Applied Geochemistry 86 (2017) 92–104

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Irrigation return flows in a mediterranean aquifer inferred from combined chloride and stable isotopes mass balances

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A R T I C L E I N F O

Article history:
Received 31 May 2017
Received in revised form
26 September 2017
Accepted 2 October 2017
Available online 5 October 2017

Editorial handling by: Elisa Sacchi.

Keywords:
Groundwater recharge
Irrigation return flow
Stable isotopes
Chloride mass balance

A B S T R A C T

The supply of irrigation water often overcomes crop evapotranspiration, and the resulting return flow may infiltrate and significantly contribute to an aquifer water budget. Despite its crucial importance for water resource management, the proportion of irrigation water that contributes to groundwater recharge, namely the return flow coefficient, often remains difficult to assess. Here, a chloride mass balance is combined with an isotopic mixing model ($\delta^{18}O$ and δD) to quantify return flow coefficients, in the Crau alluvial-type aquifer (Southern France), characterized by a long-term traditional practice of flood irrigation. Local groundwater compositions are interpreted in terms of average recharge along different flow paths. The high isotopic contrast between irrigation water and regional precipitation allows the partitioning of recharge between rainfall infiltration and irrigation return flows. Isotopic mixing proportions are then used to decipher the chloride concentration of groundwater purely recharged by return flow. This allows an original application of the chloride mass balance approach to estimate return flow coefficients, which doesn't rely on any atmospheric chloride survey. Values around 0.53 ± 0.16 were found for well defined stream lines averaging the functioning of the upstream aquifer, which leads to a return flow rate of 1190 ± 140 mm yr^{-1}. These results are consistent with a local daily time series of recharge fluxes derived from the water-table fluctuation method over the 2003-2009 period, and in line with the spatial average previously quantified over the whole aquifer. This study confirms the ability of geochemical tracers to provide recharge rates fully independent from flux measurements. They can be further used to assess the irrigation efficiency in other similar systems, or to monitor the variations of irrigation return flow, which will result from the future modifications of land use, irrigation practices and climate.

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1. Introduction

A smart and sustainable management of groundwater resource requires a comprehensive estimate of all human influences. Besides the direct impact of groundwater abstraction, land use and agricultural practices indirectly influence aquifer water budgets through a modification of recharge fluxes, especially when irrigation water is provided in excess to evapotranspiration (Scanlon et al., 2007; Meixner et al., 2016). The contribution of irrigation return flow to groundwater recharge may represent a major component of an aquifer water budget (Jimenez-Martinez et al., 2010), particularly in the case of flood irrigation, which is the most water consuming practice (Kendy et al., 2004; Liu et al., 2005; Tang et al., 2007). Improving irrigation efficiency through the reduction of the return flow is often desired for reducing water consumption, and preventing groundwater salinization mechanisms (Bresciani et al., 2014; Dewandel et al., 2008; Stigter et al., 1998; Yakirevich et al., 2013). Nevertheless, the contribution of return flows may constitute a substantial and sustainable support to local water resource, especially when irrigation supply comes from remote and well watered catchments (Kendy et al., 2004; Scanlon et al., 2007; Cruz-Fuentes et al., 2014; Tang et al., 2007).

The Crau aquifer (Southern France) is an illustration of the complex interactions and feedbacks between land-use, irrigation

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https://doi.org/10.1016/j.apgeochem.2017.10.001
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practices, climate and recharge. Supplying large areas of meadows, flood irrigation is performed following traditional practices for high quality hay production. Despite a typical Mediterranean climate with frequent drought, strong winds and high evapotranspirative demand, this water-intensive practice was made possible for hundreds of years by the abundance of water coming from the neighbouring alpine mountains, through the Durance River. Because of the high permeability of the aquifer, water rapidly infiltrates and irrigation return flow currently constitutes the main source of aquifer recharge (Albinet et al., 1969; Courault et al., 2010; Mailhol and Merot, 2008; Olioso et al., 2013; Séraphin et al., 2016). The local groundwater resource, which is intensively exploited for water consumption (drinking water, industry and other agricultural production), is thus mainly supplied by an external watershed, the Durance River Basin, through irrigation return flows. Nevertheless, this fragile equilibrium is threatened by different factors. Among them, the increasing urbanisation in the Crau Plain leads to reduce the areas devoted to flood irrigation. In addition, more frequent droughts are expected in the near future, and the increasing pressure on the water resource provided by the Durance River encourages a reduction of irrigation water consumption, and thus, a reduction of return flows. The improvement of irrigation efficiency or the reduction of irrigated surfaces would have a negative impact on the water budget of the Crau aquifer. A comprehensive evaluation of irrigation efficiency and return flows is thus necessary to manage human activities and optimize water resource use.

