Hydrochemical and $^{14}$C constraints on groundwater recharge and interbasin flow in an arid watershed: Tule Desert, Nevada

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**SUMMARY**

Geochemical data deduced from groundwater and vein calcite were used to quantify groundwater recharge and interbasin flow rates in the Tule Desert (southeastern Nevada). $^{14}$C age gradients below the water table suggest recharge rates of 1–2 m/yr which correspond to a sustainable yield of $5 \times 10^{-4}$ km$^3$/yr to $1 \times 10^{-3}$ km$^3$/yr. Uncertainties in the applied effective porosity value and increasing horizontal interbasin flow components at greater depths may bias these estimates low compared to those previously reported using the water budget method. The deviation of the groundwater $^{18}$O time-series pattern for the Pleistocene–Holocene transition from that of the Devils Hole vein calcite (which is considered a proxy for local climate change) allows interbasin flow rates of northerly derived groundwater to be estimated. The constrained rates (75.0–120 m/yr) are slightly higher than those previously calculated using Darcy’s Law, but translate into hydraulic conductivity values strikingly similar to those obtained from pump tests. Data further indicate that production wells located closer to the western mountainous margin will be producing mainly from locally derived mountain-system recharge whereas wells located closer to the eastern margin are more influenced by older, regionally derived carbonate groundwater.

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1. Introduction

In the arid southwestern United States, strategic plans for potable water development become increasingly dependent on groundwater resources, specifically those of the Deep Regional Carbonate Aquifer (DRCA); a thick and heavily deformed carbonate rock sequence extending throughout the state of Nevada and adjacent parts of California, Arizona, Utah and Idaho (Dettinger et al., 1995). In light of a recent population growth in many DRCA regions and evident effects of groundwater overexploitation such as subsidence and declining quantity and quality of groundwater (Castle et al., 2014; Lopes, 2006; Marshall et al., 2010), a thorough understanding of natural groundwater recharge in individual watersheds as well as of the degree of groundwater exchange between different watersheds (interbasin flow) is critical for sustainable reservoir operation.

Recharge at the watershed scale is commonly approximated as a residual in a soil water budget; a simple mass-balance procedure that accounts for water entering, leaving, and being stored within the plant–soil system (Flint and Flint, 2007; Hevesi et al., 2003). The method relies on meteorological and hydrologic input data that are difficult to obtain for remote regions. The water budget also only provides potential recharge estimates for below the root zone, which can result in uncertainties of recharge location and timing particularly in desert environments where unsaturated zones are thick and heterogeneous (USGS, 2008). Other recharge estimation techniques such as chloride mass balance (CMB) and isotopic (e.g., $^3$H, $^{14}$C) renewal rate (IRR) also have limitations (Cook and Boehlke, 2000; Le Gal La Salle et al., 2001); not the least of which are difficult-to-constrain input parameters such as rainfall rate (for CMB) and aquifer depth (for IRR). Moreover, they provide estimates at different temporal and spatial scales with the CMB method yielding values for the location where the water first entered the aquifer, and IRRs providing mean values for between where the sampled water first entered the aquifer and the well location (Hagedorn et al., 2011). Interbasin flow rates, on the other hand, are commonly quantified using Darcy’s Law (Bushner and Feast, 2008; Welch et al., 2007) which depends on complex variables such as aquifer cross-sectional area or hydraulic conductivity ($K$) which – in fractured rock settings – can vary over several orders of magnitude (Won et al., 2005). For systems such as the DRCA, it is also challenging to assign representative hydraulic gradient values as measured head data should reflect the combined effects of local recharge and regional interbasin flow.
In this study, hydrochemical and isotopic data from various multi-level well clusters are used to constrain rates of recharge and interbasin flow in the Tule Desert; a remote and uninhabited watershed currently investigated for its groundwater resources. Local mountain-system recharge is quantified based on vertical groundwater 14C age gradients. Interbasin flow of isotopically depleted groundwater from the north is estimated based on groundwater 14C vs. δ18O patterns. Even though the hydrochemistry of Nevada groundwater has been studied previously (Davisson et al., 1999; Dettinger et al., 1995; Hershey et al., 2007; Stuckless, 2012; Thomas et al., 2001, 2003, 1996), these studies aimed mainly at delineating regional-scale groundwater flow paths particularly in the Basin and Range Carbonate Aquifer System (BARCAS) in central Nevada and in the aquifers of the Nevada Test Site. Prior to this investigation, groundwater chemistry had not been extensively utilized for examining desert recharge and interbasin flow processes at smaller, local spatial scales. The herein presented results provide not only valuable constraints on sustainable long term groundwater yields, but also valuable details on hydrogeologic parameters of the DRCA such as K and groundwater residence time.

