Prepared in cooperation with the Arizona Department of Water Resources and Mohave County, Arizona

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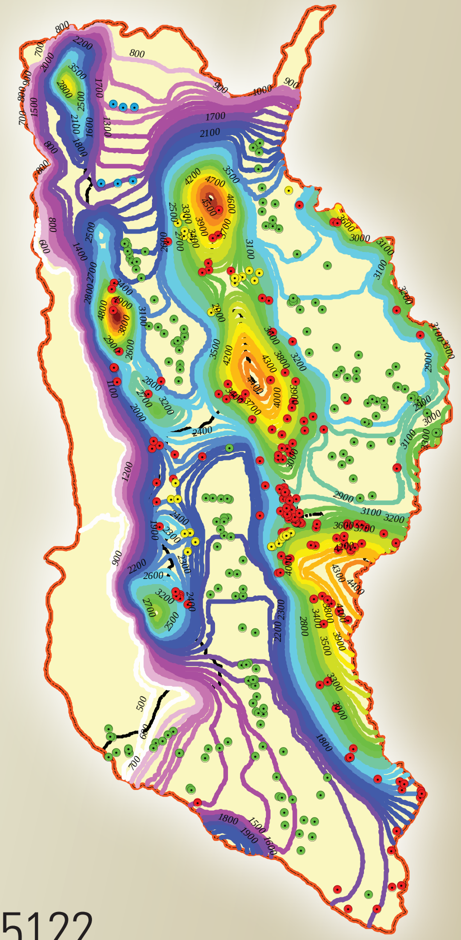

Scientific Investigations Report 2013–5122

U.S. Department of the Interior
U.S. Geological Survey

COVER
Land-surface elevation and surface-water features (left) and simulated groundwater elevations (right) for the Detrital, Hualapai, and Sacramento Valleys.

Preliminary Groundwater Flow-Model of the Basin-Fill Aquifers in Detrital, Hualapai, and Sacramento Valleys, Mohave County, Northwestern Arizona

By Fred D Tillman, Bradley D. Garner, and Margot Truini

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U.S. Department of the Interior
SALLY JEWELL, Secretary

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
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)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

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

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

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

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

Preliminary Groundwater-Flow Model of the Basin-Fill Aquifers in Detrital, Hualapai, and Sacramento Valleys, Mohave County, Northwestern Arizona

By Fred D Tillman, Bradley D. Garner, and Margot Truini

Abstract

Preliminary numerical models were developed to simulate groundwater flow in the basin-fill alluvium in Detrital, Hualapai, and Sacramento Valleys in northwestern Arizona. The purpose of this exercise was to gather and evaluate available information and data, to test natural-recharge concepts, and to indicate directions for improving future regional groundwater models of the study area. Both steady-state and transient models were developed with a single layer incorporating vertically averaged hydraulic properties over the model layer. Boundary conditions for the models were constant-head cells along the northern and western edges of the study area, corresponding to the location of the Colorado River, and no-flow boundaries along the bedrock ridges that bound the rest of the study area, except for specified flow where Truxton Wash enters the southern end of Hualapai Valley. Steady-state conditions were simulated for the pre-1935 period, before the construction of Hoover Dam in the northwestern part of the model area. Two recharge scenarios were investigated using the steady-state model—one in which natural aquifer recharge occurs directly in places where water is available from precipitation, and another in which natural aquifer recharge from precipitation occurs in the basin-fill alluvium that drains areas of available water. A transient model with 31 stress periods was constructed to simulate groundwater flow for the period 1935–2010. The transient model incorporates changing Colorado River, Lake Mead, and Lake Mohave water levels and includes time-varying groundwater withdrawals and aquifer recharge. Both the steady-state and transient models were calibrated to available water-level observations in basin-fill alluvium, and simulations approximate observed water-level trends throughout most of the study area.

Introduction

Detrital, Hualapai, and Sacramento Valleys are all in northwestern Arizona within the Basin and Range Physiographic Province (fig. 1; Fenneman, 1931). These three arid basins contain no perennial surface-water features, and so residents and industry rely on groundwater to meet water needs. Recent and projected population increases for the study area, along with proposed solar-energy-production facilities (Arizona Department of Water Resources, 2009a; Adams-Ockrassa, 2011), make management of groundwater resources in the basins an urgent priority. The U.S. Geological Survey (USGS), in cooperation with the Arizona Department of Water Resources (ADWR), began hydrogeologic investigations of the basins in 2005 as part of the Rural Watershed Initiative (RWI; Anning and others, 2006), a program created by the State of Arizona to improve understanding of rural water resources. Results from the hydrogeologic studies in these basins include an investigation of groundwater occurrence and movement and groundwater-level changes (Anning and others, 2007), an estimate of groundwater budgets (Garner and Truini, 2011), an updated geologic map of the study area (Beard and others, 2011), and a hydrogeologic framework and estimates of groundwater in storage (Truini and others, 2013). These studies, along with the preliminary groundwater-flow model presented in this report, provide information and tools for those tasked with managing water resources in the area to assist in better understanding the existing groundwater system and to help plan for potential changes in the groundwater system from future changes in water use, climate effects, and other stresses.

Purpose and Scope

This report documents the development and calibration of a preliminary numerical groundwater-flow model of the alluvial aquifers in Detrital, Hualapai, and Sacramento Valleys designed to gather and evaluate existing information and data, to test natural-recharge concepts, and to indicate directions for improving future regional groundwater-flow models of the area (fig. 1). Such models can provide insight to better understand the groundwater-flow systems in these aquifers and to help water managers plan for changes in these systems in response to future pumping strategies, climate change, and other stresses. The objective of this modeling project was to simulate steady-state and transient conditions for the alluvial aquifers in the study area. The initial approach as defined

Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983.

Figure 1. Map of study and model area within Mohave County, Arizona, showing basin boundaries, model boundaries, major surface-water features, and roads.

in the work plan included constructing a simple, one-layer model; defining a preliminary distribution of hydrologic properties; testing two concepts of aquifer recharge; testing for connectivity between the alluvial aquifers in the basins; and simulating transient conditions by including municipal and domestic groundwater withdrawals. Steady-state conditions were simulated for the pre-Hoover Dam period (pre-1935) with two aquifer-recharge scenarios investigated in the steady-state model; transient conditions were simulated for the period 1935–2010 and include changing Colorado River levels, changing aquifer recharge over time, and groundwater withdrawals from pumping.

