Chapter A: Introduction

By Victor M. Heilweil, Donald S. Sweetkind, and David D. Susong

Chapter A of

Conceptual Model of the Great Basin Carbonate and Alluvial Aquifer System

Edited by Victor M. Heilweil and Lynette E. Brooks

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
inch per day (in./d)	25.38	millimeter per day (mm/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Note: The conversion factors given above are for the entire report. Not all listed conversion factors will be in any given chapter of this report.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Temperature in kelvin (K) may be converted to degrees Fahrenheit (°F) as follows:
°F=1.8K-459.67

Temperature in kelvin (K) may be converted to degrees Celsius (°C) as follows:
°C=K-273.15

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Chapter A: Introduction

By Victor M. Heilweil, Donald S. Sweetkind, and David D. Susong

This study assesses groundwater resources in the complex Great Basin carbonate and alluvial aquifer system (GBCAAS). Located within the Basin and Range Physiographic Province, the Great Basin carbonate and alluvial aquifer system covers an area of approximately 110,000 mi^2 (fig. A–1), predominantly in eastern Nevada and western Utah. The study area encompasses the Basin and Range carbonate-rock aquifers and Southern Nevada volcanic-rock aquifers and includes a large portion of the Basin and Range basin-fill aquifers (Reilly and others, 2008, fig. 2). The aquifer system generally comprises aquifers and confining units in unconsolidated basin fill and volcanic deposits in the basins, and carbonate and other bedrock in the mountain ranges separating the basins. These same bedrock units often underlie the basins. The aquifers are, in some areas, hydraulically connected between basins. Harrill and Prudic (1998) note that because of this connectivity, the aquifers of the eastern Great Basin "collectively constitute a significant regional ground-water resource." Some mountain ranges in the study area, however, consist of less permeable rock that may impede groundwater flow between basins.

The GBCAAS study area is experiencing rapid population growth and has some of the highest per capita water use in the Nation, resulting in increasing demand for groundwater. The U.S. Census Bureau (2005) found that Nevada and Utah were among the fastest growing states in the United States, with a projected increase in population of more than 50 percent between 2000 and 2030. Growing urban areas include Las Vegas in the southern part of the study area and the Wasatch Front (extending from Cache County to Iron County, Utah) along the eastern margin of the study area (fig. A–1). A 1990 comparison of water use by states found that Utah and Nevada had per capita water uses of 308 and 344 gallons per person per day, respectively (Bergquist, 1994). These rates are the highest in the United States and nearly twice the national average of 185 gallons per person per day. The alluvial aquifers of the GBCAAS are considered part of the Basin and Range basin-fill aquifer system—the fourth most heavily pumped regional aquifer in the United States (Reilly and others, 2008). The combination of rapid population growth, high water use, and arid climate has led to an increased dependence upon groundwater resources during the past 60 years (Gates, 2004) and predictions of future water shortages (U.S. Water News, June 2005). Severe groundwater depletion, along with declining groundwater levels and spring discharge, has occurred in several basins within the study area (Hurlow and Burke, 2008; L. Konikow, U.S. Geological Survey, written commun., 2009).

Because of its regional extent and large reliance upon groundwater resources as water supplies for urban populations, agriculture, and native habitats, the GBCAAS was selected for assessment by the U.S. Geological Survey National Water Census Initiative to evaluate the nation's groundwater availability. Groundwater availability includes an understanding of the groundwater-budget components, along with other considerations such as water quality, regulations, and socioeconomic factors that control its demand and use (Reilly and others, 2008, p. 3). Within the context of the national groundwater availability assessment, the goals of regional assessments (such as the GBCAAS) are the development of (1) water budgets for the aquifer system (recharge and discharge components); (2) current estimates and historic trends in groundwater use, storage, recharge, and discharge; (3) numerical modeling tools to provide a regional context for groundwater availability and for future projections of groundwater availability; (4) regional estimates of important hydrologic variables (e.g. aquifer properties); (5) evaluation of existing groundwater monitoring networks; and (6) new approaches for regional groundwater resources analysis (Reilly and others, 2008, p. 37).

Purpose and Scope

The purpose of this report is to present an updated conceptual model of the GBCAAS for evaluating regional groundwater availability. The report provides an update to the previous Regional Aquifer-System Analysis (RASA) conceptual model (Prudic and others, 1995), integrating newer findings from several recent basin-scale studies, the Death Valley Regional Flow System (DVRFS) study (Belcher, 2004), and the Basin and Range Carbonate Aquifer System (BARCAS) study (Welch and others, 2007). Specifically, this report addresses objectives 1, 2, and 4 of the national groundwater availability assessment described in the previous section. This conceptual model includes the delineation of hydrogeologic units on the basis of lithology and hydraulic properties, construction of a detailed three-dimensional hydrogeologic framework, development of a potentiometric-surface map of the aquifer system, an evaluation of interbasin

