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Combination of lumped hydrological and remote-sensing models to evaluate water resources in a semi-arid high altitude ungauged watershed of Sierra Nevada (Southern Spain)

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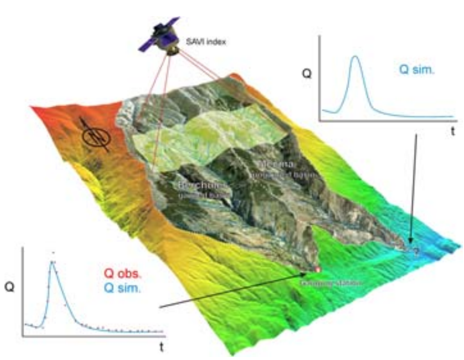
HIGHLIGHTS

- VI-ETo model used to estimate annual discharge of ungauged high-mountain basins.
- The HBV model is used to validate the VI-ETo model results.
- Groundwater discharge controls the Bérchules watershed hydrological dynamics.
- Deglaciation modifies the response of High Mountain the rivers in low latitude basins.
- Reforested trees evapotranspirate the same water as crop irrigation in Sierra Nevada.

GRAPHICAL ABSTRACT



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ABSTRACT

Assessing water resources in high mountain semi-arid zones is essential to be able to manage and plan the use of these resources downstream where they are used. However, it is not easy to manage an unknown resource, a situation that is common in the vast majority of high mountain hydrological basins. In the present work, the discharge flow in an ungauged basin is estimated using the hydrological parameters of an HBV (Hydrologiska Byråns Vattenbalansavdelning) model calibrated in a "neighboring gauged basin". The results of the hydrological simulation obtained in terms of average annual discharge are validated using the VI-ETo model. This model relates a simple hydrological balance to the discharge of the basin with the evaporation of the vegetal cover of the soil, and this to the SAVI index, which is obtained remotely by means of satellite images. The results of the modeling for both basins underscore the role of the underground discharge in the total discharge of the hydrological system. This is the result of the deglaciation process suffered by the high mountain areas of the Mediterranean arc. This process increases the infiltration capacity of the terrain, the recharge and therefore the discharge of the aquifers that make up the glacial and periglacial sediments that remain exposed on the surface as witnesses of what was the last glaciation.

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1. Introduction

In high-altitude hydrological systems located in semi-arid zones, practically all the necessary water resources available in the low zones are generated to satisfy the demand of both the biological activity of the associated ecosystems (Taylor et al., 2012) and of the users who depend on this resource (Vivirolí et al., 2007; García-Vera, 2013; López-Moreno et al., 2014). At the head of these basins, global warming is directly affecting the accumulation and melting of snow, modifying the response of these hydrological systems, at least in the discharge flows and their seasonality, causing the main peak of the hydrograph to be brought forward (Andermann et al., 2012; Hood and Hayashi, 2015; Cowie et al., 2017). In the Mediterranean region, in addition to the rise in temperature, the occurrence of prolonged dry periods and greater evaporation is also forecasted, which could increase the frequency and intensity of droughts in the areas of southern Europe (Mishra and Singh, 2010), where conditions of hydrological aridity already prevail (Wanders et al., 2010; Van Lanen et al., 2013).

In the Alpine basins of the Mediterranean arc, global change is producing a rapid retreat of the few remaining glaciers as a consequence of the 0 °C thermocline elevation (Nogués-Bravo et al., 2008; González Trueba et al., 2008; Grunewald and Scheithauer, 2010). This glacial retreat generates large permeability changes in the upper part of the basins by exposing high permeability glacial and periglacial materials that facilitate both, rainfall to infiltrate and groundwater to flow (Fedeli and Castillo, 1997; Millares et al., 2009). Additionally, the thermocline elevation has generated a reduction in the permafrost affected area and changes in the basin land use and management (Benito et al., 2011; García-Ruiz et al., 2015). The global change is modifying the role played by the different processes that control the behavior of the hydrological systems located in high mountain zones. This has to be taken into account when establishing or even updating the conceptual model of such hydrological systems.

Despite their strategic importance, the Alpine basins of the Mediterranean arc are little studied (Bocchiola et al., 2010). Furthermore, characterizing behavior of such basins is not easy, given the difficulty of access, the adverse climatic conditions of great part of the year and the instrumentation necessary to characterize the operation of the system, especially in relation to groundwater (Langston et al., 2013; Molina et al., 2014; Hood and Hayashi, 2015). As a result, the majority of the high mountain hydrological basins are completely ungauged.

