Chapter D: Estimated Groundwater Budgets

By Melissa D. Masbruch, Victor M. Heilweil, Susan G. Buto, Lynette E. Brooks,
David D. Susong, Alan L. Flint, Lorraine E. Flint, and Philip M. Gardner

Chapter D 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 D: Estimated Groundwater Budgets

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An important component of the Great Basin carbonate and alluvial aquifer system (GBCAAS) conceptual model is the quantification of groundwater fluxes moving through the region. The groundwater budgets presented in this report provide an estimate of recharge and discharge within the GBCAAS study area.

Detailed budgets are presented for average annual conditions prior to substantial groundwater development that began in the 1940s, as well as for the year 2000. In addition, annual well withdrawals are estimated for 1940–2006. In most hydrographic areas (HAs), current conditions are assumed to be representative of predevelopment conditions because groundwater development has been minimal. Predevelopment recharge estimates, however, do include the effects of surface-water development, including imported water in irrigated areas. Much of this surface-water development occurred from the 1850s to 1940; data and reports prior to 1940 are sparse. This lack of data precludes analysis of hydrologic conditions prior to surface-water development. Prior to the 1940s, recharge from irrigation with surface water was a significant part of the budget only in the Great Salt Lake groundwater flow system (38) (specifically in Utah Valley Area, HA 265; Salt Lake Valley, HA 267; East Shore Area, HA 268; Cache Valley, HA 272; and Malad-Lower Bear River Area, HA 273). Groundwater development since the 1940s has led to increased recharge, generally as groundwater irrigation return flow. In addition, surface-water development from the Colorado River and Lake Mead since the early 1940s has led to increased groundwater recharge in Las Vegas Valley (HA 212).

Because significant groundwater development in the GBCAAS study area began in the 1940s, conditions prior to 1940 represent the predevelopment budgets presented in this report. The primary objectives of this chapter are to present estimates of (1) groundwater recharge- and discharge-budgets for predevelopment conditions, and (2) the effects of groundwater development (well withdrawals) during 1940–2006 on groundwater budgets.

The current study presents an alternative groundwater-budget conceptualization to previous groundwater studies regarding groundwater recharge and discharge in the mountain block. Beginning with groundwater studies in the 1940s, recharge estimates were based on a percentage of precipitation in the mountains calibrated to groundwater discharge in the adjacent basin-fill aquifer (Maxey and Eakin, 1949). These early studies did not consider groundwater discharge in the mountain block and, therefore, they provide an estimate of "net" recharge. More recent spatially distributed water-balance recharge methods estimate "total" recharge in the mountains, a fraction of which becomes groundwater discharge to mountain streams and springs and is removed from the groundwater system. If groundwater discharge in the mountain block is not removed from the groundwater budget, estimates of groundwater discharge from an HA as subsurface outflow may be overestimated. The earlier "net" recharge estimates have typically been used by regulatory agencies for developing HA-based estimates of safe or perennial yield for allocating water rights. The newer spatially distributed "total" recharge estimates are typically higher, and should not be used for managing water resources without also considering losses associated with groundwater discharge in the mountain block.

Organization of Groundwater Budgets

The GBCAAS study area comprises 165 HAs, which typically define a topographic basin including the surrounding mountains (pl. 1). Most of the previous groundwater-budget estimates are for individual or groups of HAs. Because these previous estimates usually apply to individual HAs and because socio-political, water-related decisions often are based on HA boundaries, an HA-level approach was used to compile previous estimates and to compare previous estimates with current study estimates. For most HAs, previous groundwater-budget estimates were developed only for the basin part of an HA and did not include the surrounding mountains (except as a source of recharge to the basin). This study estimates groundwater budgets for entire HAs and, therefore, the current study estimates are not directly comparable to the previous studies' estimates for partial HAs.

The preparation of the groundwater budgets for each HA and groundwater flow system included compiling all previously published estimates (Auxiliary 2) and developing current study estimates for each budget component, except subsurface inflow and outflow. The budget component data are presented in tables by HA and groundwater flow system in the Auxiliary 3 files. Appendix 4 presents current study recharge estimates for predevelopment conditions and ranges of previously reported total recharge estimates by HA. Appendix 5 presents current study discharge estimates for predevelopment conditions and ranges of previously reported total discharge estimates by HA. More recent (year 2000) groundwater-budget estimates for each HA are presented in Appendix 7.

The HA-based groundwater-budget estimates in Appendixes 4, 5, and 7 were then used to develop budgets for each of the 17 groundwater flow systems of the GBCAAS study area, defined in Chapter C of this report (pl. 1). To determine the groundwater budgets for these groundwater flow systems, recharge and discharge components for each HA within the groundwater flow system were summed. The predevelopment groundwater flow system recharge and discharge budgets are presented in tables D–1 and D–2, respectively, along with ranges of previously reported recharge and discharge. Subsurface flow between groundwater flow systems was not estimated for the current study. For comparison purposes, the previously reported recharge and discharge estimates, therefore, were adjusted to also exclude subsurface flow. Previously reported estimates of subsurface inflow are listed by HA and groundwater flow system in Auxiliaries 3E and 3F, respectively. Previously reported estimates of subsurface outflow are listed by HA and groundwater flow system in Auxiliaries 3M and 3N, respectively. Recent (2000) groundwater flow system budgets are presented in table D–3.

Predevelopment Groundwater Recharge

Groundwater Recharge Processes

Precipitation within the GBCAAS study area is the primary source of groundwater recharge. The majority of precipitation comes as winter snowfall on the mountain ranges, with lesser amounts falling as rain. Infiltration of precipitation and snowmelt within the mountain block provides (1) discharge to mountain springs and baseflow to mountain streams; (2) inflow to the adjacent basin fill, also referred to as mountain-block recharge (Wilson and Guan, 2004); and (3) recharge to consolidated bedrock aquifers, which typically follows deeper and longer flow paths to regional discharge locations, including large springs and areas of evapotranspiration (fig. C–1). The majority of groundwater recharge within the study area is assumed to occur in the higher altitude mountain ranges as direct infiltration of precipitation (in-place recharge), which, in part, is controlled by bedrock permeability in the

Table D–1. Current study annual groundwater-recharge estimates for predevelopment conditions and ranges of previously reported estimates of annual groundwater recharge for each of the 17 groundwater flow systems within the Great Basin carbonate and alluvial aquifer system study area.

[All values (except Flow system area and In-place recharge rate) are in acre-feet per year rounded to two significant figures. Estimated error in all values is ±50 percent. Groundwater flow system name: number in parentheses following name is groundwater flow system number. Flow system area: mi², square miles. In-place recharge rate: ft/yr, feet per year. Subsurface inflow: groundwater recharge by subsurface inflow between groundwater flow systems considered possible, likely, or unlikely based on information given on plate 2. Previously reported total groundwater recharge minimum and maximum: totals adjusted to exclude reported recharge by subsurface inflow (see Auxiliary 3F). Abbreviations: N/A, Not Applicable; —, no estimate]

Groundwater flow system name	Flow system area (mi²)	Current study groundwater recharge estimates							Previously reported estimates	
		In-place recharge rate (ft/yr)	In-place recharge	Runoff	Mountain stream baseflow	Imported surface water	Subsurface inflow	Total groundwater recharge	Total groundwater recharge (minimum)	Total groundwater recharge (maximum)
Humboldt System (7)	10,375	0.04	240,000	120,000	4,400	20,000	Possible	380,000	310,000	840,000
Monte Cristo Valley (23)	282	1.33	1,200	63	0	—	Possible	1,300	400	3,300
South-Central Marshes (24)	5,790	0.06	50,000	4,700	5	—	Possible	55,000	27,000	120,000
Grass Valley (25)	598	0.63	16,000	1,400	0	—	Possible	17,000	9,100	31,000
Northern Big Smoky Valley (26)	1,313	0.29	58,000	28,000	1,400	—	Possible	87,000	52,000	78,000
Diamond Valley System (27)	3,156	0.12	94,000	15,000	390	—	Unlikely	110,000	42,000	180,000
Death Valley System (28)[1]	17,362	0.02	100,000	4,000	28	—	Possible	100,000	50,000	190,000
Newark Valley System (29)	1,446	0.26	33,000	1,500	0	—	Possible	34,000	16,000	72,000
Railroad Valley System (30)	4,120	0.09	65,000	2,900	60	—	Likely	68,000	49,000	140,000
Independence Valley System (32)	1,040	0.36	26,000	2,500	0	—	Possible	28,000	30,000	110,000
Ruby Valley System (33)	1,300	0.29	64,000	14,000	750	—	Possible	79,000	60,000	170,000
Colorado System (34)	16,508	0.02	240,000	9,600	370	—	Possible	250,000	100,000	540,000
Goshute Valley System (35)	3,658	0.10	120,000	5,500	360	—	Possible	130,000	69,000	230,000
Mesquite Valley (36)	457	0.82	1,900	14	0	—	Possible	1,900	1,000	5,500
Great Salt Lake Desert System (37)	18,849	0.02	440,000	31,000	640	—	Possible	470,000	330,000	480,000
Great Salt Lake System (38)	13,823	0.03	1,000,000	260,000	110,000	960,000	Unlikely	2,300,000	1,700,000	1,900,000
Sevier Lake System (39)	10,475	0.04	310,000	71,000	11,000	12,000	Unlikely	400,000	320,000	320,000
Study area total			**2,900,000**	**570,000**	**130,000**	**990,000**	**N/A**	**4,500,000**	**3,200,000**	**5,400,000**

[1]Penoyer Valley, which Harrill and others (1988) defined as a separate groundwater flow system, is included in the Death Valley System in this report.

mountain blocks. This assumption is supported by analysis of environmental tracers and coupled flow/thermal modeling as part of a detailed groundwater study in Salt Lake Valley (HA 267) (Manning and Solomon, 2003; 2005).

Previous groundwater studies in the eastern Great Basin, beginning with Maxey and Eakin (1949), generally developed groundwater budgets focused on the basin-fill (valley) portion of each HA, where groundwater was being developed as a resource. In recent years, groundwater development, targeting permeable consolidated rock beneath the unconsolidated basin-fill deposits and in the surrounding mountains, has increased. Also, a new class of spatially distributed recharge estimation techniques utilizing water-balance methods has been developed that provides estimates for "total" recharge of precipitation in a watershed or HA (Flint and Flint, 2007a; 2007c; Hevesi and others, 2003; Leavesley and others, 1983; Markstrom and others, 2008). This is in contrast to the earlier estimation techniques, which were typically calibrated to groundwater discharge in the valleys, and provided estimates of "net" recharge to the unconsolidated basin-fill aquifer. These earlier methods did not consider groundwater discharge within the mountain block as stream baseflow and spring discharge, nor the subsequent recharge of a portion of this water as infiltration of runoff to unconsolidated basin-fill deposits. The current GBCAAS study considers all forms of recharge to and discharge from the groundwater system, including the surrounding mountains. This can be illustrated by considering the fate of recharge from direct infiltration of mountain precipitation and subsurface inflow from adjacent HAs to permeable consolidated rock of the mountain block (R1 and R4 of fig. D–1). Part of this recharge moves directly through the subsurface from the mountain block into the adjacent unconsolidated basin fill (fig. D–1). Another part of this recharge becomes groundwater discharge to mountain streams and springs (D1 of fig. D–1). A fraction of this mountain-block groundwater discharge is consumptively

Table D–2. Current study annual groundwater-discharge estimates for predevelopment conditions and ranges of previously reported estimates of annual groundwater discharge for each of the 17 groundwater flow systems within the Great Basin carbonate and alluvial aquifer system study area.

[All values (except flow system area) are in acre-feet per year rounded to two significant figures. Estimated error in all values is ±30 percent. Groundwater flow system name: number in parentheses following name is groundwater flow system number. Flow system area: mi², square miles. Subsurface outflow: groundwater discharge to subsurface groundwater outflow between groundwater flow systems that is considered possible, likely, or unlikely based on information given on plate 2. Previously reported total groundwater discharge minimum and maximum: totals adjusted to exclude groundwater discharge by subsurface outflow (see Auxiliary 3N). Abbreviations: ETg, groundwater evapotranspiration; N/A, Not Applicable; —, no estimate]

Groundwater flow system name	Flow system area (mi²)	Current study groundwater discharge estimates							Previously reported estimates	
		ETg	Mountain streams	Basin-fill streams/lakes/reservoirs	Springs	Sub-surface outflow	Adjustment to natural discharge for well withdrawals	Total groundwater discharge	Total groundwater discharge (minimum)	Total groundwater discharge (maximum)
Humboldt System (7)	10,375	240,000	15,000	14,000	28,000	Possible	600	300,000	[2]120,000	[2]170,000
Monte Cristo Valley (23)	282	400	0	0	0	Likely	0	400	400	400
South-Central Marshes (24)	5,790	58,000	46	0	4,800	Possible	0	63,000	63,000	63,000
Grass Valley (25)	598	7,500	0	0	1,500	Likely	0	9,000	—	—
Northern Big Smoky Valley (26)	1,313	62,000	4,700	0	2,300	Possible	0	69,000	64,000	77,000
Diamond Valley System (27)	3,156	44,000	1,500	0	12,000	Likely	0	58,000	53,000	60,000
Death Valley System (28)[1]	17,362	66,000	280	61	35,000	Possible	0	100,000	86,000	110,000
Newark Valley System (29)	1,446	22,000	0	0	9,700	Possible	0	32,000	[3]20,000	[3]72,000
Railroad Valley System (30)	4,120	65,000	600	300	32,000	Possible	0	98,000	95,000	100,000
Independence Valley System (32)	1,040	26,000	0	0	3,300	Possible	0	29,000	[3]28,000	[3]130,000
Ruby Valley System (33)	1,300	64,000	2,500	0	12,000	Possible	0	78,000	[3]76,000	[3]180,000
Colorado System (34)	16,508	62,000	3,700	39,000	130,000	Possible	0	230,000	160,000	210,000
Goshute Valley System (35)	3,658	83,000	3,600	0	45,000	Possible	0	130,000	120,000	180,000
Mesquite Valley (36)	457	2,200	0	0	0	Unlikely	0	2,200	2,200	2,200
Great Salt Lake Desert System (37)	18,849	330,000	4,500	0	110,000	Possible	1,600	450,000	370,000	450,000
Great Salt Lake System (38)	13,823	430,000	370,000	570,000	520,000	Possible	260,000	2,200,000	1,800,000	2,000,000
Sevier Lake System (39)	10,475	210,000	40,000	37,000	47,000	Possible	71,000	400,000	[2]350,000	[2]350,000
Study area total		**1,800,000**	**450,000**	**660,000**	**990,000**	**N/A**	**330,000**	**4,200,000**	**3,400,000**	**4,200,000**

[1]Penoyer Valley, which Harrill and others (1988) defined as a separate groundwater flow system, is included in the Death Valley System in this report.

[2]Previously reported estimates are lower than current study estimates because there were no previously reported total groundwater-budget estimates for all of the HAs within this flow system.

[3]Previously reported estimates include those by Nichols (2000), which are suspected to be too high (did not use Nichols (2000) in calculations of current study estimates; see text for explanation).

lost as evapotranspiration, both in the mountains and as this water enters the valley in streams and canals. A fraction of the remaining mountain-block groundwater discharge, combined with surface-water runoff from precipitation in the mountains, becomes recharge to the unconsolidated basin fill (R2 and R3 of fig. D–1). This water ultimately discharges naturally in the valley lowlands as evapotranspiration and basin-fill springs and streams (D2 and D3 of fig. D–1), well withdrawals (D4 of fig. D–1), or subsurface outflow (D5 of fig. D–1). To include the partial loss of in-place recharge as groundwater discharge in the mountains to streams and springs, the newer spatially distributed recharge methods often yield higher "total" recharge estimates for an HA than the previous Maxey-Eakin type of "net" basin-fill recharge estimates. The Nevada State Engineer bases water rights appropriations by HA on perennial yield quantities that have typically been based on the earlier Maxey-Eakin type of recharge estimates. The Nevada Division of Water Resources (2010) definition of perennial yield is

> *The amount of usable water from a groundwater aquifer that can be economically withdrawn and consumed each year for an indefinite period of time. It cannot exceed the natural recharge to the aquifer and ultimately is limited to maximum amount of discharge that can be utilized for beneficial use.*

The newer spatially distributed recharge estimates may cause over-appropriations if the consumptive losses of groundwater discharge in the mountains are not also considered.

The spatial distribution of average annual 1940–2006 precipitation shown on figure D–2 is used for estimating both predevelopment and recent (2000) recharge for the study area (see "Basin Characterization Model" section below). The precipitation data were based on the PRISM (Parameter-elevation Regressions on Independent Slopes Model) 4,000-m grid (Daly and others, 1994, 2008) resampled to a 270-m grid as

Table D–3. Predevelopment and recent (2000) groundwater-budget estimates for each of the 17 groundwater flow systems within the Great Basin carbonate and alluvial aquifer system study area.

[All values (except flow system area) are in acre-feet per year rounded to two significant figures. Estimated error in recharge values is ±50 percent. Estimated error in discharge values is ± 30 percent. Values in blue are for predevelopment conditions. Values in red are for recent (2000) conditions. Groundwater flow system name: number in parantheses following name is groundwater flow system number. Flow system area: mi², square miles; Abbreviations —, no estimate]

Groundwater flow system name	Flow system area (mi²)	Groundwater recharge for pre-development conditions	Recharge from unconsumed irrigation and public supply water from well withdrawals (2000)	Groundwater recharge for recent (2000) conditions	Groundwater discharge for pre-development conditions	Well withdrawals (2000)	Decrease in natural discharge and/or storage (net well withdrawals) (2000)	Minimum decrease in groundwater storage (2000)	Groundwater discharge for recent (2000) conditions
Humboldt System (7)	10,375	380,000	[2]25,000	400,000	300,000	200,000	180,000	—	320,000
Monte Cristo Valley (23)	282	1,300	6	1,300	400	20	14	—	410
South-Central Marshes (24)	5,790	55,000	16,000	71,000	63,000	52,000	36,000	—	79,000
Grass Valley (25)	598	17,000	3	17,000	9,000	10	7	—	9,000
Northern Big Smoky Valley (26)	1,313	87,000	[2]270	87,000	69,000	5,900	5,600	—	69,000
Diamond Valley System (27)	3,156	110,000	22,000	130,000	58,000	74,000	52,000	24,000	100,000
Death Valley System (28)[1]	17,362	100,000	16,000	120,000	100,000	55,000	38,000	9,300	130,000
Newark Valley System (29)	1,446	34,000	2,000	36,000	32,000	6,700	4,700	—	34,000
Railroad Valley System (30)	4,120	68,000	760	69,000	98,000	2,500	1,700	—	99,000
Independence Valley System (32)	1,040	28,000	2,800	31,000	29,000	9,400	6,600	—	32,000
Ruby Valley System (33)	1,300	79,000	1,800	81,000	78,000	5,900	4,100	—	80,000
Colorado System (34)	16,508	250,000	[3]120,000	370,000	230,000	170,000	48,000	—	350,000
Goshute Valley System (35)	3,658	130,000	3,400	130,000	130,000	12,000	8,100	—	130,000
Mesquite Valley (36)	457	1,900	3,900	5,800	2,200	13,000	9,100	—	6,100
Great Salt Lake Desert System (37)	18,849	470,000	7,900	480,000	450,000	26,000	19,000	—	460,000
Great Salt Lake System (38)	13,823	2,300,000	160,000	2,500,000	2,200,000	520,000	360,000	—	2,400,000
Sevier Lake System (39)	10,475	400,000	93,000	490,000	400,000	310,000	220,000	34,000	520,000
Study area total		**4,500,000**	**[3]470,000**	**5,000,000**	**4,200,000**	**[4]1,500,000**	**990,000**	**67,000**	**4,800,000**

[1]Penoyer Valley, which Harrill and others (1988) defined as a separate groundwater flow system, is included in the Death Valley System in this report.

[2]Adjusted to exclude well withdrawals for mining operations, which are assumed not to be applied as irrigation and therefore do not contribute to groundwater recharge.

[3]Amount includes an additional 30,000 acre-ft of recharge from injected Colorado River water [Nevada Division of Water Resources (NDWR), Water Rights Section, pumpage inventory], and 41,000 acre-ft of recharge from imported Colorado River Water (calculated as 10 percent of total imported Colorado water (440,000 acre-ft reported in NDWR pumpage inventory) minus amount injected (30,000 acre-ft)) in HA 212; imported surface water was included in this category because HA 212 is the only HA with postdevelopment surface-water importation.

[4]Includes 3,130 acre-ft of well withdrawals that were not accounted for in total study area well withdrawals in Auxiliary 4; totals do not match as this extra amount causes rounding of total in this table to increase by 100,000 acre-ft.

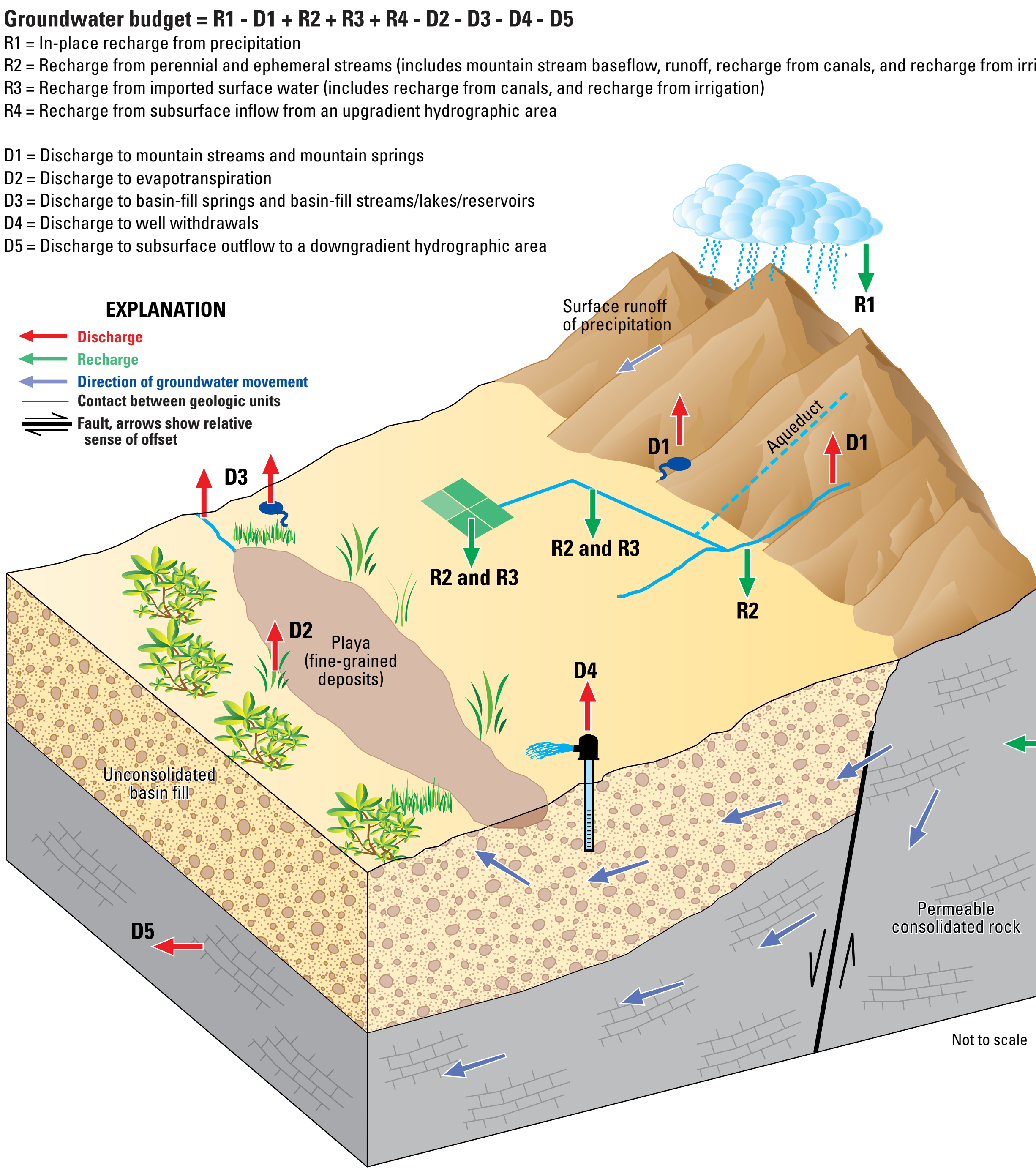

Figure D–1. Schematic diagram showing conceptualization of groundwater budget components and budget calculation for the Great Basin carbonate and alluvial aquifer system study area.

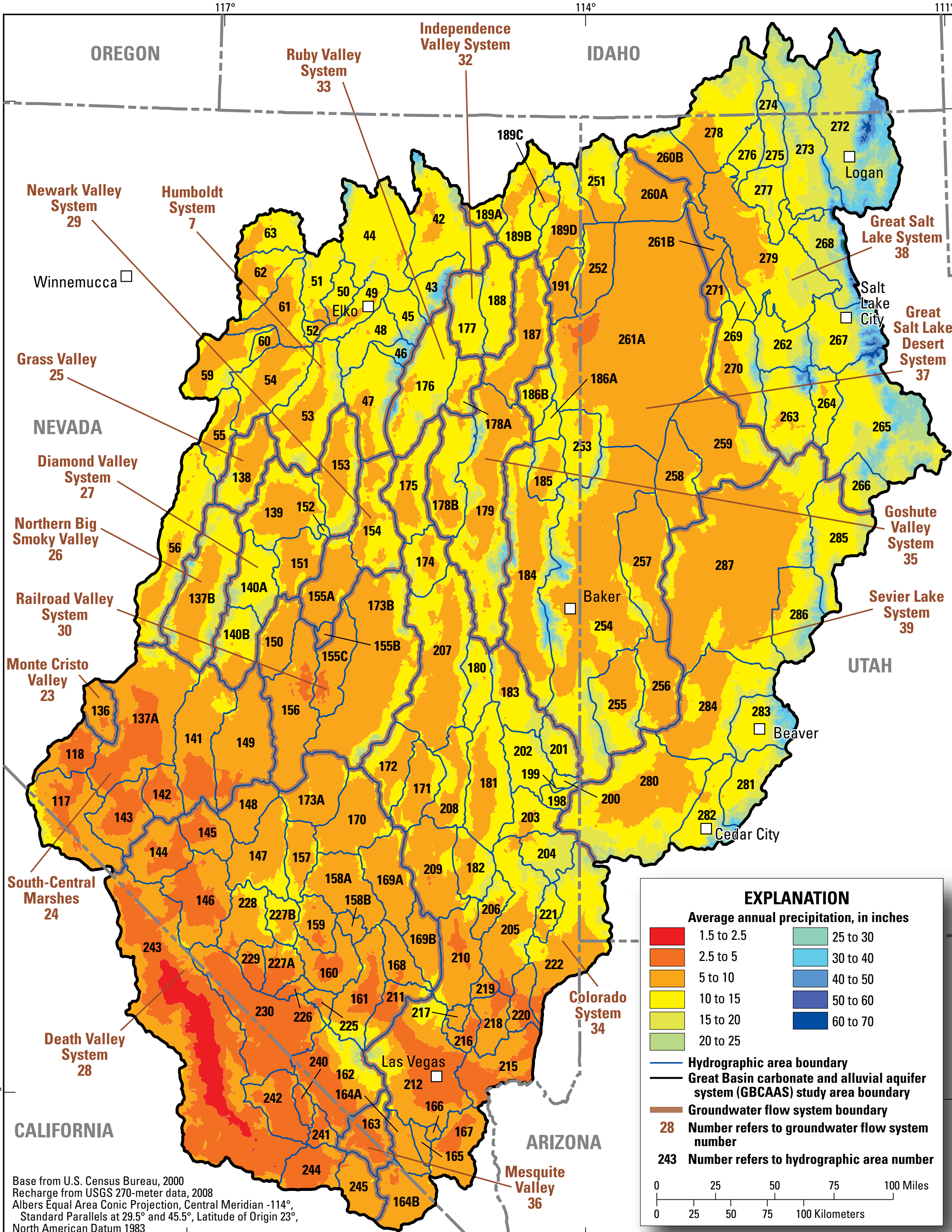

Figure D–2. Distribution of 1940–2006 average annual precipitation used as input for the Basin Characterization Model for the Great Basin carbonate and alluvial aquifer system study area.

described in Appendix 3. This 67-year period was selected for estimating predevelopment recharge because there is limited climatic data available prior to the 1940s. The highest amounts of precipitation (as much as 70 in/yr) are concentrated over the higher altitude mountains within the study area. These high precipitation areas primarily occur along the northern Wasatch Front in the Great Salt Lake groundwater flow system (38) and also in various other isolated mountain ranges throughout the study area. The driest areas are in the southwestern part of the study area in the Death Valley groundwater flow system (28), including portions of the Amargosa Desert (HA 230), Death Valley (HA 243), and Valjean Valley (HA 244), which only receive about 5 in/yr of precipitation (Appendix 2).