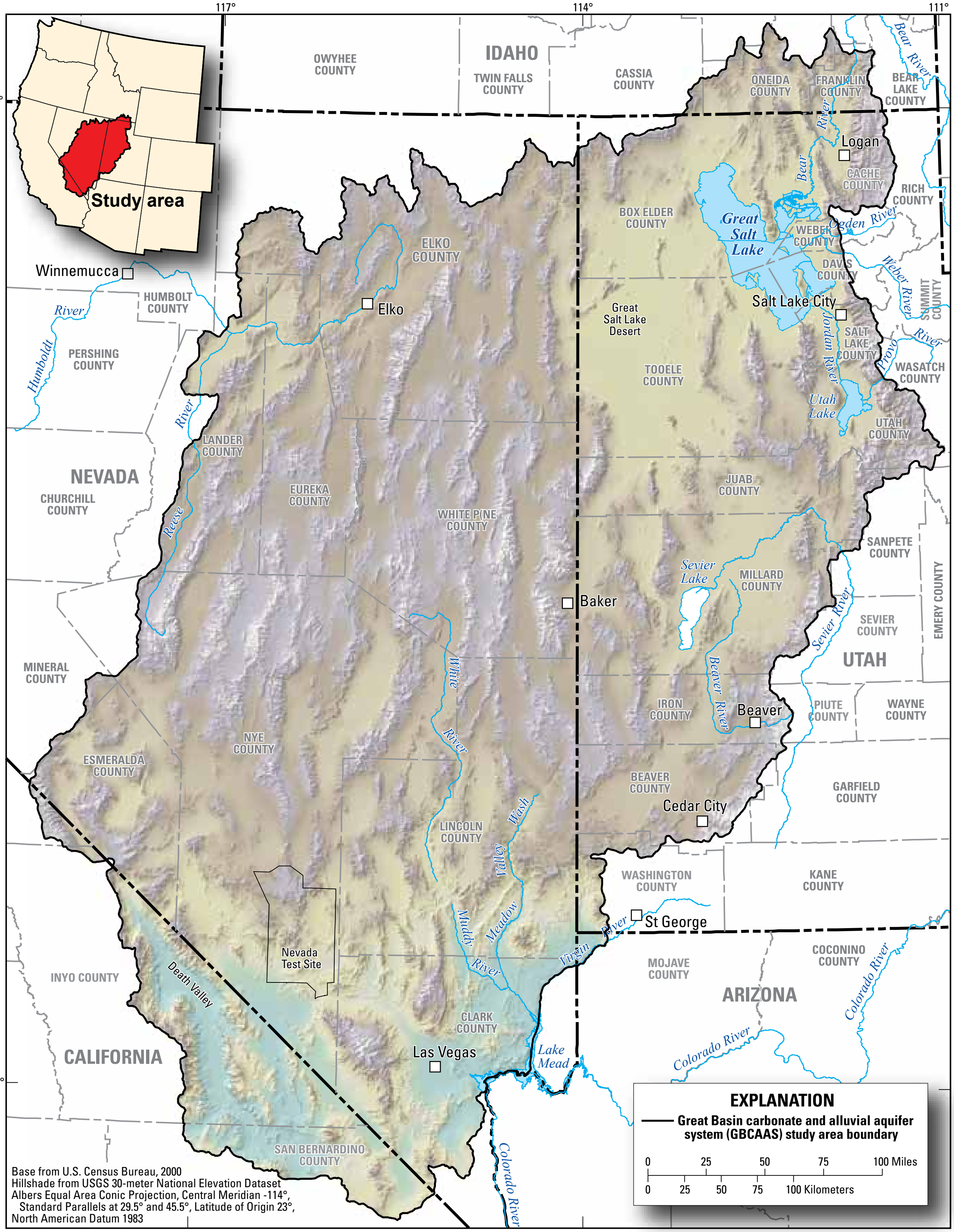

Figure A–1. Location map of the Great Basin carbonate and alluvial aquifer system study area.

bedrock hydraulic connectivity and regional groundwater flow directions, and a synthesis/interpretation of both predevelopment and recent groundwater recharge- and discharge-budget components.

The current study area is larger than that of a previous hydrogeologic study of the eastern Great Basin Carbonate-Rock Province (GB/CRP) conducted during 1981–87 as part of the U.S. Geological Survey's RASA program (fig. A–2; Prudic and others, 1995). The RASA–GB/CRP study area boundary was based on the occurrence of thick sequences of permeable carbonate and volcanic consolidated bedrock, but excluded the northern and eastern parts of the Great Salt Lake drainage area in Cache, Weber, Davis, Salt Lake, and Utah Counties (figs. A–1, A–2). Because these areas contain thick sequences of carbonate rocks, they are included in the GBCAAS study area. The GBCAAS study area also extends beyond the RASA–GB/CRP study area (1) to the northwest to include a larger portion of the Humboldt River drainage which also contains relatively thick sequences of carbonate rocks, and (2) to the west and southwest for consistency with watershed boundaries and with the DVRFS model area boundary (Belcher, 2004) (fig. A–2).

The temporal extent of data compiled for this study generally includes information through 2006. Data prior to the 1940s are scarce because (1) substantial groundwater development (well withdrawals) within the GBCAAS area did not begin until the widespread use of the deep-well turbine pump beginning in the 1940s, and (2) there were few quantitative hydrologic studies of individual basins within the study area prior to the 1940s.

This report presents components of the conceptual groundwater model within the GBCAAS study area in three subsequent chapters. Chapter B describes the stratigraphy and structure of the region in terms of the geologic setting and geologic history of the eastern Great Basin and defines hydrogeologic units used for describing aquifers and confining units. These hydrogeologic units provide the basis for the construction of a three-dimensional hydrogeologic framework of the aquifer system, described in Chapter B and detailed in Appendix 1. Chapter C describes (1) a conceptual model of groundwater flow through both bedrock and alluvial aquifers, (2) how geologic layers and structures control groundwater movement, and (3) the construction of a regional potentiometric map that is used for evaluating directions of groundwater flow. Chapter D describes the approach used for compiling and interpreting groundwater recharge- and discharge-budget components, and provides detailed groundwater-budget data for the entire study area. This includes a description of the Basin Characterization Model (BCM) used for estimating recharge from precipitation (further described in Appendix 3). Appendixes 6 and 8 describe the spatial datasets associated with this report and methods for estimating historical well withdrawals, respectively. The other appendixes are tables detailing descriptive information for each hydrographic area (HA) (Appendix 2), current study recharge and discharge estimates for predevelopment conditions (Appendixes 4 and 5, respectively), and predevelopment and recent groundwater-budget estimates for each HA (Appendix 7). In general, HA boundaries coincide with topographic basin divides that form the basis for defining watersheds; however, some divisions are arbitrary and lack topographic basis (Welch and others, 2007). Most HAs represent a single watershed, including both basin fill and adjacent mountain blocks up to the topographic divide (Harrill and Prudic, 1998).

Previous Studies

Two regional groundwater studies and two subregional groundwater studies were previously completed by the U.S. Geological Survey (USGS) within the GBCAAS study area. In the 1980s, the USGS RASA program assessed the Nation's major aquifer systems and made two regional studies as part of the Great Basin RASA: (1) delineation of aquifer systems in the Great Basin region (RASA–GB; Harrill and Prudic, 1998), and (2) a conceptual evaluation of regional groundwater flow in the Carbonate-Rock Province of the Great Basin (RASA–GB/CRP; Prudic and others, 1995). The two subregional studies include (1) the DVRFS study in the Death Valley area (Belcher, 2004) of southern Nevada and southeastern California, and (2) the BARCAS study (Welch and others, 2007) in east central Nevada and western Utah (fig. A–2).

