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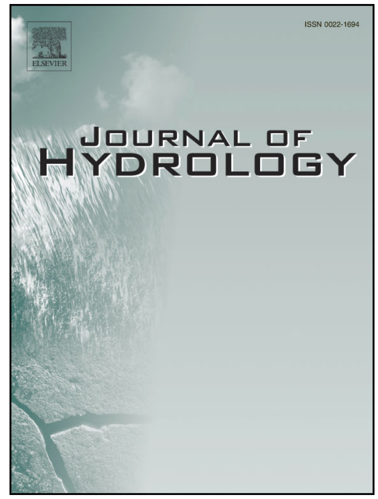

Research papers

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Rethinking a groundwater flow system using a multiple-tracer geochemical approach: a case study in Moab-Spanish Valley, Utah

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Abstract

The Glen Canyon Group Aquifer (GCGA) is the sole source of public water supply for the city of Moab, Utah, a domestic and international tourist destination. Population and tourism growth are likely to target the GCGA for future water resources, but our analysis indicates that additional withdrawals would likely be sourced from groundwater storage and not be sustained by recharge. A quantitative estimate of groundwater discharge from the GCGA is problematic because the downgradient aquifer boundary is the Colorado River, and groundwater discharge to the river is very small compared to the river flow. A water budget based on a conceptual model of GCGA discharging into an adjacent alluvial Valley-Fill Aquifer (VFA) was reported by Sumsion (1971) and numerous subsequent studies have repeated and utilized this water budget. The GCGA contains stable isotopes, tritium, $^{3}He/^{4}He$ ratios, dissolved solids, and sulfate concentrations that contrast with the VFA, indicating it is instead recharged by local streams rather than from the GCGA. Water-budget calculations, based on: (1) measured spring discharge and streamflow gains, (2) horizontal gradients in VFA groundwater age, and (3)

GCGA outcrop area vadose-zone pore waters are all less than previously thought. Using a lumped parameter model and ^{14}C groundwater ages, we estimate recharge to the deeper GCGA (DGCGA) to be 4.2 ± 2.3 X 10^6 m^3/yr, which is approximately equal to the measured discharge from wells and springs.

1 Introduction

Evaluating regional groundwater flow in the context of water resources management is a long-standing challenge in hydrogeology. As discussed by Pacheco (2015), basin-wide flow systems can include local, intermediate, and regional flow components (Tóth, 1963) that are hierarchically nested, and an evaluation of all these components is critical for water resource management (Zhou and Li, 2011).

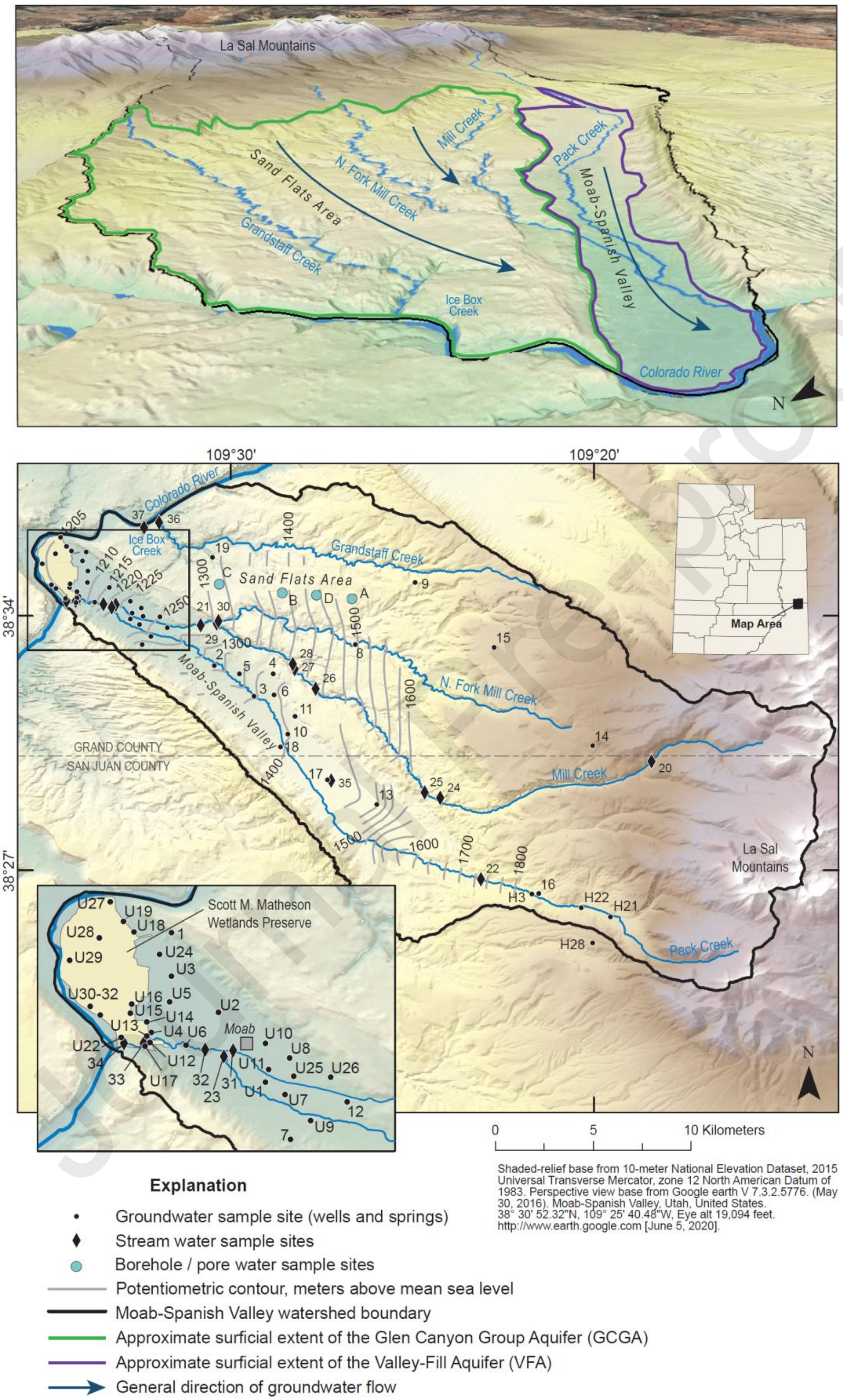
While some recent regional groundwater flow models incorporate knowledge from environmental tracers (e.g., Yao et al., 2014), many regional aquifers have been analyzed without the benefit of extensive tracer data. For example, the Regional Aquifer System Analysis (RASA) program of the U.S. Geological Survey intensively evaluated 25 regional aquifers in the United States from 1978 to 1995 and produced more than 1,000 reports (Sun et al., 1997). In the Netherlands, the National Groundwater Flow System Analysis project occurred from 1991 to 1995 with the objective of mapping regional groundwater flow systems (Kloosterman et al., 1995). These studies occurred before the common use of lumped parameter models with environmental tracers (groundwater dating with tritium/helium and industrial gases, pore-water tritium and chloride measurements from rock cores, etc.), and largely focused on water budgets and concepts of physical groundwater flow.

A major objective of this paper is to demonstrate the importance of re-evaluating the conceptual underpinning of regional aquifer studies using environmental tracer data that were not previously available. We demonstrate how environmental tracer data and a novel application of a lumped parameter model have been used to redefine a long-standing conceptual model of the available freshwater resource in a popular desert community.

The city of Moab, Utah, USA, within our study area, has become an international destination as it is in close proximity to 5 National Parks and is experiencing an exponential growth in international tourism. Rapidly growing population and tourism in much of the arid southwestern United States is increasing the demand on groundwater resources. Sustainable water resources management depends on the ability to accurately conceptualize groundwater flow systems and estimate groundwater budgets. The population in and around the city of Moab, in southeastern Utah, relies heavily on groundwater for public water supply. As in many desert communities, surface water resources are limited, and future growth depends on the development of additional groundwater resources. An increase in water rights applications and concern over future groundwater availability prompted area water managers to call for an updated evaluation of local groundwater resources. The public water supply for the greater Moab area is sourced primarily from the Glen Canyon Group Aquifer (GCGA). The GCGA is a semi-confined sandstone aquifer producing high-quality drinking water that requires little treatment before use. In contrast, groundwater in the Valley-Fill Aquifer (VFA) in Moab-Spanish Valley has higher total dissolved solids (TDS) concentrations and is used mostly by private well owners for irrigation.

A foundational water resource investigation by Sumsion (1971) estimated that 13.6 x 10^6 m^3/yr (11,000 acre-ft per year) of groundwater discharged from the VFA, mostly in lower Moab-Spanish Valley either as evapotranspiration on the Scott M. Matheson Wetlands Preserve (hereafter, the wetland) (Fig. 1) or as subsurface outflow to the Colorado River. Most of this groundwater discharging from the VFA was assumed to come from the GCGA via subsurface hydraulic connectivity between the two aquifers along the northeast valley wall, with only a small contribution from Pack Creek stream loss and/or groundwater from the Pack Creek drainage. Sumsion's estimate of groundwater discharging out of the lower valley was based on a Darcy flux estimate that utilized the average transmissivity value from 18 single-well tests (2 of which were pumped and 16 of which were conducted by bailing water from the well) and a hydraulic gradient from wells located upgradient from the wetland and valley terminus. The conceptualization describing the source of this valley-fill groundwater as subsurface inflow from the GCGA hinged on field observations of surface geology and sparse groundwater-level data available at the time.

Numerous subsequent hydrologic studies (Eychaner, 1977; Rush et al., 1982; Blanchard, 1990; Steiger and Susong, 1997; Kovacs, 2000; Lowe et al., 2007) were conducted in the Moab-Spanish Valley area, but despite the availability of significant new hydrologic and geochemical data, the basic conceptual groundwater model and estimates of groundwater discharge from the VFA in Moab-Spanish valley remained based on, and did not significantly deviate from, Sumsion (1971).


La Sal Mountains
Mill Creek
Pack Creek
Sand Flats Area
N. Fork Mill Creek
Moab-Spanish Valley
Grandstaff Creek
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109°30'
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38°34'
38°27'
Grandstaff Creek
Sand Flats Area
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Pack Creek
GRAND COUNTY
SAN JUAN COUNTY
La Sal Mountains
Map Area
Scott M. Matheson Wetlands Preserve
Moab
0 5 10 Kilometers
Shaded-relief base from 10-meter National Elevation Dataset, 2015 Universal Transverse Mercator, zone 12 North American Datum of 1983. Perspective view base from Google earth V 7.3.2.5776. (May 30, 2016). Moab-Spanish Valley, Utah, United States. 38° 30' 52.32"N, 109° 25' 40.48"W, Eye alt 19,094 feet. http://www.earth.google.com [June 5, 2020].
Explanation
Groundwater sample site (wells and springs)
Stream water sample sites
Borehole / pore water sample sites
Potentiometric contour, meters above mean sea level
Moab-Spanish Valley watershed boundary
Approximate surficial extent of the Glen Canyon Group Aquifer (GCGA)
Approximate surficial extent of the Valley-Fill Aquifer (VFA)
General direction of groundwater flow

Figure 1. Map of the study area (outlined in black) in southeastern Utah, which extends southeast from the Colorado River toward the headwaters of Pack Creek and Mill Creek in the La Sal Mountains. The upper diagram (A) is a three-dimensional (birds-eye) view from northwest to southeast showing the surficial extent of the Glen Canyon Group and Valley Fill aquifers. The lower diagram (B) is a map view showing sample sites, potentiometric contours, and an inset of the northwestern part of Moab-Spanish Valley, including the Scott M. Matheson Wetlands Preserve.

The conceptual model by Sumsion (1971) was first called into question by Gardner (2004). If the VFA is primarily recharged by GCGA water, as proposed by Sumsion (1971), then groundwater in the wetland should resemble the GCGA. The investigation by Gardner (2004) showed that groundwater in the wetland did not exhibit the unique geochemical and isotopic characteristics of the GCGA. Additionally, monitoring wells installed adjacent to the Colorado River in the wetland found dense brine (35,000 to > 100,000 mg/L) and low-transmissivity aquifer material near the water table suggesting that much less freshwater was discharging from the valley-fill aquifer than previously thought (Gardner, 2004). The implication of this finding is that Sumsion (1971) may have overestimated the groundwater discharge component of the water budget. Because recharge from precipitation on the valley is assumed to be negligible, the only other source of recharge to the VFA is from the Pack Creek drainage. Assuming groundwater inflow from Pack Creek is much less than 13.6 x 10^6 m^3/yr (11,000 acre-ft/yr), available groundwater in the study area may be less than previously thought.

An accurate conceptual model and quantitative evaluation of groundwater flow has been difficult to develop for this area using a traditional water balance approach. Hydrologic methods like that of Pacheco (2015) have utilized base flow recession analyses to quantitatively evaluate the sources of groundwater to regional flow systems. Such methods, however, are ineffective when attempting to quantify the subsurface discharge of groundwater from the study area, in part because this discharge is indiscernibly small compared to that of the Colorado River, rendering it impossible to measure. As such, alternative approaches are required to evaluate the flow system and to quantify the subsurface discharge, previously claimed to be the largest component of the groundwater budget for Moab-Spanish Valley.

This paper illustrates how multiple geochemical tracers were used to improve the groundwater budget for an important desert groundwater system. The objectives of the study were to (1) test a long-standing conceptual model and water budget against new hydrologic and environmental tracer data, (2) constrain a lumped parameter model using environmental tracer data to provide a meaningful estimate of groundwater recharge, and (3) formulate a revised conceptual model that is consistent with a broad range of hydrochemical, environmental tracer, and physical hydrologic measurements. The analyses conducted during this study provided both a solid conceptual framework of a groundwater flow system and a direct, quantitative estimate of groundwater discharge. The methods and processes presented here can be used as an approach to test long-standing concepts and groundwater budgets for other aquifers where water managers require verification in the face of increasing development pressure.