Estimated annual average precipitation for the study area was quite variable between 1940 and 2006, ranging from 6.7 in/yr (1953) to 16.7 in/yr (2005) with a mean of 10.7 ± 4.8 in/yr (2σ) for the 67-year period (fig. D–3). The driest periods (less than 8 in/yr) occurred in 1953, 1959–60, 1966, 1974, and 2002. The wettest periods (greater than 14 in/yr) occurred in 1941, 1980, 1982–84, 1995, 1998, and 2005. The 1980s and 1990s were abnormally wet decades, having five of the eight wettest years and none of the driest years in the 67-year period.

Precipitation that does not infiltrate into the subsurface or is not consumed by evapotranspiration and sublimation in the mountain block becomes runoff. The majority of runoff generated in the mountains flows into adjacent basins. A portion of this runoff recharges the unconsolidated deposits as infiltration beneath stream channels, irrigation canals, and irrigated fields (fig. D–1). Recharge from runoff occurs predominantly through coarser deposits along the margins of each basin.

In addition to runoff from precipitation, streamflow at the mountain front also includes baseflow. This water enters the groundwater system as in-place recharge from precipitation in the mountains and then discharges to mountain streams. A portion of this baseflow subsequently recharges basin-fill deposits as infiltration beneath the stream channel, canals, or irrigated fields.

Recharge from irrigation return flow of imported surface water originating from outside an HA also occurs in some parts of the GBCAAS study area. This water includes natural streamflow (such as rivers and streams flowing from upgradient HAs or from areas outside of the study area) and (or) imported surface water associated with engineered transbasin diversions that originate outside the HA or study area. The analysis of groundwater recharge, therefore, includes recharge from this imported surface water along streams, canals, and from irrigation.

Groundwater recharge to each HA also may include subsurface inflow (figs. C–1 and D–1). Recharge from subsurface inflow (or interbasin flow) is derived from groundwater that originates in upgradient areas and subsequently flows into downgradient areas through the subsurface in basin fill or consolidated rock. The amount of subsurface inflow depends on the hydraulic gradient across the HA or groundwater flow system boundary and the hydraulic conductivity and cross sectional area of the intervening bedrock and alluvium.

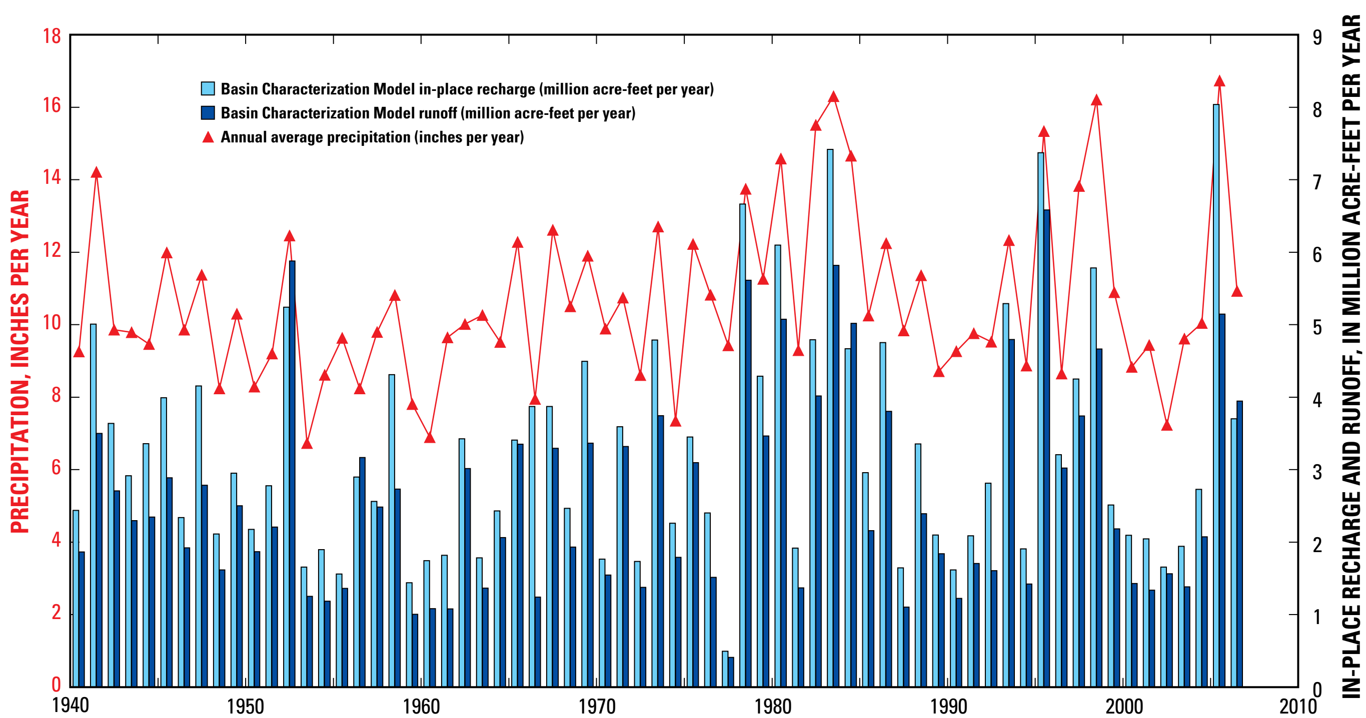

Figure D–3. Annual average precipitation and Basin Characterization Model in-place recharge and runoff for the Great Basin carbonate and alluvial aquifer system study area, water years 1940–2006.

Recharge from Precipitation

To provide estimates of annual recharge from direct infiltration of precipitation (in-place recharge) and runoff in a consistent manner across the large and climatically diverse GBCAAS study area, a regional-scale water balance method, known as the Basin Characterization Model (BCM; Flint and Flint, 2007a), was applied.

Basin Characterization Model

The BCM is a distributed-parameter water-balance accounting model used to identify areas having climatic and geologic conditions that allow for precipitation to become potential runoff or potential in-place recharge, and to estimate the amount of each. For this study, BCM calculations were made on a 270-m grid. In-place recharge is calculated as the volume of water per time that percolates through the soil zone past the root zone and becomes net infiltration to consolidated rock or unconsolidated deposits. Runoff is the volume of water per time that runs off the surface. Runoff may infiltrate the subsurface, undergo evapotranspiration further downslope, or become streamflow. The BCM does not track or route this streamflow runoff. Total groundwater recharge from precipitation is the sum of in-place recharge and the runoff that infiltrates into the subsurface (a percentage of total BCM runoff). An advantage of using a distributed-parameter water-balance model, such as the BCM, is that the model identifies likely locations of the generation of runoff and in-place recharge accounting for the temporal and spatial distribution of precipitation, snowmelt, sublimation, evapotranspiration, soil-storage capacity, and saturated hydraulic conductivity.

Input data utilized by the BCM is organized into (1) spatial data, including topography, soil porosity and coarseness for estimating soil-water storage, and saturated hydraulic conductivity for partitioning water between in-place recharge and runoff; and (2) time-series data, including precipitation and air temperature (Flint and Flint, 2007c) (Appendix 3). Other time-series input data, calculated separately, include (1) potential evapotranspiration, determined by calculations of solar radiation using topographic shading, cloudiness, and vegetation density data; and (2) snowpack accumulation and melting, modeled using precipitation and air-temperature data. A schematic illustrating the relation among the various BCM components of the model, along with specific model inputs and instructions for running the model, are given in Appendix 3.

A water-balance equation for each grid cell was developed using monthly estimates of precipitation, maximum and minimum air temperature, and potential evapotranspiration to calculate the monthly volume of runoff and in-place recharge for each grid cell. The volume of available water (AW) per unit area for soil-water storage, runoff, and in-place recharge is computed monthly for each cell in the 270-m grid on the basis of the following equation:

$$AW = P + S_m - PET - S_a + S_s \qquad \text{(D–1)}$$

where

P is the estimated precipitation for the grid cell,
S_m is the estimated snowmelt,
PET is potential evapotranspiration,
S_a is the estimated snow accumulation, and
S_s is the stored soil water from the previous month.

Energy and mass balance calculations for snow accumulation and sublimation were adapted by Lundquist and Flint (2006), as described in Appendix 3. Sublimation is controlled by radiant and turbulent fluxes and will vary from site to site. Unfortunately, sublimation rates within the study area are not well known. An initial estimate of about 0.2 in/month (5 mm/month) was applied on the basis of unpublished data from the Spring Mountains in the southwestern part of the GBCAAS study area (pl. 1); however, rates of about 0.5 in/month (12 mm/month) have been reported east of the study area in Colorado (Molotch and others, 2006). Snow accumulation that does not melt or sublimate during the month is carried over into the following month. This carry over is particularly important when temperatures are cold enough for precipitation to form snow. Because snow may persist for several months prior to melting, large volumes of water will become available for runoff and in-place recharge in the monthly time step in which melting occurs. Any remaining water in the soil zone above field capacity at the end of the month is added to soil-water storage (S_s) at the beginning of the next month. The form and amount of precipitation, the factors affecting evapotranspiration, and the mechanisms controlling drainage from the soil zone all dictate the locations where both in-place recharge and runoff occur within an HA.

Potential Evapotranspiration

Potential evapotranspiration (PET) is dependent on vegetation type and density, topography, and atmospheric conditions. Vegetation density and the percentage of bare-soil surfaces were both determined using the National Gap Analysis Program; (http://gapanalysis.nbii.gov/portal/server.pt). Daily PET values were calculated using the Priestley-Taylor Equation (Priestley and Taylor, 1972) and a detailed solar radiation model (Flint and Childs, 1987). The solar radiation model uses topographic shading, which is particularly important in mountainous terrain, and a correction for cloudiness (Flint and Flint, 2007b). PET is partitioned on the basis of vegetation cover to represent both bare-soil evaporation and transpiration due to vegetation. These results are averaged into monthly values for use in equation D–1. PET is highest during the warm summer months, which decreases the amount of water stored in the soil zone, and is lowest during the cooler winter months, which allows for increased water storage from precipitation and snowmelt. The average annual PET was approximately 55 in/yr for the study area and ranged from approximately 16 in/yr in the higher altitude mountain ranges along the Wasatch Front in Utah and in east-central Nevada to 95 in/yr on the basin floor of Death Valley (HA 243).

Soil-Water Storage

Where soils are present, thickness of the soil zone, porosity, and drainage characteristics determine how much water is stored in the soil zone. Soil properties (thickness, porosity, and particle-size distributions) used by the BCM were obtained from U.S. Department of Agriculture Natural Resource Conservation Service's State Soil Geographic Database (STATSGO) and are discussed in Appendix 3. Drainage below the root zone occurs when sufficient water is available to exceed the soil-water storage capacity of the soil (or rock), and only then does the net infiltration have the potential to become groundwater recharge.

The soil-water storage in thin soils underlain by bedrock will quickly approach saturation during and (or) after a precipitation event if the saturated hydraulic conductivity of the bedrock is low. If the soil becomes saturated, runoff will occur. In locations with thick soil, a greater volume of water is needed to exceed the soil-water storage capacity of the root zone, and saturation and runoff are less likely. If the saturated hydraulic conductivity of the underlying consolidated rocks or basin-fill deposits is low, then gravity drainage occurs slowly and evapotranspiration has more time to remove stored water between infiltration events. If the saturated hydraulic conductivity of the underlying consolidated rocks or basin-fill deposits is high, more recharge can occur during and after an infiltration event. Also, if the soil-water storage capacity is high and the saturated hydraulic conductivity of the soil zone is low (for example, for finer grained silts and clays) then drainage through the root zone occurs slowly and evapotranspiration processes can remove more stored water between infiltration events.

Geology

One factor controlling in-place recharge in the BCM is the saturated hydraulic conductivity of consolidated rocks in the mountains or basin-fill deposits on the alluvial fans and basin floor. When moisture in the soil zone exceeds field capacity, the rate of infiltration (in-place recharge) is set equal to the saturated hydraulic conductivity of the underlying consolidated rocks or basin-fill deposits, assuming a unit vertical hydraulic gradient. To account for spatial differences in saturated hydraulic conductivity, the geology of the GBCAAS study area was categorized into 57 geologic units for estimating saturated hydraulic conductivity (Appendix 3, table A3–1). These geologic units primarily are based on differences in permeability (rock and soil type) rather than geologic age. Estimates of saturated hydraulic conductivity values were based on a calibration of BCM runoff to gaged mountain stream discharge (Appendix 3, table A3–2). For an equal amount of available water (eq. D–1), areas with low saturated hydraulic conductivity will generate a higher percent of runoff relative to in-place recharge; areas with high saturated hydraulic conductivity will generate a smaller percent of runoff relative to in-place recharge.

Estimated saturated hydraulic-conductivity values used in the BCM for the study area range from about 0.00016 ft/d for quartzite to about 13 ft/d for eolian sand (Appendix 3, table A3–1 and fig. D–4). These extremes, however, occur at the surface in only small portions of the study area. For the portion of the study area where in-place recharge is significant (0.1 ft/yr or greater; fig. D–5), the primary surficial geologic units are limestone (estimated saturated hydraulic conductivity of 0.03 ft/d) and volcanic nonwelded and undifferentiated ash-flow tuffs (estimated saturated hydraulic conductivity of 0.02 and 0.007 ft/d, respectively). These two types of consolidated rock each cover about 28 percent of these higher recharge areas. Other exposed rocks in high-recharge areas include dolomite (estimated saturated hydraulic conductivity of 0.2 ft/d, covering about 10 percent of the study area) and volcanic flow and breccia andesite (estimated saturated hydraulic conductivity of 0.02 ft/d, covering about 5 percent of the study area).

Basin Characterization Model Calculations of In-Place Recharge and Runoff

Excess water is calculated in the BCM as the summed values of average monthly precipitation and snowmelt, minus average monthly PET. This excess water is the amount available to replenish soil-water storage, provide in-place recharge, or result in runoff. Runoff is calculated as the available water minus the total soil-water storage capacity (soil porosity multiplied by soil depth). In-place recharge is the available water remaining after runoff, minus the field capacity of the soil (the water content at which drainage becomes negligible). Depending on the soil-water storage capacity and the saturated hydraulic conductivity of the underlying consolidated rock or basin-fill deposits, excess water is partitioned in BCM as either in-place recharge or as runoff that can potentially become groundwater recharge from infiltration losses further downstream in the mountains, alluvial fans, or basin fill. Mountain stream baseflow is derived from in-place recharge that subsequently discharges to streams in the mountain block. Manning and Caine (2007) provide compelling environmental tracer evidence of such mountain block recharge and groundwater flow paths at the Handcart Gulch study site in the Colorado Rockies.

Basin Characterization Model In-Place Recharge

Direct infiltration of precipitation (BCM in-place recharge) is by far the most important form of recharge in the GBCAAS study area. Average annual in-place recharge rates calculated by the BCM range from 0 to 3.1 ft/yr (fig. D–5). The highest in-place recharge rates are generally located in the areas of highest precipitation in the mountains of the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems in Utah, and in the mountains of the Goshute Valley (35), Great Salt Lake Desert (37), Humboldt (7), and Ruby Valley (33) groundwater flow systems of northern and eastern Nevada. However, the effects of saturated hydraulic conductivity used by the BCM are readily apparent. An example is the Ruby

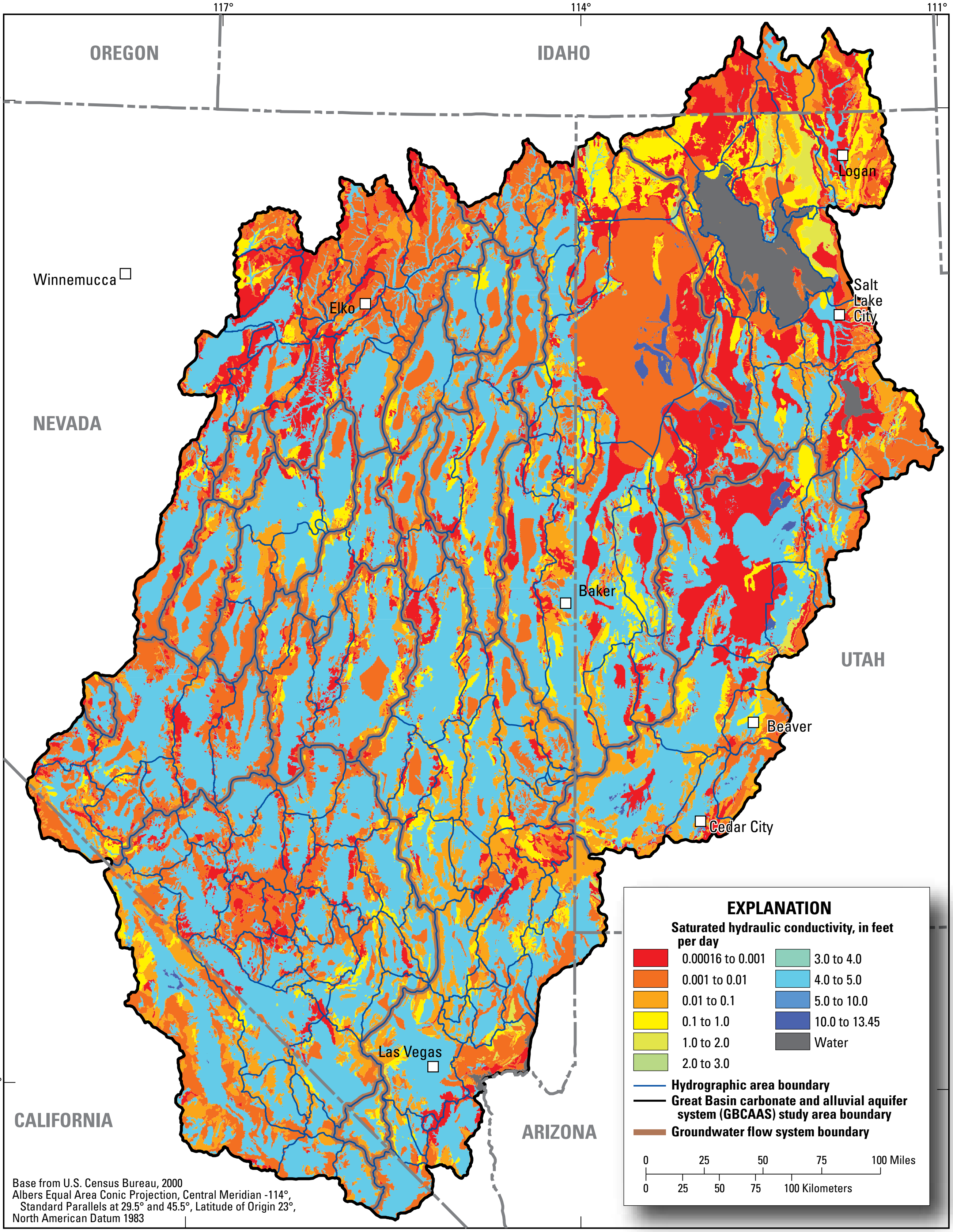

Figure D–4. Distribution of values of saturated hydraulic conductivity of bedrock and unconsolidated sediments used as input for the Basin Characterization Model for the Great Basin carbonate and alluvial aquifer system study area.

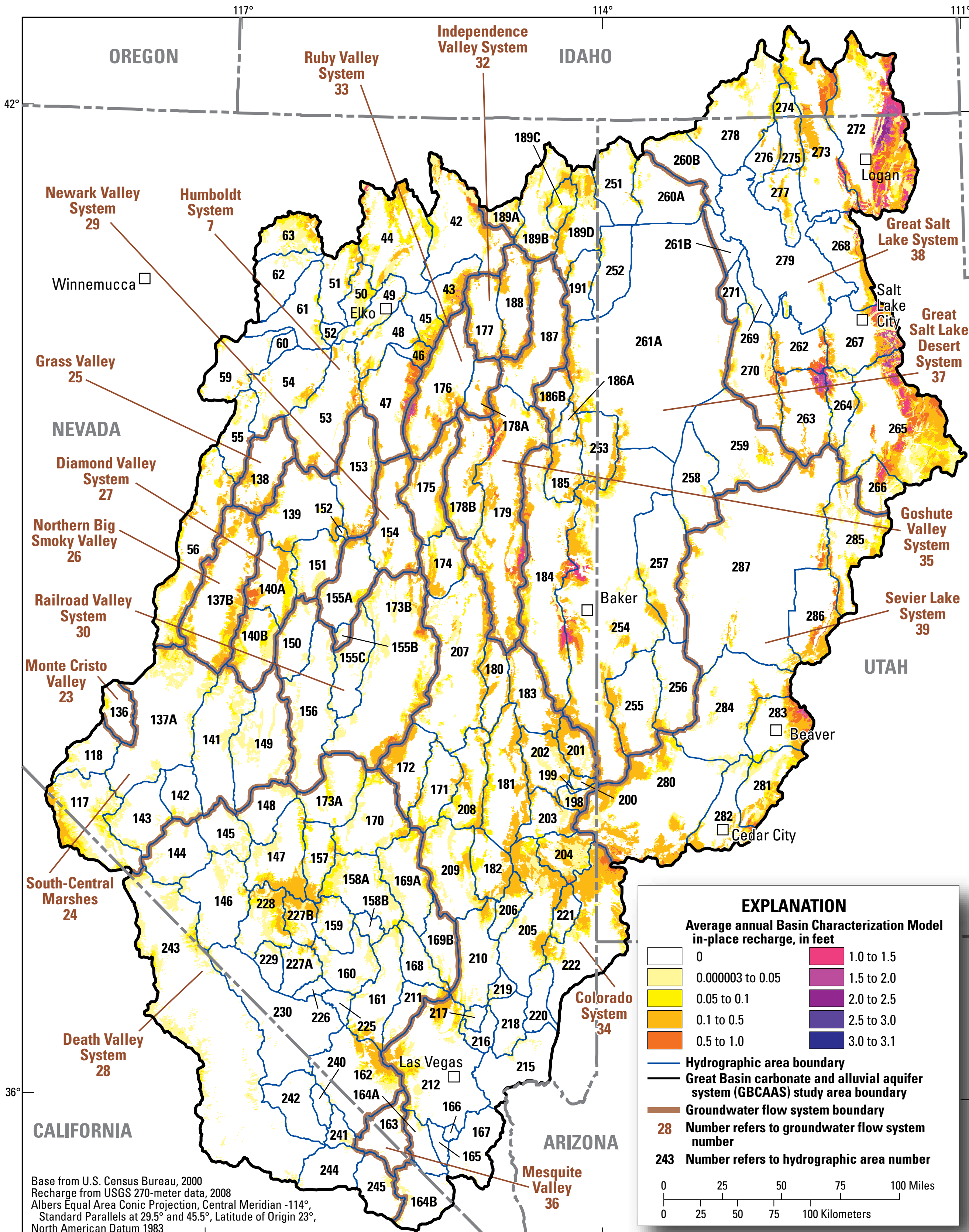

Figure D–5. Distribution of average annual 1940–2006 Basin Characterization Model (BCM) in-place recharge for the Great Basin carbonate and alluvial aquifer system study area.

Mountains, along the western boundary of the Ruby Valley groundwater flow system (33) and the eastern boundary of the Humboldt groundwater flow system (7). Although the Ruby Mountains have a relatively uniform average annual precipitation of about 25–50 in/yr (fig. D–2), the southern portion is dominated by carbonate rocks (fig. B–3) having an estimated saturated hydraulic conductivity of about 0.1 ft/d (fig. D–4) and a BCM in-place recharge rate of about 2 ft/yr. In contrast, the northern portion of the Ruby Mountains is dominated by noncarbonate rocks with an estimated saturated hydraulic conductivity of about 0.002 ft/d (fig. D–4) and a BCM in-place recharge rate of about 0.1–0.2 ft/yr.

In-place recharge computed using the BCM for the GBCAAS study area varies substantially from year to year (fig. D–3). Between 1940 and 2006, BCM in-place recharge ranged from a minimum amount of about 0.5 million acre-ft in water year 1977 to a maximum amount of 8 million acre-ft in water year 2005. Compared to precipitation, in-place recharge has larger annual variations—higher during very wet years and greatly diminished during very dry years (Gates, 2007). This is mainly because of evapotranspiration in the recharge areas (mountains). During wet periods more water is available than is needed by vegetation, and during dry periods vegetation tries to maintain its rate of evapotranspiration. As a result, the groundwater recharge is greater during wet periods and lesser during dry periods than would be estimated from the ratio of annual average precipitation to average annual 1940–2006 precipitation. As an example, the largest year-to-year change in annual average precipitation was between 1952 and 1953, when precipitation declined by 54 percent from 12.5 to 6.7 inches. During this period, estimated BCM in-place recharge declined by 67 percent, from 5.2 to 1.7 million acre-ft. Conversely, when average annual precipitation increased by 46 percent between 1977 and 1978 (from 9.4 to 13.7 in.), BCM in-place recharge increased by 1,240 percent, from 0.5 million to 6.7 million acre-ft.

The comparison of average precipitation to BCM in-place recharge for water year 1977 (fig. D–3) shows the importance of using monthly data for the BCM. Although average precipitation for 1977 (9.5 in) was only slightly below the average annual 1940–2006 precipitation (10.7 in/yr), nearly all of this precipitation occurred in May, August, and September as rain rather than winter snow. During these 3 months, evapotranspiration was at or near peak rates and effectively used all of this moisture. Winter precipitation, beginning in October 1976, was well below normal and likely resulted in little snowmelt runoff, soil-water storage, and in-place recharge. The monthly data, therefore, explain the anomalously low BCM in-place recharge for 1977 of only 0.5 million acre-ft.

Basin Characterization Model Runoff

In addition to computing in-place recharge, the BCM computes the amount of runoff that is generated from each 270-m grid cell. Figure D–6 shows the spatial distribution of average annual BCM runoff. It is important to note that the figure shows the amount and area where runoff originates and not where or how much recharge occurs. The BCM neither routes surface water, nor distinguishes where or how much runoff may subsequently infiltrate and become groundwater recharge. Some portion of the BCM-generated runoff will contribute recharge to the basin fill, either as focused infiltration along streams and canals or as diffuse infiltration of unconsumed irrigation water.

Average annual runoff rates calculated by the BCM range from 0 ft/yr in valley bottoms to 4.5 ft/yr in the higher altitude mountains. Similar to BCM in-place recharge, the largest runoff rates are generally located in the areas of highest precipitation, including the mountains along the eastern side of the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems in Utah, as well as mountains in the Goshute Valley (35), Great Salt Lake Desert (37), Humboldt (7), and Ruby Valley (33) groundwater flow systems of northern and eastern Nevada. Saturated hydraulic conductivity, which is a function of rock type, also affects locations and amounts of runoff. Although the Malad Range, between Cache Valley (HA 272) and Malad–Lower Bear River Area (HA 273) of the Great Salt Lake groundwater flow system (38) in southern Idaho, receives average annual precipitation of about 30 in/yr (fig. D–2), it has an average annual BCM runoff rate of only about 0.01–0.05 ft/yr (fig. D–6). This mountain range comprises carbonate rocks (fig. B–3) with an estimated saturated hydraulic conductivity of about 0.03 ft/d (fig. D–4). In contrast, the Toquima Range, between Northern Big Smoky Valley (HA 137B) and Monitor Valley–Northern and Southern Parts (HAs 140A and 140B) in the Northern Big Smoky Valley (26) and Diamond Valley (27) groundwater flow systems of central Nevada, receives about the same amount of precipitation as the Malad Range, but has an average annual BCM runoff rate of about 1 ft/yr (fig. D–6); this mountain range is dominated by noncarbonate rocks with a lower estimated saturated hydraulic conductivity of about 0.002 ft/d (fig. D–4).