The RASA–GB study focused on two important aquifer systems in the Great Basin, one composed of basin-fill aquifers and the other of consolidated carbonate-rock aquifers (Harrill and Prudic, 1998). Because the study area was large, encompassing 260 individual HAs or subareas, the study investigated small "type areas" (for example, Prudic and Herman, 1996; Mason, 1998; Harrill and Preissler, 1994) that were thought to be representative of larger parts of the region and assumed to have transfer value in terms of critical components of the groundwater flow system. The study also included regional assessments of hydrogeology (Plume and Carlton, 1988), geochemistry (Thomas and others, 1996), and hydrology (Thomas and others, 1986; Harrill and others, 1988). As part of the RASA–GB, the RASA–GB/CRP study included a groundwater flow model (Prudic and others, 1995). The results of the RASA studies form the basis for most subsequent conceptualizations of groundwater flow in the Great Basin. Important conclusions pertinent to the GBCAAS study area were (1) most groundwater flow moves from recharge areas in the mountains to discharge areas in adjacent valleys; (2) interbasin groundwater flow is predominantly through thick and continuous carbonate rocks; (3) not all carbonate rocks are highly permeable; (4) some highly permeable carbonate aquifers are hydraulically disconnected from shallower alluvial aquifers by low-permeability confining units; (5) while there are some long and deep interbasin groundwater flow paths to terminal sinks such as the Great Salt Lake, Great Salt lake Desert, Death Valley, and the Colorado River, most discharge along these flow paths occurs

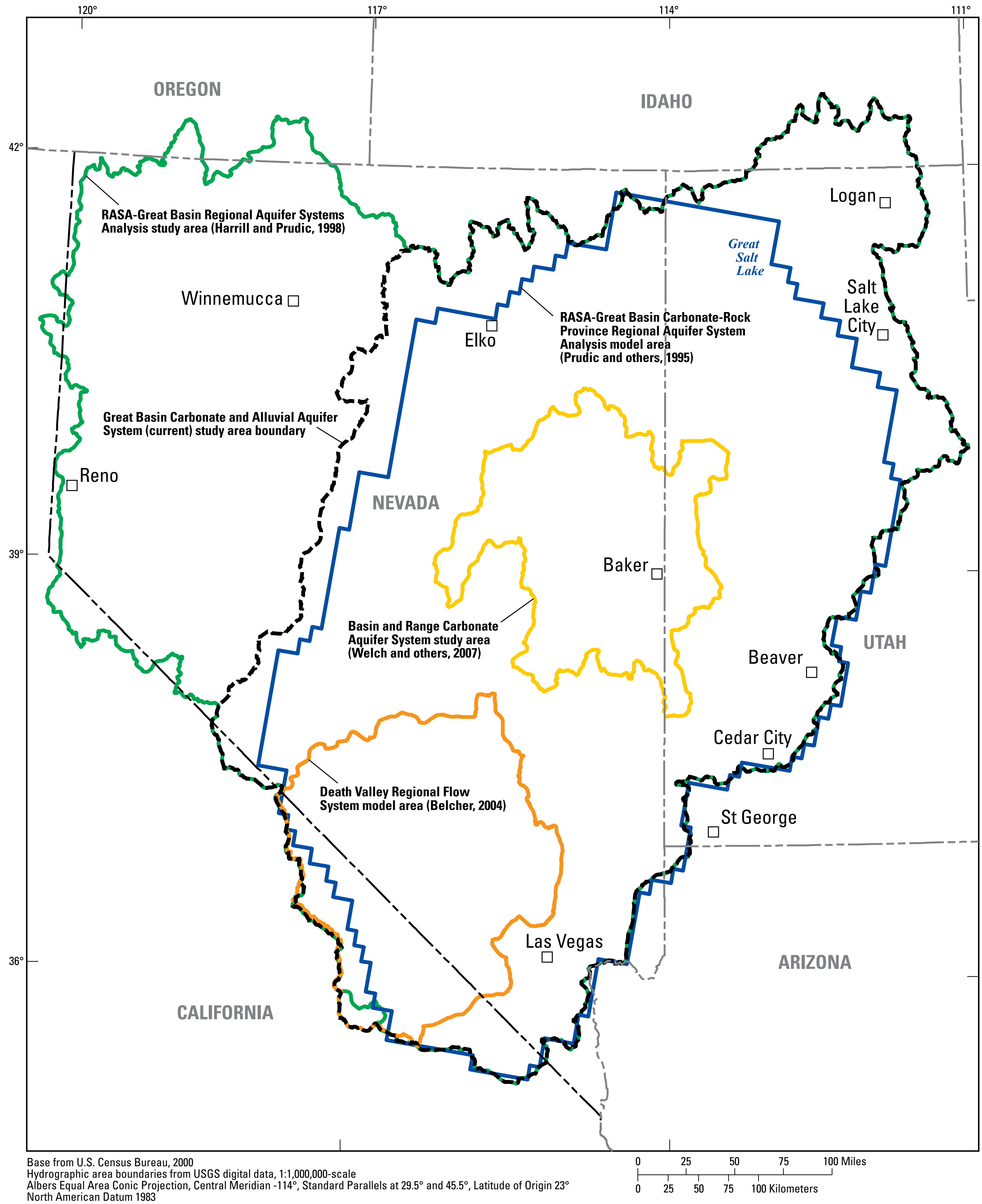

Figure A–2. Location of previous regional groundwater study and model areas within the Great Basin carbonate and alluvial aquifer system study area.

at intermediary locations as springflow and evapotranspiration (Harrill and Prudic, 1998, p. A39).

The DVRFS study, located within the southern part of the GBCAAS study area (fig. A–2), was completed by the U.S. Geological Survey in support of the U.S. Department of Energy (DOE) programs at the Nevada Test Site and at Yucca Mountain Repository, which is adjacent to the Nevada Test Site in southwestern Nevada. The study updated estimates of discharge and integrated all available information in the region to develop a numerical three-dimensional transient groundwater flow model of the Death Valley region (Belcher, 2004). The DVRFS study provided an improved understanding of regional groundwater flow in southern Nevada and the Death Valley region in California—a critical objective of the DOE program concerned with potential movement of radioactive material away from the Nevada Test Site and characterizing the groundwater flow system in the vicinity of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada (Hanks and others, 1999).

The BARCAS study, located within the central part of the GBCAAS study area (fig. A–2), was completed by the U.S. Geological Survey and the Desert Research Institute in support of federal legislation to investigate the groundwater flow system underlying White Pine County and adjacent counties in Nevada and Utah (Section 131 of the Lincoln County Conservation, Recreation, and Development Act of 2004). The BARCAS study developed potentiometric-surface maps showing groundwater flow directions in both alluvial and carbonate aquifers, derived new estimates of groundwater recharge and discharge for HAs in White Pine County, Nevada, and adjacent areas in Nevada and Utah, and assessed inter-basin groundwater flow on the basis of a combination of deuterium mass-balance modeling, basin-boundary geology, hydraulic heads, and geochemistry. Findings of the BARCAS study are available in a summary report (Welch and others, 2007) and individual reports that describe the specific methods and water-budget components used in the analysis of the groundwater flow system (Cablk and Kratt, 2007; Flint and Flint, 2007; Hershey and others, 2007; Lundmark, 2007; Lundmark and others, 2007; Mizell and others, 2007; Moreo and others, 2007; Pavelko, 2007; Smith and others, 2007; Welborn and Moreo, 2007; Wilson, 2007; Zhu and others, 2007).

