SUMMARY OF GROUNDWATER STUDIES OF THE GREAT BASIN, DEATH VALLEY REGIONAL FLOW SYSTEM, AND YUCCA MOUNTAIN AREA

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ABSTRACT

Since the last U.S. Nuclear Regulatory Commission (NRC) knowledge management report on the groundwater flow systems of the Yucca Mountain region was completed in 2011 (Winterle and Gergen, 2011), State and Federal agencies have performed a number of investigations of the regional and local hydrogeologic settings of Death Valley, central and eastern Nevada, and western Utah, which include the Nevada National Security Site and Yucca Mountain, Nevada. These investigations were conducted to address environmental problems and the increased demand for groundwater. In addition, hydrologists have continued to evaluate and quantify the occurrence and rates of groundwater flow between the internally drained watersheds of the Great Basin. These hydrologists have integrated hydrogeologic data from the Great Basin regional carbonate aquifer with more recent meteorologic data and higher resolution hydrometeorologic models to refine the understanding of the regional groundwater flow system. The reports reviewed here include investigations, analyses, and modeling studies that the NRC staff directly consulted during preparation of the Supplement to the Yucca Mountain Environmental Impact Statement (SEIS) and other studies that were referenced by these investigations, analyses, and modeling studies. The saturated zone domains pertinent to the SEIS include (from largest to smallest areal extent) the Great Basin Carbonate and Alluvial Aquifer System (GBCAAS), the Death Valley Regional Groundwater Flow System (DVRFS), especially the Fortymile Canyon, Amargosa River, Crater Flat, and Funeral Mountains sections of the Alkali Flat-Furnace Creek groundwater basin in the DVRFS, and the saturated zone site-scale flow model for Yucca Mountain. The saturated zone site-scale flow model for Yucca Mountain includes the area from north of Yucca Mountain to just south of the 18-km compliance boundary near the town of Amargosa Valley.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data. No original data were generated or presented in this report.

1 INTRODUCTION

This report contains summaries of selected documents on conceptual and numerical groundwater flow models for the Great Basin hydrographic province, Basin and Range physiographic province, Death Valley Regional Groundwater Flow System, and Yucca Mountain areas. The reports reviewed here include investigations, analyses, and modeling studies that the U.S. Nuclear Regulatory Commission (NRC) staff directly consulted during preparation of the Supplement to the Yucca Mountain Environmental Impact Statement (SEIS) (NRC, 2016) and other studies that were referenced by these investigations, analyses, and modeling studies. The NRC and Center for Nuclear Waste Regulatory Analyses (CNWRA®) staffs previously have not prepared written reviews of these documents. This report extends the summary reports prepared by Winterle and Gergen (2011) and Wittmeyer and Turner (1995). The saturated zone domains relevant to the SEIS include (from largest to smallest areal extent) the Great Basin Carbonate and Alluvial Aquifer System (GBCAAS), the Death Valley Regional Groundwater Flow System (DVRFS), especially the Fortymile Canyon, Amargosa River, Crater Flat, and Funeral Mountains sections of the Alkali Flat-Furnace Creek groundwater basin in the DVRFS, and the saturated zone site-scale flow model for Yucca Mountain.

Since the last NRC knowledge management report on the groundwater systems of the Yucca Mountain was completed in 2011 (Winterle and Gergen, 2011), State and Federal agencies have conducted a number of investigations of the hydrogeological setting for the Yucca Mountain area to address environmental and water resource problems. Rapid population increase has resulted in growing demand for municipal and industrial water in the major Great Basin population centers, including the Las Vegas-Henderson, Nevada and Salt Lake City-Provo-Orem, Utah combined statistical areas. Rapid population growth has in turn increased the region’s dependence on groundwater. Because of the region’s large areal extent, scant surface water resources, and increasing reliance on groundwater, the U.S. Geological Survey (USGS) recently undertook a comprehensive hydrogeological investigation of the GBCAAS under the National Water Census Initiative [Heilweil and Brooks (2011), Brooks et al. (2014)]. The steady state numerical model of the GBCAAS was reviewed by NRC staff to support development of the SEIS (NRC, 2016). The GBCAAS investigation incorporates the improved understanding of hydrologic processes controlling regional-scale groundwater flow within the carbonate province of the Great Basin that was gained through the Yucca Mountain program. Accordingly, a significant portion of this report is devoted to the GBCAAS investigation, particularly the conceptual model of the GBCAAS developed by Heilweil and Brooks (2011).

2 INVESTIGATIONS INTO THE HYDROLOGY OF THE GREAT BASIN, THE DEATH VALLEY REGION, AND THE YUCCA MOUNTAIN SUB-REGION

2.1 Heilweil and Brooks (2011)

2.1.1 Introduction

Heilwell and Brooks (2011) are co-editors and co-authors of a U.S. Geological Survey (USGS) scientific investigations report on the Great Basin Carbonate and Alluvial Aquifer System (GBCAAS). This report consists of separately authored chapters on the three-dimensional hydrogeologic framework, groundwater movement and geologic controls that affect groundwater movement, and groundwater budget studies used to develop estimates of the rate and nature of recharge and discharge. Heilweil and Brooks (2011), together with its companion report on a new steady-state groundwater flow model for the GBCAAS (Brooks et al., 2014), represent a revision to the Regional Aquifer System Analysis (RASA) of the Great-Basin Carbonate-Rock Aquifer System (GBCRA-RASA) by Prudic et al. (1995). In part, the GBCRA-RASA study has been revised because numerous comprehensive groundwater investigations have been conducted during the past 20 years, most supporting either the Yucca Mountain Program (YMP) or the Environmental Restoration Program for the Nevada National Security Site (NNSS), which have significantly improved understanding of the stratigraphy and structural geology of the region. The more detailed description of the regional hydrostratigraphy and identification of flow-affecting structural features, along with the availability of more rigorous scientific methods and improved data collection techniques for estimating regional patterns of evapotranspiration (ET), recharge, and runoff, allow the construction of higher fidelity and ostensibly more accurate flow models. Although advances in hydrologic methods have made it possible to improve the model, the continued increase in demand for municipal and industrial water supply within the GBCAAS region has provided the impetus for studying the GBCAAS under the USGS's National Water Census Initiative.

2.1.2 General Description of GBCAAS

The GBCAAS area covers the eastern two-thirds of the Great Basin, including most of central and eastern Nevada, western Utah, portions of southeastern California and southeastern Idaho, and the far northwest corner of Arizona. Figure 2-1 shows the boundary of the GBCAAS study area, as well as the locations boundary of the area studied in the GBCRA-RASA investigation by Prudic et al. (1995) and the boundaries for several regional-scale groundwater investigations. The GBCAAS region covers 285,000 km^2 (110,000 mi^2), whereas the Great Basin study area (Harrill and Prudic, 1998) covers 363,000 km^2 (140,000 mi^2) and the GBCRA-RASA numerical flow model (Prudic et al., 1995) covers 259,000 km^2 (100,000 mi^2). Like the GBCAAS studies, the GBCRA-RASA groundwater flow model focuses on the carbonate-rock province of the Great Basin groundwater system, which covers the eastern two-thirds of the Great Basin.

2.1.3 Hydrogeologic Framework for GBCAAS

Sweetkind et al. (2011a) provide a thorough description of the new hydrogeologic framework model developed for the GBCAAS conceptual model. As in previous studies of the Great Basin hydrogeologic province, the geologic units of the region are divided into laterally extensive hydrogeologic units (HGUs) based on distinct differences in hydraulic properties that result from major changes in lithology and the effects of structural deformation on hydraulic

