Journal of Hydrology 555 (2017) 869–880

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Mechanisms of recharge in a fractured porous rock aquifer in a semi-arid region

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ARTICLE INFO

Article history:
Available online 28 October 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Brian D. Smerdon, Associate Editor

Keywords:
Aquifer recharge
Mechanisms of recharge
Semi-arid region
California
Chloride mass balance
Vadose zone

ABSTRACT

Eleven porewater profiles in rock core from an upland exposed sandstone vadose zone in southern California, with thickness varying between 10 and 62 m, were analyzed for chloride (Cl) concentration to examine recharge mechanisms, estimate travel times in the vadose zone, assess spatial and temporal variability of recharge, and determine effects of land use changes on recharge. As a function of their location and the local terrain, the profiles were classified into four groups reflecting the range of site characteristics. Century- to millennium-average recharge varied from 4 to 23 mm y^{-1}, corresponding to <1–5% of the average annual precipitation (451 mm over the 1878–2016 period). Based on the different average Cl concentrations in the vadose zone and in groundwater, the contribution of diffuse flow (estimated at 80%) and preferential flow (20%) to the total recharge was quantified. This model of dual porosity recharge was tested by simulating transient Cl transport along a physically based narrow column using a discrete fracture-matrix numerical model. Using a new approach based on partitioning both water and Cl between matrix and fracture flow, porewater was dated and vertical displacement rates estimated to range in the sandstone matrix from 3 to 19 cm y^{-1}. Moreover, the temporal variability of recharge was estimated and, along each profile, past recharge rates calculated based on the sequence of Cl concentrations in the vadose zone. Recharge rates increased at specific times coincident with historical changes in land use. The consistency between the timing of land use modifications and changes in Cl concentration and the match between observed and simulated Cl concentration values in the vadose zone provide confidence in porewater age estimates, travel times, recharge estimates, and reconstruction of recharge histories. This study represents an advancement of the application of the chloride mass balance method to simultaneously determine recharge mechanisms and reconstruct location-specific recharge histories in fractured porous rock aquifers. The proposed approach can be applied worldwide at sites with similar climatic and geologic characteristics.

1. Introduction

Assessment of groundwater recharge is fundamental to manage and protect water resources from over-exploitation and to estimate fluxes of fluids, solutes, and contaminants from the surface to groundwater. Understanding groundwater recharge includes not only the estimation of flow rates but also the analysis of the pathways through which recharge occurs (i.e., preferential and/or diffuse flow). Preferentially-flowing water can move in smaller portions of the vadose zone porosity of both fractured and granular aquifers, from the surface to groundwater with minimal resistance. Thus, fluids and solutes can travel quickly. Conversely, diffuse recharge is more uniformly distributed and takes place more slowly throughout the entire vadose zone porosity, in either the soil or porous rock matrix. The quantification of the contribution of these two components of flow to the total recharge is a key factor with respect to vadose zone characterization and is still a challenging scientific issue.

Chloride (Cl) has been used in semi-arid regions to quantify recharge mechanisms. The approach is based on the observation that Cl concentration in groundwater is always less than or equal to that measured in vadose zone porewater by a factor proportional to the contribution of low-concentration, preferential flow to the total recharge. Sharma and Hughes (1985) analyzed five 20 m deep profiles in a sandy aquifer of Western Australia and found preferential flow was the dominant recharge process. Sukhija et al. (2003) estimated the contribution of preferential flow in three sites in India with different geological settings: fractured granites, semi-consolidated sandstones, and unconsolidated

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https://doi.org/10.1016/j.jhydrol.2017.10.060
0022-1694/

alluvial deposits. They found preferential flow was the main recharge process in granites (75% of the total recharge), whereas piston-style flow dominated in sandstones (68%) and alluvial aquifers (100%). Li et al. (2017) studied seven 10 m deep vadose zone profiles in China's Loess Plateau under different vegetation and concluded that preferential flow accounted for 87% of the total recharge. Heilweil et al. (2006) used a different approach to evaluate infiltration and recharge in the Navajo sandstone aquifer in Utah. Without quantifying the contribution of the different mechanisms of recharge, they estimated recharge at the borehole scale based on Cl concentration in the vadose zone at 13 locations and at the site-wide scale based on Cl concentration in groundwater. In all of these studies, the results were supported by the analysis of stable (deuterium and oxygen-18) and radioactive (tritium) isotopes along the profiles; however, none tested the dual recharge process by simulating Cl transport in the vadose zone or analyzed the effects of variable land use conditions on the shape of Cl profiles in the vadose zone.

Here, we analyze 11 profiles of porewater chloride concentration obtained from high-resolution, depth-discrete sampling of continuous cores from a fractured porous sandstone aquifer located on an upland ridge of southern California. At these locations, we adjust the classic chloride mass balance (CMB) approach for application to fractured aquifers and apply it to the vadose and shallow phreatic zone to quantify the contribution of the two mechanisms of flow to the total recharge and estimate the residence time in the vadose zone. Moreover, through the analysis of vertical variation of Cl concentration in the vadose zone, we examine the temporal variability of recharge and the effects of land use changes on recharge. To test the dual recharge pathway conceptual model and its effects on Cl concentration values in the vadose zone and in groundwater, we expand on the existing literature, simulating Cl transport in the sandstone vadose zone using CompFlow Bio, a multiphase, discrete fracture and porous matrix (DFM) numerical model (Forsyth and Shao, 1991; Walton, 2013). The study area is well suited for application of the CMB to quantify recharge mechanisms because it is located on an upland ridge with a relatively thick vadose zone, where flow is strongly downward everywhere and mixing of water is negligible. Therefore, we can assume that Cl concentration in the phreatic zone at the 11 locations is the result of local processes in the vadose zone and is not influenced by lateral groundwater flow.