In addition to the previous regional groundwater studies, several other studies focused on the distribution of carbonate-rock aquifers and their potential for groundwater development (Dettinger and others, 1995; Burbey, 1997), and on estimating groundwater recharge (Watson and others, 1976; Dettinger, 1989; Kirk and Campana, 1990; Nichols, 2000; Thomas and others, 2001; Epstein, 2004). Numerous other previous groundwater studies have focused on individual basins in Nevada and Utah (listed in Auxiliary 2).

The previous studies and the current GBCAAS study refer to HAs, especially when discussing locations and groundwater budgets. HAs in Nevada were delineated systematically by the USGS and Nevada Division of Water Resources (NDWR) in the late 1960s (Cardinalli and others, 1968; Rush, 1968) for scientific and administrative purposes.

Basis for Developing a Three-Dimensional Hydrogeologic Framework

The GBCAAS study area comprises many types of rocks that have been subjected to a variety of structural disruptions and, as a result, the regional geology is stratigraphically and structurally complex. These rocks form a complex, three-dimensional hydrogeologic framework that can be subdivided into multiple aquifers and confining units on the basis of their capacity to store and transmit water. The RASA–GB/CRP numerical groundwater flow model (Prudic and others, 1995) represented this complex regional geology as a two-layer hydrogeologic system: an upper model layer primarily used to represent basin-fill aquifers and adjacent mountain ranges to depths of a few thousand feet, and a lower model layer generally used to represent deeper carbonate-rock aquifers. This simplified mathematical representation of the complex geology and hydrogeology in the region was developed because of large uncertainty in the thickness of hydrogeologic units, sparse data, and limited computing resources available at that time. Since the RASA–GB/CRP model was completed, the increase in computing power and advances in numerical modeling allow the incorporation of more geologic detail in three-dimensional hydrogeologic frameworks and groundwater flow models. Subsequent conceptual models (e.g., Laczniak and others, 1996; Welch and others, 2007; Cederberg and others, 2008) and numerical groundwater flow models (Belcher, 2004; Brooks and Mason, 2005; Gardner, 2009) of parts of the region have incorporated greater geologic detail, which has resulted in finer scale, more sophisticated models that are more representative of the groundwater flow systems.

A hydrogeologic framework defines the physical geometry and rock types in the subsurface. The complex stratigraphy and structure of the GBCAAS study area significantly influences the location and direction of groundwater flow. The occurrence and juxtaposition of permeable aquifer units or impermeable confining units in three dimensions are critical factors that determine the potential for groundwater flow across HA boundaries. Thus, the development of a three-dimensional hydrogeologic framework of the GBCAAS study area is a necessary and significant step in improving the conceptualization of groundwater flow in the Great Basin, and in providing a foundation for the development of future groundwater flow models. The three-dimensional hydrogeologic framework presented in this report is a representation of the regional hydrogeology in digital form, including the spatial extent and thickness of aquifers and confining units and the geometry of major structures. The hydrogeologic framework was built by combining and extracting information from a variety of data sets, including elevation models, geologic maps, borehole logs, cross sections, and other digital frameworks. This information was combined into an integrated three-dimensional framework of the aquifer system. This framework will be used both for an improved conceptual understanding of groundwater flow in the GBCAAS study area (Chapter C) and as the three-dimensional framework for a numerical groundwater flow model of the entire area (subsequent report).

The framework incorporates abundant geologic data and information that were developed during, or subsequent to, the Great Basin RASA studies. These include advances in the understanding of the style and magnitude of Great Basin extension (for example Snow and Wernicke, 2000), the relation between extension and caldera-related volcanism (Axen and others, 1993), and an increased understanding of the role of regional-scale transverse structures (Faulds and Stewart, 1998). New geophysical methods and data have been developed to estimate the shape and size of Cenozoic basins, including the gravity-derived depth-to-basement method (Saltus and Jachens, 1995) and regional-scale seismic data (Allmendinger and others, 1987), which are used to develop a crustal cross section across the entire GBCAAS study area. Map compilations and three-dimensional hydrogeologic frameworks for the Death Valley and Nevada Test Site areas (Workman and others, 2002; Faunt and others, 2004) and lower White River/Meadow Valley Wash areas (Page and others, 2005; 2006) provide new data on the surface and subsurface extent of geologic units. Collectively, updated interpretations of subsurface geology, new surface geologic mapping, advances in geophysical methods, an improved understanding of hydraulic properties of geologic units, the development of subregional hydrogeologic frameworks, and advances in software and computing power provide the foundation for the development of a more complex, finer scale, and multi-layer hydrogeologic framework for the aquifer system.

Basis for Updating the Conceptual Groundwater Model

Recent data and interpretation of hydraulic properties in carbonate rocks (Dettinger and others, 1995; Dettinger and Schaefer, 1996) and in volcanic rocks and basin fill (Belcher and others, 2001) have advanced the understanding of the major aquifers of the eastern Great Basin. Since the RASA–GB study, developments in groundwater budget estimates include improved methods for estimating evapotranspiration and for estimating the magnitude and distribution of recharge and runoff (Flint and Flint, 2007). Subsequent to the RASA–GB study, conceptual models (e.g., Laczniak and others, 1996; Welch and others, 2007; Cederberg and others, 2008) and numerical groundwater flow models (Belcher, 2004; Brooks and Mason, 2005; Gardner, 2009) of parts of the region have incorporated greater geologic detail, which has resulted in finer scale, more sophisticated models that are more representative of the groundwater flow systems.

Another important improvement since the RASA–GB study is the development of a watershed approach to understanding Great Basin groundwater systems (Cederberg and others, 2008; Gardner, 2009; Stolp and Brooks, 2009), wherein the hydrology of both mountain-block and basin-fill aquifers are explicitly defined and linked, allowing a more comprehensive representation of groundwater recharge and discharge components (such as groundwater discharge to mountain springs and streams). Also, the availability of (1) new and higher resolution remotely-sensed data for vegetation, soil moisture, and snowpack; (2) new techniques for mapping the distribution of precipitation such as PRISM (Parameter-elevation Regressions on Independent Slopes Model; Daly and others, 1994); and (3) digital data sets of topography, soils, and geology all permit a more precise determination of the spatial variability of input data for regional groundwater studies such as the GBCAAS. The improved conceptual understanding of groundwater flow and interbasin hydraulic connections, along with the advances in water-budget estimation methods and recently collected hydrologic data, all contribute to the updated conceptual model and groundwater budgets of the GBCAAS.