Similar to in-place recharge, BCM-generated runoff for the GBCAAS study area varies substantially from year to year (fig. D–3). Between water years 1940 and 2006, BCM runoff ranged from a minimum of about 0.4 million acre-ft in 1977 to a maximum of 6.6 million acre-ft in 1995. Like in-place recharge, yearly runoff varies much more than precipitation. Runoff is greatly amplified during very wet years and greatly diminished during very dry years. For example, compared to the 54 percent decline in average precipitation between 1952 and 1953, BCM runoff declined by 80 percent from 5.9 to 1.3 million acre-ft. Conversely, the 46 percent increase in average precipitation between 1977 and 1978 resulted in an increase in BCM runoff by 1,300 percent, from 0.4 million to 5.6 million acre-ft.

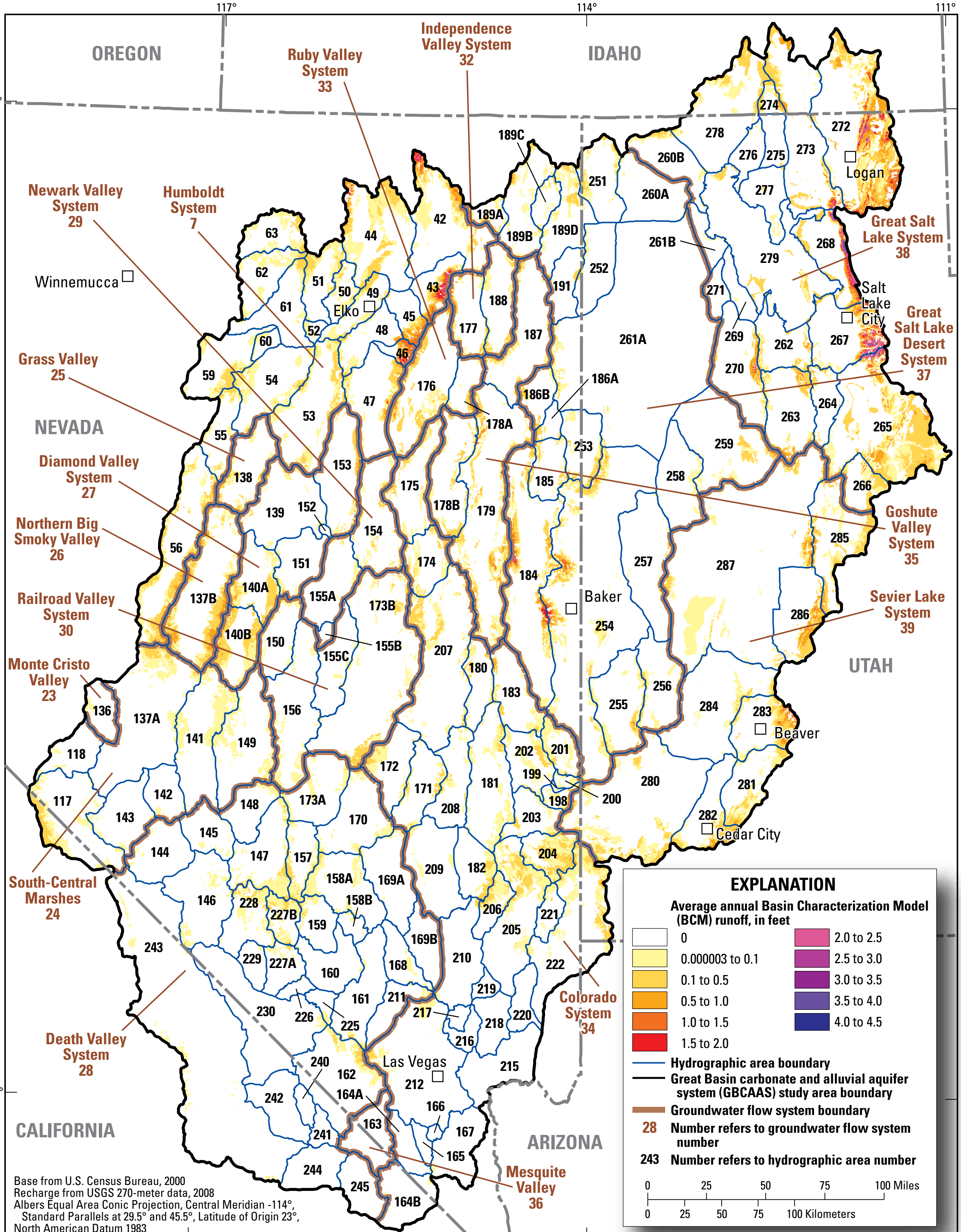

Figure D–6. Distribution of average annual 1940–2006 Basin Characterization Model (BCM) runoff for the Great Basin carbonate and alluvial aquifer system study area.

Recharge from Basin Characterization Model Runoff

The majority of runoff generated in the mountains flows into adjacent basins, some portion of which recharges the unconsolidated deposits as infiltration beneath stream channels, irrigation canals, and irrigated fields. Because BCM does not estimate how much of the runoff becomes recharge, estimates were made by assigning a percentage of runoff that becomes recharge. The predevelopment budget presented in this report includes groundwater recharge from irrigation with surface water; surface water was developed before most hydrologic studies were done. Irrigation with surface water is assumed to increase recharge because the water is removed from armored natural stream channels and spread into canals and onto fields. Areas highly irrigated with surface water were compared to areas not highly irrigated with surface water to determine how irrigation affects the amount of runoff that becomes recharge. In the Death Valley Regional Flow System (DVRFS) study, an area that is not highly irrigated with surface water, about 18,000 acre-ft/yr (25 ft^3/s) of recharge from runoff was estimated, compared to a total estimated runoff of about 180,000 acre-ft/yr (250 ft^3/s; Hevesi and others, 2003, p. 3; Belcher and others, 2004, p. 9; San Juan and others, 2004, p. 115–118). This yields a percentage of runoff that becomes recharge of about 10 percent. In comparison, the percentage of runoff that becomes recharge in 13 HAs that are highly irrigated with surface water within the Humboldt (7), Great Salt Lake (38), and Sevier Lake (39) groundwater flow systems ranges from about 10 to 50 percent, with an average of about 30 percent (Auxiliary 3C). This percentage was calculated by dividing the previously reported estimates of recharge from runoff/streams/canals and unconsumed irrigation water by the reported total available water from runoff, imported water, and groundwater withdrawals for irrigation (Auxiliaries 3B and 3C). On the basis of the above analyses, the fraction of runoff that is assumed to become recharge is 10 percent for HAs that are not highly irrigated with surface water and 30 percent for those that are highly irrigated with surface water.

To determine which percentage of runoff to use for estimating recharge from runoff in the current study, all 165 HAs within the study area were categorized as either “highly irrigated with surface water” or “not highly irrigated with surface water” on the basis of the available surface-water resources. This is centered on the assumption that in HAs where surface-water resources are plentiful, these resources would most likely be developed for irrigation, resulting in substantial irrigation return flow (infiltration of unconsumed irrigation) and a higher percentage of recharge than for nonirrigated HAs. The spreading of irrigation water on permeable surficial basin-fill deposits increases the area for surface water to infiltrate and recharge the underlying aquifer. This designation was obtained through the calculation of the “stream density” for each HA. Stream density was determined by dividing the sum of the mean discharge (period of record) for all gaged streams originating within the mountain block in each HA, by the area of the HA (Auxiliary 3D). HAs with stream densities greater than, or equal to, 0.01 ft/yr were categorized as HAs highly irrigated with surface water, while HAs with stream densities less than 0.01 ft/yr were categorized as not highly irrigated with surface water. Because stream densities were not determined for HAs with ungaged streams, HAs with no gaged streamflow (not listed in Auxiliary 3D) were assumed to be not highly irrigated with surface water and were categorized as such. Because of this assumption, the stream-density estimates and the number of highly irrigated HAs are considered a minimum. Of the 165 HAs within the study area, 30 are designated as highly irrigated with surface water, and 135 are designated as not highly irrigated with surface water (fig. D–7). Most of the HAs categorized as highly irrigated with surface water are located along the Wasatch Front in the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems of Utah, and in, or near, the Humboldt groundwater flow system (7) of Nevada.

Analysis and Adjustment of Basin Characterization Model Results

Recharge from precipitation includes in-place recharge and recharge from runoff. The amount of recharge from precipitation estimated for the current study is based on BCM results, but has been adjusted by applying a multiplication factor to BCM in-place recharge and runoff in some areas to better match estimates of predevelopment groundwater discharge (Auxiliary 3A). The process for estimating recharge from precipitation for the current study included (1) comparing the recharge from precipitation calculated by the BCM to local and regional discharge estimates, and (2) determining whether significant subsurface flow was possible and could account for differences between estimated BCM recharge from precipitation and discharge. Comparison of current study predevelopment discharge estimates (see “Groundwater Discharge” section) to recharge calculated using BCM results shows very large differences for parts, or all, of some groundwater flow systems. Spatially, these differences do not appear to be randomly distributed. A few of the groundwater flow systems, particularly Death Valley (28) and the southern portion of the Colorado (34) groundwater flow systems, have BCM-computed recharge that is 130 percent or more of discharge. The Colorado groundwater flow system has the largest difference between BCM-computed recharge and estimated discharge in both percent and amount. Recharge from precipitation, calculated using the unadjusted BCM results of in-place recharge and recharge from runoff in the Colorado groundwater flow system (34), is estimated to be 490,000 acre-ft/yr (Auxiliary 3A); this is more than 200 percent of the current study predevelopment discharge estimate of 230,000 acre-ft/yr (table D–2).

A sensitivity analysis of the BCM in-place recharge for water year 1996, in which soil thickness, monthly minimum and maximum air temperature, monthly precipitation, and sublimation as a percentage of PET were varied within the range of their respective uncertainties, showed that recharge and runoff estimates are very sensitive to small changes in

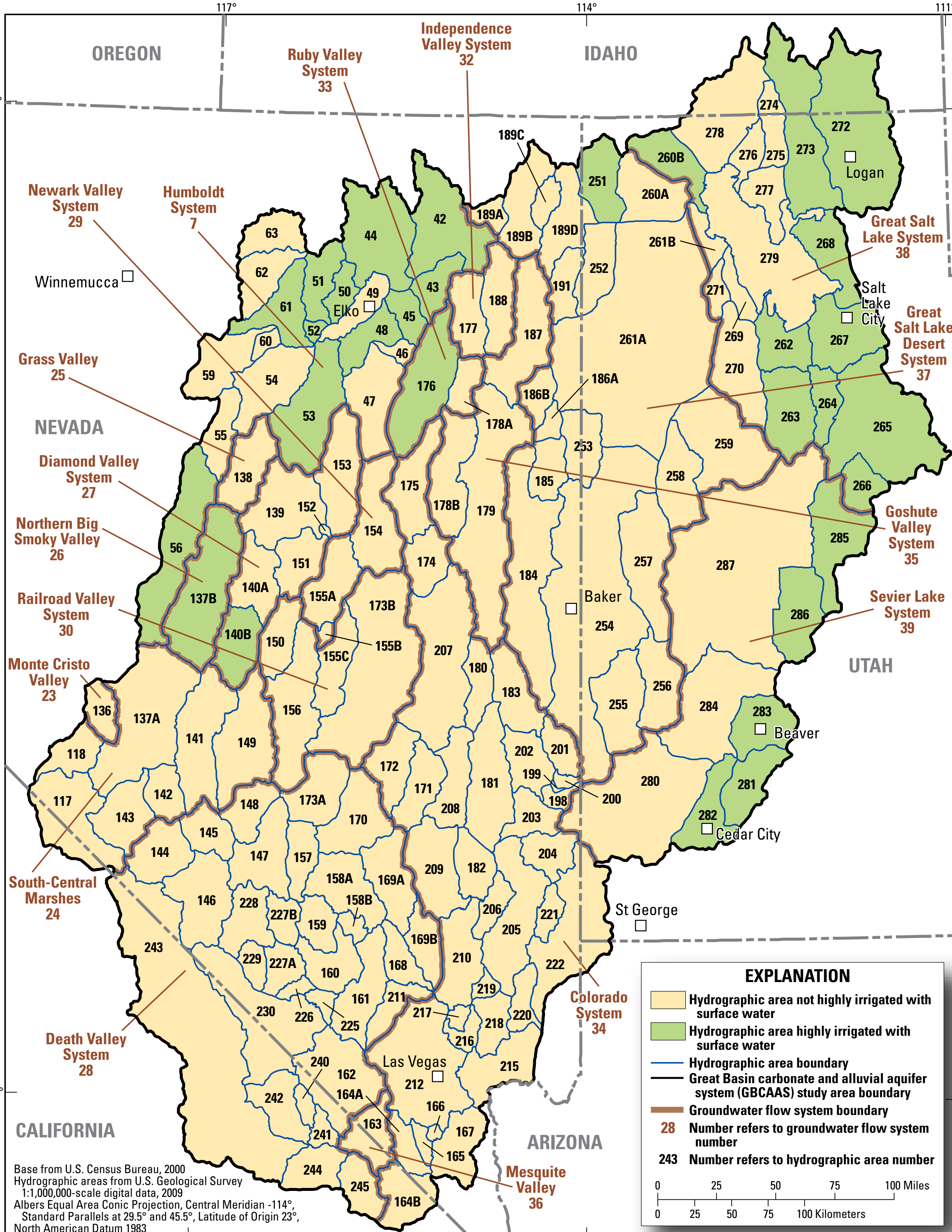

Figure D–7. Distribution of hydrographic areas highly irrigated with surface water and hydrographic areas not highly irrigated with surface water in the Great Basin carbonate and alluvial aquifer system study area.

these input parameters. The estimated uncertainty in BCM in-place recharge was ±50 percent (Appendix 3). However, this sensitivity analysis did not include all parameters (such as saturated hydraulic conductivity), which may increase the uncertainty. Much of the input data used in the BCM have been interpolated over large (coarse) grid cell sizes, and this tends to smooth factors related to heterogeneity and introduce additional uncertainty. Therefore, the ±50 percent uncertainty is a conservative estimate. Because of its smaller percentage of overall recharge, no sensitivity analysis was performed for the BCM runoff calculations.

Other possible causes for the large discrepancy between BCM results and predevelopment discharge in the Death Valley (28) and Colorado (34) groundwater flow systems may be that the saturated hydraulic conductivity used in the BCM is weakly constrained in these areas because of the lack of gaged mountain streams for calibrating modeled runoff. Because recharge from runoff is estimated to be only 10 or 30 percent of runoff for the GBCAAS study area (versus 100 percent for in-place recharge), a change in the partitioning of water within the BCM from in-place recharge to runoff would result in a substantial decline in estimated recharge. An alternative explanation is that the BCM improperly accounts for differences in water- and energy-balance processes in the southern part of the GBCAAS study area. Unlike the northern part of the study area, there is little accumulation of snow in the southern mountains, and a larger percent of precipitation occurs during summer and early autumn when evapotranspiration rates are high. These differences could mean that less water is actually available for either in-place recharge or runoff than is being estimated. A more detailed uncertainty analysis of the BCM is discussed in Appendix 3.

Because there is no evidence that input data to BCM are biased, no systematic changes could be made to BCM to reduce in-place recharge and runoff in these groundwater flow systems with excess BCM-computed recharge without introducing an unacceptable decrease in recharge for the other groundwater flow systems that had smaller discrepancies between BCM-computed recharge and estimated discharge. The following paragraphs describe how estimates of recharge from precipitation for each of the 17 groundwater flow systems were determined for this study. If combined predevelopment recharge from precipitation calculated using BCM results, recharge from mountain stream baseflow, and recharge from imported water was within 30 percent of estimated discharge in individual or selected contiguous groups of groundwater flow systems likely having interconnected subsurface flow, BCM in-place recharge and runoff were not adjusted. The ±30 percent criterion is based on the assumed 30-percent composite uncertainty in discharge estimates (discussed below).

Humboldt and Grass Valley Groundwater flow Systems

Sources of predevelopment recharge to the Humboldt groundwater flow system (7) in the current study include recharge from precipitation, mountain stream baseflow, and imported water. Combined predevelopment recharge calculated using BCM results (Auxiliary 3A), along with recharge from mountain stream baseflow and from imported water (table D-1) exceeds estimated predevelopment groundwater discharge (table D–2) by less than 30 percent. It is possible that discharge is underestimated in the Humboldt groundwater flow system (7) because (1) groundwater discharge to the Humboldt River is poorly defined, (2) subsurface outflow to areas west of the study area is possible, and (3) more springs may exist than those that have been measured and inventoried in National Water Information System (NWIS). The only source of predevelopment recharge to the Grass Valley groundwater flow system (25) estimated in the current study is from precipitation. Predevelopment recharge to the Grass Valley groundwater flow system (25) calculated using BCM results (Auxiliary 3A) exceeds the estimated predevelopment groundwater discharge (table D–2) by more than 30 percent. However, the occurrence of subsurface flow from the Grass Valley groundwater flow system (25) to Crescent Valley (HA 54) in the Humboldt groundwater flow system (7) is possible on the basis of potentiometric contours and the uncertain likelihood of a hydraulic connection (pl. 2). The combined recharge from precipitation calculated using BCM results (Auxiliary 3A), along with recharge from mountain stream baseflow and from imported surface water (table D–1) for these two groundwater flow systems, is about 400,000 acre-ft/yr. This is about 28 percent higher than the estimated predevelopment groundwater discharge of about 310,000 acre-ft/yr (table D–2). The BCM results for these two groundwater flow systems, therefore, are used as the estimated recharge from precipitation for the current study (Auxiliary 3A); a multiplication factor of 1.00 (no adjustment) is shown in figure D–8.

Monte Cristo Valley and South-Central Marshes Groundwater flow Systems

Sources of predevelopment recharge to the Monte Cristo Valley (23) and South-Central Marshes (24) groundwater flow systems in the current study include recharge from precipitation and mountain stream baseflow. Recharge calculated using BCM results in the Monte Cristo Valley groundwater flow system exceeds the estimated predevelopment groundwater discharge (table D–2) by 225 percent. However, subsurface flow to the surrounding South-Central Marshes groundwater flow system is possible on the basis of potentiometric contours and the high likelihood of a hydraulic connection at the HA boundary between Monte Cristo Valley (HA 136) and Big Smoky Valley-Tonopah Flat Valley (HA 137A) in the South-Central Marshes groundwater flow system (24) (pl. 2). Recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) in the South-Central Marshes groundwater flow system (24) is within 30 percent of estimated predevelopment groundwater discharge (table D–2). The combined recharge calculated using BCM results and recharge from mountain stream baseflow for these two groundwater flow systems is about 56,000 acre-ft/yr (Auxiliary 3A and table D–1), which is about 11 percent lower than the estimated predevelopment groundwater discharge of about 63,000 acre-ft/yr (table D–2). The BCM results, therefore,

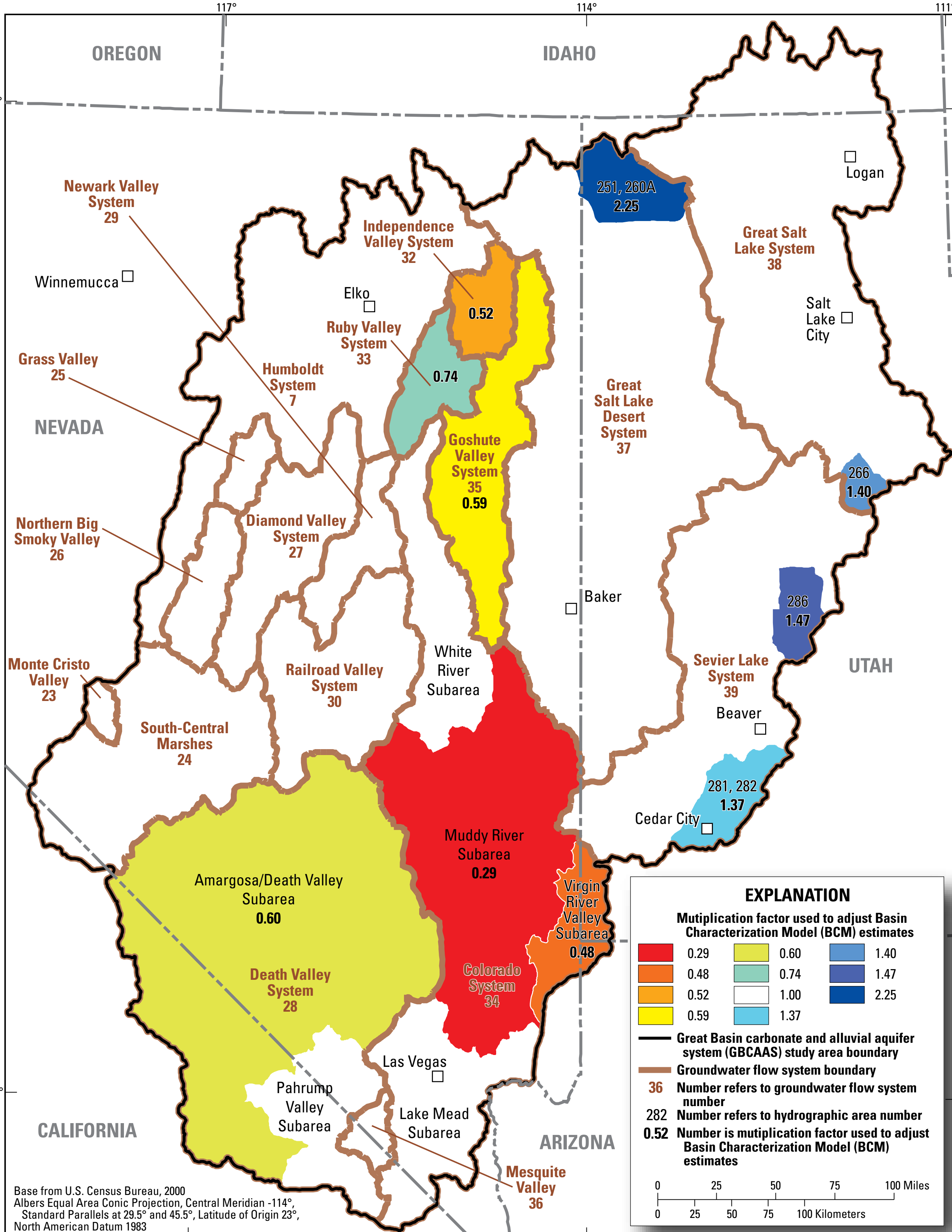

Figure D–8. Multiplication factors used for adjusting Basin Characterization Model (BCM) in-place recharge and runoff for the Great Basin carbonate and alluvial aquifer system study area.

are used to estimate recharge from precipitation for these two groundwater flow systems for the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Northern Big Smoky Valley Groundwater flow System

Sources of predevelopment recharge to the Northern Big Smoky groundwater flow system (26) in the current study include recharge from precipitation and mountain stream baseflow. Combined predevelopment recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) is 87,000 acre-ft/yr, within 30 percent of the estimated predevelopment groundwater discharge of 69,000 acre-ft/yr (table D–2). The BCM results, therefore, are used to calculate recharge from precipitation for this groundwater flow system in the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Diamond Valley, Newark Valley, and Railroad Valley Groundwater flow Systems

Sources of predevelopment recharge to the Diamond Valley (27), Newark Valley (29), and Railroad Valley (30) groundwater flow systems in the current study include recharge from precipitation and mountain stream baseflow. Recharge in the Diamond Valley groundwater flow system (27) exceeds discharge by more than 30 percent; discharge in the Railroad Valley groundwater flow system (30) exceeds recharge by more than 30 percent; and recharge in the Newark Valley groundwater flow system (29) is within 30 percent of discharge (tables D–1 and D–2). Hydraulic gradients derived from the potentiometric-surface map and the high likelihood of hydraulic connections across groundwater flow system boundaries (pl. 2) indicate the potential for groundwater flow from the Diamond Valley (27) and Newark Valley (29) groundwater flow systems to the Railroad Valley groundwater flow system (30). This flow was also indicated by the Great Basin regional aquifer-system analysis (RASA) groundwater flow model (Prudic and others, 1995, fig. 24). Combined recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) for these three groundwater flow systems is about 210,000 acre-ft/yr. This is about 13 percent higher than the estimated predevelopment groundwater discharge of about 190,000 acre-ft/yr (table D–2). The BCM results, therefore, are used to calculate recharge from precipitation for these groundwater flow systems in the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Death Valley Groundwater flow System

Sources of predevelopment recharge to the Death Valley groundwater flow system (28) in the current study include recharge from precipitation and mountain stream baseflow. Combined predevelopment recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) is 170,000 acre-ft/yr. This is 70 percent higher than the estimated groundwater discharge of 100,000 acre-ft/yr (table D–2). Because the Death Valley groundwater flow system (28) is at the downgradient end of a regional discharge area, it is unlikely that there is significant subsurface outflow, and recharge must balance discharge within uncertainty limits. The BCM results for the Death Valley groundwater flow system (28) suggest that recharge from precipitation can sufficiently provide for all of the estimated predevelopment groundwater discharge and that subsurface inflow may not be needed. This is in contrast to previous studies, which suggested the occurrence of subsurface inflow to the Death Valley groundwater flow system (28).

Recharge calculated using BCM results was compared to discharge for each HA in the Death Valley groundwater flow system (28) to determine whether the computed recharge estimates were reasonable and whether any imbalances between the BCM computed recharge and the discharge could be balanced by subsurface flow. On the basis of hydraulic gradients, the high likelihood of hydraulic connections across HA boundaries (pl. 2), and the location of major discharge areas, the Death Valley groundwater flow system (28) can be considered as two separate subareas. These subareas are defined in the current study as the Armargosa/Death Valley subarea and Pahrump Valley subareas (fig. D–8, Appendixes 4 and 5). In the Amargosa/Death Valley subarea, recharge calculated using BCM results is 140,000 acre-ft/yr (Auxiliary 3A), which is about 170 percent of the estimated predevelopment discharge of 81,000 acre-ft/yr (Appendix 5). In this subarea, therefore, BCM in-place recharge and runoff are multiplied by 0.6 for the current study estimate of recharge from precipitation (Auxiliary 3A; fig. D–8). In the Pahrump Valley subarea, the recharge calculated using BCM results of 23,000 acre-ft/yr (Auxiliary 3A) is within 30 percent of the estimated predevelopment groundwater discharge of 20,000 acre-ft/yr (Appendix 5). The BCM results, therefore, are used to calculate recharge from precipitation in the Pahrump Valley subarea in the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Independence Valley, Ruby Valley, and Goshute Valley Groundwater flow Systems

Sources of predevelopment recharge to the Independence Valley (32), Ruby Valley (33), and Goshute Valley (35) groundwater flow systems in the current study include recharge from precipitation and mountain stream baseflow. On the basis of hydraulic gradients and the high likelihood of hydraulic connections across flow system boundaries (pl. 2), the budgets in these three groundwater flow systems can be considered together. Combined predevelopment recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) for the Independence Valley (32), Ruby Valley (33), and Goshute Valley (35) groundwater flow systems is 380,000 acre-ft/yr. This is about 58 percent higher than the estimated predevelopment groundwater discharge of 240,000 acre-ft/yr (table D–2). It is possible, however, that discharge is underestimated in these three groundwater flow systems. Pavelko (2007) presents a database of numerous springs in Steptoe Valley (HA 179) in the Goshute Valley groundwater flow system (35), but very few have discharge estimates. Some of these springs in the mountains may intercept a portion of the in-place recharge in the mountain block and prevent it from infiltrating to deeper layers and becoming part of a longer flow path discharging to the basin fill. On the basis of hydraulic gradients and the high likelihood of hydraulic connections across HA boundaries (pl. 2), it is possible that subsurface outflow from the Independence Valley (32), Ruby Valley (33), and Goshute Valley (35) groundwater flow systems occurs to the Great Salt Lake Desert groundwater flow system (37), along with lesser potential for flow to the Humboldt (7) and Colorado (34) groundwater flow systems. These possible subsurface outflows, however, are not quantified in the current study because of inherent water-budget uncertainties. The Basin and Range carbonate-rock aquifer system (BARCAS) study (Welch and others, 2007) required subsurface outflow from the Goshute Valley groundwater flow system (35) of 77,000 acre-ft/yr to the Ruby Valley (33), Colorado (34), and Great Salt Lake Desert (37) groundwater flow systems in order to balance the budget. The definition of the BARCAS study area was based, in part, on political boundaries rather than complete groundwater flow systems. The current study evaluated groundwater budgets for entire groundwater flow systems, and it was determined that the groundwater flow systems surrounding the Independence Valley (32), Ruby Valley (33), and Goshute Valley (35) groundwater flow systems do not require subsurface outflow to balance estimated predevelopment discharge. In order to balance the water budgets for these three groundwater flow systems in the current study, BCM in-place recharge and runoff were decreased using multiplication factors of 0.52, 0.74, and 0.59, for the Independence Valley (32), Ruby Valley (33), and Goshute Valley (35) groundwater flow systems, respectively (Auxiliary 3A and fig. D–8).