Approach

Information from previous USGS and ADWR investigations in the study area were used to develop a conceptual model of the groundwater-flow system. Geologic and lithologic information from recent USGS investigations were used to define the alluvial aquifers and surficial bedrock areas and to divide these areas into parameter zones. A single model layer was used to simulate the groundwater system, with the aquifer bottom defined at an arbitrary elevation. The groundwater-flow system was simulated using the finite-difference groundwater-model program MODFLOW 2005 (Harbaugh, 2005). MODFLOW input files were constructed, and model output was visualized, using ArcGIS, ModelMuse (Winston, 2009), and GWChart (Winston, 2000) software. Several MODFLOW packages were used in the simulations including Recharge (RCH), Layer-Property Flow (LPF), Wells (WEL), and the solver package Preconditioned Conjugate Gradient (PCG2), among others. UCODE_2005 (Poeter and others, 2005) was used within the ModelMate interface (Banta, 2011) to investigate parameter sensitivity and in the model calibration process. Groundwater-level data for the alluvial basins from ADWR and USGS databases were used for comparison with simulated water levels to calibrate the numerical models. Although the focus of groundwater-flow modeling was the alluvial aquifers of the three valleys, mountainous areas were included in the models to allow aquifer recharge from high-elevation areas where most precipitation occurs. Minimal effort was made to match groundwater levels in mountainous and other high-elevation areas and additional information and calibration would be required to simulate the groundwater-flow system in these areas. No model calibration to groundwater levels was performed for the Lake Mohave Basin.

Description of Study Area

Basins within the study area (fig. 1) are typified by broad, gently sloping valleys separated by sharply rising mountain ranges. The alluvial aquifers that underlie the valley floors are composed of hundreds to several thousands of feet of alluvium, mostly eroded from the surrounding mountains. The study area, which encompasses about 4,670 mi^2, includes the Detrital, Hualapai, and Sacramento Valleys in northwestern Arizona. These basins are bounded by the Grand Wash Cliffs and the Music, Peacock, and Hualapai Mountains to the east; by the Mohave Mountains to the south; and by the Colorado River and Lake Mead to the north (figs. 1 and 2). The Lake Mohave Basin to the west was added to the model area in order to utilize the Colorado River as a hydrologic boundary condition along the western edge of the groundwater-flow model. Mountainous areas within the study area, in addition to the bounding mountains previously mentioned, include the Cerbat and Black Mountains and the White Hills (fig. 2). Land-surface elevation in the study area ranges from about 480 ft at Topock near the mouth of Sacramento Wash to more than 8,300 ft at Hayden Peak in the Hualapai Mountains. Mountain crests are more than 1,000 ft above valley floors, and the crest of Hualapai Mountain is as much as 5,500 ft above Sacramento Valley (Anning and others, 2007).

No perennial streams occur within the study area and only the Colorado River along the northern and western model boundaries flows year round. Major washes that bisect Detrital, Hualapai, and Sacramento Valleys flow at times in response to precipitation (fig. 1). Detrital and Hualapai Washes drain northward to Lake Mead, Sacramento Wash drains southward and then westward to the Colorado River, and Truxton Wash flows northward to an internal drainage area at Red Lake in Hualapai Valley.

Climate

Climate in the study area (fig. 1) is semiarid to arid, with average precipitation during 1940–2008 about 9.2 in/yr (PRISM Climate Group, 2008). Precipitation is generally greater in high-elevation areas than over valley floors and occurs primarily in two seasons. The winter precipitation season, which is normally from November through February, is characterized by slow-moving frontal systems with steady precipitation that may last several days, although occasional winter storms may generate large, intense precipitation events. The summer precipitation season, which is normally from June through September, follows the monsoonal pattern observed in the southern part of the State, and is characterized by brief, intense thunderstorms that may produce 1 in. or more of rainfall in some areas over short periods. Little precipitation falls from April to June, although melting winter snow and ice may produce flow in drainages. Maximum daily temperatures in the valley floors range from 90 to 110 °F during the summer and from 50 to 70 °F during the winter (Anning and others, 2007).

Land and Water Use

Except for the city of Kingman and a few small communities, the study area (fig. 1) is very sparsely populated