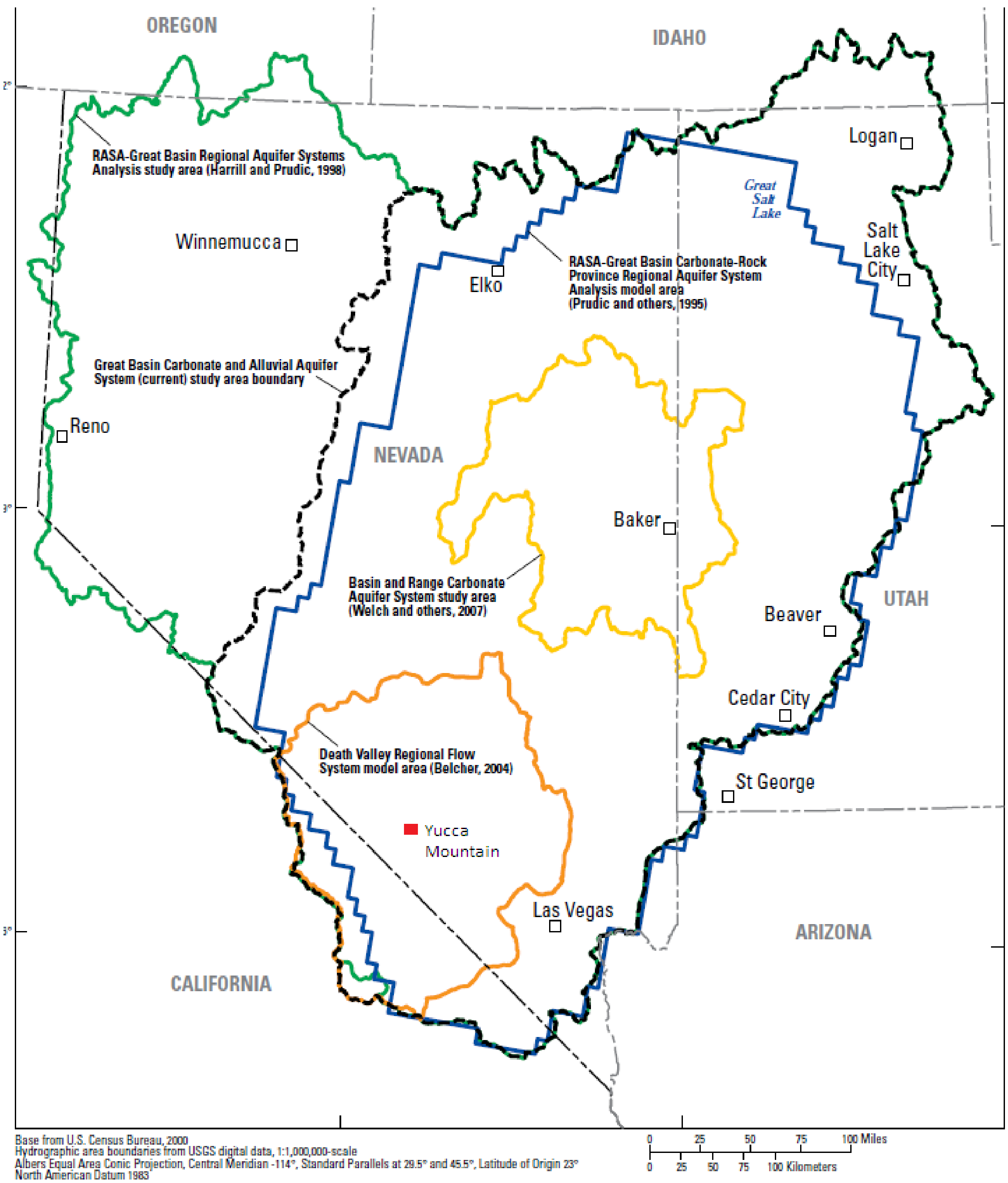

Figure 2-1. Boundaries of regional groundwater flow models for the Great Basin, Nevada, Utah, California, Idaho, and Arizona. [Electronically reproduced from Figure A-2 of Heilweil and Brooks (2011).]

compartmentation within the hydrostratigraphic column. To the extent possible, Sweetkind et al. (2011a) adopted the practice of most hydrologists investigating the Death Valley Regional Flow System (DVRFS) and retained the pre-Cenozoic HGUs first described in Winograd and Thordarson (1975) for the hydrogeology of the NNSS. The GBCAAS hydrogeologic framework model consists of nine HGUs, of which six define the pre-Cenozoic consolidated units and three define the Cenozoic basin deposits and volcanic units. Table 2-1 lists the names, abbreviations, and geologic periods for the nine HGUs. In addition, the last column in Table 2-1 shows the stratigraphic column for the DVRFS in the southwestern portion of GBCAAS where the NNSS and Yucca Mountain are located. Sweetkind et al. (2011a, Figure B-2) provides stratigraphic columns for the four other major regions of the GBCAAS.

The Non-Carbonate Confining Unit (NCCU) comprises pre-Cambrian siliciclastic formations, the Lower Carbonate Aquifer Unit (LCAU) consists of Cambrian to Devonian limestone and dolomite, the Upper Siliciclastic Confining Unit (USCU) is composed of Mississippian shale, and the Upper Carbonate Aquifer Unit (UCAU) comprises Pennsylvanian to Permian carbonate rocks. The Thrusted Non-Carbonate Confining Unit (TNCCU) and Thrusted Lower Carbonate Aquifer Unit (TLCAU) reflect incorporation of NCCU and LCAU into regional thrust faults from the late-Devonian to Mississippian Antler orogeny (Roberts Mountain thrust belt) and the late-Jurassic to Eocene Sevier orogeny, respectively. The Volcanic Unit (VU) comprises Eocene to mid-Miocene welded to non-welded tuff units of rhyolite-to-andesite composition, basalts, and lava flows. The Lower Basin-Fill Aquifer Unit (LBFAU) and the Upper Basin-Fill Aquifer Unit (UBFAU) represent the lower one-third and upper two-thirds of the Cenozoic valley fill aquifer, respectively.

Across the GBCAAS, there are significant lateral changes in grain size, lithology, degree of fracturing, and extent of karstification within the HGUs that, when combined with the diverse effects of structural deformation, result in significant lateral variations in the vertically averaged permeability across each HGU. Sweetkind et al. (2011a) represent this lateral variation in permeability by dividing each HGU into several hydrogeologic zones.

Based on summary statistics presented by Sweetkind et al. (2011a, Table B-1) for hydraulic conductivity data and the descriptions of the HGUs and hydrogeologic zones, the author determined that “low permeability” HGUs and hydrogeologic zones have permeability values that are between 10^{-15} to 10^{-13} m^2 [1 and 100 millidarcy (md)], those identified as “moderate permeability” units are between 10^{-13} to 10^{-11} m^2 (100 and 10,000 md), while the “high permeability” HGUs and hydrogeologic zones are between 10^{-11} and 10^{-9} m^2 (10,000 and 1,000,000 md). A porous medium with an intrinsic permeability of 10^{-12} m^2 (1 darcy or 1,000 md) saturated with water at 25° C (77° F) has a hydraulic conductivity of approximately 10^{-5} m/s (3 ft/day).

Within the GBCAAS, the NCCU generally has low to moderate permeability, depending on the predominant lithology and the extent of fracturing. The NCCU is divided into three laterally distributed hydrogeologic zones: (i) late Proterozoic clastic rocks with fairly well-developed fracture patterns that have moderate permeability; (ii) foliated metamorphic rocks that have low permeability; and (iii) intrusive igneous rocks with low to moderate fracture permeability that generally deceases with depth.

The moderate to high permeability LCAU is a massive regional-scale aquifer divided into three hydrogeologic zones: (i) carbonate rock deposited in shallow water that has high primary permeability; (ii) shale and other siliciclastic rocks of the Pilot Basin in the central section of the GBCAAS that have moderate to high permeability; and (iii) deep-water marine carbonates along the northwestern portion of the GBCAAS that have moderate permeability due to muddy carbonates and shale interbeds.

Table 2-1. Hydrogeologic units defined for Great Basin carbonate and alluvial aquifer system conceptual model (Sweetkind et al., 2011a).			
Hydrogeologic Unit	**Abbreviation**	**Geologic Periods**	**Stratigraphic Column Death Valley Regional Flow System**
Upper Basin Fill Aquifer Unit	UBFAU	Quaternary	Basin-fill deposits Basalt
Lower Basin Fill Aquifer Unit	LBFAU	Late Tertiary	Titus Canyon Formation
Volcanic Unit	VU	Early Tertiary	Volcanic rock
Thrusted Lower Carbonate Aquifer Unit	TLCAU	Cambrian to Permian	Thrusted rocks of the Sevier fold and thrust belt
Thrusted Non-Carbonate Confining Unit	TNCCU	Pre-Cambrian	Thrusted rocks of the Sevier fold and thrust belt
Upper Carbonate Aquifer Unit	UCAU	Pennsylvanian to Permian	Tippipah Limestone
Upper Siliciclastic Confining Unit	USCU	Mississippian	Eleana formation Chainman Shale
Lower Carbonate Aquifer Unit	LCAU	Cambrian to Devonian	Sultan Limestone Simonson Dolomite Sevy Dolomite Eureka Quartzite Pogonip Group Nopah Formation Bonanza King Formation
Non-Carbonate Confining Unit	NCCU	Pre-Cambrian	Zabriskie Quartzite Wood Canyon Formation Stirling Quartzite Johnnie Formation Noonday Dolomite

The USCU consists of mudstone, siltstone, sandstone, and conglomerate. The fine-grained units of the USCU have low primary permeability. These units have not developed significant secondary permeability, because they are not susceptible to fracturing or dissolution.

The UCAU is divided into five hydrogeologic zones: (i) high permeability, highly fractured shallow-water marine carbonates that dominate the central two-thirds of the GBCAAS; (ii) moderate to high permeability fractured silty carbonate rocks of the Oquirrh Basin in the northeastern portion of the GBCAAS; (iii) moderate permeability siliciclastic rocks of the Colorado Plateau along the eastern margin of the GBCAAS; (iv) low to moderate permeability deep-water shaley carbonates along the western margin of the GBCAAS; and (v) a low to moderate permeability zone of pre-volcanic Cenozoic rocks in the Death Valley region added for model compatibility.

The TNCCU comprises all of the low to moderate permeability siliciclastic units of the NCCU that are repeated in the hydrostratigraphic column because of large-displacement thrust faults in the Sevier fold-and-thrust belt and the Roberts Mountain thrust belt. The TNCCU occurs in the northwestern portion of the GBCAAS and the Las Vegas Valley shear zone, which is a major strike-slip fault zone of the Walker Lane Belt. The Las Vegas Valley shear zone, which extends from east of the southern end of the Sheep Range west-northwest to Mercury Valley, truncates the southern extent of the TLCAU. The TLCAU comprises all of the units in the LCAU, USCU, and UCAU that are repeated in the hydrostratigraphic column because of large-displacement thrust faults in the Sevier fold-and-thrust belt. The TLCAU occurs only in the area immediately to the north of the Las Vegas Valley shear zone.

The VU is divided into seven hydrogeologic zones: (i) high permeability welded ash flow tuffs with generally well-developed fracture systems; (ii) moderate to high permeability local lava flows; (iii) moderate permeability pre-volcanic basins where transmissive sedimentary units underlie the local volcanic outcrops; (iv) moderate permeability shallow basalts; (v) low to moderate permeability Mesozoic and Cenozoic sedimentary rock combined with volcanic rock; (vi) low to moderate permeability tuff, lava flows, and sedimentary rocks in the California section of the Death Valley region; and (vii) moderate permeability volcanic rocks related to caldera collapse.

The LBFAU is divided into five hydrogeologic zones: (i) high permeability fractured welded ash flow tuffs; (ii) moderate permeability ash flow tuffs and other diverse volcanic rocks within calderas; (iii) moderate to high permeability local lava flows; (iv) moderate permeability Cenozoic sedimentary rocks; and (v) moderate permeability coarse-grained valley fill deposits that are partially indurated.

