Journal of Hydrology: Regional Studies 3 (2015) 211–232

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Geophysical, remote sensing, GIS, and isotopic applications for a better understanding of the structural controls on groundwater flow in the Mojave Desert, California

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 31 October 2014
Accepted 8 December 2014
Available online 28 January 2015

Keywords:
Mojave desert
Groundwater flow
Structural controls
Geophysics (VLF, Magnetic, VES)
Isotopic analyses (O, H)
Remote sensing (LiDAR, GeoEye-1)

ABSTRACT

Study region: Mojave Desert, USA.
Study focus: An integrated (near-surface geophysics, remote sensing, isotopic analyses) study was conducted in the Mojave River Basin and Morongo Groundwater Basin to investigate potential effects that the Helendale Fault [HF] and basement uplifts might have on groundwater flow in the Mojave Desert.
New hydrological insights for the region: The HF traces were mapped using LiDAR and Geoeye-1 imagery (surface) and magnetic profiles (subsurface). Shallow basement parallel to and west of the HF was detected using the Vertical Electrical Soundings (VESs). Conductive water-saturated breccia was detected along the HF using the Very Low Frequency (VLF) electromagnetic measurements. Isotopic analyses (δD and $\delta^{18}O$) for groundwater samples from productive shallow wells, and springs sampled west of the HF and the basement uplift are less depleted (Group I: Fifteenmile Valley Groundwater sub-basin [FVGS]; average δD: −86.8‰; $\delta^{18}O$: −11.8‰) than samples east of the basement uplift (Group II: Lucerne Valley Groundwater sub-basin [LVGS]; average δD: −95.0‰; $\delta^{18}O$: −12.1‰), whereas samples proximal to, the fault have compositions similar to Group I but show evidence for mixing with Group II compositions (Group III; average δD: −88.8‰; $\delta^{18}O$: −11.5‰). Findings are consistent with the HF channeling groundwater from the San Bernardino Mountains with basement uplifts acting as barriers to lateral groundwater flow and could be applicable to similar settings across the Mojave Desert and elsewhere worldwide.

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http://dx.doi.org/10.1016/j.ejrh.2014.12.002

1. Introduction

The structural controls on groundwater accumulation and flow exhibit a wide range of variability. Faults can act as highly permeable pathways, or as barriers for groundwater flow depending on the aquifer lithology, aquifer hydrologic conditions, and fault characteristics (Bense and Person, 2006; Celico et al., 2006; Dewandel et al., 2006). The extent to which groundwater flows along the strike of a fault is controlled by fault properties (e.g., width of core and deformation zones, parent material), hydrologic framework (e.g., permeability of the individual fault rocks/fractures, geometric architecture in three dimensions, extent of clay core), and hydrologic parameters (e.g., fault specific resistance, transmissibility, hydraulic head) (Bense et al., 2003; Lunn et al., 2008; Caine and Minor, 2009; Faulkner et al., 2010). Various mechanisms were suggested to explain the damming effect of the fault zones across unconsolidated sediments including the cementation or mineralization of the fault zone, grain crushing and grain realignment and juxtaposition seals (Bense and Person, 2006; Knipe, 1993). In this study we adopt an integrated (geophysics, remote sensing, GIS, and isotopic analyses) approach to investigate the potential role of structural elements, faults and basement uplifts, in controlling the groundwater flow in the Mojave Desert.

The Mojave Desert occupies areas in southeastern and central California, southern Nevada, southwestern Utah, and northwestern Arizona in the United States (Fig. 1 inset). The rapidly growing population (1980 population: 64,685; 2010 population: 349,730), low humidity, high summer temperature, and the paucity of precipitation (100–140 mm/year; Londquist and Martin, 1991) in the Mojave Desert has created an ever-increasing need for freshwater resources. Surface water is limited to ephemeral flow during winter and spring storm periods.

Two main groundwater basins were recognized in the southwestern parts of the Mojave Desert, the Mojave River Groundwater Basin (MRGB), and the Morongo Groundwater Basin (MGB) (Fig. 1). Runoff and groundwater flow from the melting of snowpack over the adjacent San Bernardino Mountains constitute the principal sources of groundwater in the southern parts of the MRGB and MGB (Stamos et al., 2003; USGS, 2004), whereas the northern and central portions of the basin are largely recharged by groundwater and surface flow from surrounding mountain ranges such as the Cougar Buttes and Granite Mountains (Fig. 1), as well as infiltration via the Mojave River floodplain aquifer.

Increasing extraction of groundwater from the MRGB and the MRB has affected various sections in the basin to varying degrees. The central portions of the MRGB witnessed a progressive decline in water levels over the years (20 m from 1950 to 1986), whereas areas proximal to the mountains showed minimal or significantly less decline (Smith and Pimentel, 1998). One popular explanation for the groundwater deficits in the central parts of the basin is that the dextral faults in the area acted as barriers for lateral (across-fault) flow of groundwater from the mountains toward the central parts of the basin. A better understanding of how regional and local fault systems interact with the principle aquifers in the Mojave Desert is of key importance in meeting the rising demand for groundwater resources.

In this study, we examine the role of one of the major dextral faults in the MRGB and the MRB, the Helendale Fault (HF), and its subsequent splays as potential barriers (across strike) to groundwater flow or as enhanced groundwater flow pathways along its strike that probably feed both basins. The former widely accepted hypothesis is largely based on the observed water level differences (~40 m) across the HF in the Central Lucerne Valley area and those (3–9 m) across both the Johnson Valley Fault and the Emerson Fault (Lewis, 1972; Trayler and Koczot, 1995; GSI, 2000). This explanation is at odds with reported findings elsewhere that suggest that fractured fault planes often act as enhanced groundwater flow directions along strike (e.g., Barton et al., 1995; Caine et al., 1996; Gudmundsson, 2001; Sultan et al., 2007). If such models were applicable to the HF, it could be channeling groundwater from the San Bernardino Mountains in the south to the lowlands of the MRGB and MGB in the north.

An integrated approach utilizing remote sensing (LiDAR and GEOEye-1 images), geophysical (Very Low Frequency [VLF], magnetic, and Vertical Electrical Soundings [VES]) data, isotopic (O, H stable isotope) compositions for groundwater samples, and subsurface well data was adopted to investigate (1) the potential role of the HF as a barrier for lateral groundwater flow or as an enhanced groundwater flow pathway along its strike, and (2) the distribution and nature of barriers for lateral groundwater flow in the study area. Specifically, we investigate a previously unrecognized preferential groundwater