Geographic Setting

The GBCAAS study area extends across the eastern two-thirds of the Great Basin, a subprovince of the Basin and Range physiographic province (Fenneman, 1931), including most of eastern Nevada and western Utah, parts of southeastern California and Idaho, and a small corner of northwestern Arizona (fig. A–1). The area is generally bounded by latitudes of about 35° to 42°N and longitudes of about 111° to 118 °W. The physical geography of the study area is characterized by north or northeast trending mountain ranges separated by broad basins (fig. A–1). Mountain ranges typically are 5–15 mi wide and can be as long as 50 mi or more. Basins typically are 5–10 mi wide and 35–70 mi long, although some are as long as 150 mi. The longer basins, like Snake Valley (150 mi; pl. 1), are bordered by multiple mountain ranges. Where mountain ranges are bounded by extensive normal faults, the mountain fronts are steep and abruptly transition to alluvial fans that extend into the basins. Topographic relief between the mountain crests and basin floors typically ranges from 1,000 to 6,000 ft, with a few areas exceeding 8,000 ft. The altitude of the basin floor is below sea level in Death Valley, but typically ranges from 3,000 to 6,000 ft above sea level elsewhere. Steptoe Valley in the north-central part of the study area (pl. 1) has the highest altitude of all basin floors (approximately 6,300 ft), and basin altitude generally decreases in all directions. Mountain altitudes commonly range from 8,000 to 11,000 ft, with a few peaks exceeding 13,000 ft (for example Wheeler Peak in the Snake Range at 13,063 ft and White Mountain Peak in the White Mountains west of Fish Lake Valley at 14,246 ft (pl. 1)).

The GBCAAS study area includes numerous public lands, including two national parks, multiple national and state wildlife refuges, national conservation and wilderness areas, national and state monuments, national historic sites, national and state recreation areas, and state parks (fig. A–3). About 90 percent of the land in the study area is managed by federal and state agencies.

Climate

The climate of the GBCAAS study area varies substantially with both land-surface altitude and latitude. The eastern Great Basin is generally categorized as having a dry, mid-latitude “semi-arid” or “steppe” climate. This climate zone includes areas between latitudes of 35° to 55° N having a range in average daily temperature of about 25°C and annual precipitation from less than 4 in. to more than 20 in. (Strahler, 1989). More detailed climate zones have been described for the region, and the majority of the GBCAAS study area is within the “Great Basin Woodland and Desert” climatic zone. The southernmost portion of the study area, including the Las Vegas area and the southern part of the Death Valley region, is located within the warmer and drier “Mohave Desert” climate zone. A narrow east-west band north of Las Vegas and south of Cedar City is categorized as the “Transition Desert” climatic zone (Belcher, 2004). The highest mountains within the study area are categorized as the “Highland Climate/Alpine Biome” zone (Strahler, 1989).

Average annual precipitation within the GBCAAS study area between 1940 and 2006 ranged from 1.5 in. in Death Valley National Park to 70 in. in the Wasatch Range east of Salt Lake City and Logan, Utah (Daly and others, 2004; 2008). Precipitation data were evaluated beginning in 1940 to be consistent with the compilation of other hydrologic data, which are generally available back to the 1940s. Most of the precipitation in the study area falls as snow in the mountains at higher latitudes. Less precipitation falls in the valley bottoms and at lower latitudes and typically occurs as rainfall. Precipitation predominantly occurs in winter and early spring, with moisture coming along storm tracks from the Pacific Ocean. A second period of higher precipitation during late summer and early fall is associated with the summer monsoonal moisture from the Gulf of California and the Gulf of Mexico (Brenner, 1974; Weng and Jackson, 1999). This monsoonal precipitation is more pronounced in the southern part of the study area.

During the 20th century, greater-than-average precipitation occurred from 1977 through 1998, possibly linked with the positive warm phase of the Pacific Decadal Oscillation (PDO) and a cool phase of the Atlantic Multidecadal Oscillation (AMO; Gray and others, 2003). This conclusion is supported by tree-ring based precipitation reconstructions spanning the period 1226–2001 in the Uinta Basin of Duchesne County, Utah (east of the GBCAAS study area; fig. A–1) that show the period 1960–2000 was the second-wettest multi-decadal period of the past 775 years (Gray and others, 2004).

Surface-Water Hydrology

Because of the generally semi-arid climate within the GBCAAS study area, surface-water resources are limited and unevenly distributed across the study area. About one dozen rivers and many smaller perennial streams either originate in or flow through the GBCAAS study area (fig. A–1; pl. 1). Four of the larger rivers (the Bear, Ogden, Weber, and Provo Rivers) originate in mountains east of the study area and flow westward through the Wasatch Range. Canals and aqueducts (transbasin diversions) also bring surface water through the Wasatch Range into the study area. Rivers originating in the Wasatch Range include the Jordan, Sevier, and Beaver Rivers. All of the basins associated with these rivers drain internally within the GBCAAS study area and the rivers terminate in either Great Salt Lake or Sevier Lake (commonly a dry playa), where evaporation is the only form of discharge. These terminal lake/playa systems are saline remnants of ancestral Lake Bonneville, which inundated most of the basins in the northeast part of the study area during the Pleistocene. The areas and stages of these lakes fluctuate in tandem with pluvial cycles (Stephens and Arnow, 1987). In Nevada, the Reese River and other tributaries to the Humboldt River are fed predominantly by snowmelt that runs off various mountain ranges in the north-central part of the state. These rivers join to form the Humboldt River near where it flows through the northwestern boundary of the study area and into the lower Humboldt watershed. In southeastern Nevada, the White River, Muddy River, and Meadow Valley Wash flow southward. Both the White River and Meadow Valley Wash cease flowing towards the south, owing to evapotranspiration and (or) seepage losses. The Muddy River discharges to the Virgin River along the southeastern boundary of the study area just above Lake Mead of the Colorado River system (fig. A–1). Flow in the Muddy River is derived almost entirely from Muddy River Springs at the beginning of the river (pl. 1).

As a result of the arid climate and basin-and-range topography, surface water generally does not flow between basins. The exceptions are the larger river systems, including the Bear, Beaver, Humboldt, Jordan, Muddy, Reese, Sevier, and White Rivers (fig. A–1). Transbasin diversions also move surface water between basins. Other than Lake Mead along the lower Colorado River, most of the larger lakes in the study area are located along the Wasatch Front and include Great Salt Lake, Utah Lake, and Sevier Lake. Playas are found in some internally drained basins. Playas are dry or ephemeral lakebeds that form in semi-arid to arid regions in closed evaporative basins and either receive surface-water flow and typically are nonsaline or receive groundwater discharge and typically are saline. The largest playa is in the Great Salt Lake Desert in the northeast part of the study area. This large playa forms a salt flat and is a remnant of ancient Lake Bonneville.