The UBFAU is divided into four hydrogeologic zones: (i) moderate permeability near-surface basalt flows; (ii) low to moderate permeability sediments in the upper two-thirds of the basin fill consisting of fine-grained lake deposits and altered tuff deposits; (iii) low to moderate permeability fined-grained Pleistocene lake and playa deposits; and (iv) moderate permeability alluvial sands and gravels.

2.1.4 Representation of Flow-Affecting Structural Features

In addition to defining the TNCCU and the TLCAU HGUs to account for the regional and local hydrogeologic effects of late Devonian to Eocene compressional deformation, Sweetkind et al. (2011a) define five hydrogeologic zones across the GBCAAS to capture the hydrogeologic effects of Neogene extension and strike-slip faulting. The five hydrogeologic zones associated with Basin and Range extension include (i) greatly extended regions where the LCAU and UCAU are disrupted by faulting and thinning; (ii) less extended regions whose primary permeability and secondary permeability from dissolution features and fractures are unaffected by deformation; (iii) active seismic areas along the eastern portion of the GBCAAS where the permeability in the rupture zones is increased; (iv) regions associated with Oligocene to Miocene volcanic calderas where contact metamorphism may reduce the permeability of the LCAU and UCAU; and (v) an area of increased permeability in the Las Vegas valley shear zone that is not associated with significant faulting.

Although not explicitly enumerated by Sweetkind et al. (2011a), the author estimates that approximately 150 major fault zones are incorporated into the hydrogeologic framework model for the GBCAAS. The GBCAAS encloses 165 hydrographic areas (HA), which are topographically closed basins whose boundaries generally coincide with the ridges of north-trending mountain blocks separated by intervening alluvium-filled valleys. Each up-thrown mountain block (range) and down-thrown valley (basin) in the Basin and Range typically is associated with one or more major normal faults caused by regional crustal extension. Sweetkind et al. (2011a) used existing geologic cross-sections for the Great Basin to establish the relative position of HGUs across each major mapped fault. From a hydraulic standpoint, the most significant effect of extensional faulting occurs where the LCAU and UCAU are juxtaposed with the NCCU and USCU, impeding the flow of water within the regional carbonate aquifer system. Large volcanic centers also disrupt the continuity of the regional carbonate system and impede the regional flow system.

2.1.5 General Groundwater Flow Patterns Inferred From the Regional Potentiometric Surface and Hydrostratigraphy

Sweetkind et al. (2011b) analyzed the updated potentiometric surface within the context of the revised hydrostratigraphic model to determine whether the boundaries of the 17 regional groundwater flow systems within the GBCAAS required modification. Harrill et al. (1988) defined a "major flow system" for the Great Basin as a "…local, intermediate, or regional system…that conveys the largest percentage of flow in the area." Major flow systems consist of a terminal discharge area, such as a playa or lake, and the area(s) that contribute water to the system. Thus, a major flow system could be a single hydrologically closed HA. However, most of the major flow systems in the carbonate province comprise multiple HAs and are hydraulically connected by a river or by intermediate and regional groundwater pathways as defined by Toth (1963) and Freeze and Witherspoon (1967). Prudic et al. (1995) evaluated fluxes in the deepest layer of their MODFLOW-based GBCRA-RASA groundwater flow model and defined 17 deep flow subregions that discharge either to the five major discharge areas (Death Valley, the Colorado River, the upper Humboldt River, Railroad Valley, and the Great Salt Lake/Great Salt Lake Desert) or to other, smaller, discharge areas in the carbonate province. Although the boundaries of the 17 deep flow subregions determined by Prudic et al. (1995) are not based on HA boundaries, they do roughly correspond to the 17 major flow systems identified by Harrill et al. (1988). For clarity, it is important to note that the 17 "regional groundwater flow systems" used by Sweetkind et al. (2011b) are identical to the 17 "deep flow subregions" defined by Prudic et al. (1995).

The water level control points used by Sweetkind et al. (2011b) to construct the GBCAAS potentiometric surface coincide with single wells or collections of wells depending on spatial density, the elevations of perennial springs, and the mean water surface elevations of perennial streams. Because there is little difference in hydraulic heads measured in the overlying alluvial basin fill and the underlying carbonate aquifer across most of the GBCAAS, the depths of the open intervals in wells were not considered in developing the potentiometric surface. The predominant flow direction is assumed to be horizontal, although there are clearly significant vertical gradients near recharge and discharge areas. Sweetkind et al. (2011b) note that in areas where there is low permeability volcanic rock, such as at well UE-25 P#1 near Yucca Mountain, large vertically upward driving forces exist between the underlying carbonate aquifer and the overlying basin fill. After eliminating duplicate well records and those well locations with vertical and horizontal control errors, Sweetkind et al. (2011b) used 13,795 water level measurements to define 6,444 water level control points. Land surface elevations for 395 springs and water surface elevations for 2,135 gauged perennial streams whose discharges exceed 1.9×10^{-2} m^3/s (300 gal/min) also were used to define the potentiometric surface. Sweetkind et al. (2011b) assumed that any stream or spring with a discharge less than 1.9×10^{-2} m^3/s (300 gal/min) represents local, perched groundwater systems.

Sweetkind et al. (2011b) note that the potentiometric surface and hydraulic gradients generally follow topography within the GBCAAS, but hydraulic gradients are smaller than topographic gradients. This observation by Sweetkind et al. (2011b) appears consistent with regions of the potentiometric surface map (Heilweil and Brooks, 2011, Plate 2) where orographic effects increase local precipitation and recharge at mountain ranges; however, it seems unlikely that Sweetkind et al. (2011b) mean to suggest that GBCAAS as a whole is a topography-controlled groundwater flow system as defined by Haitjema and Mitchell-Bruker (2005) and Gleeson et al. (2011) or as illustrated in the classic regional groundwater modeling studies by Toth (1963) and Freeze and Witherspoon (1967).

Mathematical and data analyses conducted by Haitjema and Mitchell-Bruker (2005) and Gleeson et al. (2011) indicate that topography-controlled water tables, where the water table is a subdued replica of topography and groundwater mounding is evident below topographic highs, occur only where areal recharge is large relative to hydraulic conductivity, and topographic relief is low. These are conditions that do not prevail across the GBCAAS. Gleeson et al. (2011) constructed a water table classification map for the contiguous United States using topographic and hydrologic data for the smallest watersheds identified under the USGS Hydrologic Unit Code (HUC) system. These HUC-12 watersheds, which are coded using a 12-digit number, have an average area of 100 km^2. Water-table classification was based on the water-table ratio (WTR) derived by Haitjema and Mitchell-Bruker (2005) from the analytical solution to the Dupuit-Forchheimer approximation for vertically averaged horizontal flow in an unconfined flow aquifer. The water-table ratio, which is the ratio of the maximum water table rise to the maximum terrain rise, is,

$$WTR = \frac{RL^2}{mKHd} = \begin{cases} > 1 \text{ for topography controlled} \\ < 1 \text{ for recharge controlled} \end{cases}, \tag{2.1}$$

where R is the areal recharge rate, L is the distance between surface water bodies, m is 8 for one-dimensional flow and 16 for radially symmetric flow, K is the hydraulic conductivity, H is the average vertical extent of the groundwater flow system, and d is the maximum terrain rise. Unsurprisingly, a map of the logarithm of WTR for the contiguous United States (Figure 2 in Gleeson et al., 2011) shows that topography-controlled water tables are found in humid regions (high recharge) with low topographic relief (d is small) and relatively low hydraulic conductivity, while recharge-controlled water tables are found in arid (low recharge) mountainous regions (d is large) that have relatively high hydraulic conductivity. Figure 2 in Gleeson et al. (2011) also indicates that WTR is spatially consistent and continuous at scales that are considerably greater than the areal extent of the HUC-12 watersheds used for mapping. Figure 2 in Gleeson et al. (2011) also shows that water tables in the arid to semi-arid Great Basin, Southwest, and High Plains are predominantly recharge controlled, while water tables in the humid Northeast and Piedmont are primarily topography controlled. Perhaps most importantly for the arid to semi-arid GBCAAS region, analysis by Gleeson et al. (2011) shows that hydrologic provinces whose water tables are recharge controlled are likely to form extensive, regional groundwater flow systems, while hydrologic provinces whose water tables are truly topography controlled are unlikely to form regional groundwater flow systems.

Sweetkind et al. (2011b) determined the potential for groundwater to flow across the boundary or a segment of the boundary between adjacent HAs based on the shape of the local potentiometric surface and the likelihood of a hydraulic connection. Sweetkind et al. (2001b, Table C-2) lists the 14 combinations of hydrogeologic and structural geologic criteria used to determine the likelihood of hydraulic connection between HAs. Heilweil and Brooks (2011, Plate 2) show the likelihood of a hydraulic connection between adjacent HAs. At boundaries between HAs where the likelihood of a hydraulic connection is low because of the low transmissivity (product of saturated thickness and hydraulic conductivity) of the HGUs, Sweetkind et al. (2011b) assume no flow between HAs. Where there is a groundwater potentiometric high due to mounding of recharge and the potential for a hydraulic connection across the HA boundary is strong because of the presence of high transmissivity HGUs, there also is no flow between HAs. However, in this second case, it is the hydraulic divide created by the recharge mound that prevents flow between HAs. Significant flow between HAs is presumed by Sweetkind et al. (2011b) to occur only at boundaries where groundwater mounding below the mountain block is not significant and the likelihood of a hydraulic connection is high (e.g., because both HGUs have high transmissivity). The latter situation occurs frequently at boundaries that both (i) represent surface water divides and (ii) do not coincide with a mountain range that is high enough and of sufficient areal extent to have a pronounced orographic effect on precipitation (i.e., recharge is not significantly increased). Throughout the GBCAAS, regional-scale groundwater flow through the carbonate aquifer and alluvial aquifer systems is diverted around large mountain ranges, such as the Ruby Mountains, the Snake Range, and Spring Mountains, by groundwater mounding from recharge.