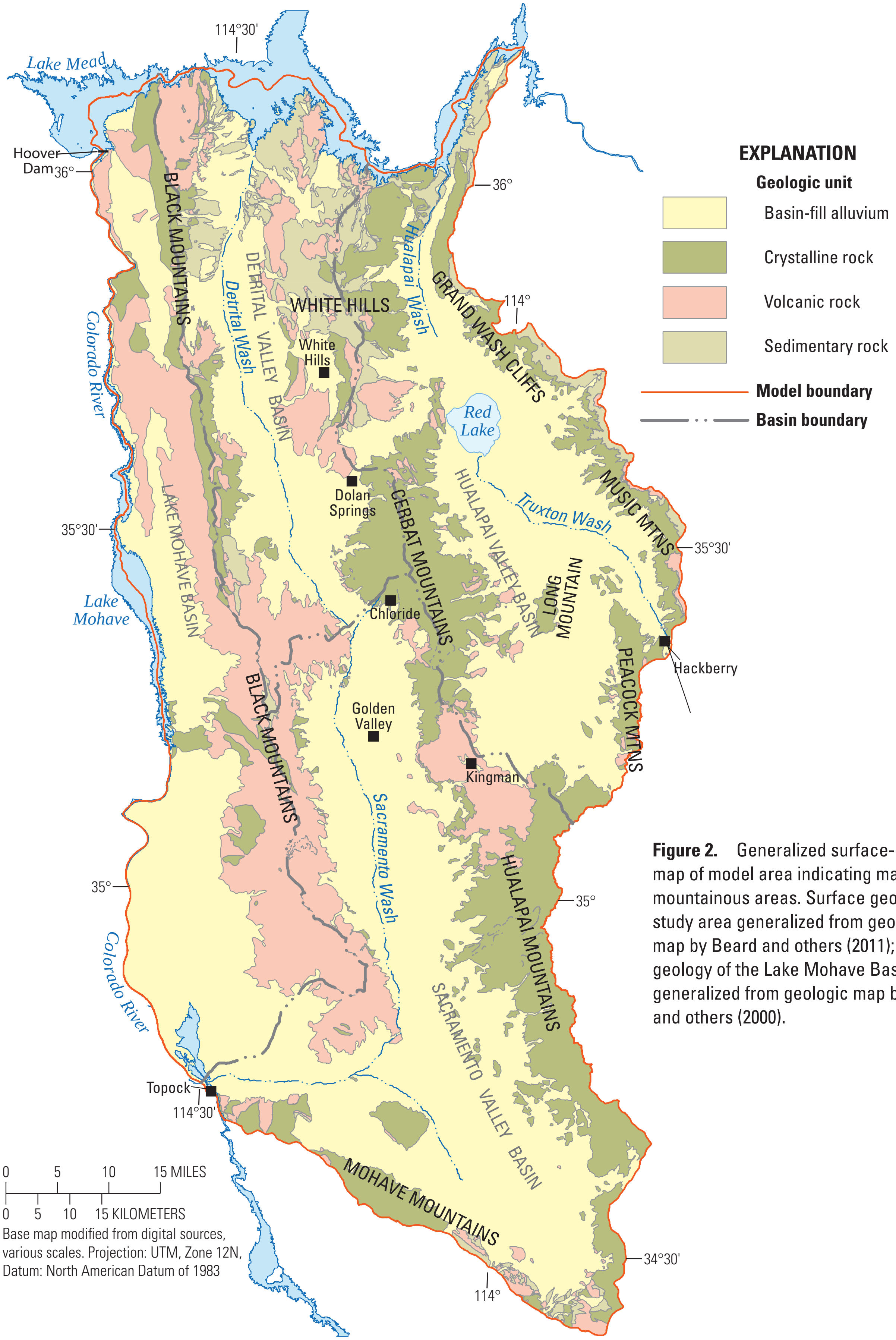


Figure 2. Generalized surface-geology map of model area indicating major mountainous areas. Surface geology in study area generalized from geologic map by Beard and others (2011); surface geology of the Lake Mohave Basin generalized from geologic map by Richard and others (2000).

as of 2000 (Garner and Truini, 2011). Urban land use occurs in city areas, with irrigated lawns, fields, and rights-of-way in urban areas such as Kingman. Municipal and Community Water Systems (CWSs) supply water for domestic use to residents in these areas. Land use and land cover outside of urban areas is almost entirely nonirrigated grazing and open desert. A limited amount of mining and electrical-power generation in Sacramento Valley uses water for operations. The small human populations outside of urban areas have their domestic water needs met either through self-supplied domestic withdrawals or by CWSs. Agricultural land use is minimal within Detrital, Hualapai, and Sacramento Valleys.

Conceptual Model of the Groundwater-Flow System

A conceptual model of a groundwater-flow system incorporates a general understanding of the location and rate of inputs into the system, how groundwater moves through the system, and where and at what rate groundwater discharges from the system. Conceptual models are based on such hydrogeologic information as estimates of aquifer recharge, measured water levels in wells, and hydrologic properties of aquifer materials, among other factors. The models will be modified through time as improved information is obtained from new data and analyses. Observed groundwater levels, to which the models in this report are calibrated, may be explained by many different conceptual models. A general description of the current conceptual model, including the hydrogeologic framework, the groundwater-flow system in the alluvial basins, and groundwater-budget components for the basins, is provided here.