2 Study Area

The hydrology of the study area is complex, in part because of its unique geologic setting. The study area watershed is defined by the Mill Creek, Grandstaff Creek, and Pack Creek drainage basins, between the northwestern flanks of the La Sal Mountains and the Colorado River (Fig. 1). Moab-Spanish Valley is a northwest-southeast trending topographic feature formed by a collapsed salt anticline, one of many in the region. The Middle Pennsylvanian Paradox Formation contains sequences of evaporite salts, dolomite, and shale. Groundwater dissolution of the salts resulted in collapse of the anticline and the formation of the valley (Doelling et al., 2002). Paradox Formation caprock that underlies the valley contains the anhydrite and shale beds left over after NaCl-evaporites were leached away and is exposed along the flanks of the lower valley adjacent to the wetland (Fig. 2). The prominent La Sal Mountains are the highest-altitude feature in the study area, rising about 2,650 m above the

Colorado River, which marks the lowest point of the study area and northwest boundary of the watershed (Fig. 1). The La Sal Mountains are comprised of Paleogene igneous rocks that are laccolithic in origin and were intruded into the mostly horizontal-lying layers of pre-existing sedimentary rock resulting in deformation and fracturing of these overlying strata along their margins (Doelling et al., 2002). Erosional escarpments (removing the Glen Canyon Group formations) along both the northeast and southwest sides of the study area, preclude the possibility of groundwater exchange between adjacent basins (Fig 2.).

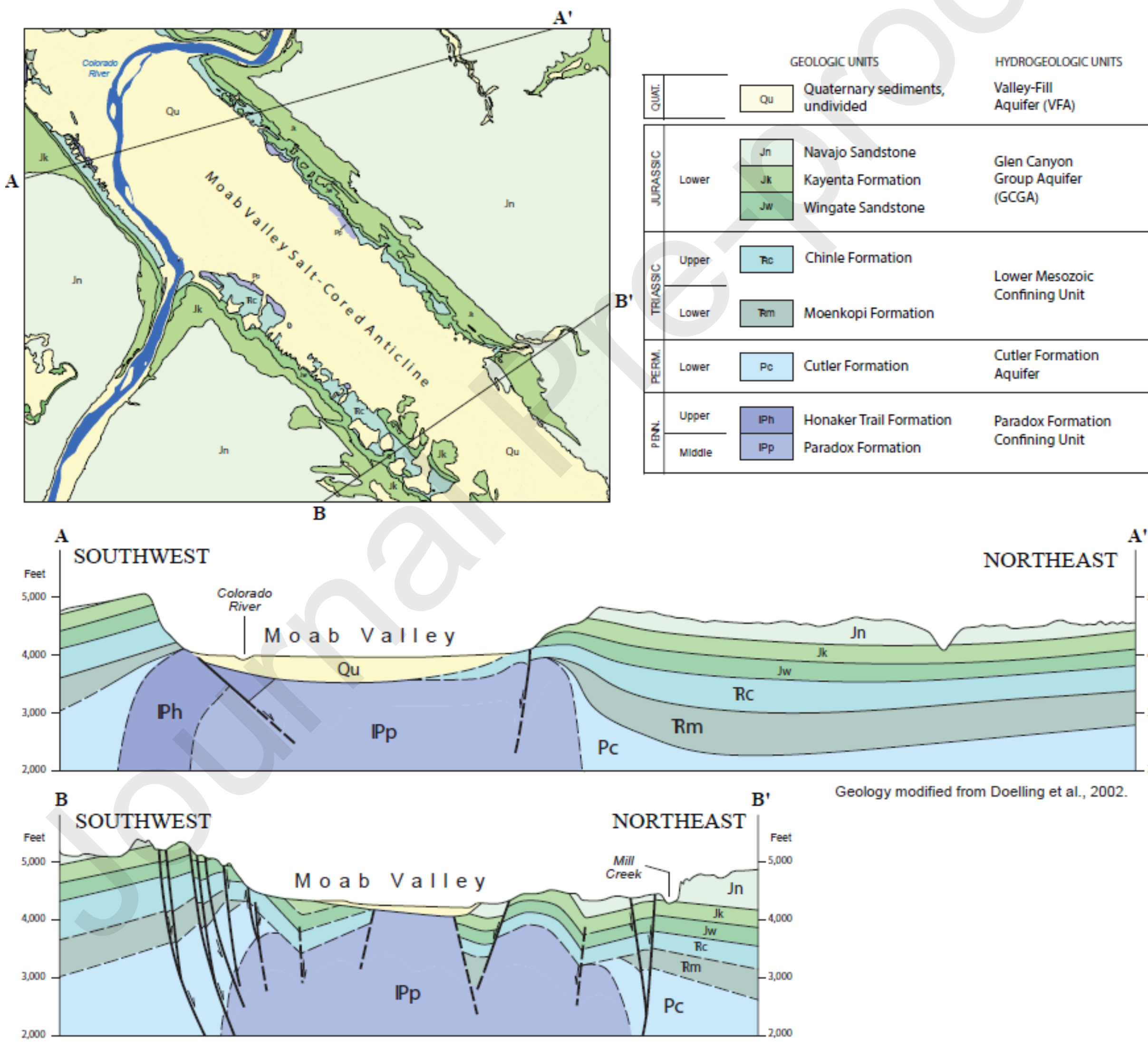

Figure 2. Geology of the study area (modified from Doelling et al., 2002) and table showing the geologic units that comprise significant local hydrogeologic units.

The two major streams in the study area are Mill Creek and Pack Creek, which meet near downtown Moab before discharging to the Colorado River. Pack Creek periodically goes dry for several miles after it enters Moab-Spanish Valley, indicating that it is a source of recharge to groundwater in the valley (Masbruch et al., 2019). The two principal aquifers in the study area are the GCGA and the VFA. The public water supply for Moab and the surrounding area is sourced primarily from the GCGA, whereas the VFA is used for irrigation primarily by private well owners and is generally not a suitable source of potable water.

The GCGA is a semi-confined sandstone aquifer, comprised of strata in the regionally extensive Jurassic Glen Canyon Group, which contains, from oldest to youngest, the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone (Rush et al., 1982; Blanchard, 1990; Lowe et al., 2007). The Wingate Sandstone is a well-sorted, very fine- to medium-grained, calcareous, massively bedded, well-cemented, cross-bedded, eolian sandstone, and has a thickness of 46-137 m in the Spanish Valley area (Sumsion, 1971; Lowe et al., 2007). The Kayenta Formation is a very fine- to coarse-grained, locally conglomeratic, fluvial sandstone, siltstone and shale, and has a thickness of 43-91 m (Sumsion, 1971; Lowe et al., 2007). The Navajo Sandstone is a well-rounded, well-sorted, fine- to medium-grained, cross-bedded eolian sandstone, and has a thickness of 0–168 m (Sumsion, 1971; Lowe et al., 2007).

The Glen Canyon Group is exposed along the northeastern and southwestern walls of Moab-Spanish Valley and to a large area east and northeast of Moab-Spanish Valley (Fig. 1). It also exists at depth, in places, beneath unconsolidated deposits along the northeast margin of the valley floor (Fig. 2) (Doelling et al., 2002; Doelling, 2004). In many areas of the Colorado Plateau, the Kayenta Formation acts as a barrier to groundwater flow; in the Spanish Valley area, however, the unit is partly comprised of sandstone and may provide hydraulic connection between the Navajo Sandstone and Wingate Formation (Blanchard, 1990; Steiger and Susong, 1997). All three units are highly faulted and fractured, especially near the valley margins and along the flanks of the La Sal Mountains (Fig. 2).

The VFA is comprised of unconsolidated Quaternary-age deposits consisting of stream, alluvial fan, mass-movement, and eolian sand deposits (Steiger and Susong, 1997; Lowe et al., 2007). These deposits contain interbedded and lenticular deposits of sand, silt, and clay, and exist within the basin of Moab-Spanish Valley. The average saturated thickness of the VFA in Moab-Spanish Valley is 21 m, but in some places can be more than 91 m (Sumsion, 1971; Lowe et al., 2007).

The groundwater flow system is driven by approximately 2,650 m of topographic relief between the La Sal Mountains (3,856 m at Mount Mellenthin) and the Colorado River (1,204 m). The higher altitudes have cooler mean air temperatures and receive more precipitation than the valley. Average annual precipitation is greater than 750 mm in the La Sal Mountains and less than 230 mm in Moab-Spanish Valley (Sumsion, 1971; Blanchard, 1990; Steiger and Susong, 1997).

Groundwater in lower Moab-Spanish Valley is assumed to discharge either by evapotranspiration on the wetland or as subsurface seepage directly to the Colorado River. A deep brine layer in the wetland prevents fresh groundwater from underflowing the Colorado River (Gardner, 2004), and the river is also the regional potentiometric low. The density contrast between the brine and the overlying fresh groundwater creates a barrier to flow and effectively delineates the bottom of the freshwater aquifer in the wetland (Briggs et al., 2019; Gardner, 2004).

3 Methods

Geochemical constituents sampled included dissolved major ions (Cl, Br, Ca, Mg, Na, K, HCO_3, SO_4), stable isotopes ($\delta^{18}O$, δD), tritium (^3H), dissolved noble gases (He, Ne, Ar, Kr, Xe), and isotopes of dissolved inorganic carbon (DIC; ^{14}C, $\delta^{13}C$). The geochemical data presented in this paper were collected by the U.S. Geological Survey (USGS) and the University of Utah

Department of Geology and Geophysics as part of a larger, collaborative groundwater resources study (Masbruch et al., 2019; Nelson, 2017).

Selected field parameters and geochemical samples were collected from 41 wells, 9 springs, and 18 surface water sites (Table A1) using standard USGS protocols (Wilde and Radtke, 1998). Field parameters measured during water-sample collection include specific conductance, pH, temperature, dissolved oxygen, and total dissolved-gas pressure.

Dissolved major-ion samples were filtered to 0.45 µm and collected in 250-mL polyethylene bottles. Cation subsamples were preserved with nitric acid. Dissolved major ion analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado, and the Geomicrobiology Laboratory at the University of Utah in Salt Lake City. Stable isotope samples were collected in 250-mL polyethylene bottles with no headspace and analyzed at the USGS Stable Isotope Laboratory in Reston, Virginia, and the Spatio-Temporal Isotope Analytics Laboratory at the University of Utah in Salt Lake City. ^{3}H samples were collected in 500-mL polyethylene bottles with no headspace and analyzed at the Dissolved Noble Gas Laboratory at the University of Utah in Salt Lake City using the Helium-in-growth method (Clarke et al., 1976).

Dissolved noble gas samples were collected in copper tubes and diffusion samplers (Gardner and Solomon, 2009). Samples from wells without a dedicated pump were obtained using a low-flow submersible pump; samples from production wells were collected utilizing existing turbine or submersible pumps. Diffusion samplers were primarily used at springs, where pumping was not necessary. Diffusion samplers were placed directly into, or as close as possible to the orifice, and were allowed to equilibrate with the formation water for a minimum of 24 hours before being removed and clamped to seal. Dissolved gas analyses were performed at the Dissolved Gas Laboratory at the University of Utah in Salt Lake City. Recharge temperature (T), excess air (A), and a fractionation parameter (F) were calculated from dissolved gas concentrations using the closed-system equilibration (CE) model described by Aeschbach-Hertig et al. (1999, 2000). Helium isotopes (^{3}He and ^{4}He) were apportioned into concentrations that originated from tritium decay (^{3}He-trit), atmospheric sources (i.e., solubility and A), and uranium/thorium-series decay in the crust (terrigenic helium-4; ^{4}He-terr). Uncertainty in apparent ^{3}H/^{3}He ages increases in samples with large values of A and ^{4}He-terr (Solomon and Cook, 2000). Tritium to tritiogenic helium-3 ratios were used to calculate apparent ^{3}H/^{3}He according to the method outlined in Solomon and Cook (2000).

Samples for ^{14}C and ^{13}C analysis were collected in 1-L glass bottles and sealed with cone-lined caps, leaving no headspace. Samples were bottom filled until three volumes had been purged through the bottle. Analyses were performed at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. Unadjusted ages were calculated from non-normalized ^{14}C activities of DIC using the Libby half-life (5,568 years), assuming an initial ^{14}C activity of 100 percent modern carbon (pmc). Corrections for carbon exchange in unsaturated zone atmosphere and reactions with carbon-bearing minerals were made using the revised Fontes and Garnier model (Han and Plummer, 2013) and the graphical method of estimation described by Han et al. (2012), respectively, in order to determine adjusted ^{14}C ages.

Vadose-zone pore-water samples from cores retrieved from four sites were analyzed for chloride, bromide, ^{3}H, and stable isotopes (δ^{18}O, δD). In order to minimize contamination of these pore waters, cores were collected with a triple-tube continuous coring system with air as the drilling fluid. To minimize evaporative loss of water, the core samples were immediately heat-sealed in the field using a layered aluminum/plastic laminate. In the laboratory, each core sample was removed from its protective packaging, crushed, and split into three parts. For chloride and bromide analysis, samples were quickly weighed (to avoid evaporative loss), then oven-dried at 105 ºC for 24 hours to determine gravimetric water content. Gravimetric water content was converted to volumetric water content assuming a bulk density of 1,980 kg/m^3 for the Navajo Sandstone (Heilweil et al., 2006). A sub-sample of about 200 mg of dried sandstone was then added to an equal mass (about 200 mg) of de-ionized water and mixed vigorously by hand for 10 minutes to leach the salts. This leachate was left 24 hours for the suspended sediment to settle out and then filtered to 0.45 micrometers (µm). A small subset of samples in which these sediments remained suspended were also centrifuged at 2,500 rotations per minute for 20 minutes to remove silts from the sample water. Chloride (Cl) and bromide concentrations in these leachates were analyzed by ion chromatography. Concentrations were corrected for dilution by gravimetric measurements of the water content. Net-infiltration rates were then determined using the Chloride Mass Balance (CMB) method (Allison and Hughes, 1978; Allison, 1988; Wood and Sanford, 1995; Heilweil et al., 2006):

$$q_{CMB} = \frac{[Cl]_{dep}}{[Cl]_{pw}} P, \quad (1)$$

where q_{CMB} is the net-infiltration or recharge rate (L/T),

$[CL]_{dep}$ is the average Cl concentration of atmospheric deposition (M/L^3),

$[Cl]_{pw}$ is the average Cl concentration of pore water(M/L^3), and

P is the precipitation rate (L/T).