Areas with low hydraulic gradients in the GBCAAS generally coincide with regions where high-permeability HGUs are thick, such as Sarcobatus Flat, Frenchman Flat, Penoyer Valley, Railroad Valley-Southern, and Amargosa Desert in the DVRFS. Steep hydraulic gradients occur in the DVRFS where low-permeability HGUs, such as the TNCCU and TLCAU, are present, and where there are large calderas, both of which occur north of Yucca Mountain in the Fortymile Canyon-Jackass Flats and Fortymile Canyon-Buckboard Mesa HAs. North of Yucca Mountain, where the Fortymile Canyon-Buckboard Mesa, Yucca Flat, Gold Flat, and Kawich Valley HAs meet, there are steep hydraulic gradients in all directions associated with groundwater mounding beneath Rainier Mesa. However, because of the poor hydraulic connection between Kawich Valley to the northwest and Emigrant Valley-Groom Lake and Yucca Flat to the southeast, much of the precipitation recharged at Rainier Mesa flows south-southwest, toward Yucca Mountain.

Strike-slip faulting along the Stateline fault system between the Amargosa Desert and Death Valley coincides with the presence of a steep hydraulic gradient along the northern two-thirds of the Funeral Range, and is believed to form a significant barrier to flow. Note, however, that groundwater from the Amargosa Desert also is believed by numerous investigators (e.g., Winograd and Eakin, 1965, Winograd and Thordarson, 1975, Bredehoeft et al., 2005, Belcher et al., 2009, Bredehoeft and King, 2010) to flow under the southern end of the Funeral Range through the carbonate aquifer to Death Valley, where it is discharged at several large springs.

2.1.6 Groundwater Budgets

Masbruch et al. (2011) provide an overview of the new conceptual and mathematical models used to estimate predevelopment groundwater budgets for each of the HAs in the GBCAAS. The new groundwater-budget estimates for each HA were subsequently used to develop groundwater budgets for each of the 17 regional groundwater flow systems.

Prior to the development of the DVRFS model described in Belcher and Sweetkind (2010), most large-scale hydrogeologic investigations of the Great Basin used the well-known Maxey-Eakin Method (Maxey and Eakin, 1949) to estimate recharge. The Maxey-Eakin Method was developed to enable the Nevada State Engineer to establish maximum groundwater pumping rates that can be sustained by each of the basin-fill aquifers in the Great Basin, which were assumed by Maxey and Eakin (1949) to be recharged primarily by runoff from the adjacent mountain ranges. For the HAs in the White River groundwater flow system, Maxey and Eakin (1949) estimated the fraction of average annual precipitation that must recharge the basin-fill aquifer in order to balance the measured or estimated annual volume of water lost through ET at the HA's springs and terminal playas. Because mean annual precipitation increases with elevation, while mean annual temperature and potential ET decrease with elevation, Maxey and Eakin (1949) hypothesized that the fraction of mean annual precipitation that runs off increases with increasing mean annual precipitation. They further assumed that runoff from the mountains infiltrates through alluvial stream channels and alluvial fans at the base of the mountains, where it recharges the basin-fill aquifer. Because the precipitation-dependent recharge percentages developed by Maxey and Eakin (1949) (Table 2-2) are based on the distribution of alluvium in their study area and the precipitation zones developed for Nevada by Hardman (1936), applications at other locations or the use of other precipitation maps require the recharge percentages to be recalibrated to match estimated basin discharge.

In part, because of the care that must be taken when applying the Maxey-Eakin Method when using newer precipitation data and updated estimates of basin discharge, Belcher and Sweetkind (2010) used a more robust physics-based approach to estimate recharge for each HA in the DVRFS. For the DVRFS, the distributed-parameter net infiltration model INFILv3 (Hevesi et al., 2003) was used to estimate potential recharge (in-place recharge) across the model domain. According to Belcher and Sweetkind (2010), "INFILv3 simulates surface-water flow, snowmelt, transpiration, and groundwater drainage in the root zone and has a climate algorithm that simulates daily climate conditions in local watersheds." Detailed spatial data for the topography, soils, and vegetation are used for each watershed. The fundamental water budget accounting model used in INFILv3 assumes that net infiltration is equal to the sum of snowmelt, precipitation, and infiltration from surface flow (runon), minus the sum of ET, runoff, and changes in soil moisture in the root zone. Using subsidiary models in INFILv3, each of the six components of the net infiltration balance equation is estimated for each cell of a digital elevation model (DEM) that has a resolution of 278.5 m (913.7 ft) in the north-south and east-west directions.

For the GBCAAS, Masbruch et al. (2011) used the spatially distributed Basin Characterization Model (BCM) developed by Flint and Flint (2007) to estimate two components of the water budget developed for each of the 165 HAs: (i) potential direct infiltration (R1) (i.e., in-place recharge); and (ii) potential recharge from runoff that is carried by perennial and ephemeral streams (R2). The water budget equation and each of its components are described and illustrated by Masbruch et al. (2011, Figure D-1), which is reproduced in Figure 2-2. In-place recharge (R1) can subsequently enter perennial and ephemeral mountain streams as baseflow (D1) from the shallow groundwater system before recharging the basin-fill aquifer (R2). Similar to INFILv3, BCM calculates in-place recharge, soil moisture, and runoff on a 270 m (890 ft) by 270 m (890 ft) grid cell using subsidiary mass and energy balance models to determine a local water balance. Available water is assumed to be equal to the sum of precipitation, snowmelt, and stored soil moisture, minus the sum of potential ET and snow accumulation. Figure 2-3 shows BCM-based estimates of mean annual in-place recharge for the GBCAAS.

The other six components (R3, R4, D2, D3, D4, and D5) of the water budget equation shown in Figure 2-2, which are not discussed in detail here, appear to have been extracted or estimated by Masbruch et al. (2011) from other technical reports and raw hydrologic data sources, then compiled and corrected so the pre-development water budget components reflect HA composite values. The GBCAAS study does not attempt to develop new estimates for subsurface flow (R4 and D5) between HAs or between the 17 major regional flow systems "…because of the uncertainty in groundwater budgets."

Table 2-2. Percentage of mean annual precipitation that recharges the basin-fill aquifer according to the Maxey-Eakin Method for the mean annual precipitation zones defined by Hardman	
Hardman Mean Annual Precipitation Zone	**Percentage of Mean Annual Precipitation that Recharges the Basin-Fill Aquifer**
MAP ≤ 203 mm (MAP ≤ 8 in)	0
203 mm < MAP ≤ 305 mm (8 in < MAP ≤ 12 in)	3
305 mm < MAP ≤ 381 mm (12 in < MAP ≤ 15 in)	7
381 mm < MAP ≤ 490 mm (15 in < MAP ≤ 20 in)	15
MAP > 490 mm (MAP > 20 in)	25

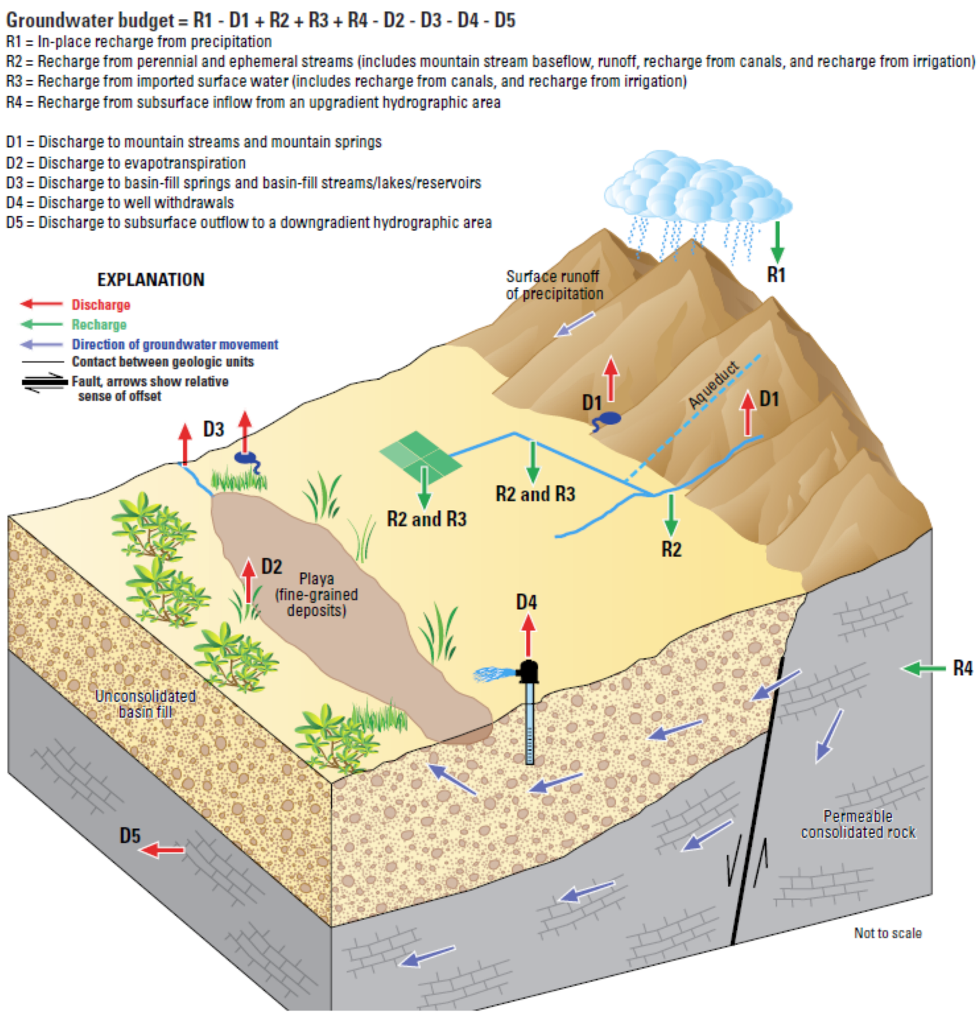

Figure 2-2. Diagram and description of water budget components. [Electronically reproduced from Figure D-1 of Masbruch et al. (2011).]