Colorado Groundwater flow System

Sources of predevelopment recharge to the Colorado groundwater flow system (34) in the current study include recharge from precipitation and mountain stream baseflow. The combined predevelopment recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow (table D–1) of 490,000 acre-ft/yr is 213 percent higher than the estimated predevelopment groundwater discharge of 230,000 acre-ft/yr (table D–2). Recharge calculated using BCM results was compared to discharge estimated for each HA in the Colorado groundwater flow system (34) to determine whether the computed recharge estimates were reasonable, and whether any imbalances between BCM computed recharge and the discharge could be balanced by subsurface flow. Based upon hydraulic gradients, the high likelihood of hydraulic connections across HA boundaries (pl. 2), and the location of major discharge areas, the Colorado groundwater flow system (34) can be divided into four separate regions, defined in the current study as the Lake Mead, Muddy River, White River, and Virgin River subareas (fig. D–8, Appendixes 4 and 5).

Recharge calculated using BCM results is much larger than estimated predevelopment groundwater discharge in the Muddy River and Virgin River Valley subareas (fig. D–8). In the Muddy River and Virgin River Valley subareas, recharge calculated using BCM results is 360,000 acre-ft/yr (Auxiliary 3A). This is about 300 percent higher than the estimated predevelopment discharge of 120,000 acre-ft/yr (Appendix 5). The high recharge portions of these subareas are dominated by volcanic nonwelded ash-flow tuffs; one possible explanation for the budget discrepancy is that the BCM overestimates saturated hydraulic conductivity of this rock type. Estimates of saturated hydraulic-conductivity values were based on a calibration of BCM runoff to gaged mountain stream discharge (Appendix 3) for watersheds dominated by different geologic formations. Volcanic nonwelded ash-flow tuffs were the predominant geology in eight gaged watersheds. The comparison of BCM runoff to gaged runoff (total streamflow less baseflow) for each of these eight gages shows that BCM overestimates runoff by an average of only 10 percent. Two of these stream gages are located in the Muddy River and Virgin River Valley subareas: Site 9413900 on Beaver Dam Wash near Enterprise, Utah, and Site 9417500 on Meadow Valley Wash at Eagle Canyon near Ursine, Nevada. Estimated BCM runoff for these two watersheds was 95 and 74 percent of gaged runoff, respectively (table A3–2). While this potential underestimation of BCM runoff would indicate a reciprocal overestimation of BCM in-place recharge, it is not nearly enough to explain the 300 percent discrepancy between recharge and discharge for these two subareas. Regardless of whether or not the BCM may be overestimating recharge, BCM results for the Muddy River subarea suggest that recharge from precipitation within the subarea can sufficiently provide for all of the estimated predevelopment groundwater discharge, which occurs mostly in Pahranagat Valley (HA 209), Muddy River Springs Area (HA 219), and Lower Moapa Valley (HA 220). Thus, the Muddy River and Virgin River Valley subareas do not require additional recharge as subsurface inflow from the northern part of the Colorado groundwater flow system (34). This is in contrast to previous studies (Maxey and Eakin, 1949; Welch and others, 2007), which suggest that subsurface inflow to this part of the Colorado groundwater flow system (34) from upgradient White River Valley (HA 207) was required to balance discharge. Because the southern part of the Colorado groundwater flow system is at the downgradient end of regional discharge areas, it is unlikely that there is significant subsurface outflow, and recharge should balance discharge within uncertainty limits. In order to balance the water budgets for this groundwater flow system in the current study, BCM in-place recharge and runoff were decreased in the Muddy River and Virgin River Valley subareas by using multiplication factors of 0.29 and 0.48, respectively (Auxiliary 3A and fig. D–8).

Other subareas within the Colorado groundwater flow system (34) do not have significant groundwater-budget imbalances. The recharge estimates calculated using BCM results for the Lake Mead and White River Valley subareas were within 30 percent of the predevelopment groundwater-discharge estimates. The BCM results, therefore, are used to calculate recharge from precipitation for these subareas for the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Mesquite Valley Groundwater flow System

The only source of predevelopment recharge to the Mesquite Valley groundwater flow system (36) in the current study is recharge from precipitation. Recharge calculated using BCM results for the Mesquite Valley groundwater flow system (36) is 1,900 acre-ft/yr (Auxiliary 3A). This is within 30 percent of the estimated predevelopment groundwater discharge of 2,200 acre-ft/yr for this small flow system (table D–2). The BCM results, therefore, are used to calculate recharge from precipitation for the current study (multiplication factor of 1.00; Auxiliary 3A; fig. D–8).

Great Salt Lake Desert, Great Salt Lake, and Sevier Lake Groundwater flow Systems

In the current study, sources of predevelopment recharge to the Great Salt Lake Desert (37), Great Salt Lake (38), and Sevier Lake (39) groundwater flow systems include recharge from precipitation, mountain stream baseflow, and imported water. Based upon hydraulic gradients and the high likelihood of a hydraulic connection across flow system boundaries (pl. 2), the budgets in these three groundwater flow systems can be considered together. Combined predevelopment recharge calculated using BCM results (Auxiliary 3A) and recharge from mountain stream baseflow and imported surface water (table D–1) is 3,200,000 acre-ft/yr. This is within 30 percent of the estimated predevelopment groundwater discharge of 3,000,000 acre-ft/yr (table D–2). The BCM results, therefore, generally are used to calculate recharge from precipitation for the current study estimate (multiplication factor of 1.00). The recharge calculated using BCM results, however, is less than 70 percent of the estimated predevelopment groundwater discharge for six HAs (Grouse Creek Valley, HA 251; Park Valley-West Park Valley, HA 260A; Northern Juab Valley, HA 266; Parowan Valley, HA 281; Cedar City Valley, HA 282; and Pavant Valley, HA 286), located at the upgradient ends of these groundwater flow systems that likely do not receive subsurface inflow (fig. D–8). In order to estimate recharge for these HAs, BCM in-place recharge and runoff were multiplied by factors ranging from 1.37 to 2.25 (Auxiliary 3A and fig. D–8).

Current Study Estimates of Recharge from Precipitation

Estimated in-place recharge from precipitation for the current study, 2,900,000 acre-ft/yr, accounts for about 62 percent of the total estimated groundwater recharge for predevelopment conditions (table D–1). The highest long-term (1940–2006) average annual amounts of in-place recharge occur in the Great Salt Lake (38), Great Salt Lake Desert (37), Sevier Lake (39), Humboldt (7), and Colorado (34) groundwater flow systems (table D–1). Estimates of long-term (1940–2006) average annual in-place recharge by HA are given in Appendix 4 and Auxiliary 3A. Because of the large range in groundwater flow system areas (282–18,849 mi^2), the mean annual in-place recharge rate (total volume of in-place recharge divided by flow system area) for each groundwater flow system also is given in table D–1. The mean rates are useful for comparing in-place recharge between the 17 groundwater flow systems within the study area.

Estimated recharge from runoff for the current study, 570,000 acre-ft/yr, accounts for about 13 percent of the total estimated groundwater recharge for predevelopment conditions (table D–1). The highest amounts of recharge from runoff occur in the Great Salt Lake (38) and Humboldt (7) groundwater flow systems (table D–1). Particularly in the Great Salt Lake groundwater flow system (38), many HAs are highly developed and have large networks of canals and diversions for irrigation purposes. Current study estimates of annual recharge from runoff by HA are given in Appendix 4 and Auxiliary 3A.

Recharge from Mountain Stream Baseflow

Estimates of recharge from mountain stream baseflow are not included in the estimates of recharge from runoff discussed above. The same percentages (30 percent for HAs highly irrigated with surface water; 10 percent for HAs not highly irrigated with surface water) are used for estimating recharge from mountain stream baseflow. Estimated recharge from mountain stream baseflow for the current study, 130,000 acre-ft/yr, accounts only for about 3 percent of total estimated groundwater recharge under predevelopment conditions (table D–1). Most of this recharge (85 percent) is concentrated within the Great Salt Lake groundwater flow system (38). Estimates of annual recharge from mountain stream baseflow by HA are given in Appendix 4. Estimates could not be made for HAs without gaged mountain streams and are made only for HAs with records of gaged perennial mountain streams.

Recharge from Imported Surface Water

Recharge from irrigation return flow of imported surface water is a major component of the groundwater-recharge budget, but it is concentrated almost exclusively within the Great Salt Lake groundwater flow system (38). Amounts of naturally imported surface water (such as rivers and streams flowing from upgradient HAs or outside of the study area) were calculated from streamgage data; amounts of water imported in association with engineered transbasin diversions that originate outside the HA or study area were either compiled from previous reports or calculated from diversion records (Auxiliary 3C). Estimated recharge from imported surface water for the current study, 990,000 acre-ft/yr, accounts for 22 percent of total estimated groundwater recharge under predevelopment conditions (table D–1). Recharge from imported surface water accounts for 42 percent of the total recharge for the Great Salt Lake groundwater flow system (38), and it includes naturally imported water from the Bear, Ogden, Weber, Jordan, and Provo rivers (fig. A–1), as well as imported water from engineered transbasin diversions east of the study area.

HAs that receive natural surface-water inflow from upgradient areas (Appendix 4 and Auxiliary 3C) include Tenmile Creek Area (HA 48) within the Humboldt groundwater flow system (7); and Utah Valley Area (HA 265), East Shore Area (HA 268), Cache Valley (HA 272), and Malad-Lower Bear River Area (HA 273) within the Great Salt Lake groundwater flow system (38). HAs that receive imported surface water from transbasin diversions include Utah Valley Area (HA 265), Salt Lake Valley (HA 267), and East Shore Area (HA 268) within the Great Salt Lake groundwater flow system (38), and Pavant Valley (HA 286) within the Sevier Lake groundwater flow system (39). Estimates of groundwater recharge from imported surface water for each HA were calculated using the same percentages that were used to determine the recharge from runoff estimates. Based on this convention, in HAs highly irrigated with surface water (fig. D–7), 30 percent of the imported water is estimated to recharge the groundwater flow system (Auxiliary 3C).

Recharge from Subsurface Groundwater Inflow

Previous estimates of both subsurface inflow and outflow within the GBCAAS study area typically have been based upon (1) water-balance methods, where subsurface inflow is determined as the residual of total discharge and the sum of all other forms of recharge; (2) Darcy flux calculations, which are based on the hydraulic gradient, hydraulic conductivity, and aquifer cross-sectional area between HAs; or (3) geochemical approaches, such as the deuterium mass-balance method (Thomas and others, 2001; Lundmark and others, 2007). Previous estimates of subsurface inflow were compiled by HA (Auxiliary 3E) and by groundwater flow system (Auxiliary 3F); the estimates compiled by groundwater flow system account for subsurface inflow that originates outside of the groundwater flow system and do not account for subsurface inflow between HAs within the groundwater flow system.

Recharge from subsurface inflow was not estimated for the current study, however, because of (1) the large uncertainty in groundwater-budget components (such as an estimated ±50 percent uncertainty in recharge from precipitation) for water-balance methods; (2) the sparse information on hydraulic gradients, hydraulic properties, and aquifer geometry at HA boundaries for Darcy flux methods; and (3) the application of geochemical approaches, such as the deuterium mass-balance method for all 165 HAs within the GBCAAS study area, was not within the scope of the current study. Subsurface flow estimates between HAs based on groundwater-balance methods are further complicated in the GBCAAS study area by conditions of subsurface outflow from one HA moving into several downgradient HAs within and between groundwater flow systems; partitioning this subsurface outflow cannot be resolved with the water-balance approach. An example of this is in eastern Nevada, where the BARCAS study (Welch and others, 2007) used a deuterium mass-balance method to help constrain subsurface outflow from Steptoe Valley (HA 179) in the Goshute Valley groundwater flow system (35) that becomes subsurface inflow to (1) Goshute Valley (HA 187) in the Goshute Valley groundwater flow system (35); (2) Jakes Valley (HA 174), White River Valley (HA 207), and Lake Valley (HA 183) in the Colorado groundwater flow system (34); and (3) Spring Valley (HA 184) in the Great Salt Lake Desert groundwater flow system (37).

Previous estimates of subsurface inflow to HAs and groundwater flow systems could not be used in the current study because, in many of these studies, balancing groundwater budgets in adjacent HAs or groundwater flow systems was not considered. For example, Maxey and Eakin (1949), Scott and others (1971), Harrill and others (1988), and Welch and others (2007) indicate subsurface inflow to HAs south of White River Valley (HA 207) in the Colorado groundwater flow system (34) ranging from 18,000 to 40,000 acre-ft/yr. These studies, however, did not necessarily consider the consequences of routing this subsurface flux southward. In the current study, the White River subarea (fig. D–8), within the Colorado groundwater flow system (34), is assumed to have a balance between groundwater recharge and discharge within ± 30 percent (see "Colorado Groundwater flow System" section under "Analysis and Adjustment of BCM Results"). Furthermore, the downgradient Muddy River subarea does not require any additional recharge from subsurface inflow; this additional flux would cause a groundwater-budget imbalance.

The current study recognizes that all groundwater-budget components have errors and that estimates of subsurface inflow as a budget residual of the recharge and discharge estimates are highly uncertain; it was assumed for most groundwater flow systems that the amounts of subsurface inflow fall within the range of these uncertainties (Auxiliary 3F). Figure D–9 shows groundwater-budget imbalances and indicates with arrows where the potentiometric contours and the likelihood of a hydraulic connection across the HA boundary (pl. 2) suggest possible groundwater subsurface flow between groundwater flow systems (table D–1). Groundwater flow-system- and subarea-budget imbalances imply that although there may be a potential for subsurface flow, this flow may not be needed to balance budgets. With the exception of South-Central Marshes (24), Railroad Valley (30), and Mesquite Valley (36) groundwater flow systems, none of the groundwater flow systems shown as possibly receiving subsurface inflow in figure D–9 and

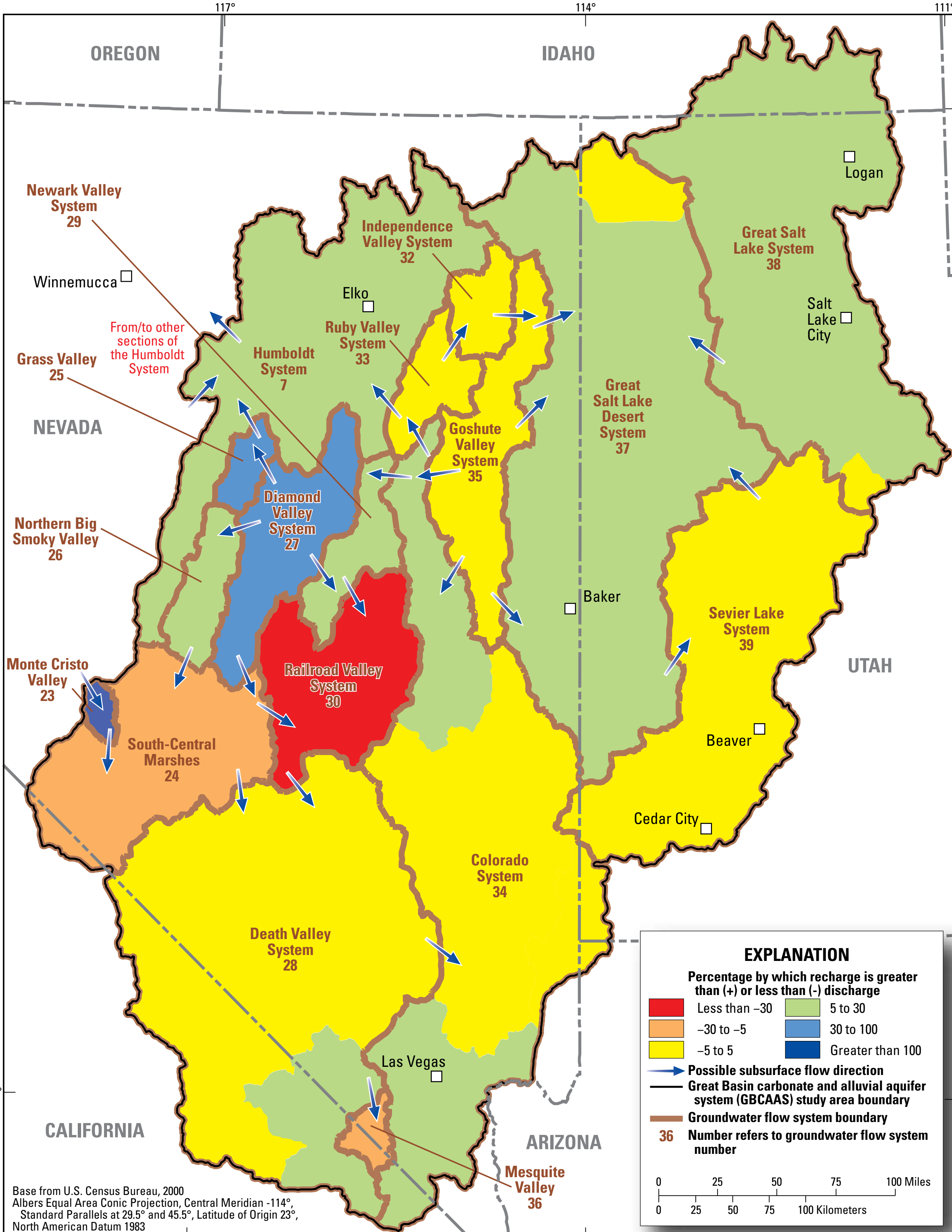

Figure D–9. Possible subsurface flow between groundwater flow systems and groundwater-budget imbalances in groundwater flow systems and subareas in the Great Basin carbonate and alluvial aquifer system study area.

table D–1 need this flux to balance predevelopment estimates of discharge within the groundwater flow system. In the South-Central Marshes (24) and Mesquite Valley (36) groundwater flow systems, however, recharge and discharge balance within a 30-percent uncertainty without subsurface inflow. Only the Railroad Valley groundwater flow system (30) has an imbalance where estimated predevelopment groundwater discharge exceeds current study recharge estimates by more than 30 percent (see "Analysis and Adjustment of BCM Results"). Therefore, using the criteria adopted for this study, Railroad Valley (30) is the only groundwater flow system within the GBCAAS study area where substantial subsurface inflow originating from inside the GBCAAS is likely.

Subsurface inflow originating from outside the study area may provide recharge to the Humboldt (7) and Monte Cristo Valley (23) groundwater flow systems on the western side of the study area (fig. D–9). This assumption is based on water levels outside the study area, hydraulic gradients within these flow systems, and the likelihood of a hydraulic connection across the study area boundary. These fluxes, however, are not required to balance predevelopment groundwater budgets in these two groundwater flow systems. The Humboldt groundwater flow system (7) is the only partial flow system in the study area, and this potential subsurface inflow toward the northeast is from sections of the flow system outside the GBCAAS study area.

Previously Published Estimates of Groundwater Recharge

Previously reported recharge estimates from HA-based groundwater studies were compiled for comparison to current study groundwater-recharge estimates. Current study estimates are for predevelopment groundwater conditions, yet estimates from previous studies are for periods from the 1940s through the 2000s. Although most HAs in the study area arguably still are in a predevelopment state, some HAs have undergone extensive groundwater development during this period. The only recharge budget components affected by groundwater development, however, are recharge from irrigation and public supply using groundwater. Recharge from irrigation with groundwater is estimated to be only a small percentage of total groundwater recharge (discussed in the "Recharge of Unconsumed Irrigation Water from Well Withdrawals" section). In Las Vegas Valley (HA 212), recharge from water imported from Lake Mead, starting in the late 1980s, needs to also be considered for recent groundwater conditions.

Previous studies in Nevada include U.S. Geological Survey/state cooperative studies beginning in the 1940s (published as Nevada Water Resources Bulletins and Nevada Water Resources Reconnaissance Reports). Recharge estimates from these studies are summarized by Harrill and others (1988). Although similar groundwater studies by the U.S. Geological Survey (USGS) in Utah also began in the 1940s (published as State of Utah Technical Publications or USGS reports), these reports were not quantitative with respect to groundwater-budget components. Previously reported recharge estimates for Utah used in this study, therefore, were from HA-based studies beginning in the 1960s. These individual reported estimates are given in Auxiliary 3G.

Beginning in the late 1940s, hydrologists working in the GBCAAS study area developed empirical techniques using precipitation zones for estimating groundwater recharge (Auxiliary 3G) that were calibrated to HA-based discharge estimates (including evapotranspiration, spring discharge, and subsurface outflow). Although subsurface flow was not quantified explicitly for each HA, some amount of inflow or outflow may have been included in the water budgets upon which these empirical techniques were based. This approach was first published by Maxey and Eakin (1949) for 13 HAs along the White River within the Colorado groundwater flow system (34), using an annual precipitation map for the State of Nevada (Hardman, 1936) for assigning the following recharge percentages for specified ranges of precipitation: 0 percent for 0–8 in. of precipitation, 3 percent for 8–12 in., 7 percent for 12–15 in., 15 percent for 15–20 in., and 25 percent for more than 20 in. of precipitation. Many of the subsequent studies published in cooperation with the states of Nevada and Utah used this Maxey-Eakin approach to estimate recharge. The use of precipitation zones for estimating groundwater recharge also was utilized by Watson and others (1976), in which Maxey-Eakin recharge estimates were revised on the basis of simple-linear and multiple-linear regression models. Harrill and Prudic (1998, p. 23–25) used the Maxey-Eakin method for estimating recharge in many of the Great Basin HAs and developed an equation for determining recharge from precipitation.

Nichols (2000) published recharge estimates based on regression modeling for selected HAs in the eastern Great Basin (Auxiliary 3G) using updated precipitation zones from PRISM mapping (Daly and others, 1994). Similar to the Maxey-Eakin approach of equating recharge estimates to discharge estimates, Nichols' (2000) empirical relations are based on discharge via evapotranspiration (ET). Because these estimates do not account for the contribution of annual precipitation to ET, they may overestimate recharge. Epstein (2004) calculated Maxey-Eakin recharge for the majority of HAs within the GBCAAS study area and developed another empirical method known as the Bootstrap Brute-Force Recharge Model for estimating recharge by utilizing coefficients applied to spatially distributed precipitation; this study was the first to evaluate uncertainty in these empirical estimates. Although each of these empirical methods indirectly accounts for subsurface inflow from, and outflow to, adjacent basins (HA reconnaissance studies include varying estimates of inflow and outflow in their estimated discharge amounts), these methods do not explicitly factor in these inflow/outflow amounts.

In addition to recharge estimates based on empirically derived formulas, estimates of HA-based recharge have been developed using other methods, such as the chloride mass-balance and deuterium mass-balance methods (Auxiliary 3G).

Using the chloride mass-balance method, Dettinger (1989) provided estimates of natural recharge for 16 HAs in the Great Basin, 10 of which are in the GBCAAS study area. Kirk and Campana (1990) developed a deuterium-based mixing cell flow model of the White River Valley subarea of the Colorado flow system (34) for estimating both recharge and interbasin groundwater fluxes. Similarly, Thomas and others (2001) developed a groundwater deuterium-calibrated mass-balance model of the White River Valley, Muddy River, and Lake Mead subareas of the Colorado groundwater flow system (34). More recently, groundwater-budget components, including recharge for the 12 HAs within the BARCAS study area of east-central Nevada and west-central Utah, were quantified using a deuterium-calibrated discrete-state compartment (DSC) model, coupled with shuffled complex evolution (SCE) optimization calibrated to groundwater deuterium values and groundwater-evapotranspiration estimates (Lundmark and others, 2007; Welch and others, 2007).

Previously reported minimum and maximum annual recharge estimates by HA (Appendix 4) are compiled by groundwater flow system and shown in table D–1. Total previously reported annual recharge for the entire study area ranges from 3,200,000 to 5,400,000 acre-ft/yr.

Summary of Recharge Components for Predevelopment Conditions

Total recharge for predevelopment conditions to the GBCAAS study area is estimated to be 4,500,000 acre-ft/yr (table D–1). In-place recharge from precipitation is the largest component of recharge and accounts for 64 percent of total recharge (figs. D–10 and D–11), followed by recharge from imported water (22 percent), runoff (13 percent), and mountain stream baseflow (3 percent). The Great Salt Lake groundwater flow system (38) receives 51 percent of the recharge within the entire study area and more than four times as much as the Great Salt Lake Desert (37) and Sevier Lake (39) groundwater flow systems, which rank second and third, respectively. In-place recharge from precipitation is the dominant form of recharge for all 17 groundwater flow systems and accounts for 43–100 percent of the total recharge for each flow system (figs. D–10 and D–11). Recharge from imported water is significant only for the Great Salt Lake groundwater flow system (38), where it ranks second in importance and accounts for nearly 42 percent of the total recharge for the flow system. With the exception of the Great Salt Lake groundwater flow

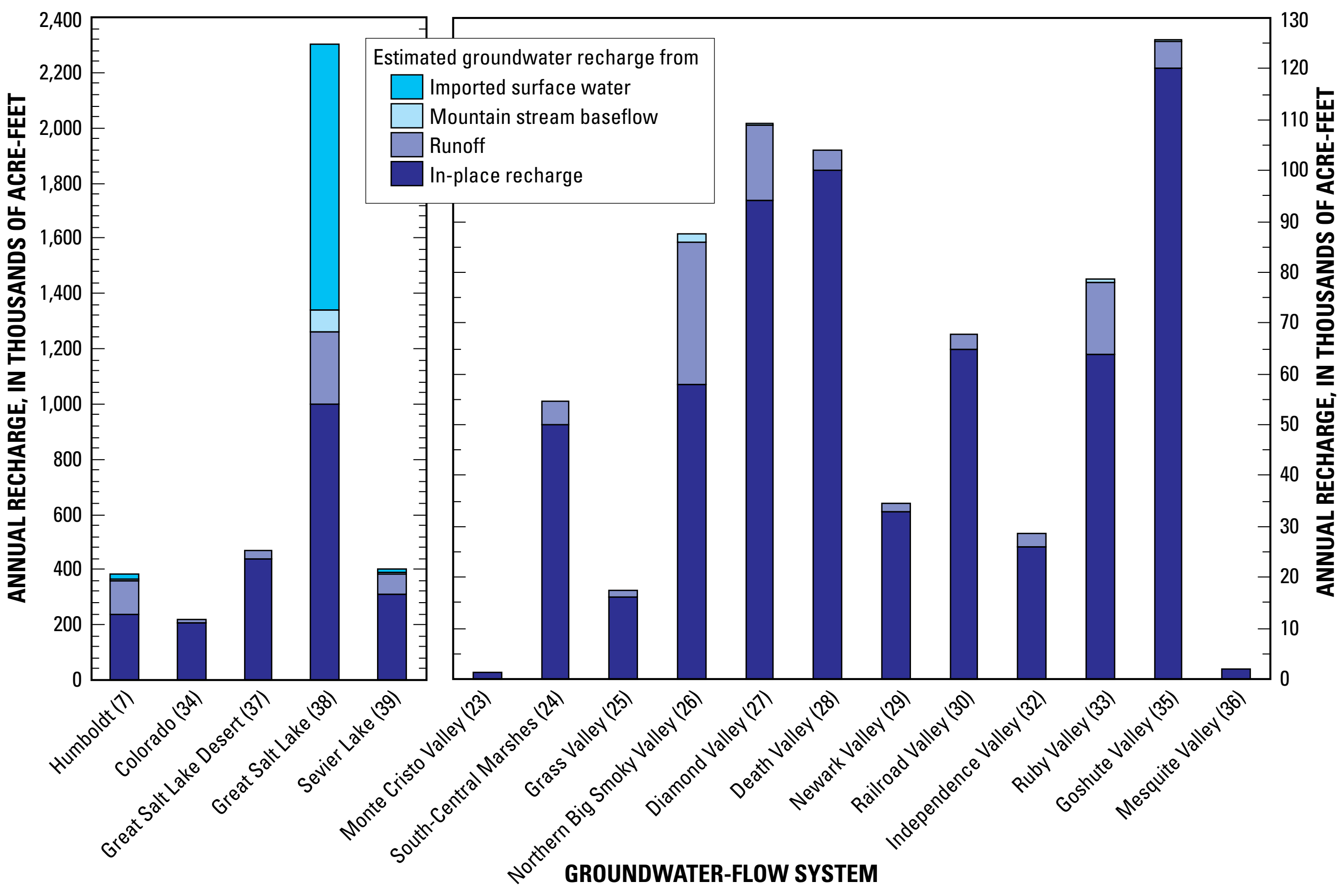

Figure D–10. Estimates of recharge components for predevelopment conditions for the 17 groundwater flow systems of the Great Basin carbonate and alluvial aquifer system study area.