For tritium analysis of vadose-zone pore water samples, approximately 2 kg of core was quickly sealed in a stainless-steel flask to avoid evaporative loss. Pore waters were then extracted by cryodistillation, yielding sample volumes of about 50 milliliters (mL). Tritium concentrations in these vadose-zone pore waters were analyzed by mass spectrometry utilizing the helium in-growth method (Clark et al., 1976) with a holding time of about 26 weeks. For stable-isotope analysis, approximately 20 g of sample was quickly sealed in 16-dram glass bottles with polycell cone lids to avoid evaporative loss. Pore waters were then extracted by cryodistillation and analyzed by isotope ratio mass spectrometry.

The tritium depth-to-peak (TDTP) method (Allison and Hughes, 1978; Allison, 1988) was used to calculate net-infiltration rates from vadose-zone pore waters:

$$q_{TDTP} = \frac{z}{t}\theta_v, \quad (2)$$

where q_{TDTP} is the net-infiltration rate (L/T),

z is the vertical distance from land surface to the 1963 ^3H peak (L),

t is the time elapsed between 1963 and the sample collection (T),

θ_v is the depth-weighted volumetric water content of the vadose zone between land surface and the ^3H peak (unitless).

Vadose-zone pore-gas samples were collected from both shallow and deep ports (depths of about 50 and 150 feet) at two sites for analysis of $\delta^{13}C$ of CO_2. These samples were analyzed at the University of Arkansas Stable Isotope Laboratory using a Gas Bench II interfaced to a Delta Plus IRMS (Thermo Sci Bremen Germany). Vadose-zone $\delta^{13}C$ of $CaCO_3$ (aquifer matrix calcite cement) was measured from core samples at two sites (15 m depth at Site A; 50 m depth at Site C) at the USGS Reston, Virginia, Stable Isotope Laboratory by continuous-flow isotope-ratio mass spectrometry on CO_2 gas generated through combustion of the powdered solid sample (Révész et al., 2012). Both the pore-gas $\delta^{13}C$ of CO_2 and the aquifer matrix $\delta^{13}C$ of $CaCO_3$ were used for groundwater ^{14}C dating.

4 Characterizing the Flow System

Results of the analyses of dissolved concentrations of major ions, nutrients, stable- and radioisotopes, and dissolved gases were used to evaluate and then redefine a conceptual model of the flow system. Most of the samples were grouped into one of three categories based primarily on their location and chemistry (both major ions and tracers). These categories are as follows: (1) Deeper Glen Canyon Group aquifer (DGCGA) water includes groundwater samples collected from wells and springs within Glen Canyon Group rocks in the vicinity of the northeast margin of Moab-Spanish Valley; (2) Shallower GCGA water (SGCGA) includes springs and gaining streams along the lower-altitude outcrop area; (3) Valley-Fill Aquifer waters (VFA); and (4) Pack Creek drainage waters (PCD) which include surface and shallow groundwaters that are shown to be tributary to alluvial material and underlying bedrock in Moab-Spanish Valley.

4.1 Recharge

Recharge to the both the DGCGA and the SGCGA is conceptualized to occur primarily as direct infiltration of precipitation. Recharge to the VFA occurs from losing reaches of Pack Creek and lower Mill Creek where they flow over the VFA, and possibly as mountain-block recharge (subsurface inflow of mountain-block groundwater) from the upper PCD into the VFA. Recharge to the PCD includes both direct infiltration of precipitation and seepage loss from upper Pack Creek and its high-altitude mountain tributaries. Evidence in support of these conceptual recharge patterns is presented in the following sections.

4.1.1 Stable isotopes

The primary source of recharge to the study area is precipitation, but differences in geochemical characteristics between sample groups indicate that there are different source areas and mechanisms of recharge. Stable-isotope compositions of all groundwater and surface-water samples range from -113 to -99‰ and from -15.5 to -13.1‰ for δD and δ^{18}O, respectively (Figures 3 and 4; Tables A2 and A4). Groundwater and surface-water samples are plotted in reference to the Global Meteoric Water Line (GMWL; Craig, 1961) and the regional "Utah" meteoric water line (UMWL; Kendall and Coplen, 2001) in Figure 3. Groundwater from the DGCGA is isotopically lighter than all VFA and surface water samples, likely indicating it was recharged as infiltrating snowmelt at high altitude. Importantly, VFA waters are isotopically distinct from DGCGA water (Fig. 3b), which is inconsistent with the conceptual model of Sumsion (1971). Instead, VFA water is isotopically similar to Mill Creek surface water, PCD waters, and two of the samples collected from the SGCGA. Two water samples (14 and 15) that were collected from altitudes of 2,130 and 2,410 m represent mountain groundwater and are consistent with the observed isotopic range of DGCGA waters ($\delta^{18}O$ = -15.5 to -15.1‰; Fig. 3b). Even though the mountain water that these samples represent may not be hydraulically connected to the DGCGA, their location in the watershed indicates that they represent recharge sourced from high-altitude precipitation. Pleistocene-age groundwaters (> 15 ka) from the nearby Lisbon Valley have been shown to be isotopically lighter ($\delta^{18}O$ = -17.4 to -16.6‰; Noyes, 2019) than any water sampled in our study area. This suggests that the range of isotopic values from DGCGA samples is representative of modern (Holocene) mountain precipitation in the region and not Pleistocene-age recharge.

Stable isotope compositions of 18 vadose-zone pore-water samples extracted from four sandstone cores collected along the Sand Flats Road (Table A3; Fig 1) above the water table exhibit a mixture of meteoric and evaporated isotopic signatures that are significantly heavier than any groundwater samples from the DGCGA or the VFA (Fig. 3). Their enriched range of isotopic values suggest that their source is local precipitation, showing that precipitation in this area is not likely to be a significant contributor of recharge to the DGCGA. Furthermore, their evaporative signature is consistent with low-infiltration rates.

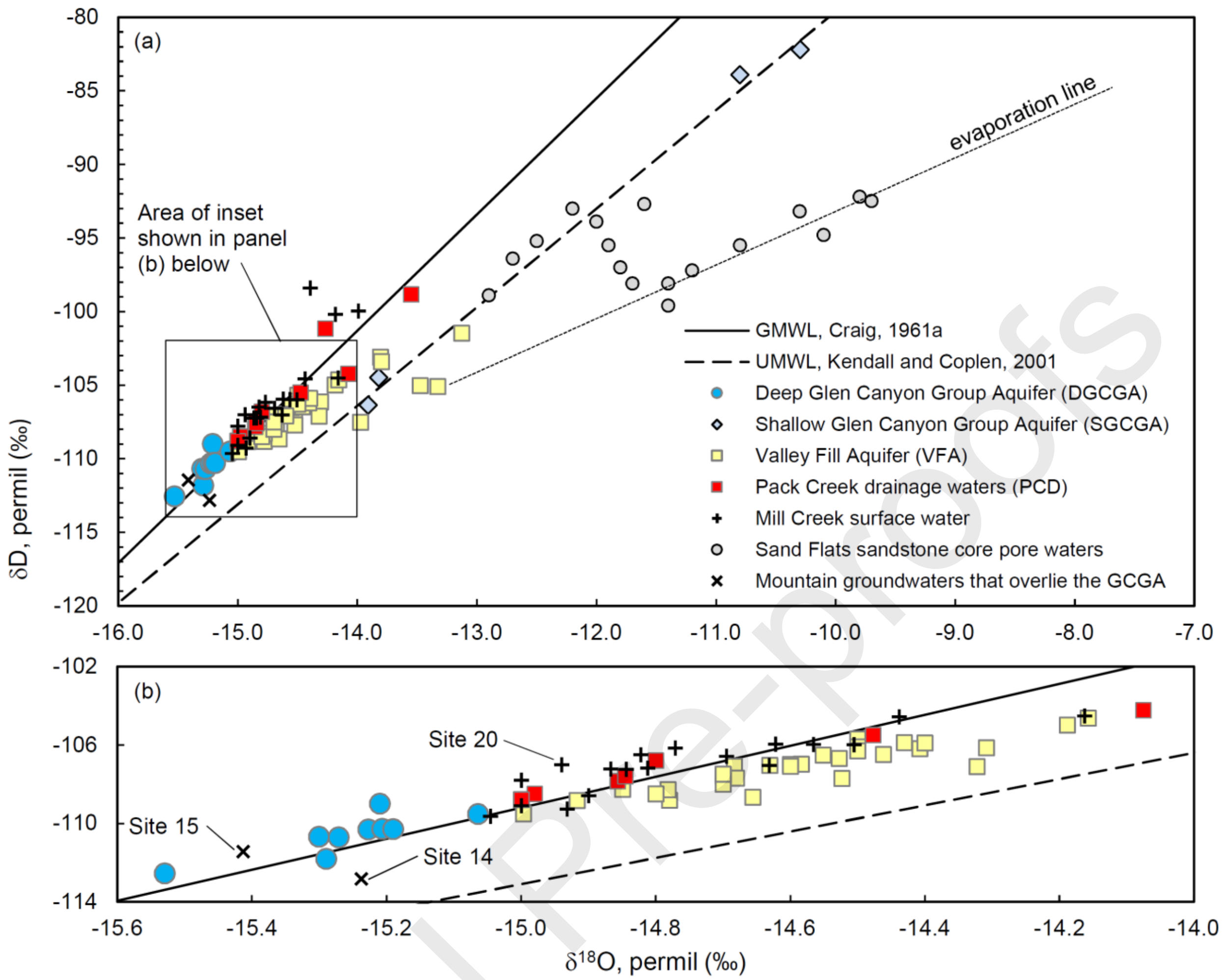

Figure 3. Stable-isotope values (a) of all water samples collected in the Moab-Spanish Valley study area and (b) inset highlighting the isotopic distinction between Deep Glen Canyon Group Aquifer (DGCGA) groundwaters and other surface- and groundwater sources compared to the Global Meteoric Water Line (GMWL) and regional Utah Meteoric Water Line (UMWL).

Samples from Mill Creek and Pack Creek were collected sporadically over 16 months to evaluate the seasonal isotopic variation of stream water (Table A4). These data are compared to the range of isotopic values observed in DGCGA and VFA groundwaters (Fig. 4). The isotopic signature of the stream water varies seasonally, becoming more enriched in the heavy isotopes during periods of high stream flow associated with snowmelt runoff and more depleted during base flow. The isotopically lighter waters observed during late summer through early winter months suggest that most groundwater sustaining base flow in these streams is recharged at higher altitudes than the average altitude of the composite snowpack during periods of peak snowmelt. The seasonal range in surface-water stable isotopes is similar to values observed in VFA groundwaters, while never intersecting the range for DGCGA groundwater. These data provide strong evidence that DGCGA groundwater originates as recharge occurring at distinctly higher altitudes in the watershed than even the groundwater that provides year-round flow to these streams.

A sample from one high-altitude modern spring (Site 14 at about 2,400 m with a modern ^{3}H concentration of 2.7 TU; Fig. 1 and 3) has depleted stable isotope values like those of DGCGA waters (Fig. 3b) suggesting that precipitation above 2,400 m likely has not changed significantly with time. Another example constraining DGCGA recharge to the highest altitudes comes from a base flow sample of Mill Creek stream water at an altitude of about 2,340 m (Site 20; Fig. 1 and 3; Table A4). This water is isotopically enriched in the heavy isotopes compared to DGCGA waters, indicating that precipitation supplying base flow to Mill Creek at this altitude remains more isotopically enriched than the recharge supplying the DGCGA for some range of altitude above this sampling point. Together these data indicate that the isotopically depleted precipitation supplying recharge to the DGCGA is constrained to altitudes above 2,400 m in the watershed.

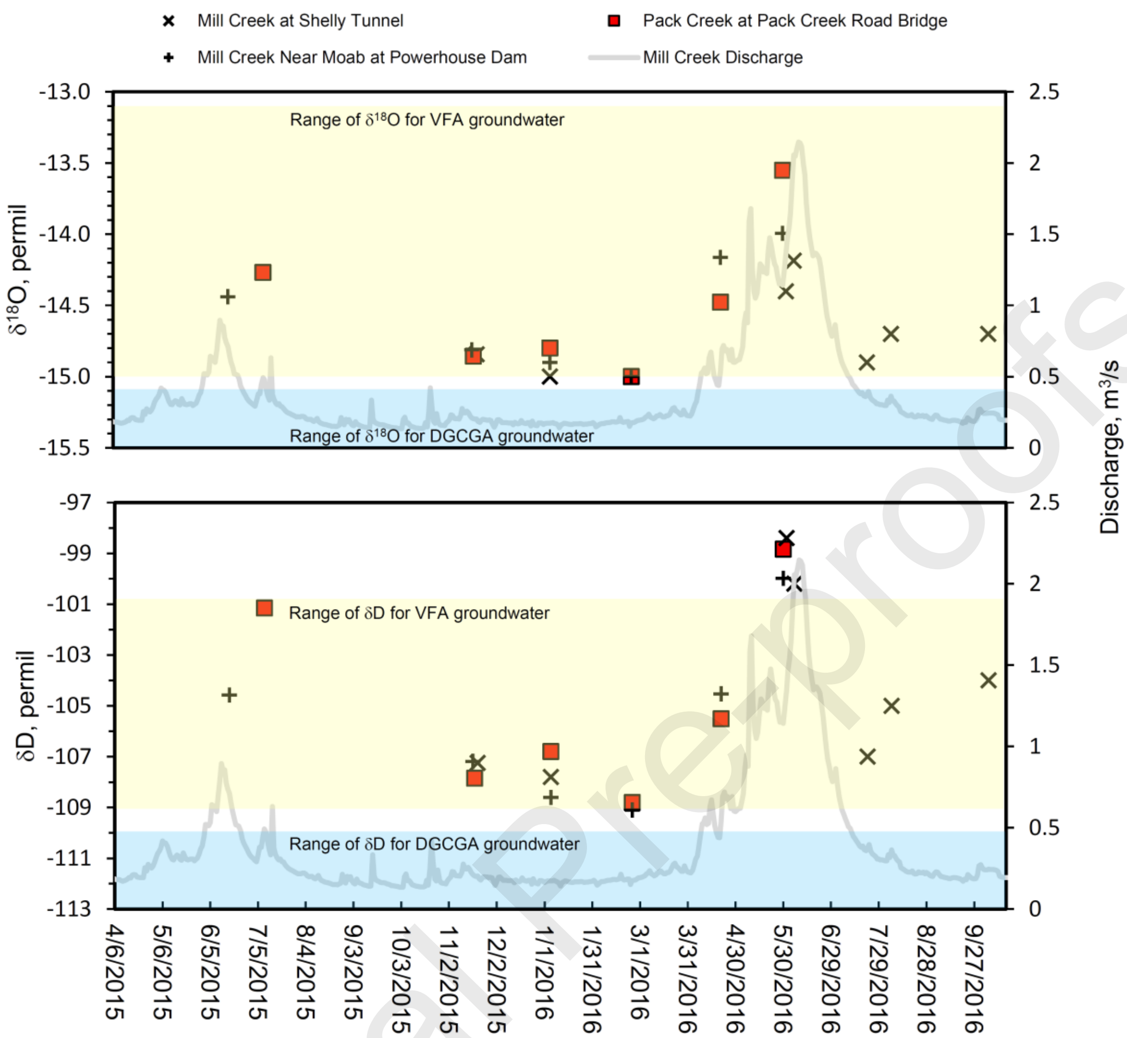

Figure 4. Stable-isotope values of surface-water samples from Mill Creek and Pack Creek compared to the range of values observed in groundwater samples from the Deep Glen Canyon Group Aquifer (DGCGA, blue area) and Valley Fill Aquifer (VFA, yellow area) in the Moab-Spanish Valley study area. Discharge from a Mill Creek stream gage at the base of the La Sal Mountains (USGS Site 09183500 MILL CREEK AT SHELEY TUNNEL, NEAR MOAB, UT) is also shown as the grey line to illustrate periods of high flow associated with seasonal snow melt.