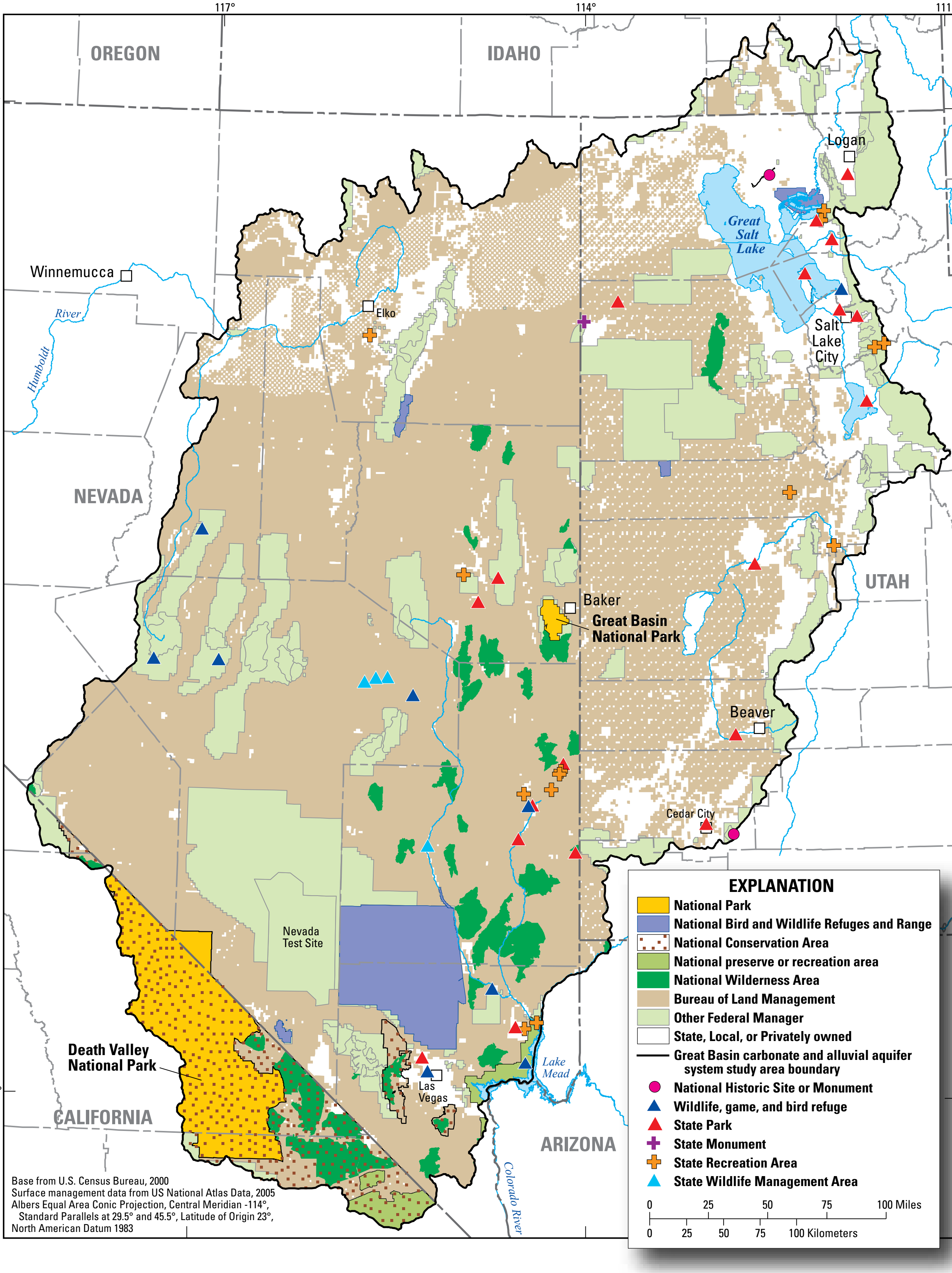

Figure A–3. Location of national and state parks, monuments, wilderness areas, and conservation areas in the Great Basin carbonate and alluvial aquifer system study area.

Summary

The Great Basin carbonate and alluvial aquifer system, located within the Basin and Range physiographic province, spans a large, topographically and climatologically diverse region that covers 110,000 mi^2. Altitudes range from below sea level in Death Valley to more than 14,000 ft in the mountains along the California border. Although most of the study area can be categorized as having a semi-arid or steppe climate, the extreme southwestern basins have an arid desert climate and the extreme northeastern mountains have an alpine/tundra climate. Annual precipitation ranges from 1.5 in. in southern Nevada and eastern California to 70 in. in northern Utah. Most of the precipitation falls during the winter as snowfall in the mountains at higher latitudes and is associated with storms originating in the Pacific Ocean, although substantial rainfall also can occur in late summer and early autumn, coincidental with monsoonal moisture that moves northward from the Gulf of Mexico and Gulf of California.

The GBCAAS study area has limited surface-water resources. The semi-arid setting, combined with rapid growth and high water use, has led to an increased dependence upon groundwater resources in many parts of the study area during the past 7 decades. The primary purpose of this report is to update and expand the conceptual model of this aquifer system that was initially developed during the RASA–GB study to evaluate regional groundwater availability. It also integrates newer subregional USGS studies such as the DVRFS and BARCAS into a comprehensive regional conceptual model. Particular objectives include (1) updating water budgets for the aquifer system (recharge and discharge components); (2) compiling current estimates and evaluating historic trends in groundwater use, storage, recharge, and discharge; and (3) updating the regional hydrogeologic framework. This updated and expanded conceptual model includes a more-detailed characterization of hydrogeologic units, the construction of a three-dimensional hydrogeologic framework, the evaluation of groundwater movement, depiction of groundwater levels in a potentiometric map, and the compilation of groundwater budgets.

References Cited

Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., Klemperer, S.L., Nelson, K.D., Knuepfer, P., and Oliver, J.E., 1987, Overview of the COCORP 40°N Transect, western United States: The fabric of an orogenic belt: Geological Society of America Bulletin, v. 98, p. 308–319.

Axen, G.J., Taylor, W.J., and Bartley, J.M., 1993, Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the western United States: Geological Society of America Bulletin, v. 105, p. 56–76.

Belcher, W.R., ed., 2004, Death Valley regional ground-water flow system, Nevada and California—Hydrogeologic and transient ground-water flow model: U.S. Geological Survey Scientific Investigations Report 2004–5205, 408 p., 2 pls.

Belcher, W.R., Elliot, P.E., and Geldon, A.L., 2001, Hydraulic-property estimates for use with a transient ground-water flow model of the Death Valley regional ground-water flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 01–4210, 28 p., 1 pl.

Bergquist, G., 1994, Per capita water use, *in* Strategic Assessment of Florida's Environment (SAFE): Florida Department of Environmental Protection, Tallahassee, Florida, p. 278–281.

Brenner, I.S., 1974, A surge of maritime tropical air—Gulf of California to southwestern United States: Monthly Weather Review, v. 102, p. 375–389.