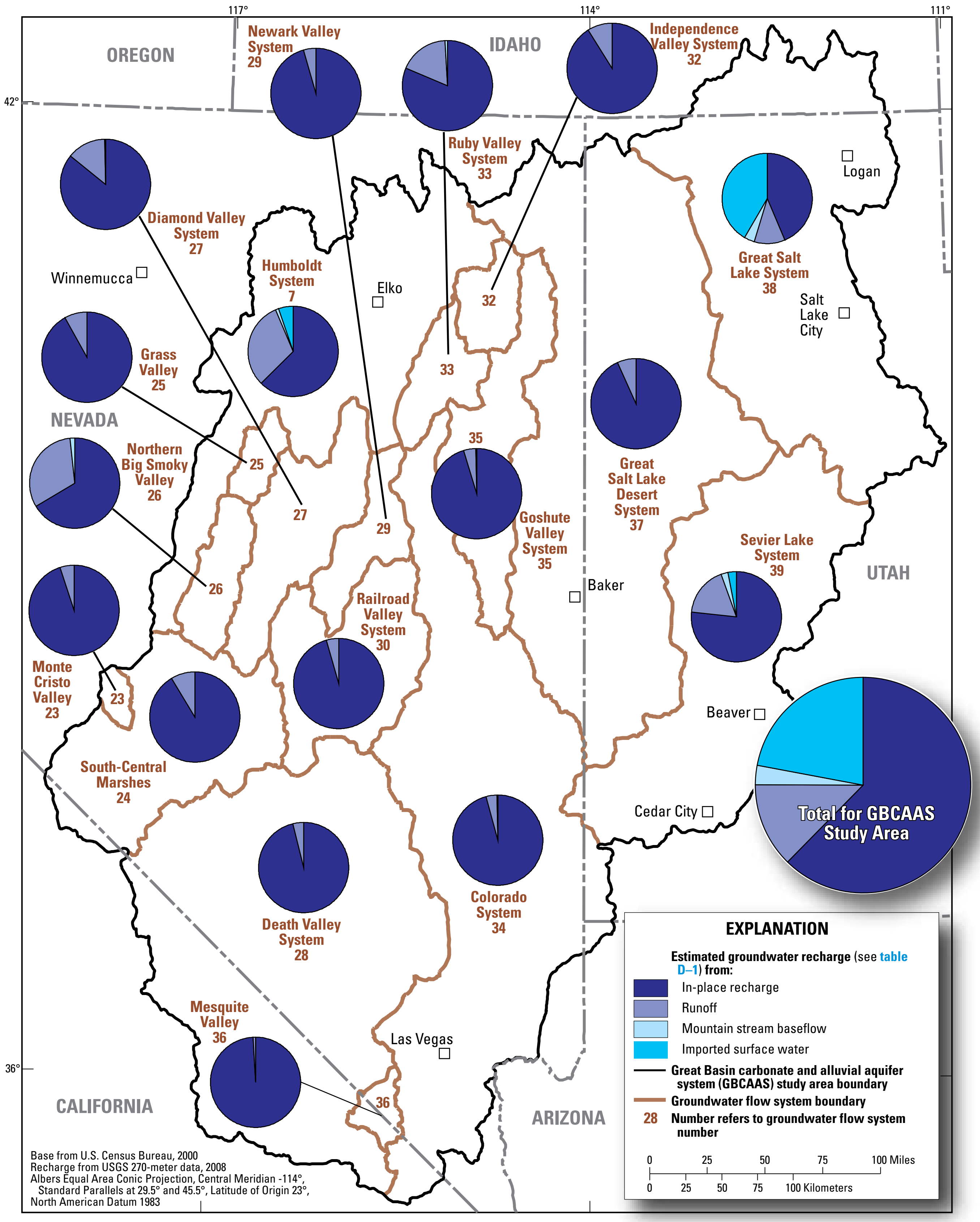

Figure D–11. Groundwater recharge components for predevelopment conditions for the 17 groundwater flow systems of the Great Basin carbonate and alluvial aquifer system study area.

system (38), recharge from runoff generally ranks second in importance.

Total recharge estimated for each groundwater flow system in the current study generally falls within the range of compiled previous estimates (table D–1). Current recharge estimates for the Northern Big Smoky Valley (26), Great Salt Lake (38), and Sevier Lake (39) groundwater flow systems, however, exceed the compiled maximum of previous estimates by 12, 21, and 25 percent, respectively. One possible reason for this discrepancy is that the previous estimates largely were based on the Maxey-Eakin method, which uses a maximum of 25 percent precipitation becoming recharge. In contrast, BCM in-place recharge exceeds 25 percent of precipitation at the highest altitudes in the Northern Big Smoky Valley (26), Great Salt Lake (38), and Sevier Lake (39) groundwater flow systems (figs. D–2 and D–5). The current recharge estimate for the Independence Valley groundwater flow system (32) is slightly less (7 percent) than the compiled minimum of previous estimates.

Predevelopment Groundwater Discharge

Groundwater Discharge Processes

Groundwater evapotranspiration (ETg) is the primary form of discharge within the GBCAAS study area (figs. C–1 and D–1). Total evapotranspiration (ET) is the process by which water is transferred from the land surface to the atmosphere and includes transpiration by plants and evaporation from bare soils and free water surfaces. ETg is the component of ET that is derived from groundwater, and it usually occurs in areas where groundwater levels are shallow or near land surface. Topographically, areas of ETg generally are found in the low areas near the center of a basin. In these areas, groundwater is discharged by springs, by diffuse seepage upward through basin-fill aquifers, by evaporation from soils and water bodies, and by evapotranspiration by plants. The amount of ETg is dependent upon the vegetation type, vegetation density, groundwater levels, soil characteristics, and micro climate.

Moreo and others (2007), Smith and others (2007), and Welch and others (2007) describe Great Basin phreatophytic vegetation types; delineate ET units based on vegetation type, density, and distribution; and provide a summary of the range of measured ET rates for various ET units. These rates range from average values of 0.71 ft/yr for dry playa areas to 5.1 ft/yr for open water. The volume of water exchanged to the atmosphere by ET is estimated as the product of the area of ET vegetation units and the rates determined from point measurements of ET. Annual ETg generally is estimated as the difference between the estimated annual ET and the annual precipitation (Laczniak and others, 1999; Laczniak and others, 2001; Moreo and others, 2007; Welch and others, 2007). The assumption is that in areas with phreatophytic vegetation, all local precipitation is consumed by plants and any remaining plant water requirements are met by groundwater utilization. Because of the combination of controlling factors, it is difficult to estimate ETg, and the estimates may have large uncertainties.

Groundwater seepage to surface water bodies is another form of groundwater discharge within the GBCAAS study area (figs. C–1 and D–1). This includes discharge to mountain streams, basin-fill streams, basin-fill lakes, and basin-fill reservoirs. Evidence for discharge to mountain streams is provided by the gaining perennial stream reaches often observed in the lower parts of the mountain ranges. Gaining reaches in the Bear, Humboldt, Jordan, and Sevier Rivers (fig. A–1), and other smaller streams, indicate groundwater discharge to perennial streams flowing through the basin fill. Groundwater discharge to lakes and reservoirs located within the basin-fill deposits occurs to the Great Salt Lake, Lake Mead, Utah Lake (fig. A–1) and various other smaller reservoirs.

Groundwater discharge to springs occurs throughout the study area, both in small amounts to local springs, as well as larger amounts to regional springs (figs. C–1 and D–1, pl. 1). The smaller springs located in mountains may represent discharge from perched aquifers not in direct hydraulic connection with the regional water table. Some of the largest regional springs may discharge water that enters the HA as subsurface inflow from adjacent HAs. It is probable that some flow paths to large regional springs incorporate groundwater from several upgradient HAs (Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Thomas and others, 2003).

Groundwater discharge also may include subsurface outflow to downgradient HAs and groundwater flow systems (figs. C–1 and D–1). Discharge as subsurface outflow is derived from groundwater that originates in upgradient areas and subsequently flows into downgradient areas through the subsurface in basin fill or consolidated rock. The amount of subsurface outflow depends on the hydraulic gradient between the HAs or groundwater flow systems, the hydraulic conductivity of the intervening bedrock and alluvium, and the cross-sectional area between the HAs or groundwater flow systems (for example, equation C–1).

Discharge to Evapotranspiration

Current study estimates of groundwater discharge to ETg were derived by compiling and re-evaluating data from more than 100 previous studies, including USGS reports, Nevada Department of Natural Resources (DNR) reconnaissance reports, Utah DNR technical publications, and journal articles (Auxiliary 2). ETg estimates from previous studies were examined closely to determine whether they represented predevelopment conditions or incorporated the effects of significant groundwater withdrawals. For ETg estimates from previous studies that were conducted during significant groundwater development, an adjustment was made to the natural discharge to account for well withdrawals (see “Adjustment to natural discharge for well withdrawals” section in this chapter); this was necessary to establish a predevelopment groundwater budget because these well withdrawals may capture water that would otherwise discharge naturally. It should be noted, however, that the adjusted ETg estimates likely represent maximum values because well withdrawals may have captured some groundwater from groundwater storage instead of from natural discharge.

Groundwater Evapotranspiration Areas

Data delineating areas of ETg were compiled from a number of previous reports and mapped for the study area (fig. D–12; Appendix 6). Most of the data used to map the ETg area boundaries are digital data from four regional-scale studies: BARCAS (Laczniak and others, 2007), DVRFS (Laczniak and Smith, 2001), eastern Nevada (Smith and others, 2000), and the Great Basin Regional Aquifer-Systems Analysis (RASA–GB; Medina, 2005). The boundaries of the ETg areas delineated in these studies define the outer extent of phreatophyte areas (including playas) where groundwater may be consumed by ET. The BARCAS, DVRFS, and eastern Nevada studies used a combination of satellite and aerial photographic imagery, as well as field studies and verification to identify areas within the HAs where ETg may occur (Smith and others, 2000; Laczniak and others, 2001; Smith and others, 2007). The ETg areas defined in the RASA study are a compilation of the data from earlier reconnaissance studies in Nevada and Utah (Harrill and others, 1988), in which ETg areas were delineated using field mapping techniques. In the current study, data from the BARCAS and DVRFS studies were used preferentially to map ETg areas because these studies are most recent and involved extensive detailed mapping of phreatophyte areas. In areas outside the BARCAS and DVRFS study areas, data from the eastern Nevada (Smith and others, 2000) and RASA–GB studies (Medina, 2005) were used, with the eastern Nevada study (Smith and others, 2000) data preferentially used because it is most recent and was derived from more detailed mapping of ETg areas.

Additional ETg areas were mapped in six HAs using information from four smaller-scale (HA-scale) studies (Rush, 1964, fig. 2; Rush, 1968, pl. 1; Bolke and Price, 1972, pl. 1; Thiros and others, 1996, pl. 1). The ETg areas delineated in these studies were manually added to the digital data set of ETg areas for HAs in which either (1) there was a previously reported ETg estimate, but no ETg area was formerly delineated in the regional-scale digital data sets; or (2) the ETg area defined in the report differed significantly from the ETg areas delineated in the regional-scale digital data sets (discussed above).

Groundwater Evapotranspiration Estimates

Current study estimates of groundwater discharge to ETg for each HA and groundwater flow system were determined by compiling data from previously published studies (Auxiliary 3H). The published reports used to derive the current study estimates can be divided into three types: (1) full-HA reports, where ETg estimates for the entire ETg area within a single HA are reported; (2) partial-HA reports, where the ETg estimates are reported only for a section of the ETg area within a single HA; and (3) multi-HA reports, where ETg estimates from two or more HAs are summed together into a single reported ETg estimate. All but seven of the HAs with mapped ETg areas had at least one previously reported ETg estimate.

For the majority of HAs within the study area, ETg estimates were taken directly from the previous reports. The ETg estimates from more recent studies were used preferentially as the current study estimates, especially in the cases of the BARCAS (12 HAs, fig. A–2), DVRFS (31 HAs, fig. A–2), and Wasatch Front studies (Tooele Valley, HA 262; Utah Valley Area (Southern section and Goshen Valley), HA 265; Northern Juab Valley, HA 266; Cedar City Valley, HA 282). ETg estimates from the BARCAS and DVRFS studies included more extensive, detailed mapping of vegetation units and detailed point measurements of ET rates. The Wasatch Front studies took advantage of information on more recently published ETg rates and included more detailed information about whether precipitation and spring discharge were included in the reported ETg than previous reports in these areas. If an HA had multiple ETg estimates from different sources, an average of these estimates was calculated and used as the current study estimate when there was no definitive reason for selecting one estimate over another. ETg estimates from partial-HA reports were used only if (1) there were no full-HA ETg estimates for the HA, or (2) the total ETg area within the HA was represented by multiple partial-HA ETg estimates.

Generally, ETg estimates from multi-HA reports were used only if there were no full-HA ETg estimates for the HA. If a multi-HA report contained an estimate for HAs that have no full-HA ETg estimates, the multi-HA ETg estimate was divided among the HAs by the fraction of the total ETg area located within each HA (Auxiliary 3I—Case 1). In some cases, a previously published ETg estimate for multiple HAs included both an HA for which no other ETg estimates existed and an HA for which there was a separately reported estimate. In this case, the ETg amount for the HA not having a separate estimate was calculated by subtracting the separately reported ETg estimate for the other HA from the total ETg estimate given in the multi-HA report (Auxiliary 3I—Case 2).

Nichols (2000) developed water-budget estimates for 16 HAs in east-central Nevada. Some of the HAs that Nichols studied were revisited by Moreo and others (2007) and Welch and others (2007). Moreo and others (2007) estimated ETg on the basis of measurements of ET over specific vegetation

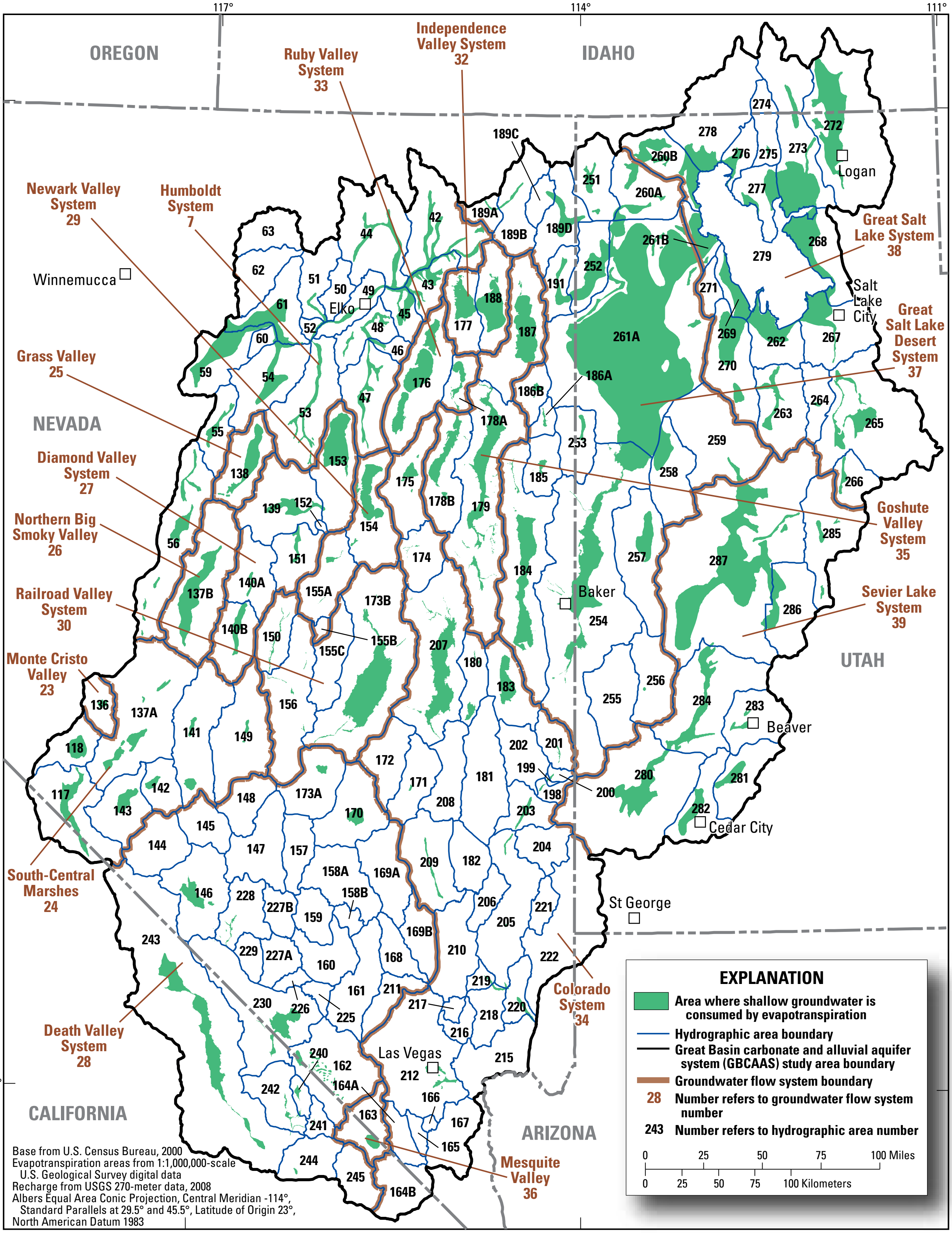

Figure D–12. Areas of groundwater evapotranspiration (ETg) in the Great Basin carbonate and alluvial aquifer system study area.

units. Moreo and others (2007) and Welch and others (2007) did extensive comparisons and uncertainty analyses on their data, as well as data published in previous studies, including Nichols (2000). Nichols's (2000) estimates of ETg generally are on the upper end of the range of reported values and are as much as two times that of the more detailed measurements and estimates made by Moreo and others (2007) and Welch and others (2007). Therefore, Nichols's (2000) ETg estimates were not used to determine ETg in the current study.

Six of the HAs within the study area had mapped ETg areas but no previous ETg estimates. These HAs include Grass Valley (HA 138), Coal Valley (HA 171), Valjean Valley (HA 244), Great Salt Lake Desert-East Part (HA 261B), Great Salt Lake (HA 279), and Sevier Desert (HA 287). As a first step in estimating the volume of ETg for these HAs, the mapped ETg areas were compared to imagery from the U.S. Department of Agriculture National Agricultural Imagery Program (NAIP) Compressed County mosaics (CCM) for Utah (2006b), Nevada (2006a), and California (2005); and the Southwest Regional Gap Analysis Project (SWReGAP) data from the RS/GIS Laboratory, College of Natural Resources, Utah State University (2004). From the NAIP imagery and SWReGAP data, it was determined that ETg areas within all of these HAs, except Great Salt Lake (HA 279), predominantly were playa. Reported ETg rates for playas within the study area generally range from 0.1 to 0.5 ft/yr (Zones, 1961, p. 21; Hood and Rush, 1965, table 6; Harrill and Lamke, 1968, table 8; Hood and Waddell, 1968, table 6; Harrill, 1971, table 5; Van Denburgh and Rush, 1974, table 8; Lines, 1979, p. 88; Malek and others, 1990, table 5; Handman and Kilroy, 1997, table 9; DeMeo and others, 2003, table 4; Welch and others, 2007, Appendix A), with the most commonly reported ETg rate for playas being 0.1 ft/yr. Therefore, ETg estimates for these HAs were determined by applying an ETg rate of 0.1 ft/yr over the ETg area within each HA.

For Great Salt Lake (HA 279), the mapped ETg areas only occur along the shoreline of the Great Salt Lake. The area of this terminal lake varies widely as lake levels fluctuate because of variations in climate and weather conditions from year to year; therefore, the ETg areas along the shoreline may or may not be inundated by the Great Salt Lake at any one point in time. It was not within the scope of this study to determine if evapotranspiration is supported by surface water or groundwater. Because of the relatively fine-grained playa deposits along the lake shore, however, and lack of evidence of inflow of freshwater into the lake along its margins (Dave Naftz, U.S. Geological Survey, oral commun., 2009; Stolp and Brooks, 2009), it is assumed that ET is mainly surface-water supported and, therefore, ETg was assumed to be negligible within this HA. Any ETg along the edge of Great Salt Lake is probably included in the estimates of groundwater discharge to Great Salt Lake.

Many of the previous reports used to derive the ETg estimates include spring discharge in the reported ETg. It was assumed in these reports that all spring discharge from the basin fill ultimately was consumed through evapotranspiration. Because groundwater discharge to springs is a separate component of the groundwater budget in the current study, spring discharge was subtracted from the ETg estimates that included spring discharge. For previous reports in which the amount of spring discharge contributing to ETg was specified, the reported amount of spring discharge was subtracted from the ETg estimate. Very few of the previous reports, however, explicitly define the magnitude of spring discharge or identify which springs in the HA were included in the ETg estimates. The current study assumes that any spring or group of springs within 2 mi of an ETg area (as this distance generally encompasses all springs that discharge within the basin fill) contributes to ETg within that HA. Discharge from these springs ("Estimated/Reported spring discharge in reported ETg" column in Auxiliary 3H) was subtracted from the ETg estimates for those reports that include spring discharge in the reported ETg but that do not specify the amount of spring discharge included. Springs that discharge less than about 300 gal/min (500 acre-ft/yr) are not counted explicitly in the groundwater budget in this study; discharge to small springs within the basin fill can be assumed to be included in the estimates of ETg.

Total estimated predevelopment groundwater discharge to ETg in the current study is 1,800,000 acre-ft/yr (table D–2) and accounts for 43 percent of the total predevelopment discharge for the study area. The Great Salt Lake (38), Great Salt Lake Desert (37), Humboldt (7), and Sevier Lake (39) groundwater flow systems have the highest amounts of discharge to ETg and account for 69 percent of the total estimated annual ETg for the study area. These four groundwater flow systems generally are wetter and host large areas of phreatophytic vegetation (fig. D–12). In contrast, Monte Cristo Valley (23), Mesquite Valley (36), and Grass Valley (25) groundwater flow systems are drier and smaller and have much less annual ETg. ETg estimates for each of the HAs are given in Appendix 5.

Discharge to Surface Water

Within the GBCAAS study area, groundwater discharge to surface water is an important component of the groundwater budget (table D–2). This includes discharge to streams (both mountain and basin-fill streams), as well as discharge to lakes and reservoirs. Groundwater discharge to springs is discussed separately in the "Discharge to Springs" section below.

Discharge to Mountain Streams

In the current study, groundwater budgets for entire HAs, including the mountains, are estimated, and discharge to mountain streams (also referred to as "baseflow") is a component of these budgets. Few previously published reports estimated groundwater discharge to mountain streams; these estimates, therefore, were derived for the current study using records from USGS gaging stations. Some of the baseflow becomes recharge from streams, canals, and irrigated fields on the basin fill as discussed in the "Recharge from Mountain Stream Baseflow" section of this report. For mountain streams that begin flowing in a watershed (that is, no flow in the upgradient part of the stream channel), only one gage is necessary to determine if a stream is gaining because any baseflow in that stream must be derived from groundwater discharge to the stream within the drainage area. It is assumed baseflow estimates do not include streamflow inputs from surface-water runoff or from streams flowing from an upgradient watershed. While there may be both gaining and losing reaches, this gaged baseflow represents net groundwater discharge upstream of the gage location.

A simplified approach for determining baseflow for gaged mountain streams was used in the current study, whereby the annual groundwater discharge was estimated to be the minimum mean daily discharge at each gage for the period of record multiplied by 365 days per year. The use of minimum daily discharge to estimate baseflow represents a minimum value because baseflow changes seasonally and annually (during periods of higher streamflow, baseflow will correspondingly increase). Rigorous hydrograph separation methods for estimating groundwater discharge to streams (Hall, 1968; Zecharias and Brutsaert, 1988; Tallaksen, 1995; Rutledge, 1998) were not used because these methods were not developed for application in snowmelt-dominated streams prevalent in the GBCAAS. Modifying these baseflow separation techniques was beyond the scope of the current study.

USGS streamflow data from the USGS' NWIS database (Mathey, 1998) and from published reports were used to develop current study estimates of groundwater discharge to streams in the mountains (table D–2, Appendix 5). Streamflow records from 105 USGS stream gages (pl. 1 and Auxiliary 3J) were chosen on the basis of the following criteria: (1) the minimum mean daily discharge was greater than 0, (2) the gage was located within 0.25 mi of consolidated rock, and (3) the gage had at least 365 continuous days of streamflow record. The minimum flow limitation was used to eliminate nonperennial streams. Although groundwater discharge from regional and locally perched sources may occur to ephemeral and intermittent streams, this amount of discharge was considered to be negligible at the scale of the current study. The geographic limitation (0.25 mi from consolidated rock) was used to minimize the effects of diversions and stream loss on alluvial fans or other deposits. It was assumed that streamgages within 0.25 mi of consolidated rock were located above all diversions and above substantial stream loss to basin-fill deposits. Where multiple gages exist along a stream, groundwater discharge between the gages was assumed to be the minimum mean daily flow at the lower gage minus the minimum mean daily flow at the upper gage to better evaluate the location of this discharge.

Groundwater likely discharges to some ungaged perennial mountain streams within the study area, particularly in eastern Nevada (Randell J. Laczniak, U.S. Geological Survey, written commun., 2009). Determining the number of these streams and associated baseflow of these streams, however, was beyond the scope of the current study. While the National Hydrography Dataset (NHD) classifies streams as either intermittent or perennial, this classification is subject to error. The NHD classification is based primarily on digitized intermittent and perennial streams from USGS 1:24,000 topographic maps. The water features on these maps were determined as follows: *"Field personnel would look at the particular stream and would attempt to determine if the stream flowed year round (except in the dry season), or flowed part of the year (intermittent). We would talk to local personnel and ask them to determine if the flow we were seeing was typical… this is a rather subjective method as opposed to a scientific method"* (William J. Smith, U.S. Geological Survey National Mapping Division, written commun., 2010). Furthermore, a perennial stream is defined as a stream that *"contains water throughout the year, except for infrequent periods of severe drought"* (National Hydrography Dataset, February 2000, accessed January 2010 at http://nhd.usgs.gov/chapter1/index.html). This implies that many streams classified as perennial in the NHD dataset dry up during drought periods and, thus, are not likely connected to the regional aquifer system. For these reasons, relying on this dataset for estimating groundwater discharge would be problematic. In addition, no basin characteristic techniques or statistics currently exist to determine baseflow in these ungaged streams (Terry A. Kenney, Surface-Water Specialist, U.S. Geological Survey, oral commun., 2010). Because the number of ungaged perennial streams and the amount of discharge from these ungaged streams could not be quantified, the current study estimate of groundwater discharge to mountain streams is a minimum estimate.