4.1.2 Recharge to the SGCGA outcrop area

Vadose-zone drilling of the SGCGA along the Sand Flats outcrop area northeast of Moab-Spanish Valley for core-sample collection was completed at 4 sites ranging in altitudes from 1440 to 1660 m. At Sites B and C, continuous cores were collected from land surface to depths of about 46 m (Fig. 5). But at Sites A and D, cores were only collected to a maximum depth of about 14 m, where perched water was encountered. This perched water prevented further drilling because a low moisture content is required for successful core recovery using the air-based drilling method.

Measured gravimetric water content of 16 vadose-zone core samples at the 4 sites ranged from 0.018 to 0.051. Multiplying by a bulk density of 1.98 g/cm^3 (based on the average of 90 core measurements from the Navajo Sandstone in southwestern Utah; Heilweil et al., 2006), yielded volumetric water contents ranging from 0.036 to 0.098. The average vadose-zone volumetric water content is 0.056 for seven depths beneath the ephemeral wash at Site B and 0.066 for seven depths beneath the area of diffuse infiltration at Site C.

Net infiltration rates were estimated using vadose-zone pore-water concentrations of both chloride and tritium extracted from borehole cores. Cl concentrations in leachate samples ranged from 0.35 to 5.6 mg/L. The gravimetric water content of each sample was used to convert the measured values to pore-water Cl concentrations, which ranged from 13 to 250 mg/L (Table A3). An assumption of the CMB method is that the only source of chloride is atmospheric (e.g., no additional geologic sources, such as halite). Chloride-to-bromide (Cl/Br) ratios of 100 to 200 have been reported for atmospheric deposition occurring over the southwestern United States, whereas geologic sources of chloride such as evaporites typically have Cl/Br ratios >1000 (Davis et al., 1998). Therefore, to use the CMB, Br concentrations of the leachate were also analyzed and ranged from less than 0.01 to 0.11 mg/L, resulting in calculated Cl/Br ratios of 25 to 274. This confirms the assumption that Cl in the vadose zone of the Sand Flats area has an atmospheric rather than geologic source. At Site C, an average vadose-zone pore-water Cl concentration of 19 mg/L was calculated from seven samples collected between 9 and 47 m deep (Table A3). The concentration of atmospheric Cl deposition in Spanish Valley is estimated to be about 0.8 mg/L, based on previous studies in southwestern Utah (Heilweil et al., 2006). Using this value in equation 1, the calculated net-infiltration rate is about 14 mm/yr. Infiltration rates were not calculated for sites A and D because perched water was encountered at a depth of about 14 m (above a silica-indurated sandstone layer) at both sites. But moderately high chloride concentrations (50 and 80 mg/L, respectively) of the perched water indicate significant evapotranspiration rates at these two sites, and the perching may suggest lateral flow is occurring towards nearby deeply incised canyons. An infiltration rate was not calculated for Site B (ephemeral wash) because Cl concentrations were higher and more variable than at Site C (Fig. 5), perhaps due to intermittent run-on of Cl-bearing water into the wash (invalidating the CMB method, which assumes no lateral run-on or run-off of chloride). The source of such Cl would be salt accumulation at the surface or in the shallow vadose zone from bare soil evaporation and plant transpiration, respectively.

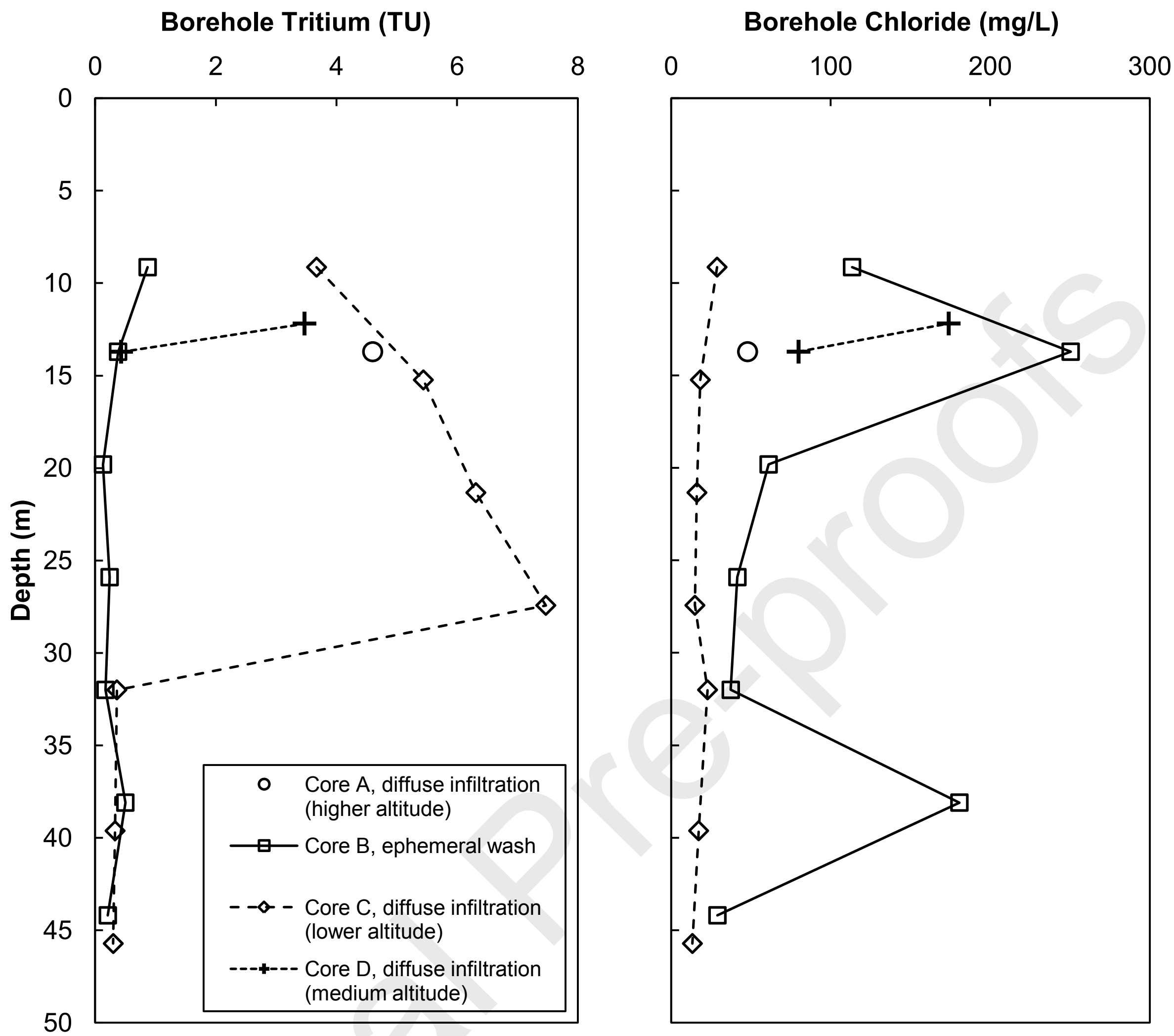

Figure 5. Graphs showing vadose-zone profiles for tritium concentration (left) and chloride concentration (right) versus depth at four borehole sites on the Glen Canyon Group outcrop area along Sand Flats Road, Moab-Spanish Valley study area, Utah.

Pore-water concentrations of ^{3}H were used to estimate net infiltration rates using the TDTP method with the same core samples as described above for pore-water Cl. Vadose-zone pore waters from all Sand Flats outcrop area boreholes had ^{3}H concentrations ranging from 0.1 to 7.5 TU, with analytical uncertainty ranging from 0.05 to 0.5 TU (Table A3). For comparison, the average of monthly interpolated precipitation ^{3}H values for the region encompassing 37 to 39 degrees north latitude and 105 to 110 degrees west longitude during 2012 (the most recent year reported) was 8.0 TU (Michel et al., 2018). The tritium profile beneath the area of diffuse infiltration at Site C shows a peak of 7.5 TU at a depth of 27 m (Fig. 5). Using this depth of 27 m, a 52-year travel time between the 1963 atmospheric ^{3}H peak and the 2015 sampling year, and an average volumetric moisture content of 6.8 percent (from land surface to 27 m) in equation 2, the net-infiltration rate is 35 mm/yr. In contrast, the tritium profile beneath the ephemeral wash at Site B shows concentrations of less than 1 TU at all depths. While a net-infiltration rate could not be calculated for Site B since there is no identifiable peak ^{3}H concentration in the profile, low ^{3}H concentrations and low water content throughout the profile indicate very low net infiltration. In contrast to previous sandstone infiltration studies (Heilweil and Solomon, 2004; Heilweil et al., 2006; Heilweil et al., 2007), this indicates higher recharge rates at the diffuse site and little focused recharge occurring beneath the wash, an unexpected finding because ephemeral washes typically have higher infiltration rates than elsewhere in arid landscapes due to focusing of flow (Stonestrom et al., 2003). Because multiple cores were not drilled at each site, an alternative explanation for the differences in ^{3}H concentrations between sites B and C might be spatial variability in infiltration. But this is considered less likely at Sand Flats because of the relatively high primary permeability of the sandstone matrix (relative to other fractured rock media), whereby the smaller pore spaces of the homogeneous sandstone (compared with fractures) would dominate vadose-zone capillary flow and smooth out small-scale variability in ^{3}H concentrations caused by fracture heterogeneity/anisotropy.

TDTP net-infiltration rates were not calculated for Sites A and D because drilling was abandoned due to shallow perched water. An important finding, however, is the decline in ^{3}H concentration at Site D from 3.47 ± 0.14 TU in the perched water collected between 12.2 and 13.7 m to 0.43 ± 0.04 TU for vadose-zone pore water extracted from 13.7 to 15.2 m (Table A3). This indicates that a thin indurated sandstone layer found beneath the perched water from the coring at Site D is preventing downward infiltration of recharge and presumably resulting in lateral flow.

In summary, recharge rates using both the CMB and TDTP methods with vadose-zone pore waters showed lower net-infiltration rates than expected for the SGCGA outcrop of the Sand Flats area, which had previously been assumed to be the primary recharge area for the DGCGA. This finding is consistent with the heavier stable isotopes found in this same pore water (described above) and may be attributable to a perching layer in the shallow vadose zone at all but the lowest altitude borehole (Site C). Evidence for this perching layer included (1) the counterintuitive finding of lower CMB rates beneath the ephemeral wash at Site B (presumably having focused infiltration) than a nearby lower altitude area of diffuse infiltration (Site C); (2) perched water above a 10-cm thick silica-indurated (low permeability) layer encountered at a depth of about 14 meters at both higher altitude Sites (A and D); and (3) low pore-water ^{3}H concentrations directly beneath the perched zone at Site D. This shallow perched water is likely migrating laterally to discharge as small springs and seeps in nearby incised canyons rather than recharging the DGCGA. In addition, the relatively “smooth” profiles of ^{3}H from Sites B and C (Fig. 5) indicate a lack of hydrologic influence of fractures on vertical infiltration in the unsaturated zone. Unless fractures become saturated, they act more as capillary barriers and thus not contribute to recharge.

4.2 Groundwater flow

The general direction of groundwater movement is southeast to northwest in the VFA, following the axis of the Moab-Spanish Valley from the La Sal Mountains toward the Matheson Wetlands and the Colorado River (Fig. 1). The general direction of groundwater movement in the GCGA is east to west from the La Sal Mountains toward Mill Creek and the northeast margin of Moab-Spanish Valley, where DGCGA waters discharge to springs and municipal wells and SGCGA waters discharge to incised bedrock streams. As water moves through the groundwater flow system, major-ion geochemistry evolves according to the geology encountered, and groundwater age increases along the length of flow paths. Groundwater from each aquifer has a unique combination of geochemical properties, which gives insight into its origin and evolution along its flow path.

4.2.1 Major ion geochemistry

Major ion geochemistry results are presented in Table A2 and plotted on a trilinear diagram to illustrate the dominant dissolved constituents of the various water groups (Fig. 6). Most samples fall along a continuum between calcium-bicarbonate- (Ca-HCO_3) and calcium-sulfate- (Ca-SO_4) type waters. DGCGA samples are all Ca-HCO_3-dominant waters, whereas PCD samples, which are tributary to the VFA, are Ca-SO_4-dominant waters. Most VFA waters plot between these groups indicating the possibility that they represent mixtures of the two. Five samples that group near or within the range for DGCGA samples are lower-valley shallow groundwaters that are influenced by seepage from Mill Creek and DGCGA springs that spill into ponds on the wetland. These samples are thus mixtures of VFA and Mill Creek or DGCGA discharge that has re-infiltrated the shallow alluvium. Four samples that clearly fall outside of the dominant Ca-HCO_3–Ca-SO_4 trend are lower-valley sodium-chloride- (Na-Cl) type waters that are influenced by Paradox Formation-derived brine, which underlies the shallow groundwater system beneath the wetland adjacent to the Colorado River (Gardner, 2004).