Hydrogeologic Framework

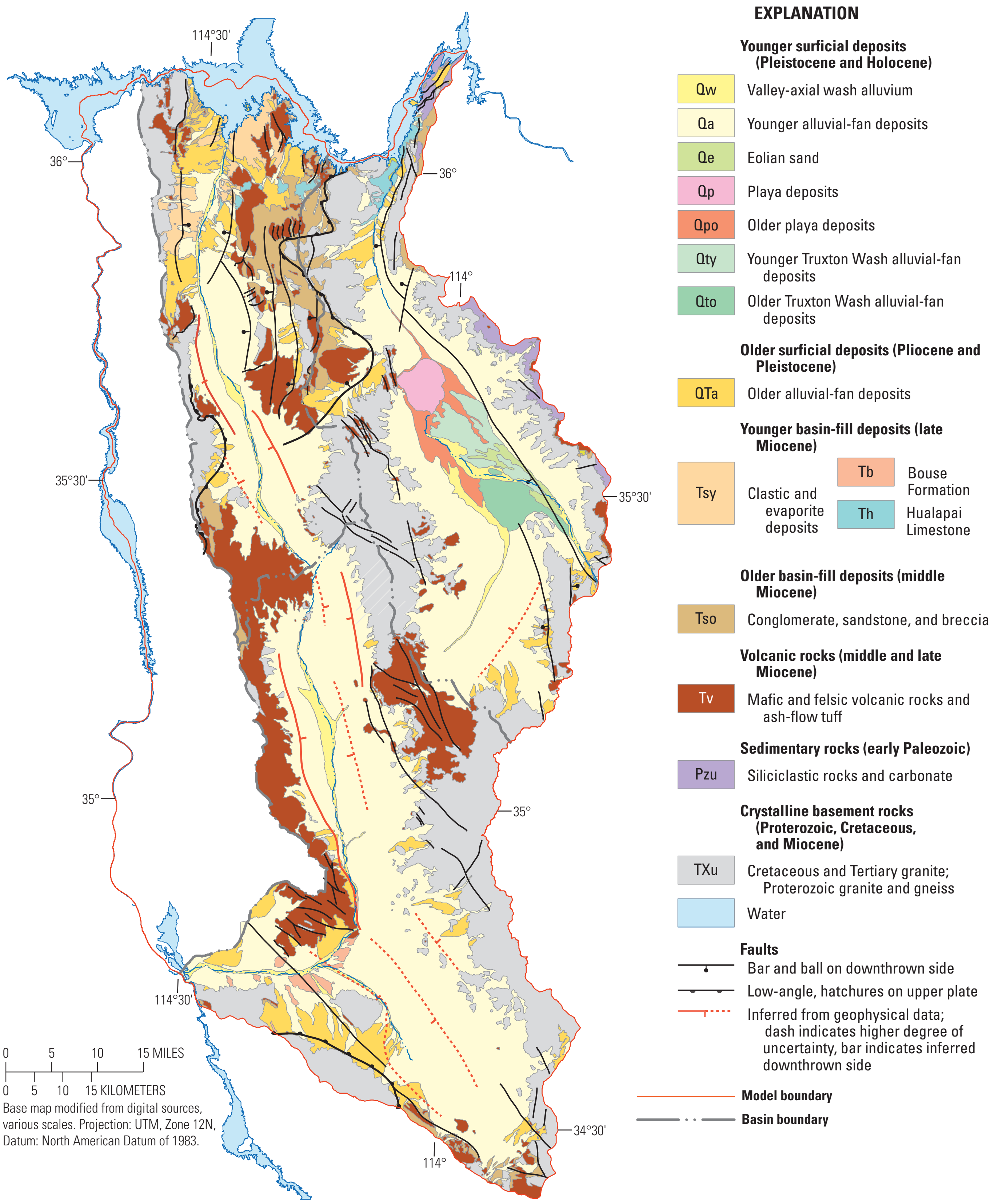
Recent investigations into the geology and hydrogeology of the study area have been published by Beard and others (2011) and Truini and others (2013) and are summarized here. The study area lies mostly within the Basin and Range Physiographic Province (Fenneman, 1931), formed by extensional faulting during the Miocene. The study area is underlain by crystalline Proterozoic rocks, either exposed at the surface or overlain by younger volcanic and sedimentary rocks. The Proterozoic crystalline basement rocks include deformed metamorphic gneiss and schist and later-intruded granite. Paleozoic sedimentary rocks were deposited on an unconformity in the basement rocks. During Late Cretaceous and Paleocene (Laramide) time, the study area was locally intruded by Late Cretaceous plutons and uplifted, exposing basement rocks in the core of the uplift. Post-Laramide erosion removed Paleozoic and Mesozoic sedimentary deposits off the uplift (Bohannon, 1984) and created a beveled erosional surface cut on lower Paleozoic rocks of the western Colorado Plateau's margin. The erosion was accompanied by the formation of large paleovalleys that drained northeastward off the uplift and onto the Colorado Plateau (Young, 2001), including a paleovalley between the Cerbat and Hualapai Mountains (Beard and others, 2011) where the city of Kingman is located (fig. 3).

Volcanism and plutonism began during the Cenozoic about 20 Ma, followed by the crustal extension that created the Basin and Range Province (fig. 4*A*; Faulds, 1995). The main extensional event, beginning about 16 Ma and peaking about 15–13 Ma, affected most of the study area and resulted in highly tilted fault blocks bounded by north-northwest-striking faults. The extensional basins that formed during this event filled with middle Miocene volcanic rocks and older sedimentary deposits (fig. 4*A*). In the northern White Hills, the basins were predominantly filled with clastic deposits, and in the southwestern White Hills and the Black Mountains, the older basin fill was predominantly volcanic rocks (Beard and others, 2011).

Later (about 13–8 Ma) extensional faulting formed subbasins, typically bounded by one or more northerly-striking normal faults that underlie the modern valleys (fig. 4*B*; Beard and others, 2011). Bedrock is 0.4–2.7 mi beneath the modern land surface in these subbasins, which were internally drained and filled with fine sand, silt, clay, and evaporite deposits (in some places) in lacustrine/playa, shoreline, and alluvial-fan and alluvial-plain settings (fig. 5). The lacustrine late Miocene Hualapai Limestone was deposited at the northern end of Hualapai Valley, and deltaic sedimentary deposits of the late Miocene Bouse Formation, consisting of clay, silt, and some gravel, were deposited along the Colorado River at the western end of the Sacramento Valley. In contrast to the older rocks, these deposits are mostly flat-lying or mildly tilted. Isolated late Miocene basalt flows overlie younger sedimentary deposits on the western side of Detrital Valley and on the northeastern flank of the Mohave Mountains. After integration of the Colorado River drainage ended interior-basin deposition, the subbasins were overlapped and mostly buried by early Pliocene and Pleistocene surficial deposits and Pleistocene and Holocene alluvial and playa deposits that form the smooth floors of the three valley basins (figs. 4*C* and 5). Although water-bearing zones also occur in volcanic, granitic, metamorphic, and consolidated sedimentary rocks in the mountains that surround the valleys in the study area, water-saturated sedimentary deposits that fill the structural basins form the principal aquifer (Anning and others, 2007) and are referred to as the "basin-fill aquifer" in this report.

Groundwater-Flow System

Natural recharge to groundwater in the study area is derived mainly from precipitation that falls in high elevations of the basins, with a small amount of recharge in Hualapai Valley coming from groundwater underflow from the upgradient Big Sandy Basin and infiltrating ephemeral



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983.

Figure 3. Map of study area in Mohave County, Arizona, showing detailed surface geology and basin structure (modified from Beard and others, 2011).