Estimates of baseflow for individual gaged mountain streams range from 10 to 57,000 acre-ft/yr (Auxiliary 3J). Mean annual streamflow for individual gaged mountain streams ranges from 270 to 140,000 acre-ft/yr (Auxiliary 3J). For individual streams, the percentage of mean annual flow that is estimated as baseflow ranges from less than 1 to 85 percent.

On the basis of historical streamgage records, total estimated predevelopment groundwater discharge to mountain streams for the current study is 450,000 acre-ft/yr and accounts for 11 percent of the total discharge for the entire study area (table D–2). Generally, mountain ranges with greater amounts of precipitation (fig. D–2) have greater amounts of discharge to mountain streams. The Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems have the highest amounts of discharge to mountain streams and account for 91 percent of the estimated discharge to mountain streams for the entire study area (table D–2). These groundwater flow systems include mountainous regions with more precipitation and larger total lengths of perennial stream reaches than the other groundwater flow systems (pl. 1). Only four HAs in the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems account for 71 percent of the total estimated discharge to mountain streams (Appendix 5). The Humboldt groundwater flow system (7) accounts for about 3 percent of the total discharge to mountain streams. The remaining 6 percent of discharge to mountain streams is distributed between nine other groundwater flow systems. Five of the groundwater flow systems and 121 HAs within the study area have no gaged perennial mountain streams. Because there are ungaged perennial streams in these areas and elsewhere, the total estimated groundwater discharge to mountain streams for the GBCAAS study area is considered a minimum value.

Discharge to Basin-Fill Streams/Lakes/Reservoirs

Current study estimates of groundwater discharge to basin-fill streams, lakes, and reservoirs (Auxiliary 3K) were derived by compiling and re-evaluating data from more than 100 previous studies, including USGS reports, Nevada DNR reconnaissance reports, Utah DNR technical publications, and journal articles (Auxiliary 2). Each reported estimate was examined in detail to ensure that the data were in agreement with gage data and other conditions (for example, groundwater levels at or above stream altitude); if the data were in agreement, these estimates were used as the current study estimate. If more than one reported discharge estimate existed for an HA, and there was no definitive reason to choose one estimate over another, then the average of the estimates was used. If the previously reported discharge estimate was not in agreement with gage data and other conditions, adjustments were made to the estimate on the basis of gage data or seepage data from other studies (Auxiliary 3K). For example, in Upper Reese River Valley (HA 56), Berger (2000) reported groundwater discharge to the Reese River of 1,000 acre-ft/yr (Auxiliary 3K); however, streamgages from NWIS showed the river losing in the basin fill, not gaining. The current study estimate of groundwater discharge to basin-fill streams, lakes, and reservoirs, therefore, was 0 acre-ft/yr for this HA. Gage data were used to estimate groundwater discharge to streams in a few HAs for which there was no previously reported groundwater discharge estimate. Some previous estimates of groundwater discharge to basin-fill streams were misreported as spring discharge and vice versa (see “Comments” column in Auxiliary 3K). In the current study, (1) groundwater discharge to streams that was incorrectly reported as spring discharge and (2) spring discharge that was incorrectly reported as groundwater discharge to streams were both reclassified under the correct discharge component (Auxiliary 3K and 3L).

Total estimated predevelopment groundwater discharge to basin-fill streams, lakes, and reservoirs for the current study is 660,000 acre-ft/yr (table D–2) and accounts for 16 percent of the estimated total discharge for the study area. The Great Salt Lake (38), Colorado (34), and Sevier Lake (39) groundwater flow systems have the highest amount of discharge to basin-fill streams, lakes, and reservoirs, and account for 98 percent of the total estimated for the entire study area. Seven HAs account for about 97 percent of the total estimated discharge to basin-fill streams, lakes, and reservoirs (Appendix 5). The remaining 3 percent is distributed among 10 other HAs, each having less than 10,000 acre-ft/yr of discharge to basin-fill streams, lakes, and reservoirs. There are 148 HAs with no estimated groundwater discharge to basin-fill streams, lakes, or reservoirs.

Discharge to Springs

Estimates of groundwater discharge to springs were derived for the current study using both spring data compiled from the USGS’ NWIS database (Mathey, 1998) and measurements of individual springs from published reports (Auxiliary 3L). Previously reported total spring discharge estimates by HA were not used in the current study because these estimates often (1) included discharge only from the largest regional springs, (2) did not include discharge to mountain springs, and (or) (3) did not separate spring discharge from ETg discharge estimates.

Within the GBCAAS study area, there are about 300 individual springs or groups of springs having discharge greater than 300 gal/min. Only springs with discharge greater than 300 gal/min (about 500 acre-ft/yr) are included because smaller springs are less likely to be perennial than larger springs. Exceptions are made when several small springs are clustered together to create a total discharge of greater than 300 gal/min. Springs that discharge less than 300 gal/min account for only about 8 percent of the total flow (about 77,000 acre-ft/yr) from springs reported in the NWIS database, and fewer than 2 percent of the total discharge for the study area, which is well within the uncertainty of 30 percent assumed for discharge estimates. For most springs, the mean flow for the entire period of record was used as the predevelopment discharge. Discharge from springs that contributes to a gaged perennial stream was assumed to be included in the gaged baseflow and was not accounted separately. In areas where groundwater withdrawals are known to have affected spring discharge, only discharge measurements before the affected period were used. For springs with data in both NWIS and a published report, only data that more accurately presented predevelopment long-term discharge were used.

The distribution of spring discharge is different from the spatial distribution of gaged perennial mountain streams (pl. 1). In particular, the east-central part of Nevada (Kobeh Valley, HA 139; Diamond Valley, HA 153; Newark Valley, HA 154; Railroad Valley-Northern Part, HA 173B; Ruby Valley, HA 176; Butte Valley-Northern Part, HA 178A; Steptoe Valley, HA 179; Lake Valley, HA 183; Spring Valley, HA 184; White River Valley, HA 207; and Snake Valley, HA 254) has many large springs, yet a relatively small number of gaged streams. The near-surface geology of this area (fig. B–3) is dominated by permeable carbonate rocks. This area has relatively high BCM estimated in-place recharge rates (fig. D–5) and low runoff rates (fig. D–6). The permeable rocks have subdued mounding of the potentiometric surface (less discharge to mountain streams) and transmit this high recharge to both nearby and distant springs. In contrast, the eastern portion of the Sevier Lake (39) groundwater flow system (Parowan Valley, HA 281; Cedar City Valley, HA 282; and Pavant Valley, HA 286) and the central portion of the Humboldt (7) groundwater flow system (Starr Valley Area, HA 43; Lamoille Valley, HA 45; Susie Creek Area, HA 50; Maggie Creek Area, HA 51; and Boulder Flat, HA 61) have few large springs, yet a relatively large number of perennial gaged streams. The surficial geology of these areas is dominated by less permeable siliciclastic and volcanic rocks (tables B–1 and A3–1), resulting in mounding of the potentiometric surface beneath these mountains (more discharge to mountain streams).

Total estimated predevelopment groundwater discharge to springs (in both the mountain block and basin fill) for the current study is 990,000 acre-ft/yr (table D–2) and accounts for 24 percent of the total discharge for the study area (table D–2). This is a minimum estimate because it does not include discharge from springs that have not been measured. Seventy-five percent of the total is discharged from the Great Salt Lake (38), Colorado (34), and Great Salt Lake Desert (37) groundwater flow systems. Ten HAs account for about one-half of the total estimated discharge to springs (Appendix 5), 59 other HAs have less than about 30,000 acre-ft/yr of estimated spring discharge each, and the remaining 96 HAs have no estimated spring discharge.

Discharge to Subsurface Outflow

As with subsurface inflow, subsurface outflow was not estimated for the current study because of (1) the large uncertainty in groundwater-budget components for using water-balance methods, and (2) the sparsity of hydraulic information for using Darcy flux methods. Previous estimates of subsurface outflow were compiled by HA (Auxiliary 3M) and by groundwater flow system (Auxiliary 3N). The estimates compiled by groundwater flow system account only for subsurface outflow that exits a groundwater flow system and do not account for subsurface outflow between HAs within a groundwater flow system. As discussed above in “Recharge from Subsurface Groundwater Inflow,” these previous estimates could not be used in the current study because in many of these studies balancing groundwater budgets in the upgradient or downgradient HAs or groundwater flow systems was not considered.

Figure D–9 shows groundwater-budget imbalances and arrows where the potentiometric contours, likelihood of hydraulic connection across HA boundaries (pl. 2), and groundwater-budget information all indicate possible groundwater subsurface flow between groundwater flow systems. Subsurface outflow is possible from all of the groundwater flow systems except Mesquite Valley (36). Subsurface outflow is likely in the Monte Cristo Valley (23), Grass Valley (25), and Diamond Valley (27) groundwater flow systems, where estimated recharge exceeds predevelopment discharge by more than 30 percent (table D–2). Although subsurface outflow is possible from the other 13 groundwater flow systems, these fluxes are not required to balance predevelopment groundwater budgets in these groundwater flow systems.

The only possible discharge to subsurface outflow leaving the GBCAAS study area occurs in the Humboldt groundwater flow system (7), which is the only partial groundwater flow system in the study area. Potentiometric contours and the likelihood of hydraulic connection across HA boundaries (pl. 2) indicate the potential for subsurface outflow toward the northwest to sections of the Humboldt groundwater flow system (7) outside of the GBCAAS study area (fig. D–9).

Adjustment to Natural Discharge for Well Withdrawals

A number of the previously reported discharge estimates include well withdrawals. Because well withdrawals may affect natural discharge, and because these previously reported discharge estimates were used to calculate previous predevelopment budget estimates, well-withdrawal estimates from these reports were taken into account in establishing a predevelopment groundwater budget for each groundwater flow system and HA. For the current study, it is assumed that previously reported well withdrawals greater than 10 percent of the total reported discharge affect natural discharge (Auxiliary 3O). The effects of withdrawals less than this likely are too small to detect and cannot be differentiated from fluctuations and errors in natural discharge.

Adjustments were only needed in a total of 16 HAs within the Great Salt Lake (38), Sevier Lake (39), Humboldt (7), and Great Salt Lake Desert (37) groundwater flow systems (Auxiliary 3O). All other HAs within the GBCAAS study area either had reported predevelopment groundwater discharge estimates or well withdrawals that were less than 10 percent of total reported natural discharge. In the HAs where adjustments were needed, it was assumed that net well withdrawals (reported well withdrawals minus irrigation return flow) were 70 percent of total reported well withdrawals (see “Recharge of Unconsumed Irrigation and Public Supply Water from Well Withdrawals” section below). Although well withdrawals may have different effects on the various components of natural discharge, the distribution of these effects amongst the individual discharge components (ETg, surface water, springs, and subsurface outflow) is not known. These net well withdrawals, therefore, are represented in table D–2 and Appendix 5 in the column “Adjustment to natural discharge for well withdrawals.” This is a maximum estimate that assumes all discharge from well withdrawals captures groundwater that would otherwise discharge naturally from the system, and it does not account for groundwater that may be released from storage within the aquifer.

The total estimated adjustment to natural discharge for well withdrawals for the current study is 330,000 acre-ft/yr (table D–2) and accounts for 8 percent of the total predevelopment groundwater discharge estimate. The largest adjustments are to the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems. Smaller adjustments are to the

Humboldt (7) and Great Salt Lake Desert (37) groundwater flow systems. No adjustments were made in the other 13 groundwater flow systems. Six HAs account for 81 percent of the total adjustment to natural discharge (Appendix 5). These HAs incorporate the heavily populated Wasatch Front area that was highly developed as early as the 1950s and 1960s, before the first detailed groundwater studies were conducted. The remaining 19 percent of the total adjustment to natural discharge is distributed among 10 other HAs; 148 HAs required no adjustment to natural discharge, either because reported withdrawals were a small portion of groundwater discharge, or because predevelopment estimates of discharge were previously reported.

Previously Published Estimates of Groundwater Discharge

Previously reported discharge estimates from regional and HA-based groundwater studies were used to derive many of the current study discharge estimates for predevelopment conditions (Appendix 5), and they also were compiled for comparison to current study groundwater-budget estimates (table D–2; Auxiliary 3P). Unfortunately, these previous studies (from the 1940s through the 2000s) were sometimes conducted in HAs undergoing extensive groundwater development, and the natural discharge reported from those studies may be less than it was prior to development. Total previously reported annual discharge for the entire study area ranged from 3,400,000 to 4,200,000 acre-ft/yr (table D–2).

Summary of Discharge Components for Predevelopment Conditions

The current study estimate of total discharge for predevelopment conditions in the GBCAAS study area is 4,200,000 acre-ft/yr (table D–2). Discharge from the Great Salt Lake groundwater flow system (38) accounts for more than 50 percent of the discharge from the entire study area. Discharge from the Great Salt Lake Desert (37), Sevier Lake (39), Humboldt (7), and Colorado (34) groundwater flow systems each account for 5 to 11 percent of total discharge. Discharge for all remaining groundwater flow systems each account for less than 5 percent of the total discharge. Estimated groundwater evapotranspiration, ETg, is the largest form of discharge and accounts for 43 percent of total discharge, followed by discharge to springs (24 percent), discharge to basin-fill streams, lakes, and reservoirs (16 percent), discharge to mountain streams (11 percent), and the adjustment to natural discharge for well withdrawals (8 percent). The relative magnitude of each discharge component by groundwater flow system is shown on figure D–13. Except for the Great Salt Lake (38) and Colorado (34) groundwater flow systems, ETg is the most important form of groundwater discharge from all groundwater flow systems, accounting for about 50–100 percent of total discharge from these flow systems (figs. D–13 and D–14). Discharge to basin-fill streams, lakes, and reservoirs is the largest component in the Great Salt Lake groundwater flow system (38), accounting for 26 percent of discharge in this flow system. Discharge to springs is the largest component in the Colorado groundwater flow system (34), accounting for 57 percent of discharge.

Total groundwater discharge estimated for groundwater flow systems in the current study generally fall within the ranges of the compiled previous estimates (table D–2). Current discharge estimates for the Humboldt (7), Colorado (34), Great Salt Lake (38), and Sevier Lake (39) groundwater flow systems, however, exceed the maximum of the previous estimate compilations by 76, 10, 10, and 14 percent, respectively. Previous estimates for the Humboldt (7) and Sevier Lake (39) groundwater flow systems were missing for various HAs within these flow systems, which explains, in part, why current estimates exceed the compiled numbers from previous estimates. Discharge in the Colorado (34), and Great Salt Lake (38) groundwater flow systems are higher than previous estimates because the previous estimates do not include discharge to mountain streams and springs.

Total groundwater-discharge estimates for HAs in the current study also generally are similar to previous estimates. Where only a minimum previously reported discharge estimate is listed in Appendix 5, this indicates that only one previous study had HA-based total discharge measurements. Previous total groundwater discharge estimates have been reported for 106 of the 165 HAs within the GBCAAS study area; 59 HAs have no previously estimated total groundwater discharge. Of the 106 HAs, only 37 have more than one estimate of total groundwater discharge. In four of these 37 HAs, the current study exceeds or underestimates the previously reported ranges by more than 30 percent. For Jakes Valley (HA 174), Dugway-Government Creek Valley (HA 259), and Cache Valley (HA 272), the current study estimates exceed the previously reported ranges by 90, 61, and 64 percent, respectively. This difference is primarily because the current study estimate includes groundwater discharge to mountain streams and mountain springs, which was not quantified in these previous studies. For Pine Valley (HA 255), the current study estimates no groundwater discharge, compared to a range of 7,000 to 7,100 acre-ft/yr from previous reports. This is because (1) the previous estimates of ETg of 5,500 acre-ft/year (Stephens, 1976; Gates and Kruer, 1981) were not used in the current study estimate because it appears that this ET is surface-water supported, on the basis of stream proximity and (or) a deep water table; (2) the 940 acre-ft/yr of reported discharge to Sheep, Indian, and Pine Grove Creeks (Stephens, 1976) was not used in the current study estimate because flow is intermittent in these streams and, therefore, were not considered gaining streams in the basin-fill; and (3) the current study estimate did not include the 650 to 1,600 acre-ft/yr of previously reported spring discharge (Stephens, 1976; Gates and Kruer, 1981) because either (1) the instantaneous discharge measured at each spring was less than 300 gal/min (Stephens, 1976), or (2) previously reported spring discharge

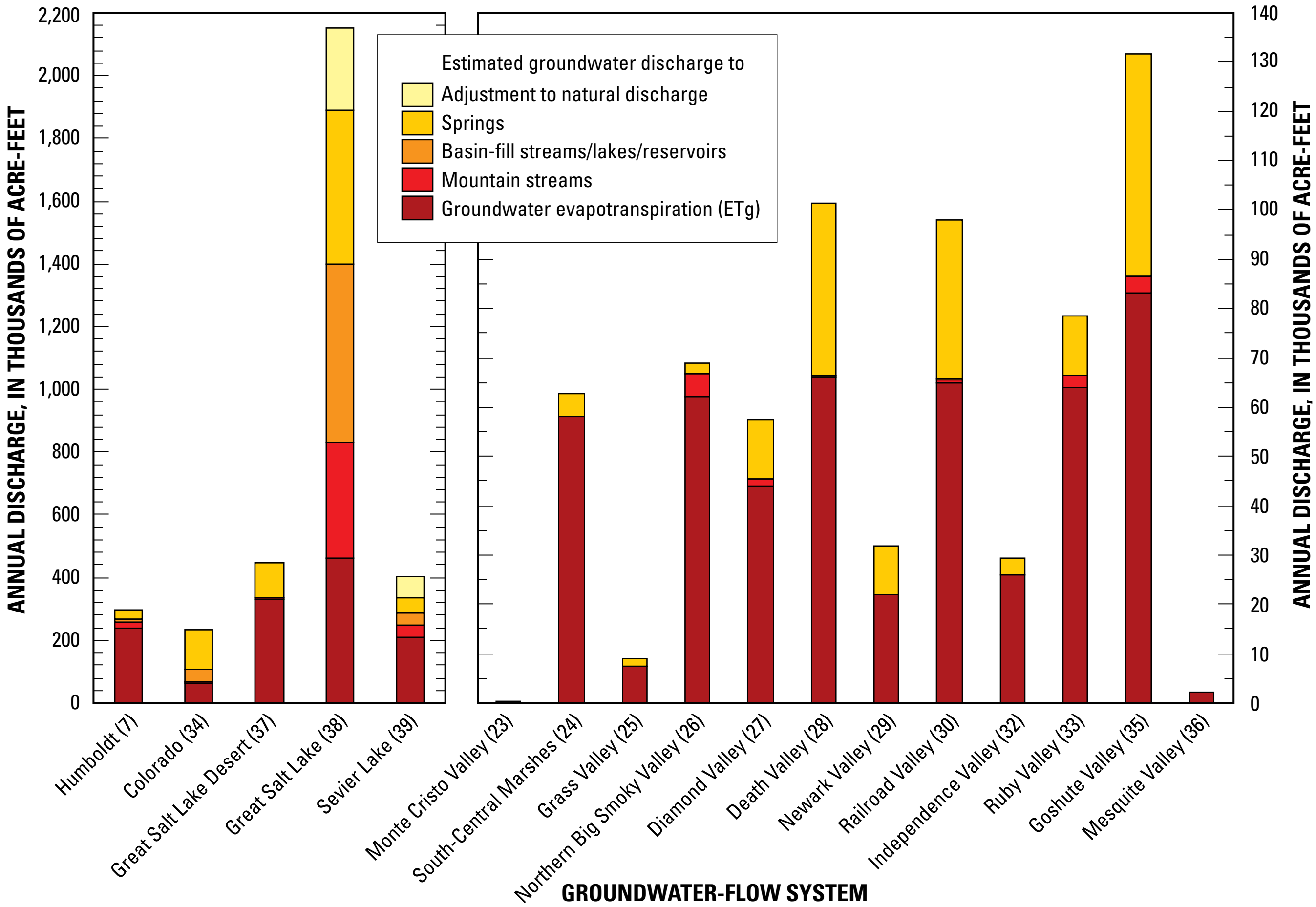

Figure D–13. Estimated groundwater-discharge components for predevelopment conditions for the 17 groundwater flow systems of the Great Basin carbonate and alluvial aquifer system study area.

measurements also included discharge from wells (Gates and Kruer, 1981).

Of the 69 HAs with only one previous estimate of total groundwater discharge, the current study exceeds or underestimates these previously reported estimates by more than 30 percent in 13 HAs (Appendix 5). For three of these HAs (South Fork Area, HA 46; Lida Valley, HA 144; and Indian Springs Valley, HA 161), the current study estimate is larger and includes groundwater discharge to mountain streams and (or) mountain springs, which was not quantified in the previous studies. For Marys Creek Area (HA 52), the current study estimate is larger because it includes both groundwater discharge to mountain streams and 9,500 acre-ft/yr of discharge to the Humboldt River not included in the previous estimate. Current study discharge estimates for the other nine HAs (Antelope Valley-Southern Part, HA 186A; Goshute Valley, HA 187; Las Vegas Valley, HA 212; California Wash, HA 218; Lower Moapa Valley, HA 220; Sink Valley, HA 271; Promontory Mountains Area, HA 277; Beryl-Enterprise Area, HA 280; and Milford Area, HA 284) are less than previously reported estimates for a variety of reasons including (1) for Antelope Valley-Southern Part (HA 186A), previously reported discharge was entirely as subsurface outflow, which is not considered at the HA level in the current study; (2) for Goshute Valley (HA 187), California Wash (HA 218), Lower Moapa Valley (HA 220), and Sink Valley (HA 271), previously reported ETg is likely supported by surface water, and is too high; (3) for Las Vegas Valley (HA 212), Beryl-Enterprise Area (HA 280), and Milford Area (HA 284), the previous studies were conducted during groundwater development and did not report discharge for predevelopment conditions; and (4) for Promontory Mountains Area (HA 277), the previously reported estimate of discharge to springs is not consistent with NWIS data and is likely too high.

Recent (2000) Groundwater Budgets

The groundwater budgets presented in previous sections of this report were developed for conditions prior to groundwater development. Significant changes in the groundwater budgets as a result of development since the 1940s include discharge by well withdrawals, recharge from irrigation with groundwater, recharge from imported water (Las Vegas Valley; HA 212), decreased natural discharge, and declines

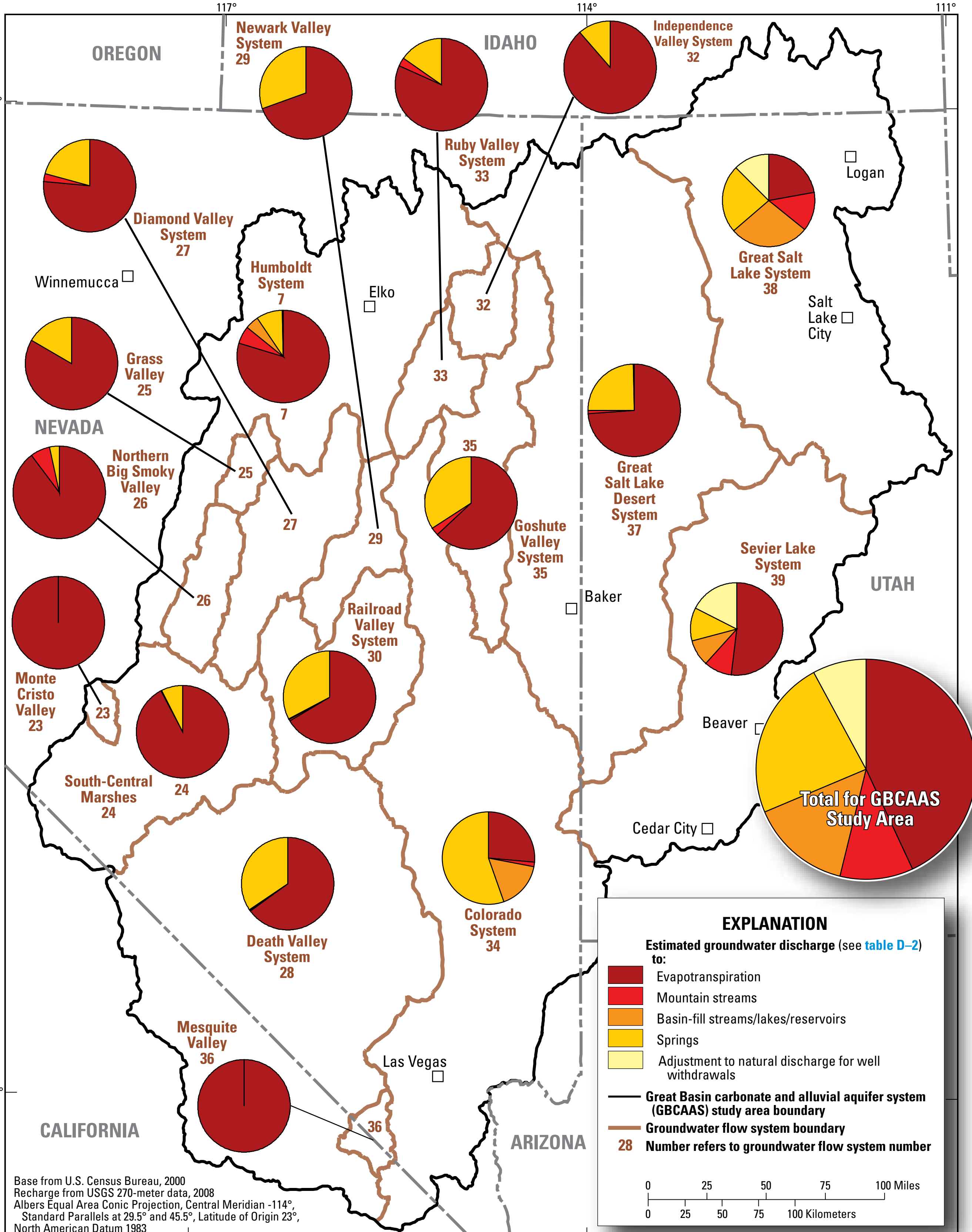

Figure D–14. Groundwater-discharge components for predevelopment conditions for the 17 groundwater flow systems of the Great Basin carbonate and alluvial aquifer system study area.

in groundwater storage (table D–3 and Appendix 7). The following sections quantify recent groundwater components for the study area.

Well Withdrawals

Well withdrawals have had the largest effect on changes in groundwater budgets during the past century. The State of Utah has compiled well withdrawals on an annual basis since 1963 (Arnow and others, 1964). The most complete compilation for the State of Nevada is for the year 2000 (pumpage and crop inventories from http://water.nv.gov; Lopes and Evetts, 2004; Matt Dillon, Nevada Division of Water Resources [NDWR], written commun., 2008; Moreo and Justet, 2008). More recent compilations by Moreo and Justet (2008), Matt Dillon (NDWR, written commun., 2008), and pumpage and crop inventories from the NDWR website (http://water.nv.gov) include very few HAs. Recent budget component estimates for the entire GBCAAS study area, therefore, are based on well withdrawals for the year 2000.

Water development in the eastern Great Basin began shortly after significant numbers of settlers arrived in the 1840s. Early water development used surface water from many of the mountain-front streams and rivers. Within the GBCAAS study area, the largest amount of surface-water development occurred in the Great Salt Lake groundwater flow system (38). Groundwater development by early settlers initially was limited to springs. For example, the settlement in the Las Vegas area was around a large spring complex. Shortly after the first settlers arrived, however, shallow hand-dug wells were developed. The oldest documented well in Salt Lake Valley was completed in 1848 (Gates, 2004). Through the late 1800s, many small-diameter flowing wells were constructed by driving or jetting casing in areas with groundwater at shallow depths (Richardson, 1906; Gates, 2004). Mechanical drilling of larger diameter wells and the installation of pumps began around 1900 and groundwater extraction accelerated. The first successful wells in the Las Vegas area were drilled around 1906 (Malmberg, 1964). The rate of construction of large-diameter wells increased during drought periods between the 1920s and the 1940s. By the late 1930s, areas of both Nevada and Utah were experiencing groundwater level declines in the more developed basins. Groundwater withdrawals have continued to increase as drilling technologies have improved and as water demand by agriculture and public supply has increased.