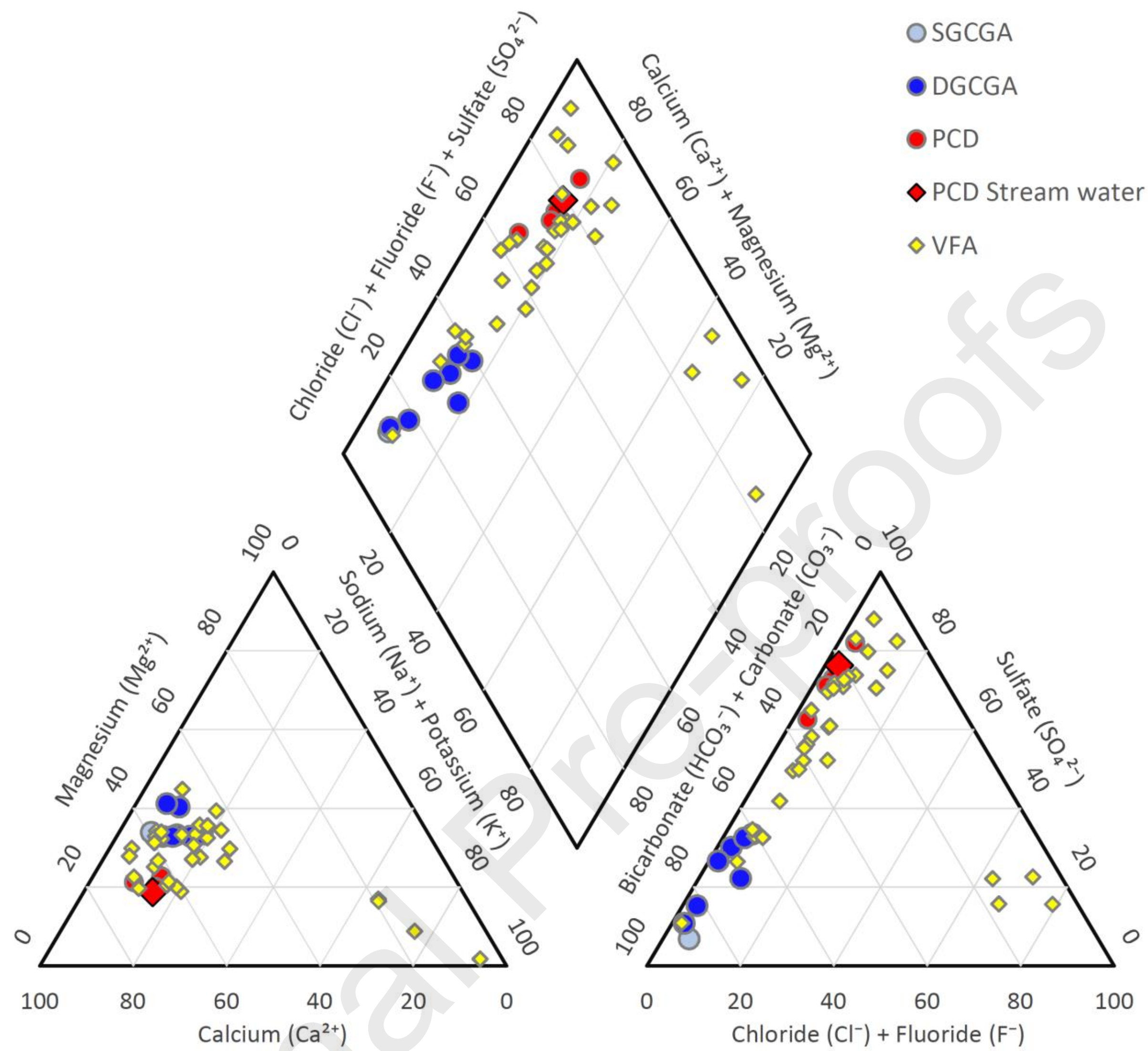

Figure 6. Trilinear diagram showing major-ion composition of selected groundwater samples from wells and springs, and one stream at base flow in the Moab-Spanish Valley study area, Utah. Samples are symbolized according to the aquifer or flow system from which they were collected: Shallow Glen Canyon Group Aquifer (SGCGA), Deep Glen Canyon Group Aquifer (DGCGA), Pack Creek Drainage (PCD), and Valley Fill Aquifer (VFA).

Total dissolved solids (TDS) concentrations for samples collected during this study ranged from 116 to 159,000 mg/L (Table A2). A map showing representative Stiff diagrams (Fig. 7) illustrates spatial patterns of major-ion geochemical types and relative TDS concentrations. Major-ion chemistry of VFA waters evolve moving downgradient through Spanish Valley in a southeast-northwest direction (Fig. 7). SGCGA and DGCGA waters north of Moab-Spanish

Valley have low TDS and are Ca-HCO_3-type. PCD waters sampled upgradient of the VFA are distinctly higher in TDS, particularly SO_4 than SGCGA and DGCGA waters. The high SO_4 in the PCD waters is likely derived from dissolution of evaporite minerals associated with the Mancos Shale, which crops out in places and underlies much of the PCD above Moab-Spanish Valley. Most VFA groundwater chemically resembles the upgradient PCD waters, possibly having experienced slight dilution in the central part of Moab-Spanish Valley (indicated by the smaller size of the Stiff diagrams), where low TDS DGCGA waters discharge from springs along the northeast valley margin. The chemical similarity between PCD and VFA waters, coupled with the general direction of groundwater movement indicated by potentiometric contours, suggests that most VFA groundwater originates as precipitation in the upper Pack Creek watershed and recharges the VFA as seepage losses from Pack Creek in the upper portion of Moab-Spanish Valley. A large increase in TDS at the northwest end of the valley is attributed to the influence of Paradox Formation evaporite minerals and associated brine that underlies the VFA adjacent to the Colorado River. Outcrops of Paradox Formation cap rock can be seen along both sides of the lower valley (Figs. 2 and 7).

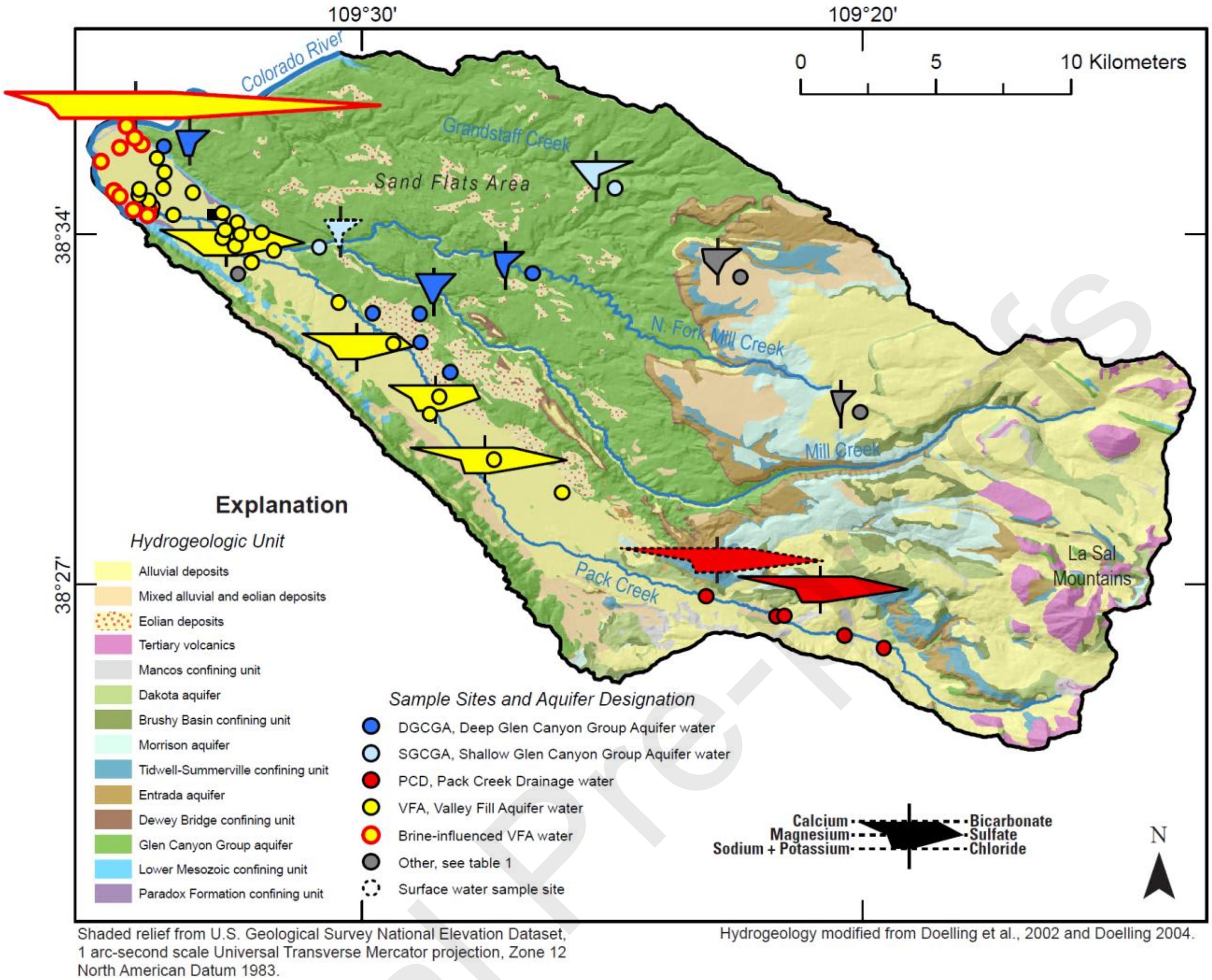

Figure 7. Map of Stiff diagrams selected to show major-ion composition of different groundwater groups in the Moab-Spanish Valley study area, Utah. Sites with dashed outlines indicate surface-water sampled during baseflow from streams sustained by groundwater discharge.

4.2.2 Groundwater age

Groundwater ^{3}H concentrations range from below detection (about 0.1 TU) to 5.1 TU (Table 1). R/R_a values range from 0.07 to 2.05 (R is the $^{3}He/^{4}He$ ratio of a sample and R_a is the $^{3}He/^{4}He$ ratio of air —1.384×10^{-6}). Terrigenic helium-4 ($^{4}He_{terr}$) concentrations range from below detection (negative calculated values) to 9.37×10^{-6} ccSTP/g. Although it is not possible to assign an absolute age based on $^{4}He_{terr}$ concentrations because its production rate within the aquifer is not known, elevated $^{4}He_{terr}$ indicates water that has been in contact with aquifer materials for significantly longer than the time required for ^{3}H to decay to below detection and contains at least some fraction of older water.

^{3}H, helium R/Ra values, and terrigenic helium ($^{4}He_{terr}$) were used for categorizing ages of groundwater within the study area. Samples are categorized as containing (1) modern water (recharge since the 1950s), (2) a mixture of modern and pre-modern water, or (3) all pre-modern water (Fig. 8). Waters are characterized as modern if they have ^{3}H concentrations greater than 1 TU, R/Ra greater than 0.95, and $^{4}He_{terr}$ concentrations less than 1.0×10^{-8} ccSTP/g. Pre-modern waters all have ^{3}H concentrations less than 0.4 TU, R/Ra less than 0.95, and $^{4}He_{terr}$ concentrations greater than 1.0×10^{-8} ccSTP/g. Pre-modern waters were assumed to be greater than 70 years old. Waters are characterized as a mixture of modern and pre-modern for (a) ^{3}H concentrations between 0.38 – 1.0 TU and R/Ra values of less than 0.95, regardless of the $^{4}He_{terr}$ concentrations; (b) ^{3}H concentrations greater than 1 TU but with elevated $^{4}He_{terr}$ concentrations (> 1.0×10^{-8} ccSTP/g), regardless of the R/Ra value; or (c) ^{3}H concentrations less than 0.38 TU but R/Ra values near 1.0 and $^{4}He_{terr}$ concentrations < $1.0\text{x}10^{-8}$ ccSTP/g. Based on these criteria, modern water was found at 17 of the 49 sample sites within the study area, pre-modern water was found at 7 sample sites (one site includes a replicate sample), and mixtures were found at 25 sample sites.

Table 1. Stable- and radio-isotope data and estimated ages for groundwater sampled in the Moab-Spanish Valley study area, Utah.