2. Local setting

The Tule watershed is located in the southeastern portion of the DRCA province in Lincoln County, Nevada (Fig. 1, Fig. 2). Covering an area of 506 km², the watershed is characterized by a subtropical desert climate with a mean precipitation of 308 mm/yr (Jeton et al., 2006) and mean temperatures ranging from 26.5 °C in August to 12.1 °C in January (WRCC, 2014). Estimated evapotranspiration rates (723–1197 mm/yr; DBSA, 2008c) drastically exceed annual precipitation which stresses the potential for shallow groundwater and surface water to evaporate throughout the year. Surface runoff at Toquop Gap, the only surface water channel out of the watershed, varies between 4.9 × 10⁻³ km³/yr and 0.0015 km³/yr (DBSA, 2008a; Clark and Van Denburgh, 1969) and occurs sporadically after winter rain storms. Springs located along fault boundaries in surrounding mountains provide generally very low (<3 L/min) discharge and are not considered to significantly contribute to surface flows (CH2MHILL, 2002).

The local stratigraphy as mapped by Page et al. (2005, 2011) is summarized from oldest to youngest as: (1) Precambrian crystalline basement (quartzite and metasediments), (2) Paleozoic limestone and dolomite, (3) Late Paleozoic and Mesozoic terrestrial sediments (sand, silt and shale with minor amounts of gypsum and limestone) of the Moenkopi Formation, (4) Paleogene intermediate volcanics; and (5) recent alluvium (basin fill deposits) (Fig. 3). As is characteristic for watersheds throughout the Basin and Range province of the southwestern United States, multiple east–west extensions during the past ~30 million years have transformed the previous depositional sequence into a complex mixture of carbonate and non-carbonate rocks of various thicknesses juxtaposed along north–south trending normal faults.

Mock (2008) and Bushner and Feast (2008) informally subdivided the local stratigraphy into (1) a shallow- and (2) a deep aquifer system. The former extends to only a few hundred meters depth and includes the porous basin fill deposits, Paleogene volcanics and the Moenkopi sediments. The latter extends as deep as 150–227 m of high quality (low TDS) water (Bushner and Feast, 2008). As a result of the complex distribution of faults and fractures in the deep carbonate aquifers, local pump test analyses revealed highly variable transmissivity and storativity estimates (43.5–335 m²/d and 0.00038–0.035, respectively (Bushner and Feast, 2008)) which underscore the heterogeneous and anisotropic characteristics of the system (Dettinger et al., 1995).

Groundwater enters the watershed via a combination of interbasin flow from adjacent basins to the north (Mock, 2008; Prudic et al., 1993; TetraTech, 2012) and local mountain system recharge (Fig. 4). Groundwater leaves the watershed through the DRCA to the south. Mean horizontal gradients are 0.016 in the shallow zone and 0.007 in the DRCA (calculated using data from Bushner and Feast (2008) and CH2MHILL (2002)). However, significant local gradient variations can occur as a result of aquifer heterogeneity and the presence of shear zones.

Approximations of mean local recharge based on empirical (Maxey and Eakin, 1949) rainfall/recharge coefficients, CMB, Darcy’s Law and water budget modeling range from 2.59 × 10⁻³ km³/yr to 3.48 × 10⁻² km³/yr (Bushner and Feast, 2008; DBSA, 2008a,b,c; Glancy and Van Denburgh, 1969). Estimates of interbasin flow derived from Darcy’s Law vary between 6.93 × 10⁻³ km³/yr and 3.23 × 10⁻¹ km³/yr (Bushner and Feast, 2008) and generally exceed those of recharge. This is supported by studies conducted by CH2MHILL (2007) who ascribed the relatively low local geothermal gradient (~17 °C/km) to significant horizontal flow components of northerly derived interbasin flow.

3. Data and analysis

The dataset includes major ion, stable isotope (D/H, 18O/16O, and 13C/12C) and radioactive isotope (14C) data of groundwater collected during multiple sampling campaigns between 2001 and 2012 (Appendix A). Also listed are available ancillary information (e.g., well depth, screen interval, etc.) for each sample. All wells were purged three casing volumes and then sampled within 24 h. Data from production well 2 (PW-2) includes zone testing conducted prior to well completion (Bushner and Feast, 2008). The test consisted of (1) constructing a temporary well in the open borehole, (2) sealing a 6 m screen interval above and below the tested zone, (3) developing the well, pumping it at 80–200 L/min for about 100 min and (4) collecting a water sample for laboratory analysis after field parameters (pH, temperature and electric conductivity) had stabilized. TestAmerica, Inc. in Phoenix, Arizona, provided analytical services for major ions. Isotopic analyses were carried out at the Environmental Isotope and Accelerator Mass Spectrometry laboratories at the University of Arizona.

13C of dissolved inorganic carbon was measured relative to NBS-19 and NBS-18 PDB values via continuous-flow gas-ratio mass spectrometry (Finnigan Delta PlusXL) on samples that had been acidified with phosphoric acid at room temperature after He gas flushing. Precision was generally ±0.30‰ or better (1 sigma). Stable O and H isotopes were measured using a Finnigan Delta S and an automated Finnigan MAT H/Device relative to internal PLRM and SLRM standards that were calibrated against accepted NIST and/or IAEA SMOW reference materials. Precision was better than ~0.9‰ for δD and 0.08‰ for δ18O. CO2 for 14C analysis was extracted from water samples in a vacuum and converted to graphite by reducing it with excess hydrogen gas in the presence of an iron catalyst. 14C concentrations were measured using a 3 MV accelerator mass spectrometer and concentrations are expressed as percent modern carbon (pmc) with a precision of ±12/14C ratios of about ±0.5%.