The present manuscript advances previous work in which Manna et al. (2016) used the CMB method based on groundwater sampling to constrain estimates of recharge of the same site. The former study relied on the availability of one year of on-site measurements of bulk atmospheric chloride deposition (comprised of dry fallout and precipitation), 1490 groundwater samples (collected over three decades from 206 monitoring wells spanning a depth range from 10 to 360 m), and measurements of chloride in surface water runoff during precipitation events. The long-term, site-wide recharge was determined to be 19 mm, equal to 4.2% of the annual precipitation. However, the study only provided site-wide and catchment-wide recharge values and did not address recharge processes and their variability in space and time. Therefore, the present study is motivated by the need to advance the understanding of recharge processes and identification of controlling factors and to inform and calibrate, qualitatively and quantitatively, a 3-D mountain-scale groundwater flow model of the site.

2. Study area

The study area is located in southern California, 45 km northwest of Los Angeles and 25 km inland from the Pacific Ocean (Fig. 1). The mean annual potential evapotranspiration (1400 mm) exceeds the average precipitation (451 mm), creating semi-arid conditions (CIMIS, 1999; Hidalgo et al., 2005). The majority of the annual precipitation occurs during winter (73% from December to March), whereas summer months are almost completely dry (10% from June to August). The average monthly air temperature reaches a maximum in July and August (21.5 °C) and a minimum in January (10.4 °C). The site is located on an upland ridge with a maximum elevation of 700 m above sea level that stands 300 m above the surrounding valleys. About 55% of the area is covered by vegetation (chaparral and coastal scrub), 30% is bare bedrock, and 15% is developed with roads and facilities (Manna et al., 2016).

Alluvial deposits with thicknesses of up to 5 m cover about 25% of the total site area (11.5 km^2). These deposits are mainly silty sands and are located along the main drainages and in flat areas or bowls. The exposed and underlying bedrock is the Chatsworth Formation, a Cretaceous turbidite marine sequence composed of coarse- (sandstone) and fine- (shale/siltstone) grained units locally dipping 30° NW (Link et al., 1984). The sedimentary sequence is densely fractured with both bedding parallel fractures and vertical or near vertical joints (Cilona et al., 2015, 2016; Meyer et al., 2014; MWH, 2016).

The depth to the main water table, monitored over three decades, ranges across the site from 10 to 62 m with a deeper area in the central region induced in part by pumping activities in past decades (Fig. 1). Groundwater flow towards seeps located in the valleys and along slopes (Pierce et al., 2017b) is dominated by a dense network of interconnected fractures (Pehme et al., 2009, 2013) as evidenced by estimates of hydraulic conductivity from a variety of tests conducted at various scales. Porous rock matrix hydraulic conductivity ranges from 1×10^{-5} to 1×10^{-13} m s^{-1} with a geometric mean of 3×10^{-9} m s^{-1} (Cherry et al., 2009); the bulk hydraulic conductivity ranges from 8×10^{-8} to 7×10^{-6} m s^{-1}, about one to three orders of magnitude greater than the geometric mean of the estimated matrix hydraulic conductivity (Allègre et al., 2016; Cherry et al., 2009; MWH, 2009, 2016; Quinn et al., 2015, 2016). However, almost all of the groundwater resides in the porous rock matrix where the matrix porosity (arithmetic mean 13.6%) is about four orders of magnitude greater than the fracture porosity (Cherry et al., 2009).

To understand the influence of different terrain settings on recharge, the profiles are classified into four groups as a function of local site characteristics (Fig. 1): group A includes two holes with thick vadose zones (62 and 45 m) in the eastern part of the site; group B comprises three holes within 20 m of each other, each with about 10 m of alluvium overlying weathered bedrock and a water table at 27 m below ground surface (bgs); group C includes three profiles in areas where land use changes occurred in the last 60 years due to industrial site operations; and group D is comprised of holes with a typical Cl bulge shape (Allison, 1988; Scanlon, 1991; Phillips, 1994) in the shallow subsurface. The effect of land use was evaluated for groups C and D, where changes in vegetation were confirmed by aerial photos.

3. Conceptual model for dual process infiltration and recharge

The main assumptions of the CMB method are that atmospheric Cl is the only source of chloride present in the sub-surface and that the system is in a steady-state condition with respect to chloride input and output for the time period of interest. When applied to the analysis of the vadose zone, other assumptions become relevant: runoff is negligible, and the main mechanism of flow is piston-flow, i.e., modern water pushes down older water and thus forms a record of past recharge conditions (Edmunds and Walton, 1980). With these assumptions, the method has been used almost