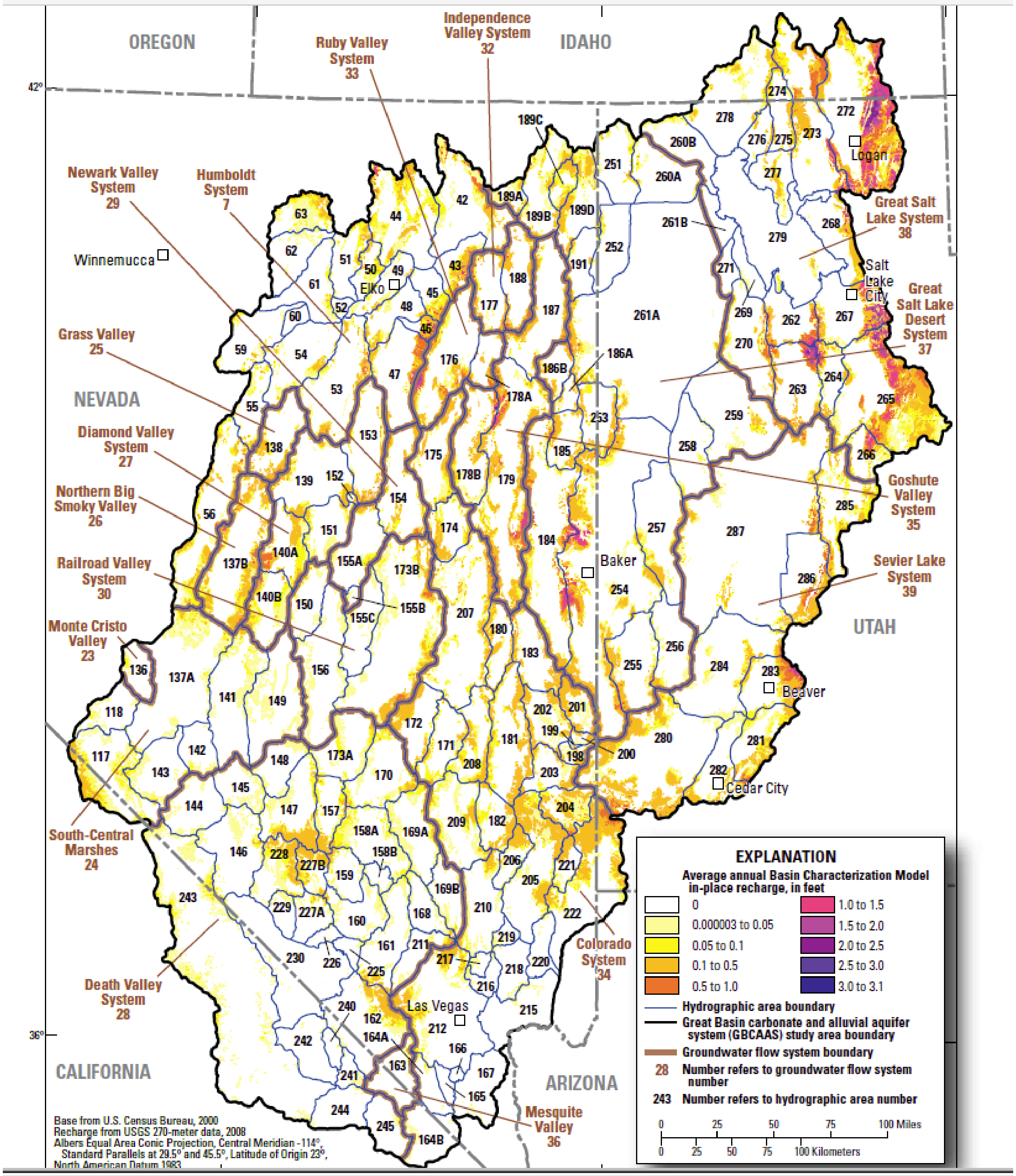

Figure 2-3. Map of basin characterization model estimates of mean annual in-place recharge for the Great Basin carbonate and alluvial aquifer system area. Yucca Mountain is located on the border shared by HA 229 and HA 227A. [Electronically reproduced from Figure D-5 of Masbruch et al. (2011).]

2.2 Brooks et al. (2014)

2.2.1 Introduction

Brooks et al. (2014) describe the construction and calibration of a multi-layer, steady-state groundwater flow model for the 289,000 km^2 (110,000 mi^2) GBCAAS. The primary purposes of the Brooks et al. (2014) study were to quantitatively test the reasonableness of the GBCAAS conceptual flow model developed by Heilweil and Brooks (2011), and to produce a model that could be used to estimate groundwater availability and the effects of groundwater use at the scale of the large interconnected carbonate and alluvial aquifer groundwater flow system. Section 2.1 summarizes much of the information regarding the physical elements of the GBCAAS groundwater flow model, except for the details of grid construction, the selection of initial parameter values, and the formal model calibration procedure that was employed. The following discussion focuses on important results obtained from the calibrated steady-state numerical model and how these compare and contrast with the results of previous numerical models of the carbonate aquifer province and the Death Valley region.

2.2.2 Structure of GBCAAS Steady-State Numerical Model

The GBCAAS hydrogeologic framework model (Section 2.1.3) identified between 27 and 39 distinct geospatial zones for defining the initial horizontal permeability structure of the numerical model (note that MODFLOW-2005 uses hydraulic conductivity instead of permeability). However, to achieve their calibration targets for measured hydraulic heads, recharge, discharge, and ET, Brooks et al. (2014) found that further spatial refinement of these zones was required. In the final calibrated model, 97 horizontal hydraulic conductivity zones (with one hydraulic conductivity parameter per zone) were used, 7 parameters were used to represent the horizontal flow barriers, and 4 parameters were used to represent the vertical to horizontal anisotropy ratio for hydraulic conductivity. Estimates of areal recharge were defined for each 1.6 km × 1.6 km (1 mi × 1 mi) horizontal computational cell at the surface of the MODFLOW-2005 model using the BCM-based water budgets. Because the measured hydraulic heads and spring discharge values that were the primary calibration targets were most sensitive to variations in estimated areal recharge, the more than 1 million (author's estimate) active cells in the model were grouped into 48 areal recharge zones with a recharge multiplier defined for each zone. Similarly, ET from groundwater estimates that were defined on a cell-by-cell basis were subsequently grouped into 16 areal ET zones with an ET multiplier for each zone. Finally, Brooks et al. (2014) defined 2 spring and river zones for defining the conductance parameters used in the MODFLOW-2005 drain sub-model, and 2 lateral flow multipliers for two very short portions of the GBCAAS boundary [Reese River Valley (HA 59) in the north, and Eldorado Valley (HA 167) and Black Mountains Area (HA 215) in the south] where lateral groundwater inflow or outflow was deemed possible. In total, there were 176 MODFLOW-2005 model parameters that were estimated during the calibration procedure.

2.2.3 Important Results

Brooks et al. (2014) determined that the steady-state GBCAAS model "…corroborates the conceptual model presented in Heilweil and Brooks (2011) of an interconnected groundwater flow system between consolidated rock and basin fill and of recharge areas in the mountains connected to the basins and to the regional flow system." Because of changes to the general conceptual model for this region, the numerical model now shows that measured discharge values for springs, creeks, and rivers provide as much information about the fitted model parameters as do the steady-state potentiometric head data.

Incorporating (i) in-place recharge estimates from BCM and (ii) discharge estimates for mountain springs and creeks into the model produces higher simulated recharge mounds in many of the mountain ranges. Moreover, many of these recharge mounds are large enough to divert regional-scale flow paths around mountain ranges and thereby preclude interbasin flow through or beneath the mountain ranges.

There are fewer large-scale regional groundwater flow systems than were identified in previous studies, but the systems exhibited longer total groundwater flow paths. Instead of the 17 regional groundwater flow systems assumed by Sweetkind et al. (2011b) (see Figure 2-3 for the boundaries and names of the 17 regional groundwater flow systems), Brooks et al. (2014) only identified six flow systems based on simulated hydraulic head contours and internal fluxes. Figure 2-4 shows the six regional groundwater flow systems identified by Brooks et al. (2014).

Brooks et al. (2014) expand the northern extent of the GBCAAS Death Valley region (Figure 2-4) to include all of the South-Central Marshes, Monte Christo Valley, and Northern Big Smoky Valley regional system (Figure 2-3). The western boundary of the GBCAAS Death Valley region now excludes all or most of hydrographic areas 170, 169A, 169B, and 211, which now appear to be in the GBCAAS Colorado region. These changes may result in part from the lower resolution computational grid used in the GBCAAS model than the DVRFS model and the use of different boundary conditions. In addition, the GBCAAS model has greater recharge [387,600 m^3/day (115,000 acre-ft/yr)] than the DVRFS model [303,000 m^3/day (89,900 acre-ft/yr)] within the DVRFS boundary, and a reduction in net boundary inflows from +57,700 m^3/day (+17,100 acre-ft/yr) to -47,300 m^3/day (-14,000 acre-ft/yr), where a positive value indicates inflow. These differences in basin recharge and interbasin inflow/outflow also may reflect the increased prevalence of groundwater mounding due to recharge in the mountain blocks.