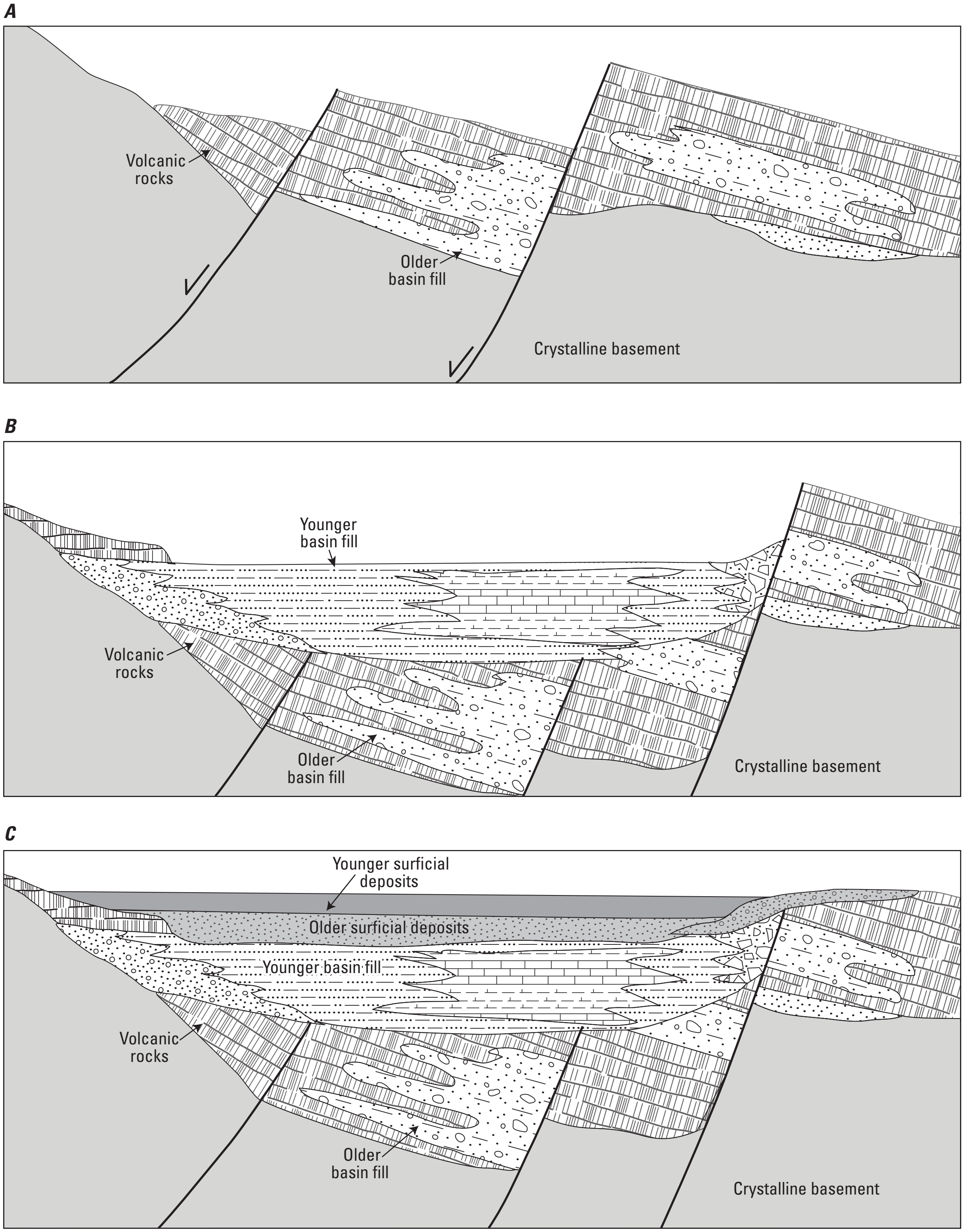


Figure 4. Schematic cross section of basins in the study area showing basin evolution and structural and stratigraphic relations between rocks and sedimentary deposits (modified from Beard and others, 2011).

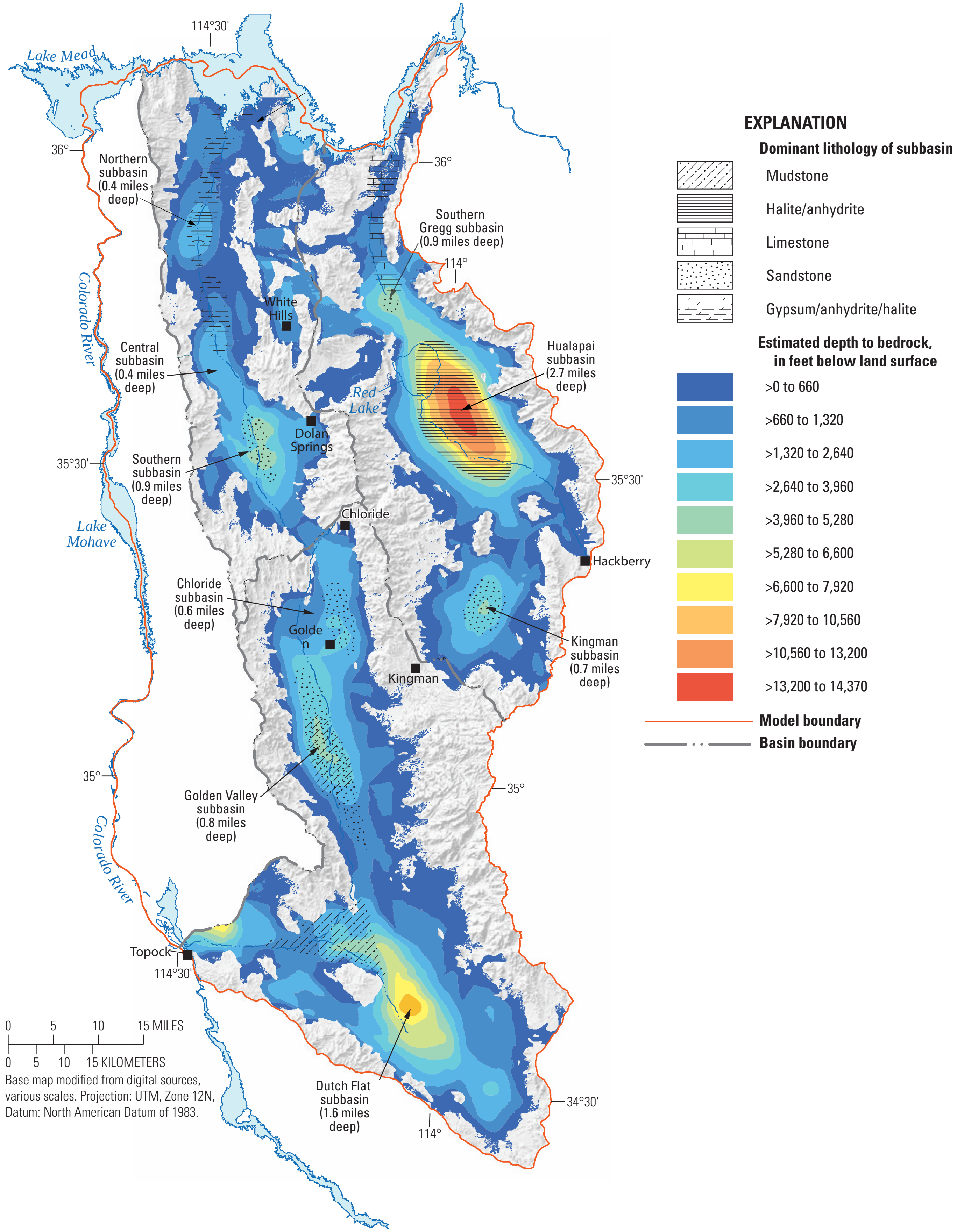


Figure 5. Map of study area in Mohave County, Arizona, showing basin geometry and dominant lithology of basin-fill alluvium (modified from Truini and others, 2013).