As an alternative to groundwater modelling tools, geochemical tracers can be used to determine sources of recharge, mixing processes, and in some cases, recharge rates independent of any hydrogeological data (Harrington et al., 2002; Scanlon et al., 2002). Stable isotopes of the water molecule (^{18}O and D) can provide the relative contributions of different sources of groundwater, when contrasted isotopic signatures are involved, for example when recharge comes from high elevation regions (Blasch and Bryson, 2007; Guglielmi et al., 1998; Liu and Yamanaka, 2012; Wahi et al., 2008), or from vertical leakage of deep aquifers with distinct isotopic signatures (Gonçalvès et al., 2015). The seasonality of precipitation composition may also help to decipher the relative contributions of different seasonal recharges (Jasechko et al., 2014; Winograd et al., 1998). Stable isotopes are particularly well suited for the tracing of irrigation return flow, as far as the signature of irrigation water is different from that of the local groundwater background (Duque et al., 2011; Séraphin et al., 2016). Nevertheless, isotope partitioning only provides flux proportions, and the quantification of recharge rates still requires a flux estimate.

A chloride mass balance approach can be used to estimate recharge rates. Initially proposed by Eriksson and Khunakasem (1969), a number of successful applications of the method have been reported (e.g. Alcala and Custudio, 2014; Dassi, 2011; Edmunds et al., 2002; Edmunds and Gaye, 1994; Gates et al., 2008; Naranjo et al., 2015). It relies on a full understanding of the origin of the chloride, and on the assumption that evapotranspiration does not export chloride. Its applicability for estimating recharge rates due to rainfall infiltration requires a robust quantification of atmospheric chloride inputs, which may limit the conditions for a robust application, particularly in coastal areas characterized by strong spatial variations. Alternatively, we propose to use the chloride mass balance to estimate irrigation return flow coefficients, defined as the proportion of irrigation water that contributes to groundwater recharge, which becomes possible if the chloride concentration of groundwater purely recharged by return flow can be isolated from that of natural recharge, using a conservative tracer of mixing proportions.

The proposed methodology focuses on the interpretation of individual groundwater sampling locations, representative of their upstream flowpath, accounting for their respective land cover. Based on a one-year survey of δ^{18}O, δD and chloride concentration in irrigation water and seven groundwater sampling locations, the chloride mass balance approach is combined with a stable isotope mixing model to propose a quantification of irrigation return flows coefficients, which is i) fully independent of groundwater flux estimates and ii) able to evaluate recharge fluxes at a more detailed scale. Results are compared with recharge rates obtained locally and independently from the analysis of water table fluctuation (WTF) over a seven-year period.

2. Site description

2.1. Environmental and hydrogeological setting

Located in Southern France, under a Mediterranean climate, the Crau plain (540 km^2) houses a shallow unconfined aquifer, which represents one of the most important regional groundwater resources. Limited to the north by the Alpilles Range, to the east by the Miramas Hills and to the west by the Rhône River delta (Fig. 1), the plain is formed by an extensive stretch of coarse alluvial deposits accumulated during the Plio-Quaternary period, and carried from the Alps by the Durance River. The alluvial material, which is more or less cemented, forms a highly permeable aquifer (average permeability of 2 10^{-3} m s^{-1}). The course of the Durance River has abandoned the Crau plain and moved to the north of the Alpilles Range, towards the Rhône River sometime between 75 and 35 ka (Molliex et al., 2013), and no natural drainage network remains nowadays. The absence of a river network comes from the very flat relief, combined with the high infiltration capacity of soil surfaces. Except along the downstream limit of the aquifer, the water table remains too deep for allowing access to groundwater for evapotranspiration (average unsaturated zone thickness of 6 m), and the natural surfaces are covered by a characteristic dry grassland plant community, forming a natural reserve with a steppic ecosystem locally called "Coussoul", where traditional itinerant sheep grazing is practiced (Buisson and Dutoit., 2006; Masson et al., 2015). Besides natural surfaces, a large proportion of the Crau plain is covered by irrigated meadows (140 km^2 in 2009). These meadows are characterised by well-developed soils resulting from the long-term accumulation of rich silty sediments carried by irrigation water during almost 500 years of traditional flood irrigation practices (Courault et al., 2010).

In the North-eastern part of the Crau plain, the Merle Experimental Domain is a 4 km^2 area, representative of the main land use types characterising the Crau Plain, with 1.5 km^2 of irrigated meadows and 2.5 km^2 of natural surfaces. In addition, the upstream part of the aquifer area corresponds to the most important density of irrigated meadows. The Merle Domain is managed with a threefold objective: agricultural production (hay production, and traditional sheep grazing), training centre for shepherds and farmers, and experimental setting for research projects.

2.2. Irrigation practices

Since the 16th Century, the Crau plain is covered by a dense network of irrigation canals that takes water from the Durance River at about 20 km North-East of Salon-de-Provence (Fig. 1). Flood irrigation is performed for high quality hay production under an official national label ("A.O.P. Foin de Crau"), which controls and maintains traditional agricultural practices. The irrigation season begins between March 15th-20th, with a progressively increasing rate of inflows. During the May-August period the irrigation inflows reach their maximum rates. The irrigation period also ends gradually: it continues at a lower rate from September until the middle

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