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Partitioning groundwater recharge between rainfall infiltration and irrigation return flow using stable isotopes: The Crau aquifer

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ABSTRACT

This study reports an assessment of the water budget of the Crau aquifer (Southern France), which is poorly referenced in the literature. Anthropogenically controlled by a traditional irrigation practice, this alluvial type aquifer requires a robust quantification of the groundwater mass balance in order to establish sustainable water management in the region. In view of the high isotopic contrast between exogenous irrigation waters and local precipitations, stable isotopes of water can be used as conservative tracers to deduce their contributions to the surface recharge. Extensive groundwater sampling was performed to obtain δ18O and δ2H over the whole aquifer. Based on a new piezometric contour map, combined with an updated aquifer geometry, the isotopic data were implemented in a geostatistical approach to produce a conceptual equivalent homogeneous reservoir. This makes it possible to implement a parsimonious water and isotope mass-balance mixing model. The isotopic compositions of the two end-members were assessed, and the quantification of groundwater flows was then used to calculate the two recharge fluxes (natural and irrigation). Nearly at steady-state, the set of isotopic data treated by geostatistics gave a recharge by irrigation of 4.92 ± 0.89 $m^3\ s^{-1}$, *i.e.* 1109 ± 202 mm yr^{-1}, and a natural recharge of 2.19 ± 0.85 $m^3\ s^{-1}$, *i.e.* 128 ± 50 mm yr^{-1}. Thus, $69 \pm 9\%$ of the surface recharge is caused by irrigation return flow. This study constitutes a straightforward and independent approach to assess groundwater surface recharges including uncertainties and will help to constrain future transient groundwater models of the Crau aquifer.

1. Introduction

Since the last century, population growth and climate change have increased the need for the preventive management of groundwater. Knowledge of the groundwater budget is a key factor in establishing sustainable exploitation of an aquifer. Because the recharge rate of an aquifer is diffuse and varies in both space and time, it is the most difficult term of a regional water balance equation to measure. Surface recharge usually comes from rainfall infiltration but can also be due to irrigation return flow in some agricultural regions.

Agricultural practices may depend on, and in turn affect, the functioning of an aquifer in various ways. While agricultural uptakes induce an obvious direct discharge, significant irrigation practices can also indirectly affect the discharge of an aquifer. Thus, raising the piezometric surface by irrigation return flow can create areas of overflow or allow some crops to reach the water table directly, producing direct groundwater evapotranspiration, (Loheide et al., 2005; Tsang et al., 2014) and even induce salinization (Bouzourra et al., 2014). Conversely, as observed with the Dan Region Project in Israel (Kanarek and Michail, 1996), and in the south of Portugal (Stigter et al., 2006), an irrigation process wisely used can be a sustainable way to preserve the water table level and the quality of an aquifer.

Quantifying recharge rate and, by extension, the groundwater budget of an aquifer is often performed using a calibrated hydrogeological model. This requires parameters such as permeability and specific yield (in the case of transient simulations), and can be highly time-consuming. Alternative methods to ascertain the groundwater budget are surface watershed water budget or geochemical tracers. The latter are crucial to improve the knowledge of aquifer hydrodynamics, especially to dissociate the respective contribution of different origins of groundwater recharges, which is very difficult to obtain with conventional methods.

Stable isotopes of water ($\delta^{18}O$, δ^2H) have been used since the pioneering work of Craig (1961) and Dansgaard (1964) to trace

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the water cycle. Unlike many physical measurements generally used for implementing hydrogeological models, stable isotopes of water can monitor the hydrologic behavior of an entire reservoir (Gat and Gonfiantini, 1981). In the absence of fractionation processes due to evaporation or condensation, stable isotopes constitute a fully conservative tracer, making it possible to determine mixing fractions of different water masses involved in groundwater fluxes (Darling et al., 1996; Gattacceca et al., 2009; Gonçalvès et al., 2015; Guglielmi et al., 1998; Huneau et al., 2011; Kim et al., 2003; McGuire et al., 2002; Williams, 1997) and to compute *e.g.*, the amount of artificial recharge of an aquifer (Liu et al., 2014; Ma and Spalding, 1996; Plöthner and Geyh, 1991).

Since the 16th century, grassland cultivation has been practiced over the Crau plain (Southern France) with a traditional irrigation technique, which consists in flooding meadows with large amounts of water withdrawn from the Durance River. Originating from the Alps, this water is distributed over the Crau plain through a dense network of irrigation channels. The excess of irrigation water flows towards the water table, providing the main contribution to the recharge of this aquifer. In recent decades, the Crau aquifer became an example of the complexity of the resource management issues that combine environmental and socio-economic considerations. Irrigated meadows contribute to providing the main drinking water resource for over 300,000 inhabitants in the area. This large-scale artificial recharge is essential for local populations, but also for several industrial complexes, for agricultural activities, and for some directly connected protected wetlands. A possible reduction in irrigation fluxes due to the need for water saving or to a future land-use change could substantially reduce the total groundwater recharge, and thus endanger the groundwater resource. A robust quantification of the groundwater budget is thus required to establish sustainable water management in the region.