In Las Vegas Valley (HA 212), measurable subsidence associated with groundwater withdrawals began in the 1930s, with total subsidence exceeding 2 ft between 1935 and 1963 (Malmberg, 1964), and nearly 6 ft since 1935 (Pavelko and others, 1999). In recent years, however, the rate of subsidence has decreased, and, in some sections of the basin, land-surface altitudes have rebounded slightly (generally less than 1.5 in.) because of direct-well injection for aquifer storage and recovery operations that began in 1988, and decreases in well withdrawals (Hoffman and others, 2001; Bell and others, 2008).

Total annual groundwater withdrawals in Utah for 1939 and 1963–2004 were compiled by Gates (2007, p. 130) on the basis of available data (Utah State Engineer, 1940) and the “Ground-water conditions in Utah” reports beginning in 1963 (Arnow and others, 1964). About 90 percent of these withdrawals in Utah, or more than 820,000 acre-ft/yr of the total 920,000 acre-ft/yr reported for water year 2004 (Burden and others, 2004), occur within the GBCAAS study area. Similar historical well withdrawals are not available for most areas of Nevada. Patterns and changes in groundwater withdrawals in Utah over time, however, are assumed to be representative of changes that have occurred throughout the entire GBCAAS study area. Gates (2007) compiled annual total, irrigation, and public-supply groundwater withdrawals in Utah for the period 1963–2002 (fig. D–15). Total Utah groundwater withdrawals for 1939 and withdrawals from six western Utah areas during 1945–1962 also were estimated. These six western Utah areas (Beryl-Enterprise Area, HA 280; Parowan Valley, HA 281; Cedar City Valley, HA 282; Milford Area, HA 284; Pavant Valley, HA 286; and Sevier Desert, HA 287) were selected because they have large withdrawals and groundwater level declines. Withdrawals have been updated through 2006 by Burden and others (2004, 2005, 2006, 2007). Withdrawals for industrial and domestic/stock use (not shown on fig. D–15) account for the difference between total withdrawals and the sum of irrigation plus public-supply withdrawals. Historically, total annual groundwater withdrawals in Utah generally have increased and range from 220,000 acre-ft in 1939 to a peak of 947,000 acre-ft in 2002. Annual withdrawals for irrigation are about two-thirds of total annual withdrawals and have an inverse relation with annual precipitation (fig. D–15). During years with above average precipitation, groundwater withdrawals decrease as irrigators use more abundant surface-water resources. During 1963–2006, withdrawals for irrigation decreased slightly, yet withdrawals for public supply more than tripled, reflecting the population growth in Utah. Some of these withdrawals for public supply have occurred through the transfer of water rights from agriculture. The conversion of agricultural to public-supply use is expected to continue as additional water supplies are needed to serve a growing population in the region.

In order to evaluate general groundwater development trends within the GBCAAS study area, historical annual well withdrawals for the period of 1940–2006 were estimated on the basis of the compilation and interpolation of existing well withdrawal data (Appendix 8). Historical estimates were developed for the 78 HAs with more than 500 acre-ft of well withdrawals in the year 2000 (Auxiliary 4). Historical withdrawals were not estimated for the other 87 HAs and withdrawals for these HAs, were not included in the summation of yearly withdrawals within the groundwater flow system; these HAs accounted for less than 0.4 percent of the total withdrawals in 2000 (Appendix 7).

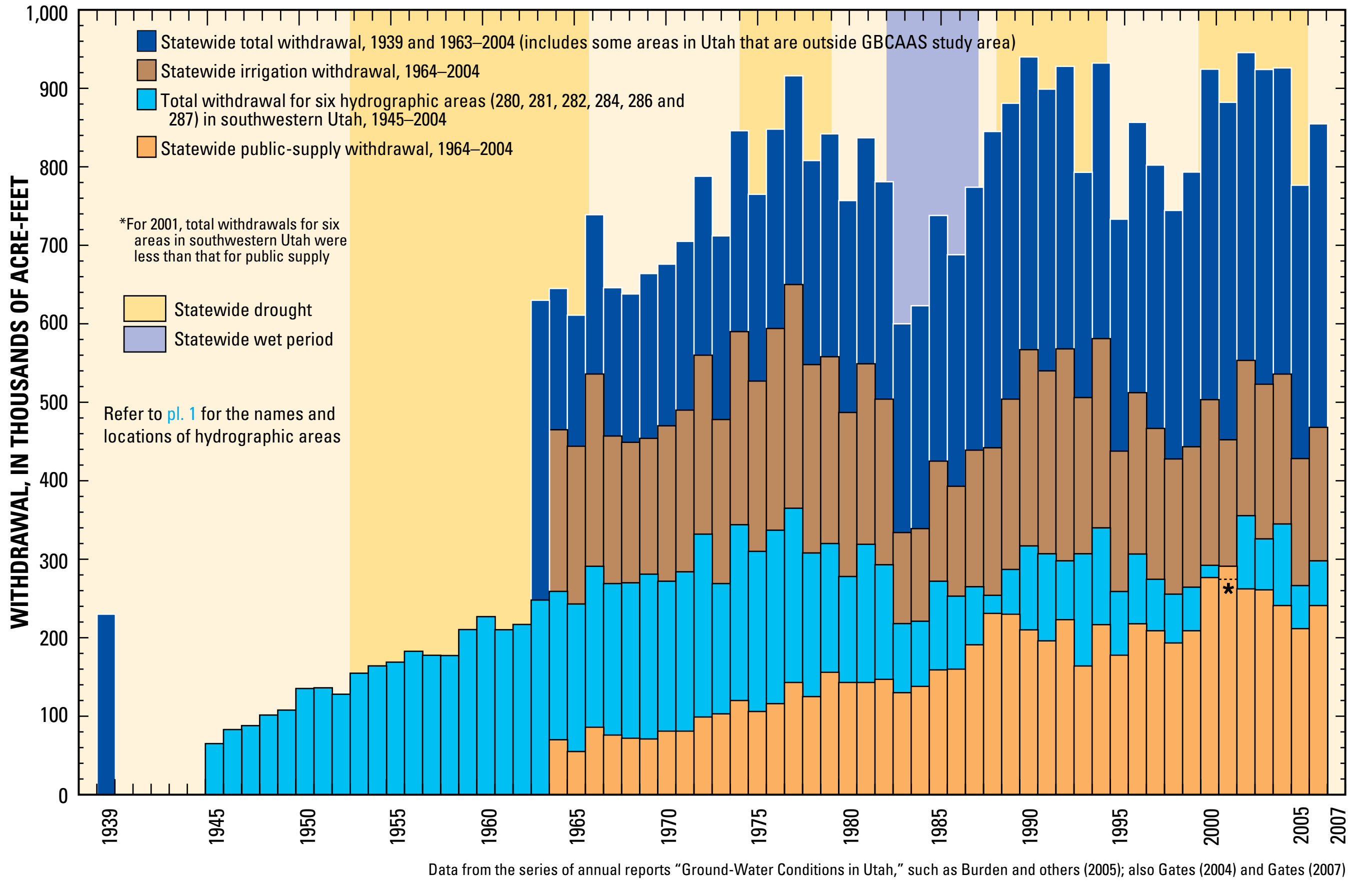

Figure D–15. Groundwater withdrawals from wells in Utah, 1939 and 1945–2006.

The estimated total annual well withdrawals by HA for 1940–2006 are given in Auxiliary 4. These estimates include withdrawals for mining, irrigation, and public supply. Figure D–16 shows historical estimated well withdrawals for 7 of the 17 groundwater flow systems (those with maximum annual withdrawals greater than 50,000 acre-ft) and for the entire study area. Withdrawals for each groundwater flow system were computed by summing yearly estimated withdrawals from each HA within the groundwater flow system. Recent (2000) well withdrawal estimates by groundwater flow system are given in table D–3. The total estimated amount of well withdrawals during the year 2000 for the GBCAAS study area is 1,500,000 acre-ft. The greatest amount of estimated withdrawal during 2000 was from the Great Salt Lake groundwater flow system (38), followed in decreasing order by the Sevier Lake (39), Humboldt (7), and Colorado (34) groundwater flow systems. Both the Great Salt Lake (38) and Colorado (34) groundwater flow systems have had increases in withdrawals through the 1990s and 2000s, associated with rapid population growth during the past two decades along the Wasatch Front and in Las Vegas and Mesquite. The Humboldt groundwater flow system (7) has experienced increasing withdrawals since the 1970s and 1980s, mainly related to gold mining along the Carlin trend. In contrast, groundwater development in the South-Central Marshes (24), Diamond Valley (27), Death Valley (28), and Sevier Lake (39) groundwater flow systems has not increased substantially since the 1980s (fig. D–16). Well withdrawals in these areas have stabilized because of more efficient irrigation practices and the change from agricultural to municipal water use.

To determine the HAs in which recent (2000) pumping significantly affects natural hydrologic conditions, estimated net well withdrawals were compared with estimated natural predevelopment discharge. Net well withdrawals were calculated as the total well withdrawals minus the recharge from unconsumed irrigation and public supply water from well withdrawals in each HA (Appendix 7). Fifteen HAs had estimated net well withdrawals exceeding estimated natural predevelopment discharge by at least 1,000 acre-ft/yr (fig. D–17, Appendix 7). The buffer of 1,000 acre-ft/yr was chosen in order to highlight HAs where pumping clearly exceeds natural discharge and to acknowledge uncertainties in both the discharge and withdrawal estimates. In the HAs with withdrawals exceeding natural discharge, predominant water uses generally are mining (Maggie Creek Area, HA 51; Crescent Valley, HA 54; Lower Reese River Valley, HA 59; and Boulder Flat, HA 61), agricultural (Diamond Valley,

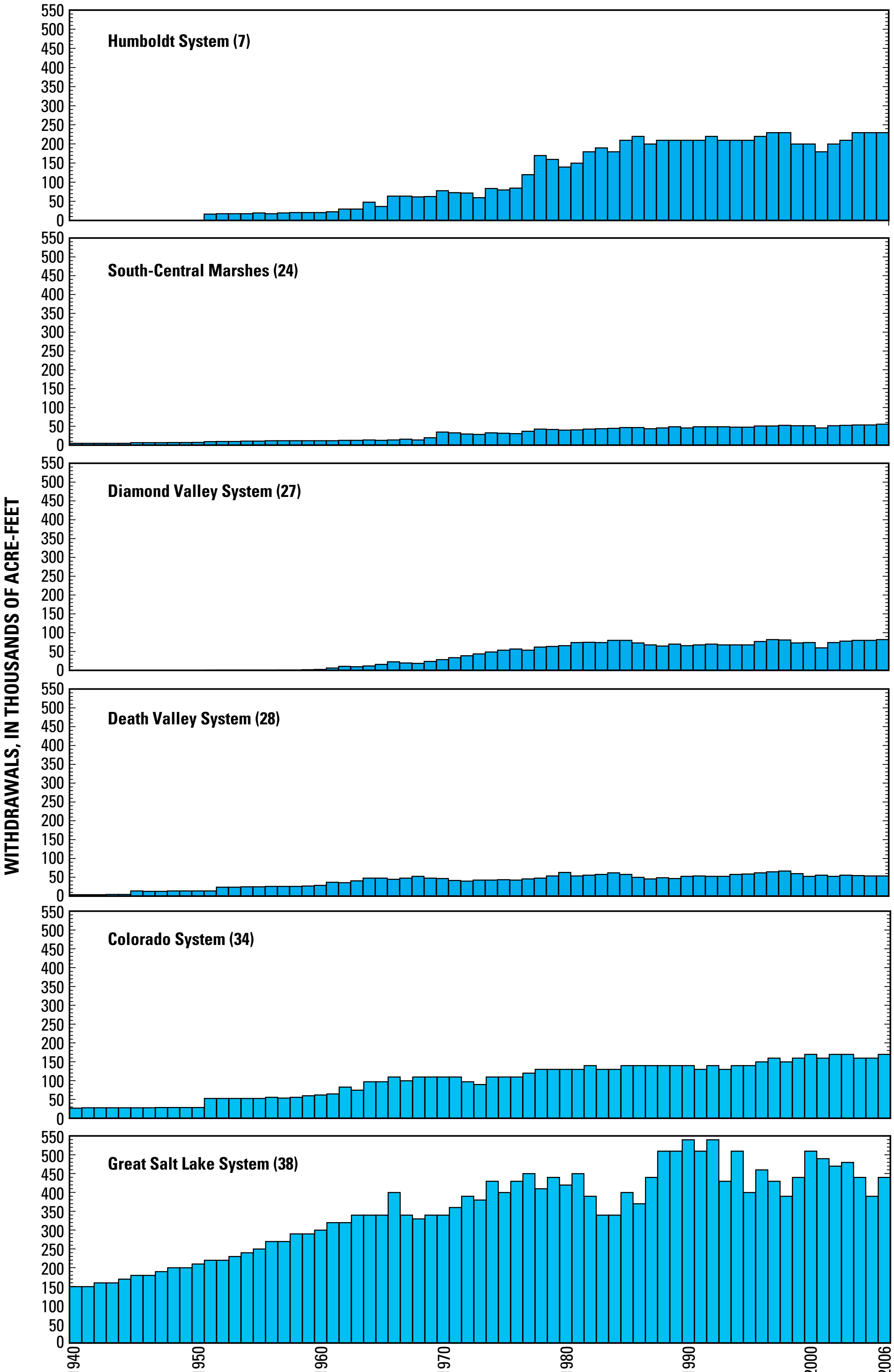

Figure D–16. 1940–2006 estimated annual well withdrawals for groundwater flow systems that have maximum annual withdrawals greater than 50,000 acre-feet and total well withdrawals for the entire Great Basin carbonate and alluvial aquifer system study area.

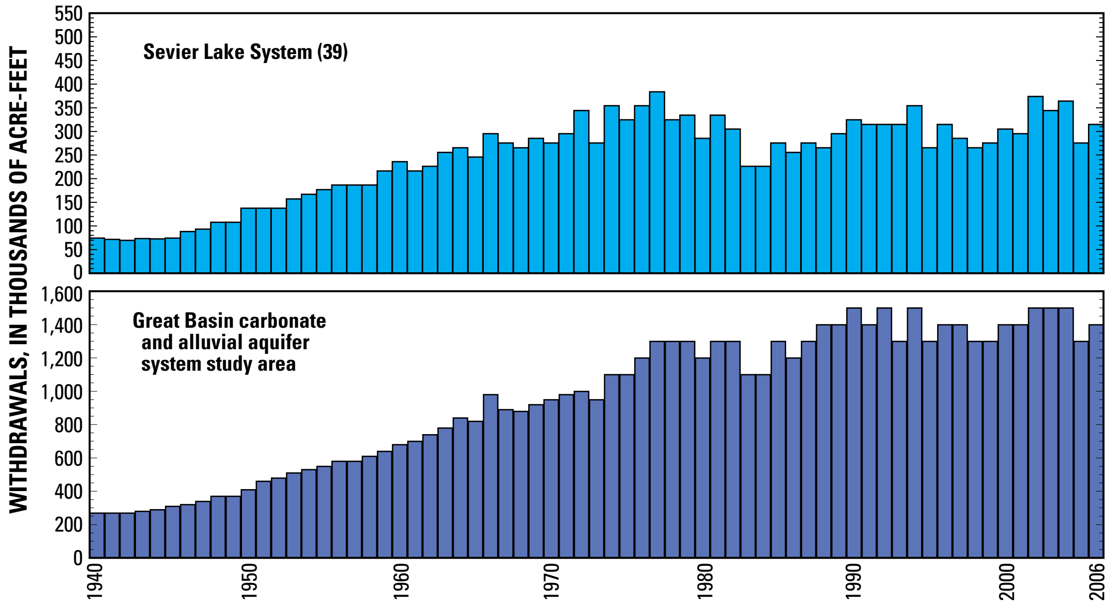

Figure D–16. Graphs showing 1940–2006 estimated annual well withdrawals for groundwater flow systems that have maximum annual withdrawals greater than 50,000 acre-feet and total well withdrawals for the entire Great Basin carbonate and alluvial aquifer system study area.—Continued

HA 153; Pahrump Valley, HA162; Mesquite Valley, HA 163; Penoyer Valley, HA 170; Dry Valley, HA 198; Patterson Valley, HA 202; Cedar Valley, HA 264; Curlew Valley, HA 278; Beryl-Enterprise Area, HA 280, and Milford Area, HA 284), and public supply (Virgin River Area, HA 222). Total estimated well withdrawals from these 15 HAs was 550,000 acre-ft during 2000, accounting for 37 percent of the total 1,500,000 acre-ft of well withdrawals for the GBCAAS.

In some HAs, groundwater pumping since the 1940s has reduced or eliminated natural discharge and has caused significant water-level declines. Examples of decreased natural discharge include Manse Springs in Pahrump Valley (HA 162), Muddy River Springs in Muddy River Springs Area (HA 219) (fig. D–18), and Las Vegas Springs in Las Vegas Valley (HA 212). Another example is the 80-percent decline in spring discharge at Locomotive Springs (Hurlow and Burk, 2008) in Curlew Valley (HA 278) since the 1960s. These effects are partly attributed to a rapid increase in withdrawals for irrigation. Fourteen HAs also have one or more wells showing long-term water-level declines of more than 50 ft during the latter half of the 20th century that are assumed to be in response to increased well withdrawals (figs. D–17 and D–19). In other HAs, either (1) the impact of groundwater withdrawals is less significant and water levels respond predominantly to climatic variations or climate-driven pumping variations (Gardner and Heilweil, 2009); or (2) insufficient historical data are available to document declining water levels and decreased natural discharge.

Recharge of Unconsumed Irrigation and Public Supply Water from Well Withdrawals

For HAs that have undergone significant groundwater development, recharge from unconsumed irrigation and public supply water from well withdrawals also must be considered. Most well withdrawals are used for irrigation; in addition, much of the well withdrawals used for public supply are applied as irrigation to lawns and gardens (Hely and others, 1971; Mower and Cordova, 1974; Clark and others, 1990; Kariya and others, 1994; Brooks and Mason, 2005; Cederberg and others, 2009; Gardner, 2009). It is assumed that part of this groundwater recharges the aquifer system, either as focused infiltration along irrigation canals or infiltration of unconsumed irrigation water applied to fields, lawns, and gardens. This “recycled” groundwater is difficult to quantify, but it is an important form of groundwater recharge in HAs that have undergone substantial groundwater development. Irrigation return flow studies in the Amargosa Desert (HA 230) and the Milford Area (HA 284) show that recharge from irrigation on sprinkler-irrigated fields ranges from 8 to 16 percent of the applied irrigation (Susong, 1995, table 3; Stonestrom and others, 2003, p. 1) and recharge on flood-irrigated fields can be as high as 50 percent of the applied irrigation (Susong, 1995, table 3). Current study estimates of groundwater recharge of unconsumed irrigation and public supply water from well withdrawals, therefore, were calculated assuming that 30 percent of this applied irrigation and public supply water is recycled back into the aquifer.

Estimated recharge from unconsumed irrigation and public supply water within the study area in the year 2000 was

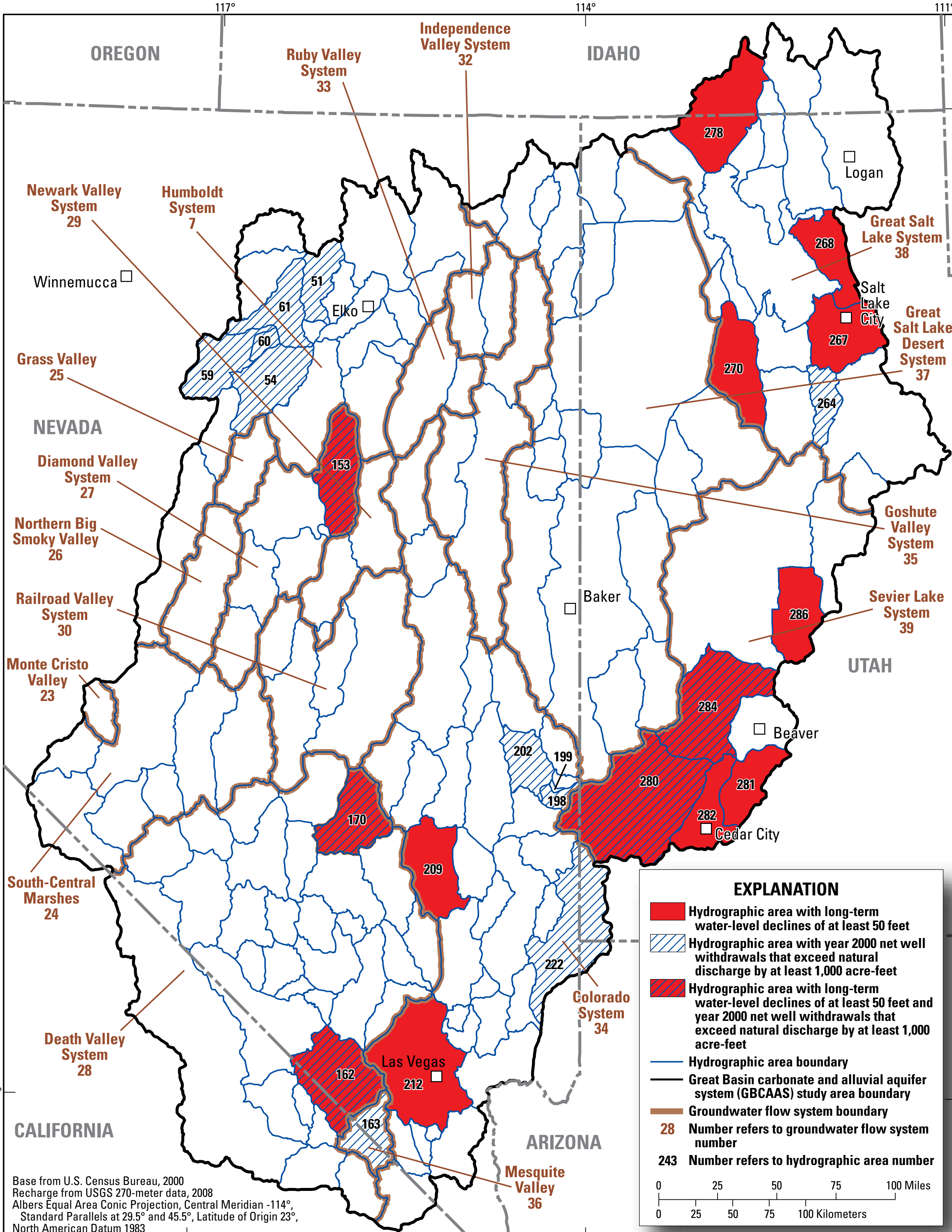

Figure D–17. Hydrographic areas with 2000 estimated net well withdrawals exceeding natural discharge by at least 1,000 acre-feet per year and areas where one or more wells show long-term water-level declines of at least 50 feet during the latter half of the 20th century within the Great Basin carbonate and alluvial aquifer system study area.

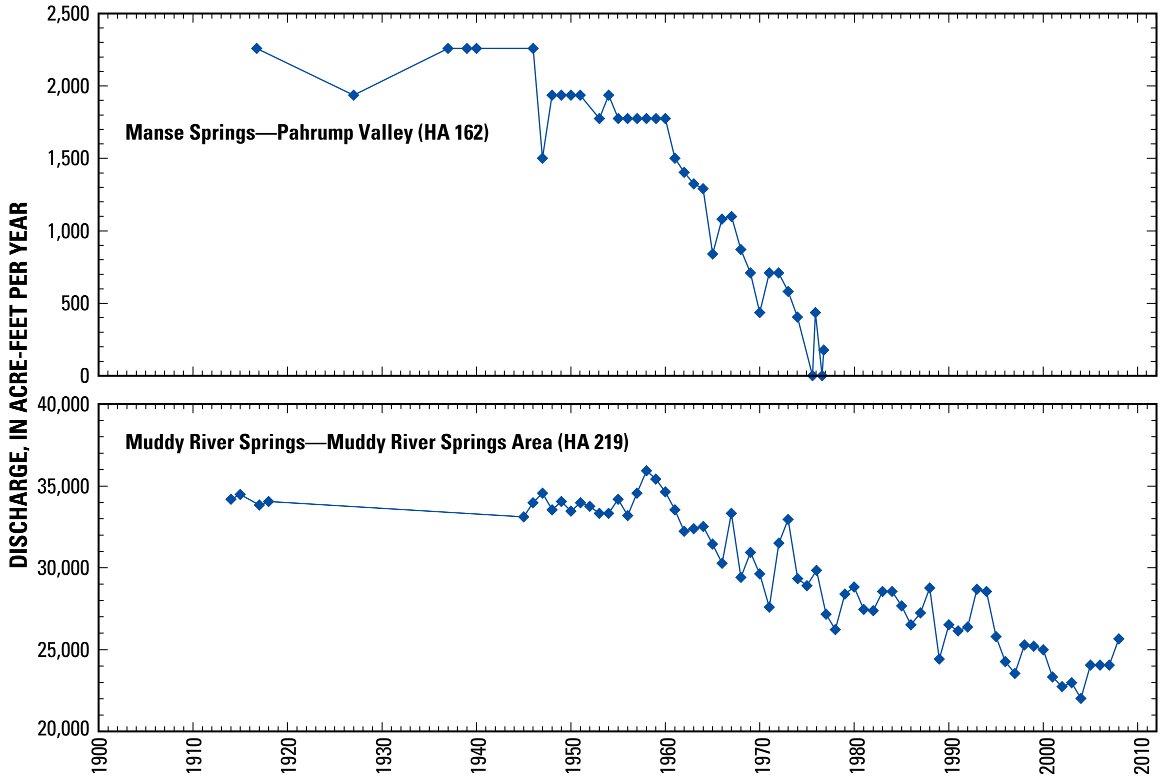

Figure D–18. Declining spring discharge at Manse Springs, in the Pahrump Valley (HA 162) and Muddy River Springs, in the Muddy River Springs Area (HA 219), within the Great Basin carbonate and alluvial aquifer system study area.

470,000 acre-ft. These estimates are presented by groundwater flow system in table D–3 and by HA in Appendix 7. The highest amounts of recharge from unconsumed irrigation and public supply water from groundwater withdrawals occur in the Great Salt Lake (38) and Sevier Lake (39) groundwater flow systems. These two areas account for more than 60 percent of total recharge from irrigation with groundwater within the study area. Both of these groundwater flow systems are highly developed; in the case of the Sevier Lake groundwater flow system (39), there is very little surface water available for irrigation and, therefore, most of the water for irrigation is derived from groundwater resources.

Artificial Recharge and Recharge of Unconsumed Irrigation and Public Supply Water from Lake Mead

In Las Vegas Valley (HA 212), increased recharge also occurs from the importation of Lake Mead water that began in 1942. In the year 2000, a total of 440,000 acre-ft of water was imported from Lake Mead; 30,000 acre-ft was injected in the aquifer directly (NDWR pumpage inventory; http://water.nv.gov, accessed on July 6, 2009). As in other HAs with imported surface water, the same percentage was used to determine the recharge from imported water as was used for determining recharge from runoff (see “Recharge From Imported Surface Water”); therefore, 10 percent (41,000 acre-ft) of the remaining imported water was assumed to become recharge as seepage from lawns and gardens . This results in a 2000 total estimated recharge from imported water for Las Vegas Valley of 71,000 acre-ft; this recharge is included in the “Recharge from unconsumed irrigation and public supply water from well withdrawals” column in table D–3 under the Colorado groundwater flow system (34) and Appendix 7 under HA 212.