Making reliable Predictions in "Ungauged Basins" (PUB, Sivapalan, 2003) has long been recognized by hydrologic sciences (Sivapalan et al., 2003; Kundzewicz, 2007). A better understanding of the hydrological processes involved and the effect on them of the different landscapes and landcover changes (Pisano et al., 2017) are necessary to characterize the response of hydrological systems. These geographical features can be considered one of the most rapid drivers of global change (Slaymaker et al., 2009). Additionally, it is also necessary to obtain coherent and concurrent data at different spatio-temporal scales to correctly define the hydrological systems dynamics (Blöschl et al., 2007; Wagener et al., 2007; Hrachowitz et al., 2013). The problem may be even more complex if it is not clear how different hydrological processes (e.g. evapotranspiration, surface runoff generation, percolation and underground discharge) interact with each other to end up generating total discharge from the basin.

The use of hydrological models reduces the problem of PUB to the appropriate selection of the effective parameters corresponding to the "ungauged basin". Despite the hydrological aphorism that each basin is different ('uniqueness in place', Beven, 2000), the most common practice is to apply the concept of regionalization (Buytaert and Beven, 2009), through which the model parameters that have been calibrated in the gauged basin are migrated to the ungauged one. In the literature, there are several regionalization techniques whose functional complexity varies from the nearest neighbor (Merz and Blöschl, 2004) to the use of complex functional dependencies and statistical techniques (see Vandewiele and Elias, 1995; Sefton and Howarth, 1998; Wagener et al., 2004; Hundecha and Bárdossy, 2004; Wagener and Wheater, 2006; Skøien and Blöschl, 2006).

To facilitate the process of regionalization, several authors suggest the use of "parsimonious conceptual rainfall-run-off models" (see Seibert, 1999; Bergström et al., 2002; Merz and Blöschl, 2004; Parajka and Blöschl, 2008; Skaugen et al., 2015). These models express, through more or less simple functions, the different physical processes that control the operation of the hydrological processes governing the functioning of the basin. From the perspective of parameterization, these models are the most efficient (parsimonious), and avoid the problems generated by the over parameterization of the model in the identification of parameters (Kirchner, 2006; McDonnell et al., 2007; Wagener et al., 2007).

Nowadays, due to the availability of new sensors on board the satellites it is possible to estimate the discharge of some rivers remotely (Smith et al., 1996; Bjerklie et al., 2003; Alsdorf et al., 2007; Temimi et al., 2007; Smith and Pavelsky, 2008; Neal et al., 2009; Birkinshaw et al., 2010; Tarpanelli et al., 2013a, 2013b; Tarpanelli et al., 2015), something that is fundamental to be able to validate the discharge flows calculated in the "ungauged basins". Although the different techniques for estimating the flow through the rivers have great potential, their application in "ungauged basins" is still limited, since the flow estimate finally depends on detail information of the basin that cannot be obtained completely remotely (e.g. flow rate through different river control sections, river bed depth, river rating curve, etc.). However, remote observation of hydrological variables, such as the extension of flood zones (Di Baldassarre et al., 2009; Domeneghetti et al., 2014), the soil uses and the associated evapotranspiration (Anderson et al., 2012), or even the depth of the water table (Urqueta et al., 2018) have recently been postulated as an additional source of information to help to establish the conceptual model of hydrological systems, and to improve the calibration of corresponding numerical models.

This work evaluates the discharge of the Mecina River basin, an ungauged basin located in a high mountain area in the SE Iberian Peninsula, from the response observed in the neighboring Bérchules River basin. From the perspective of the global change impact on the hydrological systems located in high mountain zones, both basins are examples of what could happen in other higher latitude basins. The Bérchules and Mecina basins are located in Sierra Nevada, a mountain area where the latest glaciers disappeared by the middle of the last century (Hughes and Woodward, 2009), almost the total permafrost has disappeared (Oliva and Gómez-Ortiz, 2012), glacial and periglacial quaternary sediments favor the infiltration capacity of practically all the precipitations, increasing the underground component (Jódar et al., 2017), and where the vegetation has adapted to arid conditions that bear no relation with the prevailing climate conditions in high mountain basins located at high latitudes in the Northern Hemisphere, which have been the object of a deeper research (Theurillat and Guisan, 2001; Kullman, 2002; Benito et al., 2011).

In this work, a lumped hydrological HBV model (Bergström, 1976, 1992, 1995) has been calibrated to simulate the observed response in the discharge flow of the Bérchules basin. This conceptual rainfall-runoff model has not only been thoroughlly used in hydrological characterization studies (Singh and Woolhiser, 2002; Bergström, 2006, Seibert and McDonnell, 2013 and references therein), but also in numerous regionalization studies (Seibert, 1999; Merz and Blöschl, 2004; Parajka et al., 2005; Götzinger and Bárdossy, 2007; Samuel et al., 2011); however, its implementation has been limited in high mountain basins with semi-arid conditions. With the parameters of the calibrated model of the Bérchules basin, the hydrological response is simulated in the