surface water at Truxton Wash (fig. 1). Precipitation is greater at these high elevations owing to orographic processes, and cool average temperatures reduce evapotranspiration (ET) rates so that, at times, excess precipitation becomes available water for direct aquifer recharge and runoff (fig. 6). The limited precipitation that falls directly onto alluvial-valley floors generally does not become aquifer recharge owing to high rates of evapotranspiration from the land surface and the unsaturated zone. As is common for groundwater basins throughout the Basin and Range, available water in mountainous areas may recharge groundwater directly by infiltrating faults and fractures in mountain blocks or through such permeable rocks as limestone (Stonestrom and others, 2007). Groundwater from directly recharged mountainous areas flows through interconnected mountain-block faults and fractures toward the low-elevation alluvial basins, which are the focus of the groundwater-flow model in this report. Available water from mountainous areas that does not infiltrate—typically observed only during periods of intense or extended precipitation—becomes runoff and enters ephemeral stream channels. This runoff flows onto alluvial-valley floors in stream channels, where a portion infiltrates through streambeds and becomes recharge for basin-fill aquifers (fig. 6).

In the alluvial basins in the study area, groundwater flows through permeable sediments from areas of high hydraulic head towards discharge areas mainly along the Colorado River, although groundwater just east of Kingman flows toward a cone of depression created by the city's groundwater withdrawals (Anning and others, 2007). Modern groundwater-flow directions are probably similar to those in the predevelopment system, except for the cone of depression described above and other localized pumping effects. In the Hualapai Valley Basin, groundwater flows northeastward from just east of the Kingman cone of depression, then north-northwestward to discharge at Lake Mead. Red Lake playa in the Hualapai Valley collects surface-water runoff that is transported there, but observed depth to groundwater in the area (>200 ft) effectively prohibits aquifer recharge through the playa (Scanlon and others, 1999; Walvoord and others, 2004). On the basis of observed groundwater elevations, a groundwater divide has been inferred near the town of Chloride, near the border between the Detrital and Sacramento Valley Basins. Groundwater flows north-northwestward from the groundwater divide through the Detrital Valley to discharge sites along Lake Mead, and south-southeastward in Sacramento Valley, until the flow turns westward to discharge into the Colorado River near Topock (fig. 2).

Wells within some mountain-pediment areas with overlying alluvium have water levels that are much higher than in other basin-fill wells in nearby valley floors; these areas include a small valley northeast of Dolan Springs, an area north of White Hills, and an area southwest of Kingman (fig. 2; Anning and others, 2007). Water levels in these wells are as much as 1,000 ft higher than in other basin-fill wells less than 2 mi distant in the valley floors.

A study using satellite data to estimate basin-scale groundwater discharge by vegetation for the Basin and Range of Arizona by Tillman and others (2011, 2012), indicated phreatic evapotranspiration along several washes and along the shoreline of Lake Mead. Subsequent spatial analysis by Garner and Truini (2011) determined that bank storage and soil moisture were the most likely sources of water for this vegetation, and the amount of groundwater discharge through evapotranspiration from the alluvial basins in the study area is considered negligible.

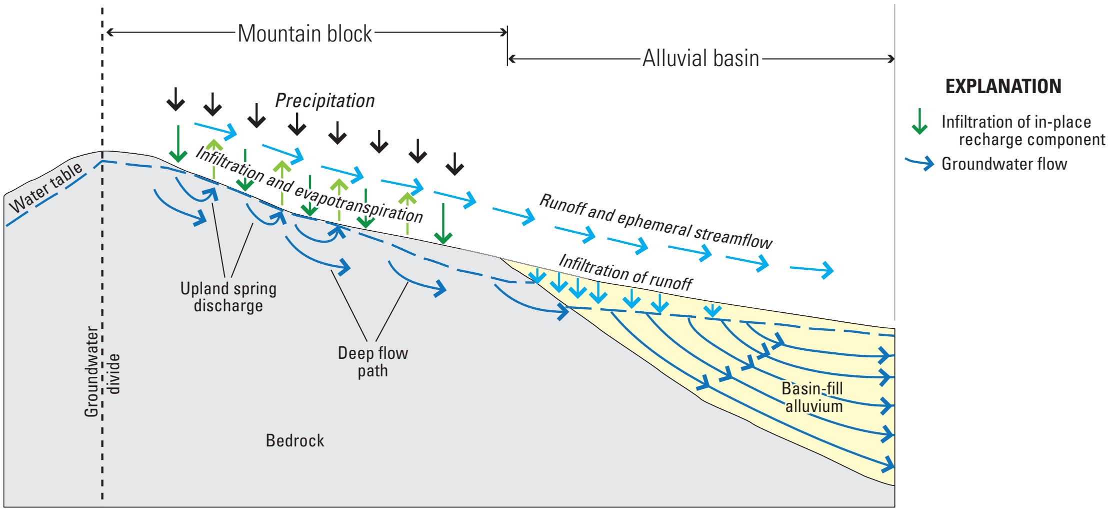


Figure 6. Schematic diagram showing general groundwater-recharge processes in the study area (modified from Garner and Truini, 2011).