Decrease in Natural Discharge and Change in Storage

All water withdrawn from wells in the study area is balanced by some combination of varying amounts of increase in recharge, decrease in natural discharge, and decrease of groundwater in storage. In general, withdrawals reduce groundwater storage by an equivalent amount until

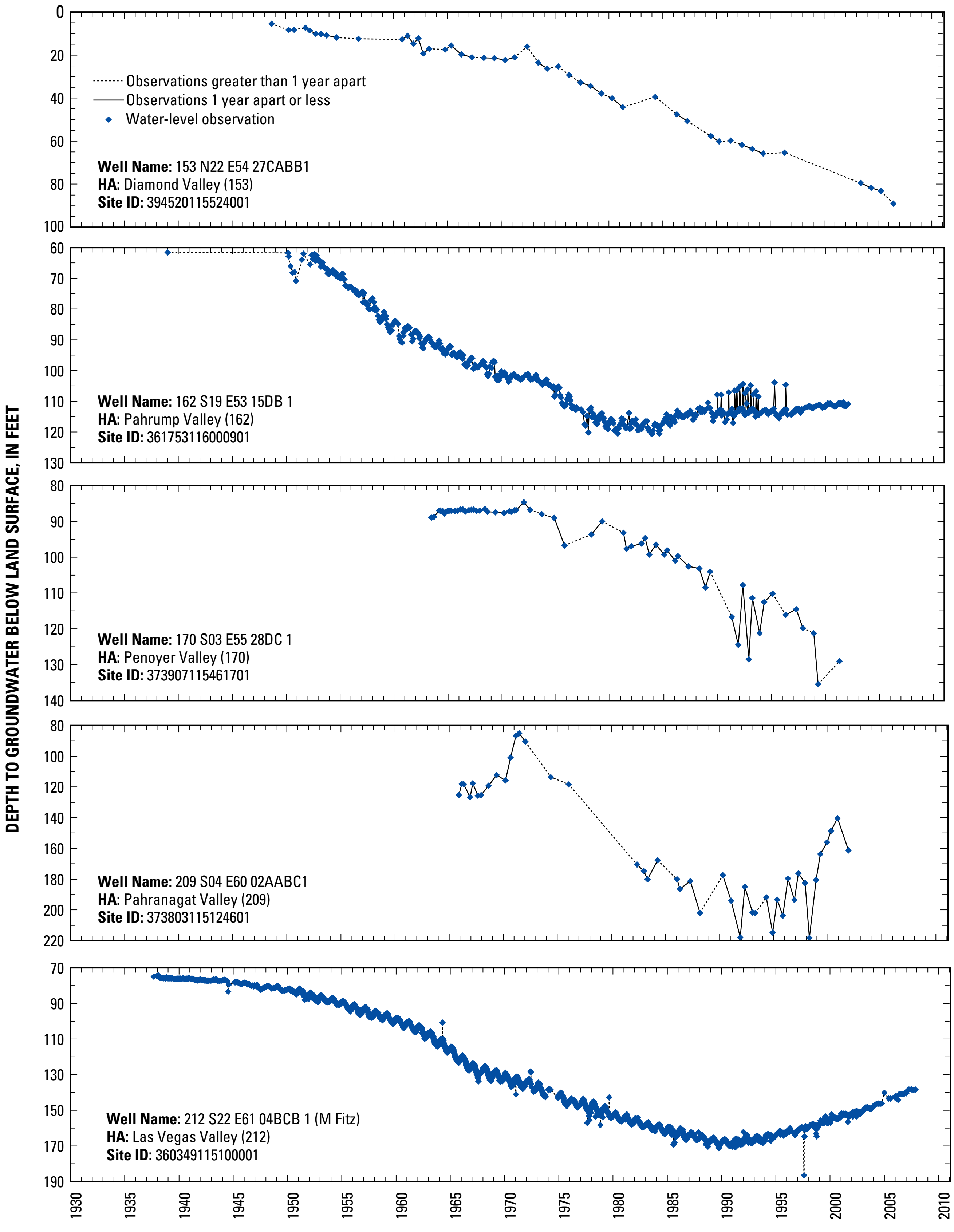

Figure D–19. Examples of well hydrographs from hydrographic areas in the Great Basin carbonate and alluvial aquifer system study area where one or more wells show long-term water-level declines of at least 50 feet during the latter half of the 20th century.

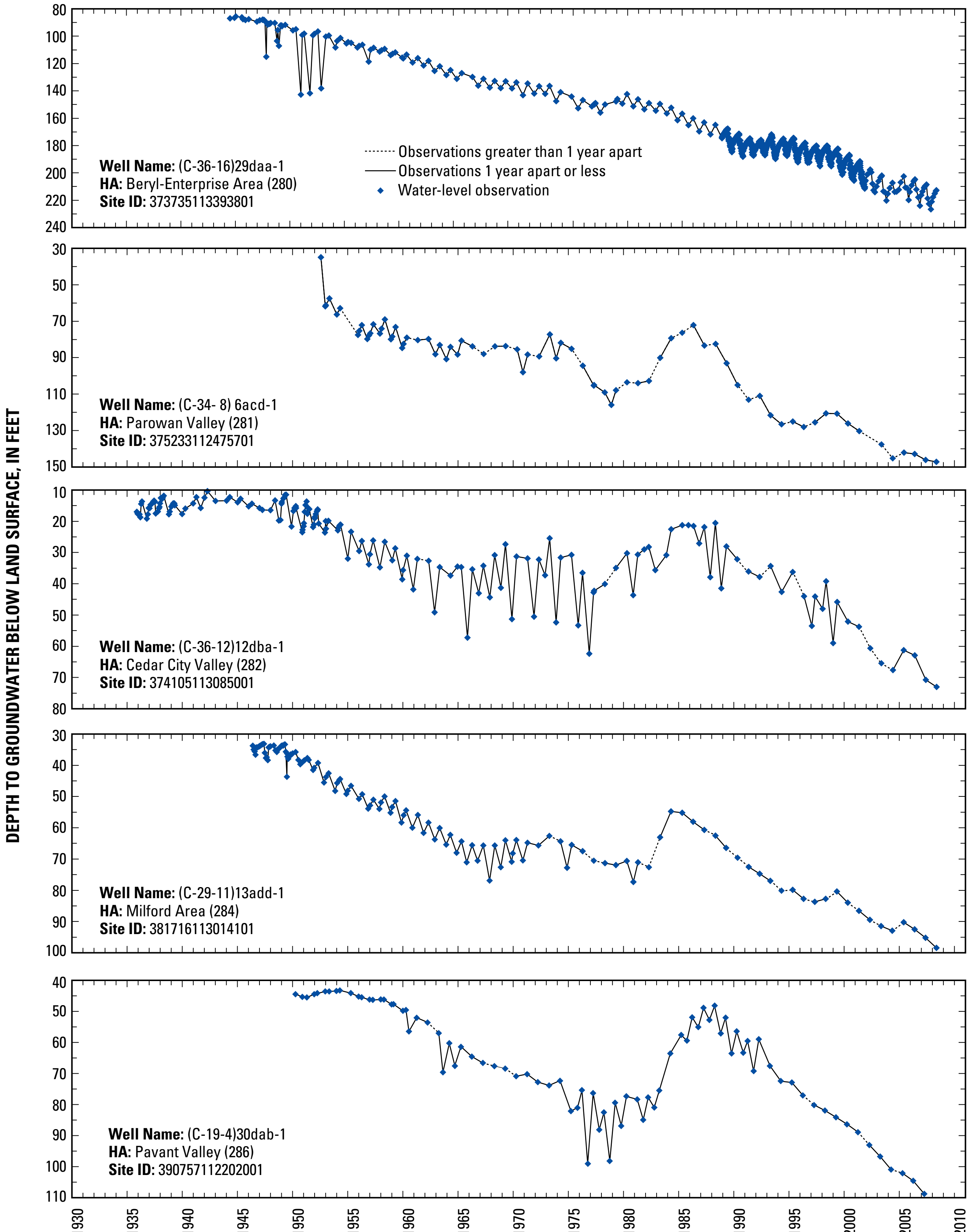

Figure D–19. Examples of well hydrographs from hydrographic areas in the Great Basin carbonate and alluvial aquifer system study area where one or more wells show long-term water-level declines of at least 50 feet during the latter half of the 20th century.—Continued

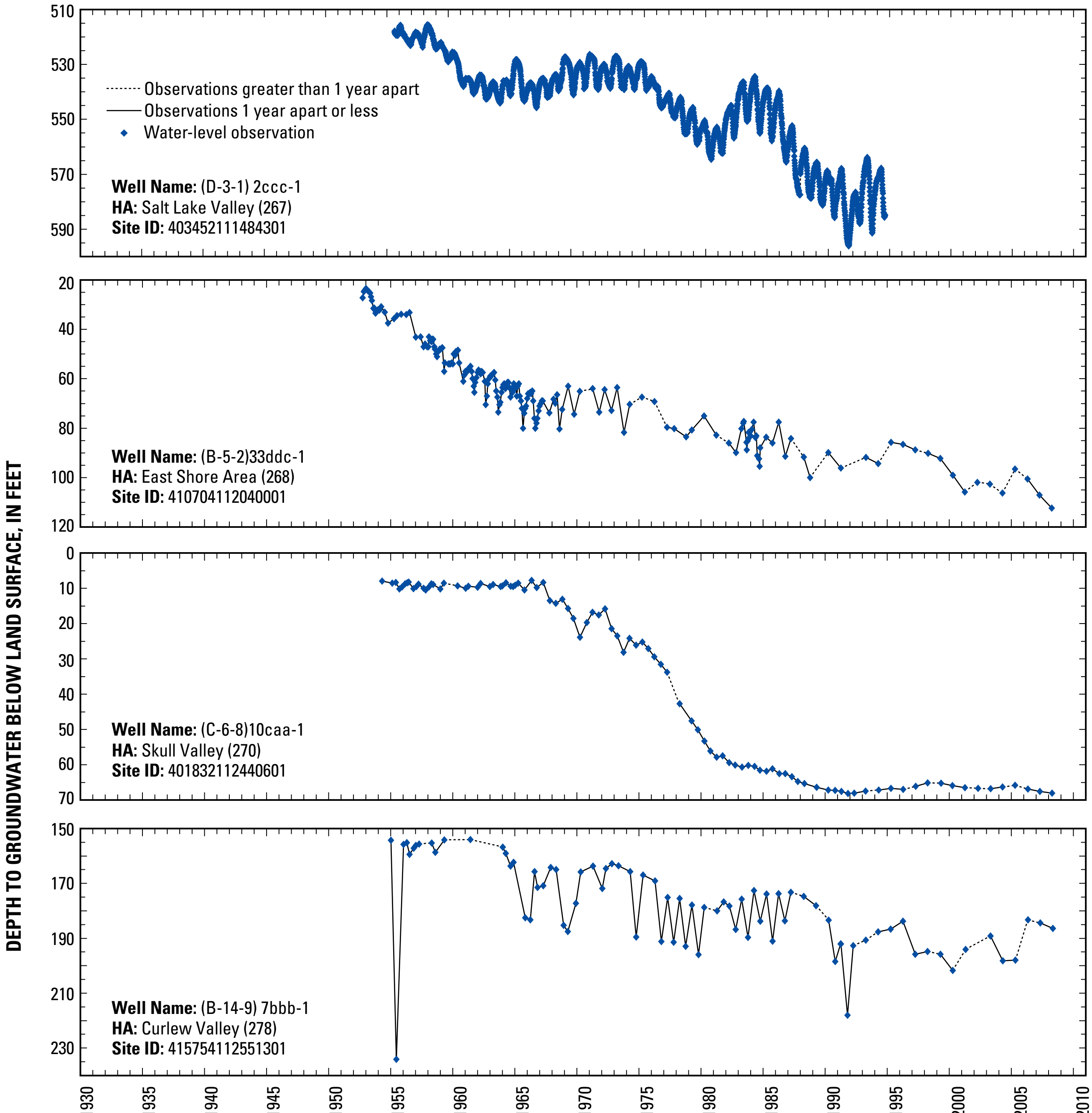

Figure D–19. Examples of well hydrographs from hydrographic areas in the Great Basin carbonate and alluvial aquifer system study area where one or more wells show long-term water-level declines of at least 50 feet during the latter half of the 20th century.—Continued the drawdown from the withdrawals reaches areas of natural discharge or areas of potential recharge. Potential recharge is typically captured from lakes and streams. In the GBCAAS study area, however, the small number of lakes and basin-fill streams are generally in areas of groundwater discharge (hydraulic gradients have not been reversed). Capture of potential recharge, therefore, is not considered in the current study. If sufficient quantities of natural discharge cannot be captured at the rate at which the groundwater is withdrawn, groundwater storage will continue to decrease and groundwater levels will continue to decline. If sufficient quantities of natural discharge can be captured, a new pumping equilibrium will be established such that the change in storage becomes minimal. For most of the HAs that have undergone groundwater development for agriculture, the increase in withdrawals generally occurred between the 1940s and 1980s. Thus, many of the developed HAs have been equilibrating with respect to pumping for decades. The budget calculations assume that the majority of these HAs have equilibrated, except for a few HAs where groundwater levels continue to decline (figs. D–17 and D–19).

Decrease in natural discharge and (or) storage was estimated as the net well withdrawals in each HA. The estimated decrease in groundwater storage in the current study is a minimum value; it assumes that all natural discharge is captured before groundwater storage is reduced, and that groundwater storage is reduced only if net well withdrawals exceed predevelopment groundwater discharge (Appendix 7). Long-term well hydrographs having at least one measurement prior to 1980 were examined to determine whether water levels were declining. If an HA had at least one well in which long-term water levels declined by 50 ft or more that did not appear to be influenced by climate or aquifer testing and had net well withdrawals that exceeded predevelopment groundwater discharge by 1,000 acre-ft or more, it was assumed that well withdrawals were capturing groundwater from storage.

The estimated decreases in natural discharge and (or) groundwater storage and the minimum decrease in storage for each groundwater flow system were calculated as the sum of these components in each HA within the flow system (table D–3). This sum represents the change in the groundwater system caused by well withdrawals. Additional water-level and discharge measurements would help refine these estimates. Unless well withdrawals in a particular HA or groundwater flow system are very large, it is unlikely that this stress will affect discharge and storage in an adjacent HA or groundwater flow system. For that to occur, groundwater levels would need to decline over wide areas. The analysis of water levels did not indicate substantial water-level decline in adjacent basins caused by well withdrawals. It is possible, however, that subsurface outflow to a downgradient HA could be reduced by withdrawals in an upgradient HA or upgradient recharge could be increased.

The estimated decrease in natural discharge and (or) groundwater storage caused by well withdrawals for the year 2000 was 990,000 acre-ft (table D–3). The Great Salt Lake (38), Sevier Lake (39), and Humboldt (7) groundwater flow systems account for 77 percent of the total estimated decrease in natural discharge and (or) groundwater storage for the GBCAAS. The estimated minimum decrease in groundwater storage for the study area in 2000 was 67,000 acre-ft and occurred in only five HAs (Appendix 7) within three groundwater flow systems (table D–3): the Sevier Lake (39) system (34,000 acre-ft), the Diamond Valley (27) system (24,000 acre-ft), and the Death Valley (28) system (9,300 acre-ft).

Uncertainty of Estimated Groundwater Budgets

For the GBCAAS study area, the total estimated predevelopment groundwater recharge of 4,500,000 acre-ft/yr is 7 percent greater than the total estimated predevelopment groundwater discharge of 4,200,000 acre-ft/yr. Because of uncertainty in these estimates, however, recharge and discharge for the entire study area are considered to be about equal. It is estimated that the uncertainty in the total recharge estimate is about ±50 percent, or about ±2,200,000 acre-ft/yr. This was derived predominantly from estimated error in the two largest recharge components: direct infiltration of precipitation and recharge from runoff, both calculated using results from the BCM.

It is estimated that the uncertainty in the total predevelopment groundwater-discharge estimate for the GBCAAS study area is about ±30 percent, or about ±1,300,000 acre-ft/yr. This composite uncertainty was derived predominantly from estimated error in the three largest discharge components: ETg, springs, and discharge to basin-fill streams, lakes, and reservoirs, which account for 82 percent of total discharge. Although there are few published estimates of uncertainty with regard to ETg measurements, 12 HAs in Nevada and Utah within the GBCAAS study area have 95-percent confidence intervals of ±22 to ±227 percent of reported estimates (Lundmark and others, 2007, table 2). The estimated uncertainty in gaged stream baseflow used for estimating groundwater discharge to mountain streams (current study does not estimate ungaged stream discharge) and spring discharge measurements was estimated to be ±30 percent. This is based on an assumed ±10 percent error in individual discharge measurements and an additional ±20 percent error to account for (1) temporal averaging of measurements made over a 60-year period, (2) the natural fluctuation in predevelopment discharge associated with climate variability, and (3) general error associated with extrapolating regional estimates from more site-specific studies.

As mentioned in the "Analysis and Adjustment of BCM Results" section of this report, the groundwater-budget differences between recharge estimates calculated using BCM results and estimates of predevelopment discharge were not evenly distributed spatially. There are larger differences between the recharge estimates calculated using BCM results and discharge estimates in the Death Valley (28) and Colorado (34) groundwater flow systems of central and southern Nevada than elsewhere in the GBCAAS study area. The adjustments to recharge calculated using BCM results for groundwater flow systems or subareas do not necessarily result in balanced recharge and discharge within each HA (fig. D–20). Some of the imbalances may be caused by budget uncertainties and some by the adjustment of BCM recharge. Extreme imbalances may indicate areas where subsurface flow occurs between HAs, especially from HAs that have very little or no measured groundwater discharge. These extreme differences are important in each HA, but not in each subarea or groundwater flow system.

Uncertainty in reported discharge probably is not the main reason for the large discrepancies between recharge and discharge in the groundwater flow systems. It is unlikely that large springs, streams, and ETg have been completely overlooked in previous studies. It is also unlikely the reported discharge measurements would have a consistent bias toward underestimation. For example, ETg is the largest component of discharge within the study area; this has been extensively studied, especially in Nevada (Smith and others, 2000; Laczniak and Smith, 2001; Laczniak and others, 2007; Moreo and others, 2007; Smith and others, 2007; and Welch and others, 2007). These ETg estimates are based on mapped phreatophyte and playa areas, and measured ETg rates, both of which have no apparent bias toward underestimation.

Limitations of Estimated Groundwater Budgets

The following limitations should be considered when utilizing the water-budget information presented in Chapter D:

- Previously published recharge estimates (“net” recharge to the basin-fill portion of an HA) typically have been used by regulatory agencies for developing HA-based estimates of perennial yield for allocating water rights. The newer spatially distributed recharge estimates (“total” recharge to an HA) in the current report are typically higher and should not be used for managing water resources without also considering losses associated with groundwater discharge in the mountain block.

- The total estimated predevelopment discharge to mountain streams (450,000 acre-ft/yr) and springs (990,000 acre-ft/yr) are minimum values because they do not account for ungaged perennial streams and unmeasured spring discharge. Additional mountain stream and spring discharge measurements are needed to refine these values.

- The estimated percentages of BCM calculated runoff that recharges the basin fill (30 percent for HAs highly irrigated with surface water; 10 percent for HAs not highly irrigated with surface water) are only approximate. Additional seepage studies along streams and canals, and deep percolation studies of irrigation return flow are needed to improve these estimates.

- The current study summarizes previously published quantities of subsurface flow between HAs, but does not provide new estimates because of the uncertainty in groundwater budgets. The current study also does not quantify subsurface flow between groundwater flow systems; rather such flows only are indicated qualitatively on the basis of water budget, hydraulic gradient, and geological constraints.

Summary

Detailed groundwater budgets were compiled for the GBCAAS study area for average annual conditions before extensive groundwater development began in the middle of the 20th century and for the year 2000. Total estimated predevelopment groundwater recharge is 4,500,000 ± 2,200,000 acre-ft/yr. Predevelopment recharge comprises five components: direct infiltration of precipitation (in-place recharge), infiltration of surface-water runoff, infiltration of mountain stream baseflow, infiltration of imported surface water, and subsurface inflow. Direct infiltration of precipitation and associated snowmelt for the GBCAAS study area is estimated to be about 2,900,000 acre-ft/yr, providing more than 64 percent of groundwater recharge. The majority of this recharge is assumed to occur in the higher altitude mountain ranges as direct infiltration of precipitation. Precipitation that does not infiltrate into the subsurface or is not consumed by evapotranspiration in the mountain block becomes runoff. The majority of runoff generated in the mountains flows into adjacent basins, some portion of which recharges the unconsolidated deposits as infiltration beneath stream channels, irrigation canals, and irrigated fields. Estimated recharge from infiltration of runoff is 570,000 acre-ft/yr. In addition to recharge from runoff, there is recharge from mountain stream baseflow that infiltrates beneath stream channels, irrigation canals, and irrigated fields; this recharge is estimated to be 130,000 acre-ft/yr. Recharge from imported surface water (both natural and through transbasin diversions) is estimated to be 990,000 acre-ft/yr, and is concentrated almost exclusively within the Great Salt Lake groundwater flow system (38). Although subsurface inflow may be an important component of recharge in some HAs and groundwater flow systems, it is less important at the scale of the GBCAAS study area. Estimates of subsurface inflow between groundwater flow systems typically are computed as a residual in groundwater budgets, and because of the large uncertainties in other water-budget components, subsurface inflows are not quantified in this study. Rather, such fluxes between groundwater flow systems are qualitatively described

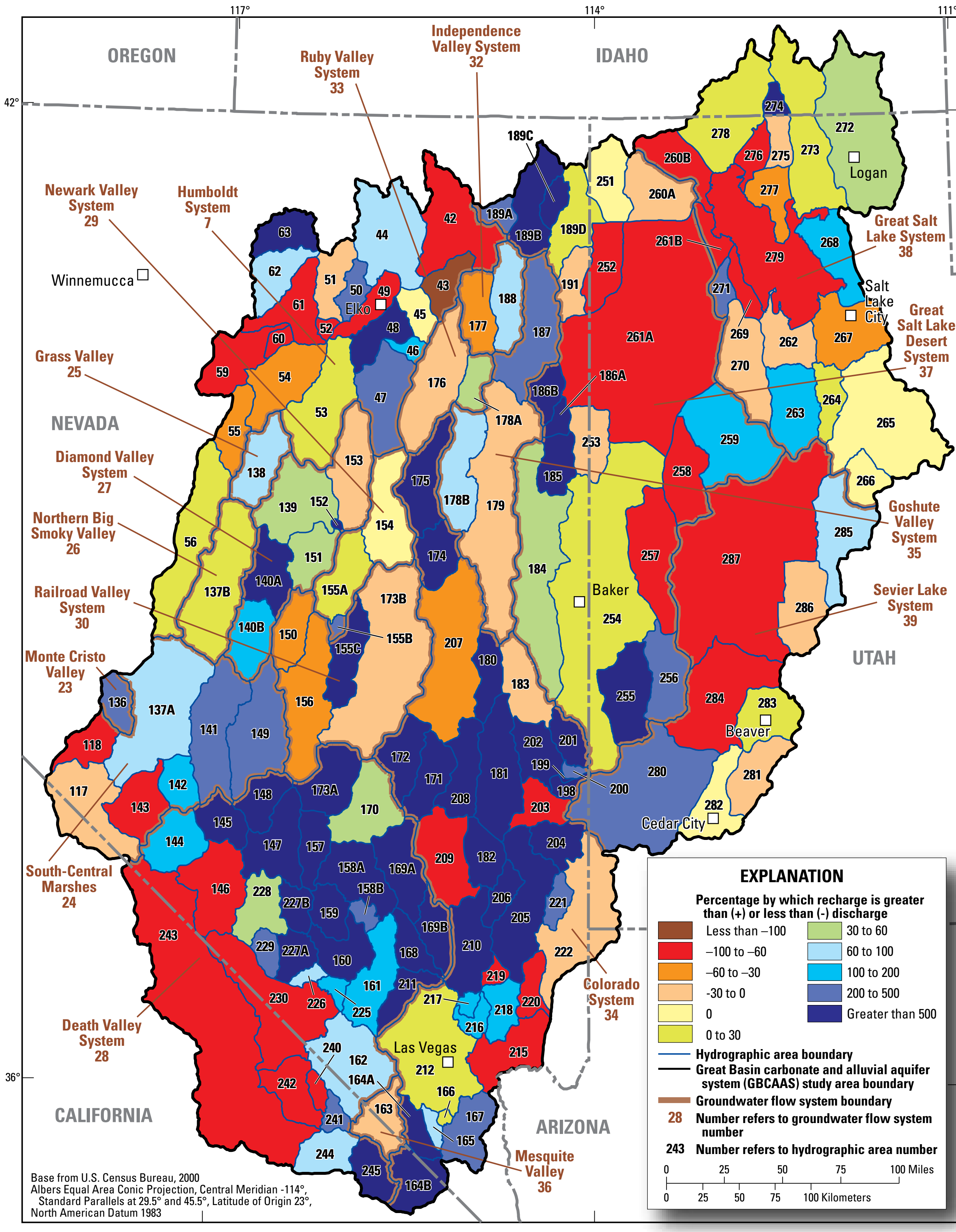

Figure D–20. Predevelopment groundwater-budget imbalances for each hydrographic area in the Great Basin carbonate and alluvial aquifer system study area.

as likely, possible, or unlikely, on the basis of the hydraulic gradients; the likelihood of hydraulic connections across HA boundaries; and whether substantial groundwater-budget imbalances exist. Findings of the current study indicate that subsurface inflow to Railroad Valley groundwater flow system is likely, while subsurface inflow to many other groundwater flow systems within the GBCAAS study area is possible.

Total estimated predevelopment groundwater discharge for the GBCAAS study area is 4,200,000 ±1,300,000 acre-ft/yr. Predevelopment discharge comprises six components: groundwater evapotranspiration (ETg); groundwater discharge to mountain streams; groundwater discharge to basin-fill streams, lakes, and reservoirs; groundwater discharge to springs; adjustment to natural discharge for well withdrawals; and subsurface outflow. Estimated predevelopment groundwater discharge to ETg is 1,800,000 acre-ft/yr and accounts for 43 percent of the total predevelopment discharge for the study area. On the basis of historical streamgage records, estimated predevelopment groundwater discharge to mountain streams is 450,000 acre-ft/yr. Estimated predevelopment groundwater discharge to basin-fill streams, lakes, and reservoirs is 660,000 acre-ft/yr and to springs is 990,000 acre-ft/yr. The estimated adjustment to natural discharge for well withdrawals is 330,000 acre-ft/yr. Although subsurface outflow may be an important component of discharge in some HAs and groundwater flow systems, these fluxes are not quantified in the current study because of uncertainties in the other water-budget components. Such fluxes between groundwater flow systems are qualitatively described as likely, possible, or unlikely on the basis of the same factors described above for subsurface inflow. Findings of the current study indicate that subsurface outflow is likely from the Monte Cristo Valley (23), Grass Valley (25), and Diamond Valley (27) groundwater flow systems; subsurface outflow to many other groundwater flow systems within the GBCAAS study area is possible.

Between 1940 and 2006, groundwater development has occurred in various parts of the GBCAAS study area. Although well withdrawals have been minimal in the majority of HAs and groundwater flow systems, some areas have undergone substantial development, sometimes causing significant water-level declines. Total well withdrawals for the study area increased from less than 300,000 acre-ft/yr in 1940 to almost 1,300,000 acre-ft/yr in the late 1970s. Since the late 1970s, well withdrawals have fluctuated between about 1,100,000 and 1,500,000 acre-ft/yr. Most of the well withdrawals (as much as 900,000 acre-ft/yr) have occurred in Utah. Although the majority of well withdrawals are used for irrigation, there has been a general increase in withdrawals for public supply and a decrease in withdrawals for irrigation (as water use changes from irrigation to public supply and as more efficient irrigation practices are implemented) since the late 1970s. It is assumed that about 30 percent of this water is recycled back to the aquifer as recharge from unconsumed irrigation and public supply water.

The estimated decrease in combined natural discharge and groundwater storage within the GBCAAS study area caused by well withdrawals for the year 2000 was 990,000 acre-ft. The Great Salt Lake (38), Sevier Lake (39), and Humboldt (7) groundwater flow systems account for most of this decrease. The minimum estimated decrease in groundwater storage for the study area in 2000 was 67,000 acre-ft and was limited to only the Sevier Lake (39), Diamond Valley (27), and Death Valley (28) groundwater flow systems.

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