[Premodern, groundwater that recharged prior to the mid-1950s; Mixture, sample that contains a mixture of pre-modern and modern groundwater. **Abbreviations:** ^{3}H, tritium; TU, tritium units; R/R_a, R is the $^{3}He/^{4}He$ ratio of the sample, and R_a is the $^{3}He/^{4}He$ ratio of air ($1.384\text{x}10^{-6}$); ^{4}He, helium-4; ccSTP/g, cubic centimeters per gram of water at standard temperature and pressure; ^{3}He, helium-3; ^{14}C, Carbon-14; pmC, percent modern carbon; $\delta^{13}C$, ratio of carbon-13 to carbon-12 in sample compared to reference standard; A_o, initial carbon-14 of groundwater total dissolved inorganic carbon; BP, before present; DGCGA, Deep Glen Canyon Group Aquifer; VFA, Valley Fill Aquifer; SGCGA, Shallow Glen Canyon Group Aquifer; PCD, Pack Creek Drainage; —, no data]

[1] Sample ID	Aquifer	^{3}H (TU)	R/R$_a$	Measured ^{4}He (ccSTP/g)	[2] Terrigenic ^{4}He (ccSTP/g)	Age category based on ^{3}H and ^{4}He	Tritio-genic ^{3}He (TU)	[3] Apparent ^{3}H/^{3}He age (years BP)	^{14}C (pmC)	δ^{13}C (permil)	^{14}C in vadose zone gas (pmC)	A$_o$ (pmC)	Corrected ^{14}C (pMC)	Corrected ^{14}C age (years BP)
1	DGCGA	0.33	0.64	6.26×10^{-8}	2.40×10^{-8}	Premodern	1.0	>70	54	-9.4	100	79.1	[4] 67.9	3,200
2	VFA	2.1	1.14	6.47×10^{-8}	9.66×10^{-9}	Modern	10.6	34	65	-9.4	100	98.2	65.7	3,500
3	VFA	3.9	1.35	5.92×10^{-8}	1.07×10^{-8}	Mixture	17.3	30	83	-11.4	[5] 140	112	74.1	2,500
4	DGCGA	0.75	0.86	5.26×10^{-8}	1.27×10^{-8}	Mixture	3.0	—	57	-9.8	100	69.6	[4] 81.6	1,700
5	DGCGA	0.27	0.80	5.59×10^{-8}	1.54×10^{-8}	Premodern	2.3	>70	63	-10.4	100	66.1	95.8	350
5	DGCGA	0.17	0.82	5.55×10^{-8}	2.38×10^{-8}	Premodern	7.4	>70	63	-10.4	100	66	95.8	360
6	DGCGA	0.38	0.88	4.97×10^{-8}	7.10×10^{-9}	Mixture	0.6	—	53	-9.7	100	71.2	[4] 75.1	2,400
7	[5] Other	0.33	1.00	4.09×10^{-8}	2.10×10^{-9}	Mixture	1.1	—	52	-8.0	100	97	[4] 53.3	5,200
8	DGCGA	2.3	1.05	4.02×10^{-8}	-4.68×10^{-10}	Modern	0.8	6	52	-9.8	100	73.7	[4] 70.8	2,900
9	SGCGA	0.30	0.99	4.09×10^{-8}	1.20×10^{-9}	Mixture	0.5	—	91	-10.2	[5] 140	104	87.5	1,100
10	VFA	4.2	1.13	6.42×10^{-8}	1.17×10^{-8}	Mixture	11.3	23	85	-11.1	[5] 140	102	83.8	1,500
11	DGCGA	0.84	0.59	7.38×10^{-8}	3.20×10^{-8}	Mixture	1.2	—	50	-9.1	100	78.4	[4] 63.7	3,700
12	VFA	1.8	1.00	5.37×10^{-8}	3.26×10^{-9}	Modern	2.2	13	92	-11.6	[5] 145	93.2	98.4	130
13	VFA	5.1	1.17	4.33×10^{-8}	-1.02×10^{-11}	Modern	4.4	11	76	-9.1	100	87.8	86.2	1,200
14	[6] Other	2.7	1.04	3.70×10^{-8}	-2.44×10^{-9}	Modern	-0.4	< 1	98	-15.3	[5] 140	100	98.1	160
15	[6] Other	0.05	0.55	1.16×10^{-7}	6.03×10^{-8}	Premodern	4.5	>70	22	-7.9	100	100	[4] 21.9	13,000
16	PCD	2.7	0.96	4.14×10^{-8}	3.77×10^{-9}	Modern	1.5	9	77	-12.6	[5] 140	102	75.5	2,300
17	VFA	3.6	1.22	4.34×10^{-8}	3.43×10^{-9}	Modern	7.4	20	75	-9.0	100	104	72.3	2,700
18	VFA	0.29	0.83	6.46×10^{-8}	1.97×10^{-8}	Premodern	4.9	>70	70	-9.2	100	102	83.8	3,100
19	DGCGA	0.53	—	—	—	[7] Mixture	—	—	52	-9.7	100	69.7	74.7	2,400
U1	VFA	3.12	1.01	4.7×10^{-8}	-1.23×10^{-9}	Modern	0.1	1	—	—	—	—	—	—
U2	VFA	2.35	1.12	6.3×10^{-8}	2.08×10^{-8}	Mixture	15.7	37	—	—	—	—	—	—
U3	VFA	3.01	1.68	5.0×10^{-8}	9.64×10^{-9}	Modern	24.1	39	—	—	—	—	—	—
U4	VFA	2.19	1.17	6.8×10^{-8}	2.02×10^{-8}	Mixture	17.4	39	—	—	—	—	—	—
U5	VFA	3.14	0.49	1.1×10^{-7}	5.86×10^{-8}	Mixture	-0.5	—	95	-14.3	—	—	—	—
U6	VFA	1.59	1.01	5.0×10^{-8}	6.67×10^{-9}	Modern	4.3	24	—	—	—	—	—	—
U7	VFA	2.33	0.95	5.4×10^{-8}	3.93×10^{-9}	Modern	0.9	6	—	—	—	—	—	—
U8	VFA	2.31	1.10	4.3×10^{-8}	-2.06×10^{-9}	Modern	1.7	10	—	—	—	—	—	—
U9	VFA	0.51	0.93	4.5×10^{-8}	2.97×10^{-9}	Mixture	0.3	—	—	—	—	—	—	—
U10	VFA	2.2	1.04	5.0×10^{-8}	4.14×10^{-9}	Modern	3.7	18	—	—	—	—	—	—
U11	VFA	2.84	1.00	4.2×10^{-8}	9.37×10^{-10}	Modern	0.8	4	—	—	—	—	—	—
U12	VFA	1.34	0.83	6.6×10^{-8}	1.68×10^{-8}	Mixture	2.9	21	—	—	—	—	—	—
U13	VFA	1.73	1.14	7.2×10^{-8}	2.44×10^{-8}	Mixture	18.7	44	—	—	—	—	—	—
U14	VFA	3.36	2.05	5.5×10^{-8}	6.87×10^{-9}	Modern	36.4	44	—	—	—	—	—	—
U15	VFA	3.82	1.79	4.8×10^{-8}	-3.47×10^{-9}	Modern	19.6	33	—	—	—	—	—	—
U16	VFA	4.79	1.10	3.9×10^{-7}	1.70×10^{-7}	Mixture	111	—	—	—	—	—	—	—
U17	VFA	0.93	0.65	8.7×10^{-8}	4.02×10^{-8}	Mixture	4.8	—	—	—	—	—	—	—
U18	VFA	0.6	0.47	1.4×10^{-7}	7.98×10^{-8}	Mixture	2.4	—	—	—	—	—	—	—
U19	VFA	0.57	0.44	1.2×10^{-7}	7.89×10^{-8}	Mixture	3.2	—	—	—	—	—	—	—
U20	VFA	1.07	0.64	1.1×10^{-7}	6.62×10^{-8}	Mixture	13.2	—	—	—	—	—	—	—
U22	VFA	3.35	0.33	3.6×10^{-7}	3.15×10^{-7}	Mixture	33.2	—	—	—	—	—	—	—
U24	VFA	1.55	0.32	2.9×10^{-7}	2.39×10^{-7}	Mixture	19.3	—	—	—	—	—	—	—
U25	VFA	3.05	1.25	5.0×10^{-8}	3.79×10^{-9}	Modern	13.1	25	—	—	—	—	—	—
U26	VFA	0.79	0.94	4.8×10^{-8}	7.00×10^{-9}	Mixture	2.4	25	—	—	—	—	—	—
U27	VFA	0.72	0.53	7.5×10^{-8}	3.01×10^{-8}	Mixture	-3.4	—	85	-10.9	—	—	—	—
U28	VFA Brine	0.49	0.21	3.1×10^{-7}	2.69×10^{-7}	Mixture	4.8	—	—	—	—	—	—	—
U29	VFA Brine	0.29	0.09	8.6×10^{-6}	8.56×10^{-6}	Premodern	163	>70	—	—	—	—	—	—
U30	VFA	2.23	0.15	7.0×10^{-7}	6.57×10^{-7}	Mixture	14.6	—	—	—	—	—	—	—
U31	VFA Brine	0.27	0.07	7.4×10^{-6}	7.31×10^{-6}	Premodern	65.8	>70	—	—	—	—	—	—
U32	VFA Brine	0.01	0.07	9.4×10^{-6}	9.37×10^{-6}	Premodern	68.6	>70	3.3	-8.1	—	—	—	—

[1] Sample dates are the same as in Table A2.
[2] Interpreted value derived using the closed-equilibrium dissolved-gas model (Aeschbach-Hertig et al., 2000; Kipfer et al., 2002).
[3] Apparent ^{3}H/^{3}He ages were not calculated *for samples categorized as age-mixtures* due uncertainty introduced by either low ^{3}H (< 1 TU) or elevated $^4He_{terrigenic}$ (> 2.5×10^{-8} ccSTP/g), or if samples do not have independently measured ^{3}He.
[4] Reasonably well-defined carbon-14 'single-sample' analytical correction. Falls below "zero-age" line as defined by Han et al., 2012.
[5] Unsaturated zone gas was changed to greater than 100 pMC, representing the presence of elevated carbon-14 activities associated with above-ground nuclear testing; geochemical models with 100 pMC unsaturated zone gas activities for these samples produced unreasonable results.
[6] Sample sites not in one of the primary aquifers: Site 7 is a spring discharging from Glen Canyon Group bedrock on the southwest valley margin, physically disconnected from GCGA; Site 14 is a shallow mountain aquifer spring discharge above 2,400 m in altitude; Site 15 is an isolated aquifer location stratigraphically above the GCGA.
[7] Mixture designation based on ^{3}H and ^{14}C, site was not sampled for dissolved He.
[8] Replicate sample included for quality assurance.

Two of the seven waters that discharge from the DGCGA (samples 1 and 5) are categorized as pre-modern, four (samples 4, 6, 11, and 19) are mixtures with ^{3}H concentrations less than 1 TU (19 has no helium data, this categorization considers low pMC carbon-14), and one (sample 8) is modern (Table 1; Fig. 8). The modern DGCGA sample (sample 8) is from a spring discharging to the North Fork of Mill Creek which is tributary to Mill Creek near its mouth where it enters Moab-Spanish Valley. One groundwater sample (sample 9) discharging from the SGCGA is categorized as a mixture of modern and pre-modern water representing a slow, localized flow path in an area of little recharge.

Groundwater sampled throughout the VFA in Moab-Spanish Valley is dominantly modern or a modern mixture, most often containing ^{3}H concentrations greater than 1 TU (Fig. 8; Table 1). The clear pattern of age categories showing younger water in the VFA and older water in the DGCGA forms the basis of a revised conceptual model.

^{3}H to tritiogenic helium-3 ratios were used to calculate apparent ^{3}H/^{3}He ages for twenty-four groundwater samples from the GCGA and VFA and one from the PCD. In samples of mixed age, the ^{3}H/^{3}He$_{trit}$ age is typically representative of the young fraction. ^{3}H/^{3}He$_{trit}$ ages were not calculated for waters characterized as mixtures where uncertainty was high due to either low ^{3}H (< 1 TU) or elevated ^{4}He$_{terrigenic}$ (> 2.5x10-8 ccSTP/g), or if samples do not have independently measured ^{3}He. Also, the high end of the ^{4}He$_{terr}$ concentrations and low end of the R/R$_a$ values clearly indicate that some of the samples contain water that is older than can be dated using the ^{3}H/^{3}He$_{trit}$ method. The apparent ^{3}H/^{3}He ages for the modern groundwaters range from less than 1 to 44 years (Table 1).

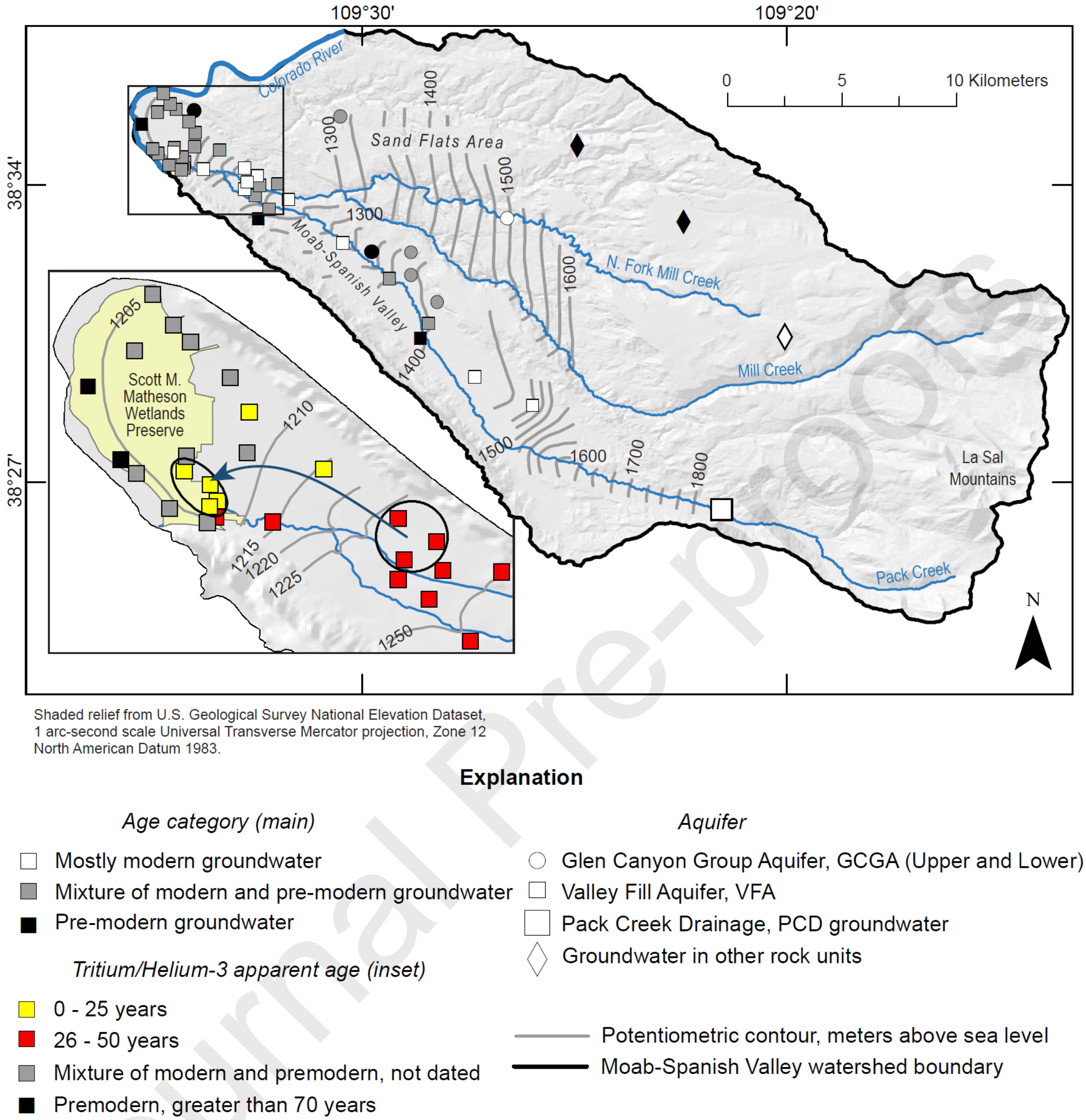

Figure 8. Map showing tritium- and helium-based age categories of selected samples from wells and springs in the Moab-Spanish Valley study area, Utah, and inset map showing the $^3H/^3He$ ages from valley-fill aquifer water in the lower valley. The circles indicate the sample clusters where average $^3H/^3He$ ages were used in an age-gradient based Darcy calculation of subsurface discharge to the Colorado River through the Matheson Wetlands Preserve.