Groundwater Budget

Annual groundwater budgets quantifying volumes of water flowing into and out of Detrital, Hualapai, and Sacramento Valley alluvial aquifers were presented in Garner and Truini (2011). These water budgets were calculated as average basin-wide conditions for 2007–08 except for natural aquifer recharge from precipitation, which was calculated as a long-term average for 1940–2008. Rates of natural aquifer recharge from precipitation were calculated using a physically based distributed model that calculated surface energy and surface mass flux in a grid with cells 885 ft on each side (Flint and Flint, 2007a, 2007b). Natural-discharge rates were assumed to be equal to natural-recharge rates, meaning that alteration of natural-discharge or natural-recharge rates by groundwater pumping was assumed to be negligible.

Predevelopment

A predevelopment water budget describes the long-term steady-state condition that existed prior to any human development of groundwater resources. Predevelopment water budgets, although not expressly presented by Garner and Truini (2011), can be inferred by omitting groundwater withdrawals and incidental recharge (table 1). Human activity was assumed to have not affected natural recharge or discharge rates as of 2007–08, and natural-recharge rates were calculated as long-term averages in the study.

Predevelopment natural-recharge rates were small in Detrital, Hualapai, and Sacramento Valleys relative to those in other groundwater basins in Arizona (Freethey and Anderson, 1986; Tillman and others, 2011), consistent with the arid conditions that prevail in these three valleys. Natural aquifer recharge in Detrital Valley from precipitation was the lowest of the three valleys (1,400 acre-ft/yr); natural aquifer recharge from precipitation in Hualapai and Sacramento Valleys was about the same (5,700 and 6,000 acre-ft/yr, respectively). Total natural aquifer recharge from precipitation in the three valleys (13,100 acre-ft/yr) was less than 1 percent of the total precipitation estimated to fall on the three valleys (1,740,000 acre-ft/yr), indicating high evapotranspiration rates from the land surface and soil moisture in the study area.

Predevelopment natural discharge from the three valleys was mainly to the Colorado River with a minor component to the atmosphere through groundwater evapotranspiration by phreatophytic plants in limited localities. Predevelopment groundwater budgets have no groundwater storage change (Healy and others, 2007), meaning predevelopment natural discharge rates were equal to recharge rates (table 1).

Postdevelopment

Garner and Truini (2011) calculated that during 2007–08 about 90 percent of the water withdrawn from Detrital, Hualapai, and Sacramento Valleys was used for municipal and domestic water supplies, mostly in and around the city of Kingman (fig. 1; table 2). About 10 percent of withdrawn groundwater was used for industrial uses. No other classifications of water use (for example, agriculture) were identified. Of the estimated 14,300 acre-ft/yr of groundwater withdrawn, about 6,300 acre-ft/yr was estimated to return to aquifers through incidental recharge using assumptions from other studies in comparable areas (Nishikawa, 2004). Discharge of effluent from septic-system drain fields accounted for about 75 percent of this incidental recharge, and the rest came from leaking water-supply pipes and infiltration of treated effluent from two wastewater-treatment plants in the city of Kingman.

Table 1. Predevelopment groundwater-budget values for Detrital, Hualapai, and Sacramento Valleys from Garner and Truini (2011).

[Groundwater-budget values are in acre-feet per year; <, less than; –, no data]

Water-budget component	Detrital Valley Basin		Hualapai Valley Basin		Sacramento Valley Basin	
	Inflow to aquifer	Outflow from aquifer	Inflow to aquifer	Outflow from aquifer	Inflow to aquifer	Outflow from aquifer
Natural recharge						
Mountain-block recharge	1,200		4,400		5,200	
Named ephemeral stream-channel recharge	–		600		–	
Other ephemeral stream-channel recharge	<300		400		800	
Underflow in	–		[1]300		–	
Natural discharge to Lake Mead or Colorado River		1,400		5,700		6,000
Totals	**1,400**	**1,400**	**5,700**	**5,700**	**6,000**	**6,000**

[1] Underflow occurs where Truxton Wash enters Hualapai Valley.

Table 2. Summary of groundwater-budget components from Garner and Truini (2011).

[Groundwater-budget values are in acre-feet per year; <, less than; WWTP, wastewater treatment plant]

Water-budget component	Detrital Valley Basin		Hualapai Valley Basin		Sacramento Valley Basin	
	Inflow to aquifer	Outflow from aquifer	Inflow to aquifer	Outflow from aquifer	Inflow to aquifer	Outflow from aquifer
Natural recharge						
Mountain-block recharge	1,200		4,400		5,200	
Named ephemeral stream-channel recharge	–		600		–	
Other ephemeral stream-channel recharge	<300		400		800	
Underflow in	–		[1]300		–	
Natural discharge						
to Lake Mead or Colorado River		1,400		5,700		[2]4,000
Phreatic evapotranspiration (ET)		<300		<300		[2]2,000
Groundwater withdrawals		<300				
Kingman municipal		–		7,600		500
Community water suppliers		–		500		2,000
Self-supplied domestic		–		500		100
Industrial		–		–		1,900
Interbasin transfer				1,200		([3])
Incidental Recharge	<300		500		[4]<300	
Infrastructure leakage			3,000		[4]1,700	
Septic systems			800		[4]<300	
Treated WWTP effluent						
Totals	**1,600**	**1,600**	**9,900**	**15,500**	**8,200**	**10,500**

[1] From Freethey and Anderson (1986) predevelopment conditions.

[2] Partitioning between Colorado River and phreatic evapotranspiration uncertain because of a lack of data.

[3] Groundwater is transferred in from Hualapai Valley Basin, but is not shown here because it is not part of the groundwater budget of Sacramento Valley Basin.

[4] Includes the effects of 1,200 acre-feet/year of water transferred from Hualapai Valley for Kingman.