Brooks, L.E., and Mason, J.L., 2005, Hydrology and simulation of ground-water flow in Cedar Valley, Iron County, Utah: U.S. Geological Survey Scientific Investigations Report 2005–5170, 114 p.

Burbey, T.J., 1997, Hydrogeology and potential for ground-water development, carbonate-rock aquifers, southern Nevada and southeastern California: U.S. Geological Survey Water-Resources Investigations Report 95–4168, 65 p., 1 pl. in pocket.

Cablk, M.E., and Kratt, C., 2007, A methodology for mapping shrub canopy cover in the Great Basin Desert using high spatial resolution satellite imagery: Desert Research Institute Publication No. 41236, 22 p.

Cardinalli, J.L., Roach, L.M., Rush, F.E., and Vasey, B.J., 1968, State of Nevada hydrographic areas, scale 1:500,000, *in* Rush, F.E., ed., Index of hydrographic areas: Nevada Division of Water Resources Information Report 6, 38 p.

Cederberg, J.R., Gardner, P.M., and Thiros, S.A., 2008, Hydrology of northern Utah Valley, Utah County, Utah, 1975–2005: U.S. Geological Survey Scientific Investigations Report 2008–5197, 97 p.

Daly, C., Gibson, W.P., Doggett, M., Smith, J., and Taylor, G., 2004, Up-to-date monthly climate maps for the conterminous United States, *in* Conference on Applied Climatology, 14th, American Meteorological Society 84th Annual Meeting, January 13–16, 2004, Seattle, Paper 5.1.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., and Pasteris, P.A., 2008, Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States: International Journal of Climatology, v. 6, no. 15, p. 2,031–2,064, doi: 10.1002/joc.1688, accessed March 6, 2008 at http://onlinelibrary.wiley.com/doi/10.1002/joc.1688/abstract.

Daly, C., Nielson, R.P., and Philips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, no. 2, p. 140–158, accessed June 11, 2007 at doi: 10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2 link to the publication at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0450%281994%29033%3C0140%3AASTMFM%3E2.0.CO%3B2.

Dettinger, M.D., 1989, Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-balance calculations: Journal of Hydrology, v. 106, p. 55–78.

Dettinger, M.D., Harrill, J.R., Schmidt, D.L., and Hess, J.W., 1995, Distribution of carbonate-rock aquifers and the potential for their development, southern Nevada and parts of Arizona, California, and Utah: U.S. Geological Survey Water-Resources Investigations Report 91–4146, 100 p., 2 pls. in pocket.

Dettinger, M.D., and Schaefer, D.H., 1996, Hydrogeology of structurally extended terrain in the eastern Great Basin of Nevada, Utah, and adjacent states, from geologic and geophysical models: U.S. Geological Survey Hydrologic Investigations Atlas HA–694-D, 1 sheet.

Epstein, B.J., 2004, Development and uncertainty analysis of empirical recharge prediction models for Nevada's desert basins, Reno, University of Nevada, M.S. Thesis, 131 p.

Faulds, J.E., and Stewart, J., eds., 1998, Accommodation zones and transfer zones—The regional segmentation of the Basin and Range: Geological Society of America Special Paper 323, 257 p.

Faunt, C.C., Sweetkind, D.S., and Belcher, W.R., 2004, Three-dimensional hydrogeologic framework model, Chap. E *of* Belcher, W.R., ed., 2004, Death Valley regional ground-water flow system, Nevada and California—Hydrogeologic framework and transient ground-water flow model: U.S. Geological Survey Scientific Investigations Report 2004–5205, p. 165–256.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Company, Inc., 534 p.

Flint, A.L., and Flint, L.E., 2007, Application of the basin characterization model to estimate in-place recharge and runoff potential in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5099, 20 p.

Gardner, P.M., 2009, Three-dimensional numerical model of ground-water flow in northern Utah Valley, Utah County, Utah: U.S. Geological Survey Scientific Investigations Report 2008–5049, 95 p.

Gates, J.S., 2004, Ground-water development in Utah and effects on ground-water levels and chemical quality *in* Spangler, L.E., ed., Groundwater in Utah: Resource, protection, and remediation: Utah Geological Association Publication 31, p. 3–26.

Gray, S.T., Betancourt, J.L., Fastie, C.L, and Jackson, S.T., 2003, Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains: Geophysical Research Letters v. 30, no. 6, p. 1,316, doi:10.1029/2002GS016154, accessed April 14, 2008 at http://www.agu.org/pubs/crossref/2003/2002GL016154.shtml.

Gray, S.T., Jackson, S.T., and Betancourt, J.L, 2004, Tree-ring based reconstructions of interannual to decadal scale precipitation variability for northeastern Utah since 1226 A.D.: Journal of the American Water Resources Association, Paper No. 03148, p. 947–960.

Hanks, T.C., Winograd, I.J., Anderson, R.E., Reilly, T.E., and Weeks, E.P., 1999, Yucca Mountain as a radioactive-waste repository: U.S. Geological Survey Circular C1184, 19 p.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA–694-C, 2 sheets, scale 1:1,000,000.

Harrill, J.R., and Preissler, A.M., 1994, Ground-water flow and simulated response to several developmental scenarios in Stagecoach Valley—a small partly-drained basin in Lyon and Storey Counties, Nevada: U.S. Geological Survey Professional Paper 1409–H, 74 p.

Harrill, J.R., and Prudic, D.E., 1998, Aquifer systems in the Great Basin region of Nevada, Utah, and adjacent states—Summary Report: U.S. Geological Survey Professional Paper 1409–A, 66 p.

Hershey, R.L., Heilweil, V.M., Gardner, P.M., Lyles, B.F., Earman, S., Thomas, J.M., and Lundmark, K.W., 2007, Ground-water chemistry interpretations supporting the Basin and Range regional carbonate-rock aquifer system (BARCAS) study, eastern Nevada and western Utah: Desert Research Institute, Division of Hydrologic Sciences, Publication No. 41230, 86 p.

Hurlow, H.H., and Burk, N., 2008, Geology and ground-water chemistry, Curlew Valley, northwestern Utah and south-central Idaho—Implications for hydrogeology: Utah Geological Survey Special Study 126, 185 p., 2 pls.

Kirk, S.T., and Campana, M.E., 1990, A deuterium-calibrated groundwater flow model of a regional carbonate-alluvial system: Journal of Hydrology, v. 119, p. 357–388.

Laczniak, R.J., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on groundwater flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96–4109, 59 p., 4 pls.

Lundmark, K.W., 2007, Regional water budget accounting and uncertainty analysis using a deuterium-calibrated discrete state compartment model: White Pine County, Nevada, and adjacent areas in Nevada and Utah: Reno, University of Nevada, Master's Thesis, 177 p.