2.3 Basin-Scale Hydrogeologic Investigations in the Great Basin

The following sections describe five investigations of interbasin groundwater flow between the Amargosa Desert (HA 230,Figure 2-3) and the Furnace Creek spring system in Death Valley (HA 243, Figure 2-3) that consider different lines of hydraulic, hydrostratigraphic, and hydrochemical evidence. These investigations both support and weaken hypothesized occurrences of interbasin groundwater flow within the DVRFS and the larger GBCAAS.

2.3.1 Bredehoeft et al. (2005)

Bredehoeft et al. (2005) propose and evaluate several hypotheses regarding the geometry and hydraulic continuity of the LCAU from its location beneath the VU at Yucca Mountain through the Amargosa Desert and the southern end of the Funeral Mountains to the Furnace Creek spring system in Death Valley. All but one of the Furnace Creek springs discharge from the late-Pliocene conglomerates of the Funeral Formation; however, the chemical signature of the spring water is similar to that of water sampled from the LCAU in Ash Meadows and other up-gradient locations, which suggests that most, if not all, of the water comes from the LCAU and not from local recharge in the southern Funeral Mountains.

At Yucca Mountain, the hydraulic head in the LCAU is approximately 20 m (67 ft) higher than in the overlying VUs at UE-25 P#1, located about 920 m (3,000 ft) west-northwest of the northern end of Fran Ridge. Bredehoeft et al. (2005) suggest that, while the LCAU could be a pathway for radionuclides potentially released from the proposed repository at Yucca Mountain to be transported to the Furnace Creek springs, the vertically upward hydraulic gradient observed in

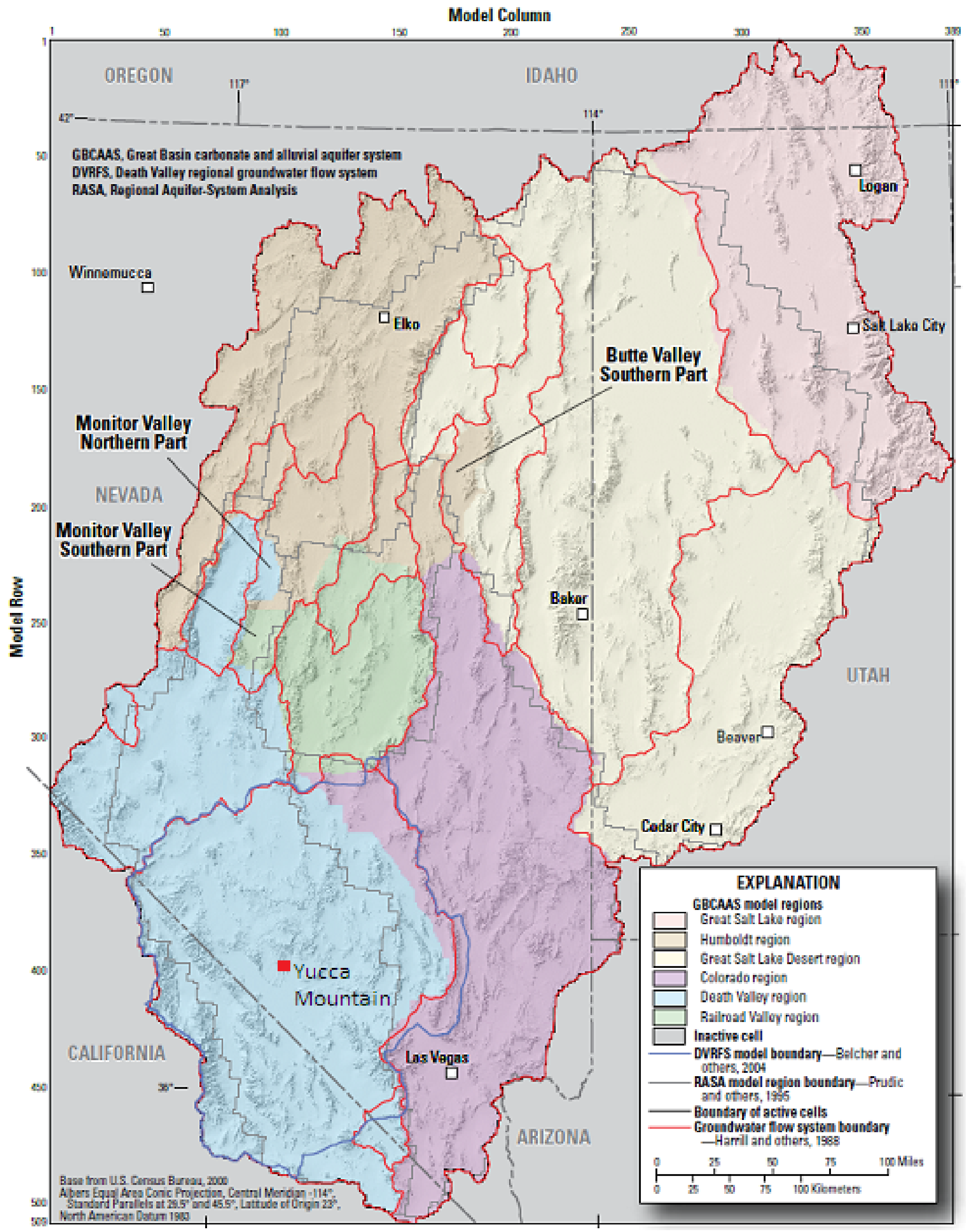

Figure 2-4. Map of major flow systems identified from results of the steady-state numerical groundwater flow model for the Great Basin carbonate and alluvial aquifer system area. [Electronically reproduced from Figure 43 of Brooks et al. (2014).]

UE-25 P#1 should prevent radionuclides from entering the LCAU. Bredehoeft et al. (2005) note that, conversely, water and radionuclides could flow vertically downward from the VUs into the LCAU if hydraulic heads in the LCAU were reduced by excess pumping.

Using geologic data from two boreholes (BLM-1, BLM-2) drilled into the LCAU in Inyo County, California, near the eastern margin of the Funeral Mountains, Bredehoeft et al. (2005) developed alternate models for the elevation of the base of the LCAU through the southern end of Funeral Range and the contact between the LCAU and the Funeral Formation. In the first model, where the elevation of the base of the LCAU is assumed to follow shallow dipping fault planes, the saturated thickness of the LCAU where it abuts the Funeral Formation is approximately 90 m (300 ft). Conversely, in the second model, where the elevation of the base of the LCAU is assumed to follow steeply dipping fault planes, the saturated thickness is approximately 305 m (1,000 ft), which increases the width of the LCAU section (the “spillway”) that can pass groundwater flow from the Amargosa Desert to Furnace Creek. When implemented into a MODFLOW-based groundwater flow model, both hydrogeological models reproduced measured spring flows without unreasonable hydraulic properties being assigned to the LCAU. Bredehoeft et al. (2005) further conclude that direct recharge to the Funeral Formation may provide no more than 10 percent of the total discharge of the Furnace Creek springs.

2.3.2 Anderson et al. (2006)

Anderson et al. (2006) examined ^{18}O and ^{2}H depletion ratios, ^{14}C dates, temporal variations in discharge, hydrostratigraphic relationships in the southern Funeral Mountains, and water-rock chemical interactions along potential groundwater pathways for Texas, Travertine, and Nevares springs in the Furnace Creek springs area of Death Valley, California (see Figure 2-5 for locations of these and other hydrogeologic features). The combination of high depletion ratios ($\delta^{18}O_{SMOW}=-18‰$ and $\delta D_{SMOW}=-102‰$) and high total spring discharge [greater than 10,000 L/min (2,600 gal/min)] was interpreted by the authors to indicate that the source of the springs cannot be solely from present-day local recharge, especially given the arid climate of the Furnace Creek watershed. Although this conclusion is consistent with more than 50 years of studies of the Furnace Creek springs beginning with Winograd and Eakin (1965), Anderson et al. (2006) state that on the basis of the geology of the southern Funeral Mountains, apparent water ages, and simple precipitation-recharge relationships that interbasin flow from the Amargosa Desert cannot be the source for the springs.

Anderson et al. (2006) argue that the geology of the southern Funeral Mountains does not provide a sufficiently permeable flow path from the Amargosa Desert to Furnace Creek based on several lines of evidence. First, groundwater flowing in the LCAU must pass through the cores of approximately one dozen normal faults in the southern Funeral Mountains. Second, eastward-dipping strata cause the cross-sectional area of the highly permeable LCAU to decrease from east to west across the southern Funeral Mountains, thus restricting interbasin flow. Third, the dissolution-enhanced fracture networks that make the LCAU highly permeable must bypass impermeable units, such as the Ely Quartzite, that crop in the southern Funeral Mountains, as well as siliciclastic units within the LCAU. Fourth, many of the fractures that have been observed in boreholes drilled in the LCAU are sealed with secondary calcite or calcareous clays. Finally, confining beds within the Furnace Creek and Funeral Formations inhibit upward flow from the LCAU.

