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Groundwater dynamics in a hydrologically-modified alpine watershed from an ancient managed recharge system (Sierra Nevada National Park, Southern Spain): Insights from hydrogeochemical and isotopic information

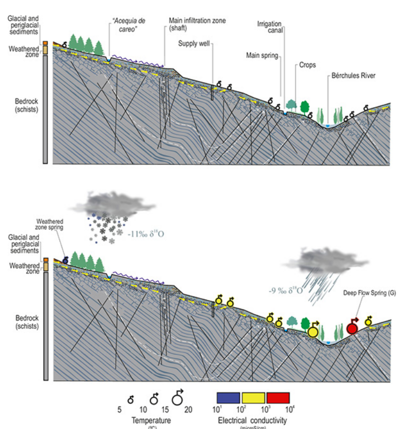
Barberá J.A. [a], Jódar J. [b,c,*], Custodio E. [b,f], González-Ramón A. [e], Jiménez-Gavilán P. [d], Vadillo I. [a], Pedrera A. [e], Martos-Rosillo S. [e]

[a] Centre of Hydrogeology of the University of Málaga (CEHIUMA), Spain
[b] Groundwater Hydrology Group, Dept. Civil and Environmental Eng., Technical University of Catalonia (UPC), Spain
[c] Hydromodel Host S.L. and Aquageo Proyectos S.L., Spain
[d] Department of Ecology and Geology, Faculty of Science, University of Málaga, Spain
[e] Geological and Mining Institute of Spain (IGME), Spain
[f] Royal Academy of Sciences of Spain, Spain

HIGHLIGHTS

- The *acequias de careo* is a water management system that enhances aquifer recharge.
- The ancient managed aquifer recharge ensures water availability downstream.
- Environmental tracers are essential to study alpine hydrologic systems.
- Concentration by evaporation controls the dissolved salts content in groundwater.
- Chemical weathering of silicate minerals is behind GW mineralization.

GRAPHICAL ABSTRACT



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ABSTRACT

In many of the alpine watersheds of Sierra Nevada (Southern Spain) exists an ancient network of dug canals that collect, transport and facilitate the recharge the snowmelt in the underlying aquifer during the spring season. This practice, known as *careos*, in the lower part of the watersheds supply drinking water as spring discharge during the dry season. To study how this managed recharge technique modifies the natural response of these basins this work focuses on characterizing the hydrological behavior of one of the sites, the Berchules watershed. The mechanisms for mineralization of groundwater are based on geochemical processes such as evapo-concentration in the soil layer and silicate mineral weathering due to dissolved CO_2 originated from both soil biogenic processes and the atmosphere. Groundwater presents a main hydrogeochemical calcium magnesium-bicarbonate type facies, which is associated to groundwater flowing through the upper weathered silicates and quickly drained through springs located in the uplands and in the intermediate altitude catchment zone.

* Corresponding author at: Groundwater Hydrology Group, Dept. Civil and Environmental Eng., Technical University of Catalonia (UPC), Spain.
E-mail address: jorge.jodar@hydromodelhost.com (J. Jódar).

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Additionally, in the lower part of the basin some springs discharge mineralized groundwater with a sodium–calcium–bicarbonate composition associated to regional groundwater flow. In natural conditions, this hydrogeological system behaves as a sloping aquifer, occurring recharge between 1400 and 2500 m a.s.l. The springs discharge groundwater with an isotopic content and temperature in coherence with the local rainfall isotopic and thermal atmospheric altitudinal lines. Nevertheless, once the *careo* recharge begins the affected springs reveal the fingerprint of the concentrated recharge system by blurring the fingerprint of both the isotopic and thermal altitudinal dependence in the springs discharge. This validates the previous conceptual model and supports average recharge values of 141 ± 140 mm/yr and total average water resources of 181 ± 111 mm/yr which include a 40% increase in the study period due to the effect of the *acequias de careo*.

1. Introduction

Water from high mountains, known as "water towers", generates 30% of the global discharge (Meybeck et al., 2001). This role is even more important in semiarid and arid zones, where its contribution varies between 50% and 90% (Messerli et al., 2004; Viviroli et al., 2007). Meltwater from "water towers" is essential not only for human sustenance, but also to maintain associated downstream ecosystems and enhance their ecological diversity (Beniston et al., 1997). Yet these hydrological systems are vulnerable to the impact of climate change (Immerzeel et al., 2010). The early effect of an ongoing global climate change has been observed in terms of glacial recession in the world's highest mountain systems, including the Andes (Fraser, 2012), the Himalayas (Scherler et al., 2011), the Rocky Mountains (Moore et al., 2009) or the Alps (D'Agata et al., 2014), among others. From the perspective of high mountain hydrological basin behavior, the increasing temperatures that are currently observed may well lead to earlier runoff in spring or winter, and to reduced discharge in summer or autumn (Barnett et al., 2005, and references therein). Nevertheless, assessment of the most likely impact of climate change on such high mountain hydrological basins calls for historical characterization. This is not an easy task given the difficulty of access, the adverse working conditions and the type of instruments required for measuring hydrological variables in high mountain zones (Clow et al., 2003; Langston et al., 2013; Molina et al., 2014; Hood and Hayashi, 2015).