Lundmark, K.W., Pohll, G.M., and Carroll, R.W.H., 2007, A steady-state water budget accounting model for the carbonate aquifer system in White Pine County, Nevada, and adjacent areas in Nevada and Utah: Desert Research Institute, Division of Hydrologic Sciences, Publication No. 41235, 56 p.

Mason, J.L., 1998, Ground-water hydrology and simulated effects of development in the Milford area, an arid basin in southwestern Utah: U.S. Geological Survey Professional Paper 1409–G, 69 p., 2 pls. in pocket.

Mizell, S.A., Russell, C.E., and Kluesner, T.L., 2007, Reconnaissance estimation of groundwater recharge to selected hydrographic basins of eastern Nevada and western Utah using the chloride mass-balance method: Desert Research Institute Publication No. 41232, 29 p.

Moreo, M.T., Laczniak, R.J., and Stannard, D.I., 2007, Evapotranspiration rate measurements of vegetation typical of ground-water discharge areas in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah, September 2005–August 2006: U.S. Geological Survey Scientific Investigations Report 2007–5078, 36 p.

Nichols, W.D., 2000, Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada: U.S. Geological Survey Professional Paper 1628, 82 p., 4 pls. in pockets, optical disc in pocket.

Page, W.R., Dixon, G.L., Rowley, P.D., and Brickey, D.W., 2005, Geologic map of parts of the Colorado, White River, and Death Valley groundwater flow systems, Nevada, Utah, and Arizona: Nevada Bureau of Mines and Geology Map 150, 21 p., scale 1:250,000.

Page, W.R., Scheirer, D.S., and Langenheim, V.E., 2006, Geologic cross sections of parts of the Colorado, White River, and Death Valley regional ground-water flow systems, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 2006–1040, 23 p., 1 pl.

Pavelko, M.T., 2007, Spring database for the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Data Series 272, 10 p., with downloadable database, accessed November 29, 2010, from http://pubs.usgs.gov/ds/2007/272/.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA 694–A, 1 sheet, scale 1:1,000,000.

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995, Conceptual evaluation of regional ground-water flow in the Carbonate-Rock Province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409–D, 102 p.

Prudic, D.E., and Herman, M.E., 1996, Ground-water hydrology and simulated effects of development in Paradise Valley, a basin tributary to the Humboldt River in Humboldt County, Nevada: U.S. Geological Survey Professional Paper 1409–F, 92 p.

Reilly, T.E., Dennehy, K.F., Alley, W.M., and Cunningham, W.L., 2008, Ground-water availability in the United States: U.S. Geological Survey Circular 1323, 70 p.

Rush, F.E., 1968, Index of hydrographic areas in Nevada: Nevada Division of Water Resources Information Report 6, 38 p.

Saltus, R.W., and Jachens, R.C., 1995, Gravity and basin-depth maps of the Basin and Range province, western United States: U.S. Geological Survey Geophysical Investigation Map GP–1012, 1 sheet, scale 1:2,500,000.

Smith, J.L., Laczniak, R.J., Moreo, M.T., and Welborn, T.L., 2007, Mapping evapotranspiration units in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5087, 20 p., with downloadable video, accessed November 29, 2010, at http://pubs.usgs.gov/sir/2007/5087/.

Snow, J.K., and Wernicke, B., 2000, Cenozoic tectonism in the central Basin and Range; magnitude, rate, and distribution of upper crustal strain: American Journal of Science, v. 300, p. 659–719.

Stephens, D.W., and Arnow, T., 1987, Fluctuations of water level, water quality, and biota of Great Salt Lake, Utah, 1847–1986, *in* Cenozoic Geology of Western Utah—Sites for precious metal and hydrocarbon accumulations: Utah Geological Association Publication 16, p. 182–194.

Stolp, B.J., and Brooks, L.E., 2009, Hydrology and simulation of ground-water flow in the Tooele Valley ground-water basin, Tooele County, Utah: U.S. Geological Survey Scientific Investigations Report 2009–5154, 86 p., 3 appendixes, 1 pl., accessed December 3, 2010 at http://pubs.usgs.gov/sir/2009/5154/.

Strahler, A.N., 1989, Elements of Physical Geography, 4th edition: John Wiley and Sons, New York, 565 p.

Thomas, J.M., Calhoun, S.C., and Apambire, W.B., 2001, A deuterium mass-balance interpretation of groundwater sources and flows in southeastern Nevada: Desert Research Institute Publication no. 41169, p. 46.

Thomas, J.M., Mason, J.L., and Crabtree, J.D., 1986, Ground-water levels in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–B, 2 sheets, scale 1:1,000,000.

Thomas, J.M., Welch, A.H., and Dettinger, M.D., 1996, Geochemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409–C, 100 p., 2 pls. in pocket.

U.S. Census Bureau, 2005, Population projection program: U.S. Department of Commerce, accessed April 21, 2005 at http://www.census.gov/ipc/www/usinterimproj/.

U.S. Water News, June 2005, Utah searches for ways to satisfy thirst of a growing state, accessed July 7, 2005 at http://uswaternews.com/archives/arcsupply/5utahsear6.html.

Watson, P., Sinclair, P., and Waggoner, R., 1976, Quantitative evaluation of a method for estimating recharge to the desert basins of Nevada: Journal of Hydrology, v. 31, p. 335–357.

Welborn, T.L., and Moreo, M.T., 2007, Irrigated acreage within the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Data Series 273, 18 p., with downloadable geodatabase, accessed November 29, 2010, at http://pubs.usgs.gov/ds/2007/273/.

Welch, A.H., Bright, D.J., and Knochenmus, L.A., eds., 2007, Water resources of the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5261, 96 p., 4 pls., with downloadable appendix, accessed November 29, 2010, at http://pubs.usgs.gov/sir/2007/5261/.

Weng, C., and Jackson, S.T., 1999, Late glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona: Paleogeography, Paleoclimatology, Paleoecology, v. 153, p. 179–201.

Wilson, J.W., 2007, Water-level surface maps of the carbonate-rock and basin-fill aquifers in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5089, 10 p., with downloadable appendix, accessed November 29, 2010, at http://pubs.usgs.gov/sir/2007/5089/.

Workman, J.B., Menges, C.M., Page, W.R., Taylor, E.M., Ekren, E.B., Rowley, P.D., Dixon, G.L., Thompson, R.A., and Wright, L.A., 2002, Geologic map of the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2381–A, 26 p., 2 sheets, scale 1:250,000.

Zhu, J., Young, M.H., and Cablk, M.E., 2007, Uncertainty analysis of estimates of ground-water discharge by evapotranspiration for the BARCAS study area: Desert Research Institute, Division of Hydrologic Sciences, Publication No. 41234, 28 p.