Anderson et al. (2006) also refer to (i) groundwater ages inferred from a combination of ^{14}C measurements of dissolved inorganic carbon (DIC) and stable isotope ratios, (ii) data for strontium and other radioisotopes, and (iii) the concentrations of major dissolved chemical species. All further support the hypothesis that water discharged at the Furnace Creek springs is not from interbasin flow. The arguments developed from these data, which the authors use to support the hypothesis that interbasin flow is not the primary source of water for the Furnace

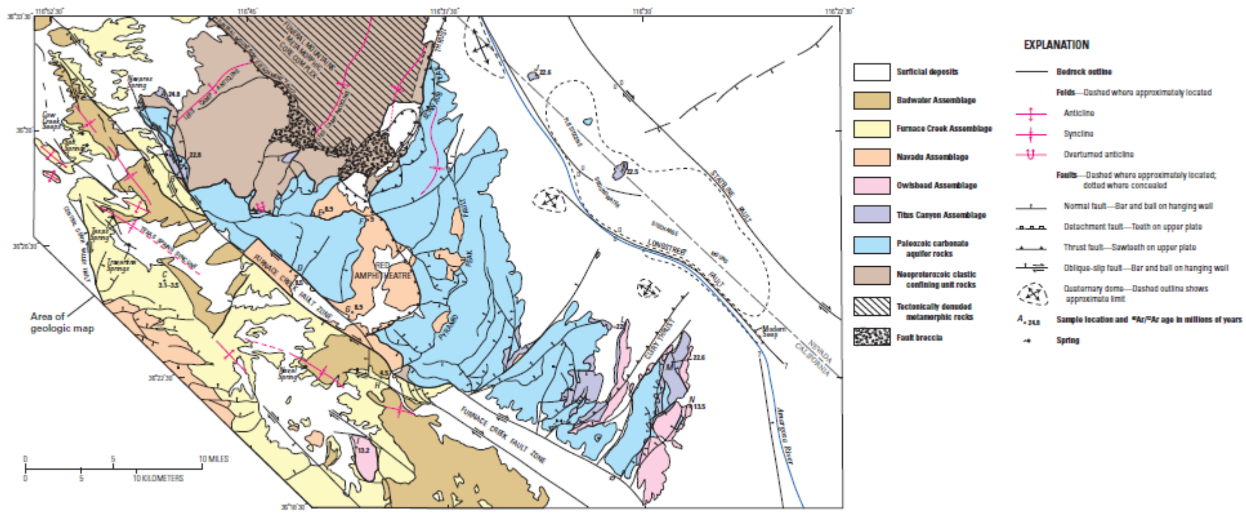

Figure 2-5. Map showing the surficial geology, major faults and fault zones, and the locations of springs and spring deposits in the southern Funeral Range and Furnace Creek areas of Death Valley, California and Amargosa Desert, Nevada. [Electronically reproduced directly from Figure 2 of plate from Fridrich et al. (2012).]

Creek springs, are complex. In simple terms, (i) the estimated age of the discharge water is consistent with the water being recharged during the Younger Dryas (13,000 years ago), when the climate was cooler and wetter and precipitation was depleted of ^{18}O and ^{2}H; (ii) the relatively depleted ^{13}C ratios for the Furnace Creek springs, as well as uranium and strontium radioisotope data, strongly suggest that the source of the water cannot be Ash Meadows; and (iii) the sodium-bicarbonate waters that discharge at the Furnace Creek springs are consistent with local recharge through the Funeral Formation basin-fill aquifers.

Finally, Anderson et al. (2006) show that discharge at the Furnace Creek springs and at other major springs 100 km (60 mi) to the north near Scotty's Castle responds rapidly to wet-dry cycles in the current climate. Anderson et al. (2006) conclude that the observed spring discharge patterns and geochemistry are consistent with predominantly pluvial recharge mixed with a component of modern recharge, supported by mass balance calculations indicating current discharge at Furnace Creek springs could be sustained for up to 40,000 years from water recharged to the Furnace Creek and Funeral Formations during the last pluvial period. Anderson et al. (2006) use this conclusion to bolster their argument against interbasin flow as the source for the springs.

2.3.3 Belcher et al. (2009)

Motivated in large part by the alternate conceptual model proposed by Anderson et al. (2006), Belcher et al. (2009) revisit the technical bases for groundwater flow between topographically closed basins in the carbonate province of the Great Basin—a concept first suggested by Mendenhall (1909) that became widely accepted following the Maxey and Eakin (1949) investigation of the White River groundwater flow system of central Nevada. Belcher et al. (2009) present a detailed and comprehensive hydrogeologic analysis of the Furnace Creek springs illustrating the multiple lines of evidence that have been used to demonstrate the presence of interbasin flow. All of the Furnace Creek springs discharge directly from the

Funeral Formation, except for Nevares Spring, which discharges directly from the LCAU. Belcher et al. (2009) reiterate that the concept of interbasin flow in the GBCAAS has become an integral part of the methods and models used for regional water use planning and for evaluating the transport of radionuclides from weapons tests at NNSS and radionuclides that could hypothetically be released from the proposed high-level radioactive waste repository at Yucca Mountain.

Belcher et al. (2009) describe the hydrogeologic structure of the southern Funeral Mountains as a wedge-shaped, up-thrown block consisting of the NCCU, LCAU, USCU, and UCAU that is bounded by the Furnace Creek fault to the southwest; the Schwaub Peak thrust to the northwest; and the Pahrump-Stewart Valley fault zone to the northeast. Along the Furnace Creek fault and Pahrump-Stewart Valley fault zone, the southern Funeral Mountains have been partially buried by the middle Miocene Furnace Creek Formation, part of the low-permeability LBFAU, and the overlying Pliocene to Pleistocene Funeral Formation, part of the high-permeability UBFAU. Belcher et al. (2009) indicate that the LBFAU in this area acts as a confining unit because its permeable beds have been offset by normal faults and because most of the unit is composed of very fine-grained sediments, while the UBFAU in this area, particularly near Amargosa Farms, is a productive aquifer. Belcher et al. (2009) cite results of several in-depth hydrogeologic studies that support interbasin flow through the LCAU as the source of the Furnace Creek springs. These results include (i) faults and bedding planes in the LCAU are aligned with the presumed northeast-southwest direction of groundwater flow inferred from potentiometric maps; (ii) deformation has created an extensive network of fractures and secondary faults that cut bedding planes in all directions within the LCAU; (iii) the mechanisms that enhance the secondary permeability of the LCAU [i.e., (i) and (ii)] also may increase the bulk hydraulic conductivity of the NCCU and NSCU in the southern Funeral Mountains; and (iv) similar to the springs at Ash Meadows, the Furnace Creek springs are directly associated with outcrops of the LCAU.

Belcher at al. (2009) identify several discrepancies in the arguments used by Anderson et al. (2006) to conclude that local, pluvial recharge to the Funeral Formation is the source for the Furnace Creek springs and that interbasin flow is not. First, Belcher et al. (2009) cite the master's thesis by Anderson (2002) indicating that that water from the springs reaches a maximum temperature of 58°C (135°F) along its subsurface trajectory based on silica geothermometry[1]. The average temperature of water currently recharging the Funeral Formation is estimated to be 14.6°C (58°F). Based on the regional geothermal gradient of 33°C/km (18°F/1,000 ft), recharge must flow downward to a depth of 1,300 m (4,300 ft) to reach a temperature of 58°C (135°F). However, Belcher et al. (2009) note that the Cenozoic deposits are at least 1,300 m (4,300 ft) deep only where Furnace Creek empties into Death Valley and here there is neither an obvious hydraulic pathway back up through the impermeable beds of the Furnace Creek Formation, nor sufficient hydraulic head to produce the observed spring flow. Second, using smaller and more realistic values for the storage coefficient where the Cenozoic deposits are confined, and the drainable porosity or specific yield where unconfined, Belcher et al. (2009) demonstrate that the volume of water stored in the local aquifer during the last pluvial period could not sustain the observed spring discharge. Third, the chemical signature of the spring water is similar to the sodium-sulfate bicarbonate facies observed in the western part

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[1] The maximum measured temperature of water discharged at the Furnace Creek springs is approximately 35°C (100°F). This temperature suggests that the water flows many hundreds of meters vertically upward from the lowest point of its pathway where it reached a temperature of 58°C (135°F) before discharging.

of the Amargosa Desert, which according to Winograd and Thordarson (1975) represents a mixture of waters from Oasis Valley and the springs at Ash Meadows. Belcher et al. (2009) also identify other discrepancies in the interpretation of stable isotope and ^{14}C data by Anderson et al. (2006), which Belcher et al. (2009) use to bolster their argument that the water discharged from the Furnace Creek springs cannot be solely derived from direct recharge to the Furnace Creek Formation.

2.3.4 Bredehoeft and King (2010)

Bredehoeft and King (2010) constructed a simple, single-layer MODFLOW-MODPATH model for groundwater flow and advective transport through the LCAU for a region between Yucca Mountain and Death Valley that includes the Ash Meadows area. This model is based on the hydrostratigraphy used in the DVRFS transient flow model described by Belcher and Sweetkind (2010), supplemented with site-specific information from the few boreholes in this region that penetrate the Paleozoic carbonate system. The authors suggest that the existence of a continuous flow path from Yucca Mountain to Death Valley through the LCAU is reasonable and based on well-tested theory, stating that "[s]ince the 1960s the conceptual idea of a large Carbonate Aquifer integrating much of the groundwater hydrology of eastern and southern Nevada has become something more than a hypothesis; it is the prevailing doctrine."

The steady-state flow model uses prescribed head boundary conditions to the north and the east, while to the west at the Furnace Creek springs and to the south near Shoshone, prescribed flux boundary conditions are used. Bredehoeft and King (2010) obtained initial estimates for the transmissivity of the LCAU from data compiled and reported by Southern Nevada Water Authority (2006). The authors' analysis of these data show that the median value of transmissivity is approximately 100 m^2/day (1,000 ft^2/day), which is very close to the 120 m^2/day (1,300 ft^2/day) estimated for the entire model domain through calibration. Bredehoeft and King (2010) use their calibrated model to estimate unretarded travel times from Yucca Mountain to the Furnace Creek springs if radionuclides from the proposed repository were to enter the LCAU. Bredehoeft and King (2010) state that this radionuclide pathway cannot occur under current conditions, because the hydraulic head in the LCAU, which lies 2 km (1.2 mi) below the repository horizon at Yucca Mountain, is 15 m (49 ft) higher than in the overlying VU, LBFAU, and UBFAU.

