an increase in evaporation losses can be expected. Hence, land-use change alters the ratio of the balance between canopy interception and evapotranspiration losses, as well as the runoff generation processes. The overall impact of these actions on the water yield of a catchment is still an open question of debate and research in the literature (Brown et al., 2005; Guo et al., 2008). The impact depends on the climate, soil and vegetation interactions at basin scale, and research is still necessary to clearly evaluate this.

Hydrological modeling is a helpful approach which can be used for identifying the impact of climate and land-use change on the catchment hydrology. Physically-based hydrological models simulate the spatially distributed streamflow time series, and so they can be used to estimate the relative contributions of land cover changes and climate change/variability at daily, monthly or annual time steps. Due to these characteristics they are suitable for use as part of scenario studies, which investigate the impact of expansion or reduction of the planted area, and the effect of climate change/variability on runoff production. The assessment of the effects of land-use or climate on hydrological processes is often done by calibrating and validating models for current land-use and climate conditions. The past (or future) climate or vegetation scenarios are then defined, and the model is ran again for these conditions. Finally the differences between the two sets of model simulations are then quantified. For example, a similar approach to this was used by Elfert and Bormann (2010) and Niehoff et al. (2002) using the WaSiM-ETH model, by Li et al. (2009) using the SWAT model, and by Legesse et al. (2003) using the PRMS model.

In this research, a physically based rainfall–runoff model was integrated into a daily lake water balance model and was applied to Lake Baratz, a closed catchment-lake system in Sardinia, Italy (Niedda and Pirastru, 2013a). The lake water levels ranged from a maximum in the first half of the last century to almost drying out in the first decade of the 21st century. This might be attributable to changes in precipitation and to the conversion of parts of the basin from Mediterranean maquis and forest to agriculture. Lake Baratz is a closed basin lake with little or no outflow. There may be great changes in the water levels in this type of lakes, in conjunction with changes in the balance between input (mainly precipitation and runoff) and output (mainly evaporation). This leads to the lake levels being largely controlled by the rainfall–runoff processes in the broader catchment, and makes these places ideal for exploring the sensitivity of the ecosystem to climate and vegetation changes (Vallet-Coulomb et al., 2001; Legesse et al., 2004; Niedda and Greppi, 2007; Shanahan et al., 2007). Hence knowledge about the hydrological regimes of closed catchment-lake systems, and how these responded to changes in the past, is useful in helping us to predict changes in the long-term availability of water resources, especially in the context of future climate change and the increasing impact of human activities. Precipitation, temperature, lake water level, streamflow data, and land-use maps from the last century (see Table 1) have been used with the following objectives:

- to calibrate and evaluate the reliability of a coupled catchment-lake water balance model, reconstructing the historical water levels of Lake Baratz;
- to understand the effects of the climate and land-use changes on the water balance of this catchment-lake system;
- to understand the effects of deforestation and deterioration of soil hydrological properties on water yield in the semi-arid Mediterranean environment.

2. Site and data description

2.1. Site description

Lake Baratz is a small closed-basin lake in North-Western Sardinia, Italy (Fig. 1a). The contributing catchment area (Fig. 1b) is 12 km^2. The maximum lake volume is 5.1×10^6 m^3, which corresponds to a surface area of 0.6 km^2, a water level of 32.5 m a.s.l., and a maximum depth of 16 m (Fig. 1c). Above this level there is an overflow spillway towards the nearby sea. The climate is Mediterranean, semi-arid with a mild and wet winter, and a warm and dry summer. The geological substratum of the basin consists of fractured sericite phyllite on the metamorphic Paleozoic base of Sardinia in the upstream Northern half, and Permian sandstone and conglomerates of alluvial deposits, in the downstream Southern half. The Permian sandstone provides the almost impermeable support layer for the lake. In the Northern part of the basin there are narrow valleys covered in Mediterranean maquis (e.g. *Myrtus communis* L., *Arbutus unedo* L., *Erica arborea* L., *Phillirea latifolia* L., *Pistacia lentiscus* L., *Quercus ilex*, L.). The soil is loam or loamy sand and thin or medium in depth. In the Southern part of the basin there are flattish plains, mainly covered with pasture and cultivated areas. Here the soils are deep, sandy loam in the surface layers and from sandy clay loam to clay in the deeper layers.

2.2. Monitoring design

The catchment-lake system has been furnished with instruments since 2008, with a land station in the middle of the catchment, and since July 2011 there has been a raft station in the middle of the lake, as shown in Fig. 1b. The raft station was fitted with sensors for measuring net solar radiation (NR-Lite), air temperature and relative humidity (CS215), wind velocity (WindMonitor) at 2 m above the lake surface, atmospheric pressure (CS100), six thermistors (CS107) submerged in the uppermost three centimeters of water beneath the lake surface and at depths of 1, 2, 4, 6, and 8 m, all logged to a CR1000 Campbell Scientific Inc. datalogger, and a pressure transducer (Schlumberger Mini-Diver) to measure the water level of the lake. The lake water levels were also measured manually every one or two weeks from 2008. The land station was located near the main tributary of the lake, 40 m a.s.l. (Fig. 1b). At this cross-section, the sub-catchment area is 7.4 km^2, which is about 62% of the lake catchment area. It was equipped with the same datalogger and climatic sensors as the raft station, plus a rain gauge (ARG100, tipping bucket, 254 mm diameter) and a current meter (SonTek Argonaut-SW) with sensors for the