A great effort therefore goes into characterizing high mountain hydrological systems, and especially the aquifers located in these physiographic settings. The water they store can be used to alleviate the potentially adverse effects of climate change (Viviroli et al., 2011; Taylor et al., 2012). The study of such hydrological systems typically involves a multidisciplinary approach that combines data from different information sources: geophysical (McClymont et al., 2010, 2012), hydrological (Kahn et al., 2008; Liu et al., 2008; Roy and Hayashi, 2009; Lauber et al., 2014; Chen et al., 2017), and geochemical, including environmental isotopes (Lauber and Goldscheider, 2014; Lambán et al., 2015; Herrera et al., 2016; Jódar et al., 2016). Processes such as snow accumulation and melting, as well as groundwater discharge, would play a major role in the dynamics of such alpine hydrological systems. A number of authors report high groundwater discharge with respect to the total alpine basin runoff (Clow et al., 2003; Huth et al., 2004; Liu et al., 2004; Hood et al., 2006; Cras et al., 2007; Jódar et al., 2017) in high slope areas with presumably low-permeability hard rock substrates. This fact highlights the importance of groundwater contribution in the behavior of high mountain rivers, which is even more relevant when they are located in semi-arid and arid environments, given that groundwater provides a critical resource downstream by sustaining river base flow during long-lasting dry periods.

This paper explores the functioning of the Bérchules River Watershed (BRW), an alpine hydrologic system where the groundwater component feeding the total basin discharge is anomalously high (Jódar et al., 2017, 2018). The study area is located along the southern edge of Sierra Nevada (Southern Spain), which is the highest mountain range of the Iberian Peninsula. Despite its altitude, the mountainous system has been fully de-glaciated since the middle of the past century (Gómez-Ortiz et al., 2012, 2015), a process most likely accelerated by the semi-arid climate conditions prevailing in the region (Gómez-Zotano et al., 2015). The southern edge of Sierra Nevada has been colonized since many centuries ago (Martín-Civantos, 2007).). In this area an ancient water management system, still currently in operation, was designed to supply water to the local population for domestic use, crop irrigation and cattle. The artificial water management system is known in Spanish as "acequias de careo" which can be translated as "hillside ditches". It constitutes a means of artificially recharging the aquifer with snowmelt by means of long channels excavated in the terrain (Pulido-Bosch and Sbih, 1995; Martos-Rosillo et al., 2017). The recharge system is so efficient and resilient that it has been maintained, with very few modifications, at least since the Middle Ages (Delaigue, 1995).

The main objective of this work is to investigate the role played by this ancient water management system in the hydrologic behavior of the BRW. A multidisciplinary approach is adopted by integrating basin hydrodynamic data with groundwater geochemistry and its isotopic composition. From data integration, a conceptual model of the hydrological basin is established and the recharge to the underlying aquifer is estimated.

2. General setting

The BRW is located at the southern edge of the Sierra Nevada mountain range (Granada province, Southern Spain; Fig. 1). It is approximately 30 km north of the Mediterranean coast, where the watershed drains the Guadalfeo River. The study area covers a rugged land surface of 68 km^2, with conspicuously asymmetric V-shape valleys dug by the river network. The average slope is 37%. The average altitude is 2070 m a.s.l. (above sea level), reaching a maximum of ~2900 m a.s.l. at the northern border of the watershed, while the lower altitude zones (<1000 m a.s.l.) coincide with the southern border of the BRW, where the gauging station of the Bérchules River is located (Narila station; S8 in Fig. 1B). The soil cover is mainly represented by sparse scrub, conifers and grasses adapted to low temperatures and low humidity. Cultivated cropland includes fruit trees and irrigated horticulture crops, particularly in the lowlands —but also on a limited scale in the uplands— totalling about 260 ha (4% of the total catchment surface area).

The climate of the study area is continental. At the Bérchules meteorological station (Fig. 1) the average values of precipitation (P), temperature (T) and potential evapotranspiration (ETP) calculated with the Hargreaves (1994) formula are 828 mm/yr, 12.9 °C and 1033 mm/yr, respectively. These three variables show a seasonal variation (Fig. 2) and elevation dependence (Jódar et al., 2017). The vertical gradient of mean precipitation ($\nabla_z\overline{P}$), mean temperature ($\nabla_z\overline{T}_{atm}$) and mean potential evapotranspiration ($\nabla_z\overline{ETP}$) are 222 mm/yr/km, −5.6 °C/km and −249 mm/yr/km, respectively. Hereinafter, and for any variable ξ, the expression $\nabla_z\xi$ is used to refer the vertical gradient of that variable (i.e. dξ/dz). Additionally, any variable with a tilde accent (e.g. $\overline{\xi}$)