Estimates of the LCAU's thickness and kinematic porosity are needed to calculate groundwater velocities and travel times, and the product of thickness and kinematic porosity must appropriately represent the cross-sectional area that is open to flowing water. Bredehoeft and King (2010) propose a model for the general structure of the highly conductive fracture zones in the LCAU based on borehole data from Southern Nevada Water Authority (2006) and observations from the few boreholes that tap the LCAU in the modeled area. Bredehoeft and King (2010) state that the LCAU in this area consists of "…large thicknesses of low-permeability carbonate rock in which there are interspersed, at intervals of several hundred meters, thin, highly-transmissive zones several meters thick." Based on the borehole data and professional judgement, Bredehoeft and King (2010) estimate that the cumulative fracture zone thickness of the 1,000 to 5,000 m (3,000 to 15,000 ft) thick LCAU ranges from 10 to 100 m (33 to 330 ft). The authors cite a study of earth tide signals at borehole UE25 P#1 by Galloway and Rojstaczer (1988), from which the estimated storage coefficient suggests a porosity that is less than 0.01. Based on this single value of porosity and their conceptual model, Bredehoeft and King (2010) assume that the kinematic porosity ranges from 0.001 to 0.1, but caution that this critical parameter is very uncertain. A parametric uncertainty analysis conducted by Bredehoeft and King (2010) using these ranges for the composite fractured interval thickness and kinematic porosity shows that travel time from Yucca Mountain to the Furnace Creek springs through the LCAU is between 100 and 2,000 years.

2.3.5 Nelson and Mayo (2014)

The objective of the Nelson and Mayo (2014) study is to refute the longstanding theory of ubiquitous interbasin flow within the LCAU of the Great Basin. In their overview, Nelson and Mayo (2014) note that arguments supporting the occurrence of interbasin flow have been based on (i) imbalances in hydrographic basin water budgets; (ii) hydraulic head differences between hydrographic basins; (iii) stable isotope data; and (iv) groundwater flow models. However, Nelson and Mayo (2014) stress that (i) water budgets are too imprecise; (ii) the interpretation of hydraulic head differences are too dependent on the analyst's *a priori* conceptual model; and (iii) stable isotope data are too likely to be affected by climate change and too open to interpretation to provide unequivocal evidence of interbasin transfer of water. Nelson and Mayo (2014) state, "[s]tructural and stratigraphic considerations in a geologically complex region like the great basin should produce compartmentalization, where increasing aquifer size increases the odds of segmentation along a given flow path." In other words, within the Great Basin groundwater flow system compartmentation should be the rule, and interbasin flow the exception except, according to the authors, in select cases where flow is conducted between basins through the damage zones of basin-bounding faults.

Nelson and Mayo (2014) focus their examination of interbasin flow in the GBCAAS on topographically closed basins where there is no potential for flow to leave the basin through the shallow groundwater system comprised by the Upper or Lower Basin Fill Aquifers (UBFA and LBFA). Of the 165 HAs included in the GBCAAS, 57 are endorheic basins in which most water that either recharges the groundwater system or runs off, discharges into a terminal playa where it is lost to ET. Where water budget studies of the endorheic basins show a significant disparity between independent estimates of basin recharge and discharge, it has been assumed that the unaccounted water is transferred within the deep groundwater flow system through the high-conductivity LCAU or highly fractured zones within the NCCU and USCU, through and below the intervening mountain blocks. Nelson and Mayo (2014) state that water budgets conducted as part of the comprehensive study of the GBCAAS by Heilweil and Brooks (2011) show that most recharge does indeed discharge locally, which Nelson and Mayo (2014) describe as "…a great departure from prior studies." For 29 of the 57 endorheic basins, the water budgets from Heilweil and Brooks (2011) show evidence of both groundwater inflow and groundwater outflow, which Nelson and Mayo (2014) attribute "…to the cumulative effect of up-gradient water budget imbalances where it is necessary to transfer calculated up-gradient excess groundwater recharge to down-gradient basins." Inasmuch as Masbruch et al. (2011) report water budget errors of approximately 50 percent, Nelson and Mayo (2014) imply that the transfer of apparent up-gradient excess recharge to down-gradient basins is simply an accumulation of errors and does not constitute evidence of large-scale interbasin flow.

Nelson and Mayo (2014) note that using potentiometric maps to determine the potential for interbasin flow, particularly when the contours are based on water levels from different aquifers or from different open borehole sections, can lead to incorrect conclusions. Nelson and Mayo (2014) illustrate possible misinterpretation of potentiometric data by evaluating the cases for interbasin flow in the Snake Range and Death Valley areas. For Death Valley, Nelson and Mayo (2014) examine the construction and interpretation of potentiometric maps in the area along the eastern border formed by the Grapevine Mountains, Funeral Range, Black Mountains, and Greenwater range, focusing on Furnace Creek springs and the southern Funeral Range. They compare two potentiometric contour maps: Figure 2 of Belcher et al. (2009), which is based on information from Bedinger and Harrill (2004), and Map A of Potter et al. (2002), the origin of which is not apparent. Map A of Potter et al. (2002) appears to the author to consist of computer-generated contours based on all available water level measurements, including high altitude mountain springs in the Grapevine Mountains and Funeral Range.

The two sets of contours are very different in configuration, with the former set appearing to present a picture of regional flow and the latter showing groundwater mounding in mountainous areas. Hydraulic head differences exceed several hundred meters in numerous locations. The contours presented by Belcher et al. (2009) were used to support their discussion of interbasin flow through the LCAU, whereas the contours in Map A were, according to Potter et al. (2002), designed to "…allow users to consider the potential interactions among these [structural] features, and their collective impact on ground-water flow in the region." Obviously, Nelson and Mayo's deliberate comparison of these different sets of contours illustrates how potentiometric data may be misinterpreted. However, it is unclear that these kinds of errors in interpreting contoured water level data have actually contributed to the controversy regarding the source of the Furnace Creek springs. Nelson and Mayo (2014) close their section on the use potentiometric data with a caution to infer groundwater mounding in mountainous regions only if the water level data are known not to represent a perched or local groundwater system.

Nelson and Mayo (2014) also review how stable isotope data have been used to support the hypothesis of large-scale interbasin flow in the GBCAAS and identify the recharge locations(s) of water from springs in Ash Meadows and Furnace Creek. On the one hand, prevailing theory holds that water discharged at Ash Meadows is late-Holocene (2,000 to 3,000 years), but is depleted in ^{2}H and ^{18}O because it reflects recharge in the cooler, high elevation regions of the Spring Mountains mixed with the even more depleted water from Pahranagat Valley. On the other hand, ^{14}C ages presented in Anderson et al. (2006) indicate water discharged at Ash Meadows is several thousand to several tens of thousands years old, which suggests recharge occurred during a pre-Holocene cold climate. Nelson and Mayo (2014) note that these ^{14}C ages are consistent with ages of paleo-spring deposits in the region, which indicate that large spring flows occurred during the last glacial maximum. They further assert that the ages of the paleo-spring deposits are "…consistent with the notion that large regional springs in the Death Valley area are fed by groundwaters recharged during cooler climates in pre-Holocene time." Recall from Section 2.3.3 that the statement in quotation marks is nearly identical to the fundamental premise of Anderson et al. (2006) regarding the source of the Furnace Creek springs.

Finally, Nelson and Mayo (2014) state that the existence of a hydraulic head difference between adjoining basins is a necessary, but not sufficient condition for interbasin flow. They then proceed to examine features and processes that affect the required presence of high-permeability pathways transecting the faulted and fractured rock through and below the mountain blocks that separate the hydrographic basins. These features and processes include (i) dissolution and precipitation of carbonate and other minerals that widen and narrow the fractures of the LCAU and UCAU; (ii) the tendency for aquitards, such as the NCCU and USCU, and impermeable beds within the LCAU and UCAU, to impede groundwater flow where strata are deeply dipping; and (iii) the presence of very low permeability fault gouge within the basin bounding normal fault zones. Except for the limited potential for waters undersaturated with respect to carbonate, such as those from the VU, to mix with oversaturated waters in the LCAU and UCAU, where they may enhance dissolution and increase fracture apertures, Nelson and Mayo (2014) assert that taken together these three mechanisms significantly decrease the likelihood of continuous, large-scale, high-permeability pathways needed for interbasin flow throughout the GBCAAS.

3 CONCLUSIONS

Rapid population growth has increased the demand for municipal and industrial water in major Great Basin population centers, which has led to a need for more accurate studies of the water resources. Increased understanding of the region's complex stratigraphy, including the role of flow-affecting structural features, as well as the availability of more rigorous scientific methods and improved data collection techniques for estimating regional patterns of precipitation, ET, and recharge, have allowed hydrogeologists to develop what should be more accurate hydrogeologic models.

For more than 100 years, the general conceptual model for groundwater flow within the carbonate province of the Great Basin has assumed that many of the topographically closed alluvial valleys in the Basin and Range are hydraulically connected at depth by the highly permeable Paleozoic carbonate aquifer. Indeed, this conceptual model underlies the most recent flow model of the Great Basin Carbonate and Alluvial Aquifer System developed by the U.S. Geological Survey, and has been used to support plans being developed by water utilities to transport water from large well fields pumping the carbonate aquifer to major metropolitan areas within the Great Basin. In the last decade, several peer-reviewed journal papers have been published that suggest that the locations of the recharge zones that supply major springs in several sub-regions in the Great Basin may be much closer to the springs than has been assumed under the prevailing regional groundwater flow hypothesis. If, as implied by this alternate hypothesis, local groundwater flow systems are more prevalent in the Great Basin one could infer that the overall flow system is more compartmented, which may limit the flow of water and contaminants between hydrographic areas.

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