Implemented in a hydrogeological model, the groundwater mass balance, including recharge, of the Crau aquifer was already proposed by Berard et al. (1995). Another groundwater recharge estimate and its excess irrigation fraction were also calculated through a distributed crop model simulating irrigated meadow production processes over the Crau area (Olioso et al., 2013). The constant and poorly argued infiltration fraction applied on irrigation inflows in the first model, the lack of water budget closure arguments in the second approach, and the absence of sensitivity analysis in both these methods represent the major limitations of these previous estimates.

A preliminary seasonal stable isotope survey over the 2008–2009 period showed that, at the local scale, groundwater isotopic composition clearly records the mixing between two water masses that contribute to groundwater recharge of the Crau aquifer. Here, our sampling strategy aims at characterizing the entire aquifer, with a multi-annual survey in order to quantify temporal variations in the groundwater composition. Such a stable isotope survey over the entire Crau aquifer has never been performed before. This paper presents an updated piezometric contour map, a new interpretation of the geometry of the aquifer, the spatial distribution of $\delta^{18}O$ and $\delta^{2}H$, and proposes to merge these data in a geostatistical approach involving an equivalent homogeneous reservoir. This conceptualization makes it possible to apply a parsimonious isotopic mixing model between two end-members in order to assess the global mass balance and specifically the contributions, and notably their uncertainties, of irrigation return flow and precipitation to the groundwater recharge of the Crau aquifer. This quantification will constitute a straightforward and independent approach to be compared with previous published or unpublished estimates, and will help to constrain a future transient groundwater flow model of this aquifer.

2. Study site

2.1. Hydrogeological setting

Located near the Rhône delta, in Southern France, the Crau plain (540 km^2 of surface area) is subject to a Mediterranean climate. It is limited (Fig. 1) to the north by the Alpilles Range, to the east by the Miramas Hills and to the west by the present-day Rhône River delta (an area also known as "Camargue"). The Crau aquifer is a quaternary formation created by the accumulation of rough alluvial deposits carried from the Alps by the Durance River. Different paleo-channels of this river have been identified across the Crau Plain, corresponding to the succession of sea level drops during glacial periods (Colomb and Roux, 1978). Three main sedimentation episodes (dated from 2 Ma to 20 ka) have formed, after cementation, a heterogeneous layer of puddingstone. At the end of the Würm period (125 to 11 ka), a tectonic movement led to subsidence of the natural threshold of Orgon (Molliex, 2010; Terrier, 1991) and opened the current passage of the Durance River, towards the North of the Alpilles Range, becoming a tributary of the Rhône River (Cova, 1965; Gouvernet, 1959). Filling the paleo-channels of the Durance River, this puddingstone covers all the Crau Plain and constitutes now the main phreatic aquifer of the region, no longer connected to the Durance River aquifer (Archambault, 1950).

The French Geological Survey (BRGM) published a piezometric contour map of the Crau aquifer (Fig. 1), based on data from October 1967, and including a spatial distribution of transmissivity (Albinet et al., 1969). It is so far the only available piezometric map.

There is no natural river network over the Crau plain and all the surface water transfers occur through an artificial irrigation canal network. The absence of a river network comes from the very flat relief, combined with the high infiltration capacity of natural surfaces, where the puddingstone outcrops with almost no soil layer (Dellery et al., 1964). However, a large proportion of the Crau plain is covered by artificial meadows (140 km^2 in 2014) where well-developed soils result from a long-term traditional flood irrigation practice.

Starting nearly 500 years ago, the cultivation of grasslands for hay production is still the main agricultural activity of the Crau plain. Irrigation water is supplied from April to October, withdrawn from the Durance River through a dense network of canals. The water also carries a large amount of fine sediments, which have progressively led to the development of a soil layer on irrigated plots (Courault et al., 2010; Dellery et al., 1964). This irrigation method is highly water consuming and produces significant return flows (Courault et al., 2010; Mailhol and Merot, 2007). It is well known that the recharge of the Crau aquifer originates mainly from irrigation excess, but a robust quantification of the water balance remains necessary for the whole Crau aquifer.

2.2. Existing groundwater mass balance data

In addition to surface recharge, a lateral groundwater inflow draining two Miocene surrounding Lamanon reliefs has been described (Fig. 1). This zone is located upstream (Northeast) of the Crau aquifer and is clearly identified using a local piezometric map established in January 1950 (Archambault, 1950). This contribution was estimated at 0.74 $m^3\ s^{-1}$ in 1950.

The main natural discharge occurs along the western margin of the Crau plain (Fig. 1) and supplies a permanent flow of water towards some protected and environmentally sensitive wetlands. Beyond this constant head boundary, groundwater flows into a confined portion of the aquifer, beneath the Rhône delta to the west. Two additional outflows have been identified (Fig. 1): a drai-