Carbon-14 activity measured from DIC in groundwater samples from 22 sites within the study area ranges from 3.3 to 98 pmC (Table 1). DGCGA groundwater (samples 1, 4, 5, 6, 8, 11, and 19) has a narrow range of ^{14}C values of 50 to 63 pmC. DGCGA groundwater sampled from a spring in the upper portion of Left-Hand Fork of Mill Creek (sample 8) has 52 pmC of ^{14}C indicating that it contains a component of pre-modern water, despite being categorized as "modern" based on ^{3}H, R/Ra, and $^{4}He_{terr}$ concentrations. Except for one spring that discharges at a bedrock-alluvial contact along the southwest valley margin (sample 7; 52 pmC) and one dense brine sample that underlies the active fresh groundwater system (sample U32; 3.3 pmC, 159,000 mg/L TDS), groundwater from the VFA have ^{14}C values from 65 to 95 pmC (samples 2, 3, 10, 12, 13, 17, 18, U5, U27). The consistently higher ^{14}C of the VFA groundwater when compared to DGCGA groundwater provides yet another line of evidence that the VFA receives substantial recharge from a source other than the DGCGA.

When calculating ^{14}C ages, corrections typically are required to account for physical processes and chemical reactions other than radioactive decay that alter ^{14}C activity in the unsaturated zone and below the water table. A correlation between decreasing ^{14}C and $\delta^{13}C$ enrichment (fig. 9) illustrates that significant water-carbonate mineral reaction occurs in these aquifers and that unadjusted radiocarbon ages may be biased old. Notable in this comparison is that DGCGA waters plot together in a cluster below the dominant trend, showing that they have undergone more radioactive decay than waters experiencing a similar degree of carbonate mineral reaction. This relationship is the result of DGCGA groundwater movement through distinctly different geology than all other waters sampled for carbon isotopes during this study.

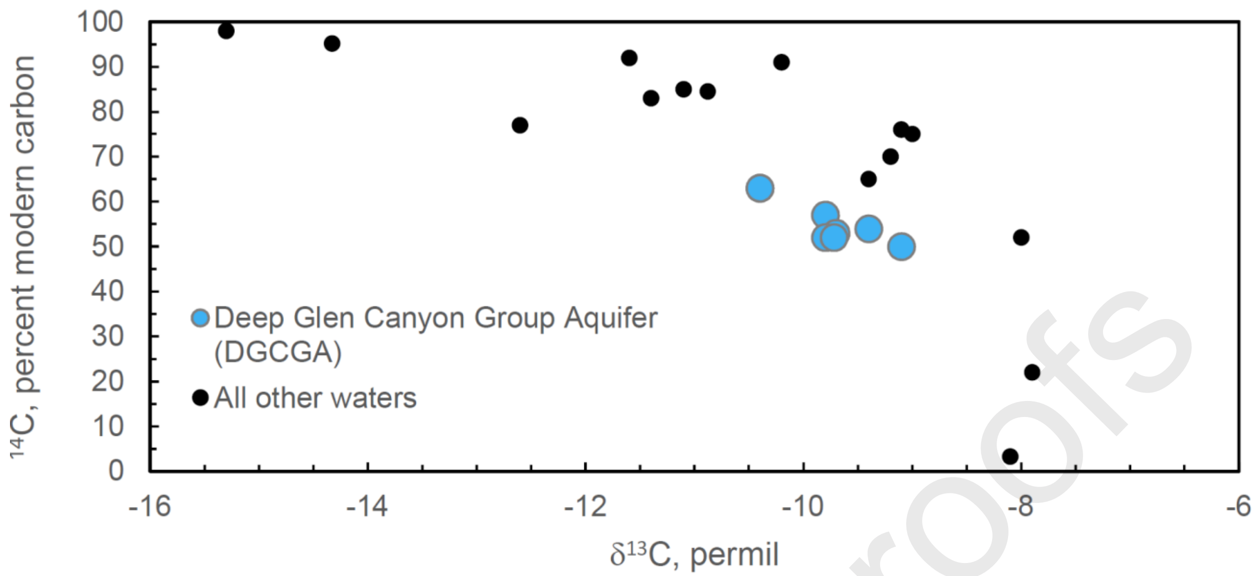

Figure 9. Plot showing ^{14}C vs $\delta^{13}C$ for all water samples with radiocarbon analyses in the Moab-Spanish Valley study area.

We have calculated corrected ^{14}C ages by correcting for the dissolution of carbonates in the vadose zone and aquifer using the revised Fontes and Garnier model described by Han et al. (2012). Samples were assumed to be dominantly affected under open-system conditions with free exchange between soil gas and atmosphere. Soil CO_2 was assumed to have a ^{14}C activity of 100 pmC (except where footnoted in Table 1) and $\delta^{13}C$ of -15.7‰ which represents the average value measured in pore gas from eight samples collected during this study (Table A5) and is approximately the value reported by Huth et al. (2019) derived from soil carbonate in southwestern Utah. The carbonate source in the saturated GCGA is calcite cement and was assumed to have a ^{14}C activity of 0 pmC and $\delta^{13}C$ of -5.5‰, based on the graphical method of Han and Plummer (2013). This estimated value is within the $\delta^{13}C$ range of -5.5 to -6.6 ‰ measured in calcite cement from two samples collected during this study (Core A10 and Core C32; Table A5). Corrected ages for VFA samples where ^{14}C was measured range from 130 to 3,500 years with a mean and standard deviation of 2,100 ± 1,200 years (sites 2, 3, 10, 12, 13, 17, and 18 in Table 1). Corrected ages for DGCGA samples range from 1,700 to 3,700 years with a mean and standard deviation of 2,700 ± 700 years (sites 1, 4, 6, 8, 11, and 19; note that we omit site 5 due to observed aerated conditions and likely partial equilibration with atmospheric CO_2).[1]

4.3 Groundwater Discharge

Discharge of groundwater from the GCGA, VFA, and PCD occurs to streams, springs, wells, evapotranspiration along streams or in the wetland, and as subsurface outflow to the Colorado River (only from the VFA). Flow measurements were conducted by the U.S. Geological Survey on springs and streams (differentials at two or more sites) over three consecutive years (2014-2016). Smaller flows were measured with a 2-inch Parshall flume; larger flows were measured with a Pygmy meter. Measurements were made during dry periods in late fall (November-December) and assumed to represent base flow conditions not affected by seasonal evapotranspiration and groundwater pumping for irrigation. During this time of year, all springs in Moab-Spanish Valley either discharge into Mill Creek and lower Pack Creek, flow into the Matheson Wetlands and are assumed to eventually reach the Colorado River as surface-water flow, or are captured for municipal use (all springs that supply municipal use are metered by Moab City). Averages of measured discharge to the GCGA (both SGCGA and DGCGA) during 2014-2016 (Table 2) are (1) 6.6 x 10^6 m^3/yr for Mill Creek at the GCGA/valley-fill boundary; (2) 2.5 x 10^6 m^3/yr for Mill Creek diversions to Ken's Lake; (3) 3.6 x 10^6 m^3/yr for Moab City municipal wells and springs; (4) 0.9 x 10^6 m^3/yr for springs discharging along the northeast margin of lower Moab-Spanish Valley; and (5) 1.4 x 10^6 m^3/yr for Grandstaff and Ice Box Creeks. Components 1, 2, and 5 represent flows out of the SGCGA, while 3 and 4 are discharge from the DGCGA. Therefore, the average measured discharge was 10.6 x 10^6 m^3/yr

[1] The spring sample from site 5 could not be collected from the orifice. Rather, the sample was collected an unknown distance downstream from the orifice where shallow turbulent flow was accessible in an underground culvert. Although the sample water was observably aerated, the sample was collected and noted as potentially contaminated by partial equilibration with atmospheric CO_2.

from the SGCGA and 4.4 x 10^6 m^3/yr from the DGCGA. In addition, gain in lower Mill Creek representing discharge from the VFA (component 6) was 1.9 x 10^6 m^3/yr. The combined average measured discharge during 2014-2016 of both the GCGA and VFA was 17 x 10^6 m^3/yr.

Table 2. Summary of total measured baseflow groundwater discharge from the GCGA and VFA in the Spanish Valley study area, Utah. Values are reported in millions of cubic meters per year (m^3/yr x 10^6) except in the final column where the 3-year average is repeated in acre-feet per year (acre-ft/yr), units commonly used by water managers in the western United States (1 acre-ft is equal to 1,233.48 m^3).

	(m^3/yr x 10^6)				(acre-fr/yr)
Site(s)	**2014**	**2015**	**2016**	**Average**	**Average**
(1) Mill Creek at valley fill boundary	7.8	6.8	5.4	6.6	5,400
(2) Ken's Lake diversion from Mill Creek	0.0	4.0	3.6	2.5	2,000
(3) Municipal springs & wells	3.0	3.7	4.1	3.6	2,900
(4) Springs in lower Spanish Valley	0.7	0.8	1.1	0.9	700
(5) Grandstaff and Ice Box Creeks	1.6	1.3	1.3	1.4	1,100
Total GCGA	**13.1**	**16.6**	**15.5**	**15.0**	**12,200**
(6) Gain in Mill Creek from VFA	3.0	1.5	1.3	1.9	1,600
Total GCGA + VFA	**16.1**	**18.2**	**16.7**	**17.0**	**13,800**

The most problematic groundwater discharge components to measure are evapotranspiration in the wetland and subsurface flow to the Colorado River. The combined flow associated with both were estimated using horizontal changes in groundwater age. The age difference between samples (Δt) was determined using two "clusters" of samples (Table 1; sites U8, U10, and U11 for cluster 1 and sites U4, U13, U14 and U15 for cluster 2) located approximately 3.2 km apart (Fig. 8, inset). These samples were selected because they lie along a groundwater flow path and have similar geochemistry. Furthermore, minimal recharge to VFA is likely to occur in this area and thus changes in travel time occur mostly in the horizontal dimension. Using $^3H/^3He$ apparent ages for each cluster, the average age difference between the clusters was determined to be 30 ± 14 years, which is similar to CFC-12 apparent age gradients reported in Masbruch et al. (2019). The distance between the clusters was determined to be 2,740 ± 460 m. The error in the distance includes uncertainty introduced by spatial variations within a cluster of samples from which discharge was calculated.

Assuming a porosity (θ) of 0.3, a typical value for polydisperse sands (Nimmo, 2004), the resulting specific discharge (q) is 27 ± 14 m/yr using the $^{3}H/^{3}He$ apparent ages. Using an aquifer width of 1,500 m and thickness of 30 m, the resulting volumetric discharge estimate (ET plus subsurface outflow to the Colorado River) is approximately 1.2 x 10^{6} ± 1.2 x 10^{5} m^{3}/yr (1,000 ± 100 acre-ft/yr), using the $^{3}H/^{3}He$ apparent ages.[2] Adding this to the measured 3-year average gain in Lower Mill Creek of 1.9 x 10^{6} m^{3}/yr (1,600 acre-ft/yr) results in a total VFA discharge of 3.1 x 10^{6} m^{3}/yr (2,600 acre-ft/yr), which is much less than the 13.6 x 10^{6} m^{3}/yr (11,000 acre-ft per year) estimated by Sumsion (1971).

4.4 Revised Conceptual Model and Groundwater Budget

The environmental tracers combined with physical flow measurements in streams and springs lead to a revised conceptual model and quantitative water budget. The original conceptual model of Sumsion (1971) assumed that all VFA groundwater was derived from subsurface inflow of DGCGA water. For that reason, the water budget for the DGCGA was estimated by calculating groundwater flow in the VFA using Darcy's Law. It also assumed that the shallower and deeper parts of the GCGA are hydraulically connected, which new evidence points to as being unlikely in the lower-altitude GCGA outcrop area (Sand Flats area). Furthermore, the original conceptual model left open the possibility that significant ungauged discharge from the DGCGA was occurring directly into the Colorado River and hence there was

[2] Note that two of the samples (U4 and U13; Table 1) in the downgradient cluster 2 used in the calculation of specific discharge for the age-gradient method are classified as mixtures of modern and pre-modern water. This is due to a small measured amount of terrigenic ^{4}He in the samples that precludes them from begin classified as all modern according to the previously presented criteria for classifying age categories. This terrigenic ^{4}He is not likely sourced from old water, but rather by upward diffusion from Paradox Formation brines known to underlie the lower end of the valley and to contain elevated dissolved 4He (Gardner, 2004). If these waters do contain a fraction of old water, the resulting velocity use in the calculation would be lower, resulting less discharge. Thus, this calculation represents a conservative estimate.

a potential of "undeveloped" water from a resource point of view. The revised conceptual model showing regional flow (such as reported by Pacheco and Van der Weijden, 2014) in the DGCGA is illustrated in Figure 10; this regional flow is ultimately captured by well withdrawals in Moab-Spanish Valley screened deeper in the Glen Canyon Group. This revised conceptual model also indicates the presence of local to intermediate flow systems (not shown in Figure 10), as reported by Pacheco and Van der Weijden (2014). Local flow systems are indicated by mid-elevation recharge to the SGCGA and VFA moving along shallow flow paths and discharging into Mill Creek and Pack Creek to the east and northeast, respectively, of Spanish Valley; intermediate flow systems are indicated by higher-elevation recharge that discharges to DGCGA springs along the margins of Spanish Valley. No evidence exists for longer (older and deeper) flow paths that discharge water sourced from outside of the catchment boundaries, despite extensive sampling and searching for such water. We deem an outside source of water to be unlikely because: (1) the regional topographic high is located within the catchment, and (2) such water would be forced to discharge near the Colorado River because brines and Paradox Formation form an effective bottom to the active flow system, yet no such discharge has been observed.

The combined total groundwater budget for the VFA and GCGA (both SGCGA and DGSGA) and including the Grandstaff Canyon drainage is estimated to be about 18 X 10^6 m^3/yr (15,000 acre-ft/yr), based on measured discharge and calculated subsurface outflow to the Colorado River. Based on stable-isotope evidence described above, recharge to the SGCGA is assumed to occur in the mid-altitude benches along the eastern front of the La Sal Mountains (2,100 – 2,750 m) with lesser amounts occurring to the lower- altitude sandstone outcrop area in Sand Flats (1,400 – 1,700 m) (Fig. 1); as discussed above, estimated discharge from the SGCGA occurs as gain in upper Mill Creek above the contact with the VFA (including diversions to Ken's Lake), along with flow in Grandstaff and Ice Box Creeks. Recharge to the DGCGA is assumed to occur above 2,750 m within the La Sal Mountains; discharge from the DGCGA includes springs on the western margin of Spanish Valley and municipal wells screened in the GCGA.

5 Lumped Parameter Model

Future water development in Spanish Valley is likely to target the high-quality water from the DGCGA. As stated above, the current estimate of total DGCGA discharge is 4.4 X 10^6 m^3/yr (3,600 acre-ft/yr). To evaluate the possibility of additional (as of yet undiscovered) DGCGA discharge, such as seeps directly into the Colorado River or its riparian zone, we independently estimated recharge to the DGCGA using environmental tracers to constrain a lumped parameter model (LPM) of groundwater age (Maloszewski and Zuber, 1996; Cook and Böhlke, 2000). Lumped parameter models are powerful in that they relate the fundamental definition of groundwater age (storage volume divided by recharge rate equals mean transit time (MTT)) to the aquifer dimensions and groundwater age distribution. The difficulty implementing lumped parameter models at many sites is that the MTT-recharge relationship depends on the aquifer-wide transit time distribution, which in general is not known. However, the conceptual model developed in this study strongly indicates the transit time distribution can be represented by an exponential piston model (EPM) as shown in Figure 10, with recharge to the DGCGA only occurring at high altitude. The aquifer-wide age distribution can then be defined by the aquifer dimensions and MTT of all groundwater flow paths discharging from the down-gradient boundary of the aquifer. For an EPM, the relationship between the recharge rate and MTT is given by equation 3 (Cook and Böhlke, 2000):

$$\tau = \frac{L\theta(1+x_{con}/x)}{R}, \qquad (3)$$

where τ is the mean transit time;

L is the aquifer thickness;

θ is the porosity;

R is the recharge rate (applicable to the portion defined by x);

x_{con} is the confined portion of the aquifer that receives no recharge;

x is the portion of the aquifer that receives recharge at a rate of R.

Stable isotope values from the DGCGA indicate that only high-altitude precipitation is recharging this part of the aquifer. Accordingly, we have constrained the recharge area in the LPM to approximately 45 km^2 including the Brumley Creek, Mill Creek, and North Fork Mill Creek drainages in the La Sal Mountains bounded by the drainage divide on the north, east, and south, and the 2,750 m altitude contour on the west (Fig. 10).

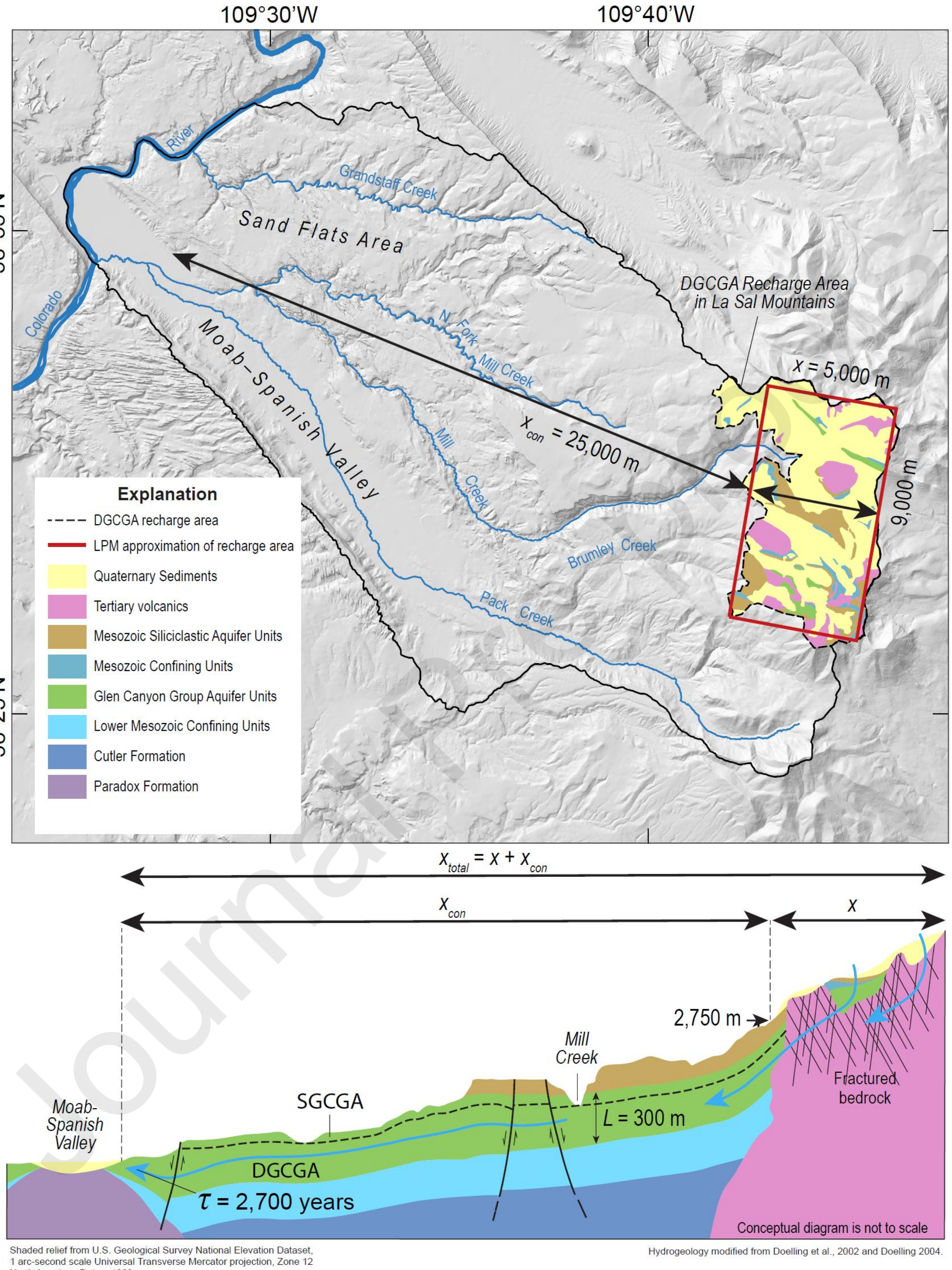

Figure 10. Map view and cross-section illustrating the conceptual model of groundwater recharge and flow through the Deep Glen Canyon Group Aquifer (DGCGA) and parameters used in the lumped parameter model estimate of DGCGA recharge.

Evaluation of surface geology mapped by Doelling (2004) of the region above the 2,750 m altitude contour shows five generalized hydrogeologic units. These are geologic formations that comprise the GCGA (permeable sandstones of the Glen Canyon Group Formation), other sandstone aquifer units, alluvial material (alluvium, colluvium, fanglomerates), Tertiary volcanics, and confining units. The potential recharge area can be approximated by a rectangle of dimensions 5,000 m by 9,000 m; however, about 30% of this area is underlain by undifferentiated Mesozoic confining units (Fig. 10). Accordingly, we relate the recharge area (A) to the value x in Eq. (3) as: $A = 0.7x(9/5)x$ ($A=1.26x^2$), where our geologic-based estimate of x is 5,000 m. Total recharge (Q) is simply $R*A$. We define the total distance from the drainage divide to where most DGCGA springs are located (the edge of the VFA) as $x_{total} = x_{con} + x$. Substituting into Eq. (3) and solving for Q we have:

$$Q = \frac{1.26 L \theta x_{total} x}{\tau}, \tag{4}$$

The parameters L, θ, x, and τ in Eq. 4 are moderately uncertain, which leads to uncertainty in Q. If we assume that each of these parameters is statistically independent (i.e., not correlated with each other), then the uncertainty in Q can be approximated by:

$$\sigma_Q = \overline{Q}\sqrt{\left(\frac{\sigma_L}{\overline{L}}\right)^2 + \left(\frac{\sigma_\theta}{\overline{\theta}}\right)^2 + \left(\frac{\sigma_x}{\overline{x}}\right)^2 + \left(\frac{\sigma_\tau}{\overline{\tau}}\right)^2 + \left(\frac{\sigma_{x_{total}}}{\overline{x_{total}}}\right)^2}, \tag{5}$$

where σ is the standard deviation and the overbars signify mean values.

The average of corrected ^{14}C ages of water that has the isotopic signature of the DGCGA is 2,700 ± 700 years (sites 1, 4, 6, 8, 11, and 19 in Table 1), and we assume that this is representative of the MTT (τ) in the DGCGA. Using this age with our best estimate for L, θ, x_{total}, and x, along with uncertainty values (as 1-sigma standard deviations) shown in Table 3, we estimate the average annual recharge to the DGCGA to be 4.2 X 10^6 ± 2.3 X 10^6 m^3/yr (3,400 ± 1,800 acre-ft/yr). This value is similar to the measured discharge of 4.4 X 10^6 m^3/yr (3,600 acre-ft/yr), leading us to conclude that it is unlikely that significant quantities of undiscovered DGCGA water exist. In other words, if recharge to the deeper part of the GCGA were significantly higher or if the area over which recharge occurs were significantly greater, then water discharging from this source would be notably younger than what we observe. Furthermore, if unsampled DGCGA does exist, it is likely to be older which would increase the MTT in Equation 4, resulting in a reduced estimate of Q.

Table 3. Parameters used to estimate recharge in a lumped parameter model.

Parameter	Value	1σ-uncertainty
L	300 m	50 m
θ	0.2	0.05
x_{total}	30,000 m	3,400 m
x	5,000 m	1,700 m
τ	2,700 yr	700 yr

6 Conclusions

The use of geochemistry and environmental tracers provided critical information for the revision and refining of the conceptual groundwater model in the Moab-Spanish Valley area. Specific findings include: (1) recharge to the deeper part of the Glen Canyon Group Aquifer occurs only at high altitudes in the La Sal Mountains; (2) recharge to the shallower (and possibly perched) part of the Glen Canyon Group Aquifer likely occurs at middle altitudes along the mountain front, with relatively small amounts as infiltration of precipitation at the lower-altitude Sand Flats area (infiltration to the deeper part of the Glen Canyon Group Aquifer is likely impeded by a low-permeability layer); (3) recharge to the Valley Fill Aquifer occurs from subsurface groundwater inflow from the upper Pack Creek Drainage and loss from Pack Creek; (4) subsurface outflow from lower Moab-Spanish Valley to the Colorado River was greatly constrained (reduced) and shown to be a small amount, based on the thin freshwater thickness found at new boreholes in the wetlands, along with Darcy flux calculations using differences in groundwater age along a flow path; and (5) the overall groundwater budget is much less than previous estimates, informed by additional groundwater discharge data, improved Darcy-flux calculations using additional geochemical tracer data, and new lumped parameter modeling using additional groundwater dating tools.

The use of a combination of environmental tracers and groundwater geochemistry has been shown here to significantly improve our understanding of groundwater availability in a desert environment where water resources are scarce. For this study, tracers and geochemistry suggested that a previous estimate of groundwater discharge to the Colorado River was based on incorrect assumptions about the source of water entering the Valley Fill Aquifer of Moab-Spanish Valley and subsequently discharging to the river. This study is an example of a scenario in which building a water budget based on a conceptual model formed solely from available physical aquifer properties led to a mischaracterization of the flow system and ultimately an overestimated groundwater budget. The new estimate of the total groundwater budget is about 18 X 10^6 m^3/yr (15,000 acre-ft/yr, rounded), with about 3.1 X 10^6 m^3/yr (2,500 acre-ft/yr) discharging from the Valley Fill Aquifer (VFA), 10.6 X 10^6 m^3/yr (8,600 acre-ft/yr) discharging from the Shallow Glen Canyon Group Aquifer (SGCGA), and 4.4 X 10^6 m^3/yr (3,600 acre-ft/yr) discharging from the Deep Glen Canyon Group Aquifer (DGCGA). Groundwater from the DGCGA is the likely target for future water resources development in Moab-Spanish Valley. Our analysis indicates that additional withdrawals from this aquifer would likely deplete storage and not be sustained by recharge.

This study shows how a multiple-faceted approach using geochemical tracers and groundwater discharge measurements can be used to improve water budget estimates for an important aquifer in a desert environment where drinking water supplies are stressed. An important first step in improving the groundwater budget was refinement of the conceptual model in the study area. Previous conceptual models of the area suggested there was more recharge and water available for human use than was found in this study. Testing and rethinking groundwater systems in light of new geochemical tracers and additional hydrologic data is an important task for contemporary hydrogeologists.

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Highlights:

- Sustainable management depends on accurate concepts and water budgets.
- Tracers and geochemistry yield conceptual revision of vital groundwater resource.
- Water-budget estimates verified using lumped-parameter model of groundwater age.