Simulation of Groundwater Flow

Groundwater flow in the basin-fill aquifers of Detrital, Hualapai, and Sacramento Valleys was simulated by using the MODFLOW-2005 program (Harbaugh, 2005), which is the most recent version of the finite-difference groundwater model MODFLOW and uses a block-centered, finite-difference approach to simulating groundwater flow. Sources and sinks to the groundwater system were simulated by using the RCH package for natural aquifer recharge from precipitation; the WEL package for wells, natural aquifer recharge from groundwater underflow, and incidental recharge; and the time-variant specified-head (CHD) package for specified water levels in the Colorado River and associated reservoirs (Harbaugh and others, 2000). The layer-property flow (LPF) package was used to formulate the internal flow terms of the single convertible layer of the models and the preconditioned conjugate-gradient (PCG) solver package (Harbaugh and others, 2000) was used to solve the groundwater-flow equations. The head-observation (HOB) package (Hill and others, 2000) was used to compare model-generated head values with observed water levels from wells for the steady-state models. HYDMOD (Hanson and Leake, 1999) was used to extract and process time-series hydraulic head data for the transient model. ZONEBUDGET (Harbaugh, 1990) was used to calculate basin-scale water budgets from MODFLOW simulation results. Groundwater flow was simulated for both pre-1935 steady-state conditions and for 1935 through 2010 transient conditions. For the steady-state conditions model, two groundwater models were calibrated for different natural aquifer recharge from precipitation scenarios: one in which aquifer recharge from precipitation occurs in-place at the mountain site of available water, simulating mountain-block recharge, and one in which runoff from mountain areas drains to the alluvial valleys and recharges the aquifer at model cells in the alluvium, simulating mountain-front recharge. For the transient-conditions model, only in-place recharge was simulated.

Previous Models

Information provided to the USGS by the ADWR (T.G. Whitmer, written commun., 2010) indicated that four groundwater-flow models were developed by consulting firms as part of adequate-water-supply determinations for proposed developments in the Hualapai and Detrital Valley Basins. Summaries of models for Hualapai Valley by Clear Creek Associates and Errol Montgomery and Associates were provided by ADWR (W.E. Hipke, written commun., 2012). The Clear Creek model covers the northern half of Hualapai Valley and consists of four model layers that simulate upper basin fill, lacustrine, lower basin fill, and bedrock lithologies (W.E. Hipke, written commun., 2006). Clear Creek Associates' model has a specified flux of about 5,600 acre-ft/yr at the southern boundary and simulates transient groundwater conditions (W.E. Hipke, written commun., 2006). Errol Montgomery and Associates' model simulates groundwater flow in the entire Hualapai Valley Basin using three layers for upper alluvial, middle alluvial, and lower alluvial sediments (W.E. Hipke, written commun., 2006). All boundary conditions are no-flow with the exception of specified head cells at Lake Mead (W.E. Hipke, written commun., 2006). Errol Montgomery and Associates' model is copyrighted and not publicly available (T.G. Whitmer, written commun., 2010).

Model Area

Basin boundaries specified by the ADWR were used to define the model area for the groundwater-flow simulations. These basin boundaries generally follow watershed boundaries through mountainous areas and follow State lines along the Colorado River between Arizona and Nevada and between Arizona and California (fig. 1). Although the focus of the groundwater-flow model developed for this investigation is simulation of basin-fill aquifers of the Detrital, Hualapai, and Sacramento Valley Basins, additional areas were included in the model domain to provide physical hydrologic boundaries and locations of potential aquifer recharge. The Lake Mohave Basin to the west of Sacramento Valley was included in the simulated area so that known Colorado River elevations could be used with the CHD package to define the model boundary condition along both the western and northern borders of the model area. Mountainous areas were included in the model domain because these areas are the sites of greatest precipitation and are used as the places of aquifer recharge in one of the steady-state models and in the transient model.

Spatial and Temporal Discretization

The model domain was discretized in the horizontal dimension into uniform 0.62×0.62-mi (1,000×1,000-m) grids, requiring 201 rows and 94 columns to cover the model area. A single convertible model layer was used to simulate regional groundwater flow in the basin-fill aquifers of the model domain, and so no vertical groundwater movement was simulated. An arbitrary elevation of -1,148 ft (-350 m) mean sea level (MSL) was used to define the single-layer model bottom. Evidence from available water levels in the study area indicates primarily horizontal flow throughout the alluvial aquifer (Anning and others, 2007). Anning and others (2007), however, discussed results from deep drilling at a site in Detrital Valley that revealed a water-bearing zone beneath the basin-fill aquifer with higher water levels than the primary aquifer above it. Future drilling may better define this deeper, confined water-bearing zone, and additional model layers may be needed if the zone is to be simulated as part of the regional groundwater-flow system in the study area. The current model, however, assumes no upward groundwater flow from this deeper zone.

Steady-state groundwater conditions were simulated for the predevelopment period before large-scale management of the Colorado River. The simulation of transient groundwater conditions begins with the completion of Hoover Dam on the Colorado River in 1935 and the filling of Lake Mead behind Hoover Dam along the northern model boundary (fig. 1) and continues through the end of 2010. The period of transient groundwater simulations—January 1, 1935 through December 31, 2010—was divided into 31 stress periods to approximate the changes in system stresses over time (table 3); the stress periods range in length from 122 days to 5.8 years. Although the stress periods do not capture all annual changes in model input, breaks in stress periods were chosen to approximate the most important changes in the model stresses of Colorado River and reservoir levels, natural and incidental recharge, and groundwater withdrawals. Spatial and temporal model units are in meters and days, respectively, while this report is presented in units of feet and years.

Boundary Conditions and System Stresses

No-flow conditions were assumed to occur along the eastern and southern boundaries of the model, which generally coincides with watershed elevations in the Grand Wash Cliffs, Music Mountains, Peacock Mountains, Hualapai Mountains, and Mohave Mountains (fig. 2) and at the base of the single-layer model. Ephemeral-flow recharge at Truxton Wash and groundwater underflow from upgradient sources where Truxton Wash enters the model area were simulated by using the WEL package to inject water into the first model cell in Hualapai Valley where Truxton Wash enters the basin (fig. 1). Incidental recharge and groundwater withdrawals were not simulated in the Lake Mohave Basin.

River and Lake Levels

The Colorado River and associated reservoirs provide the northern and western boundaries of the model domain (fig. 7), and are modeled using the time-variant specified-head (CHD) package. For predevelopment steady-state simulations,

Table 3. Description of the 31 stress periods for the transient simulation model.

Stress period	Start date (month-day-year)	Start day	End date	End day	Length (days)
1	pre-dam	-1	01-01-1935	0	steady state
2	01-01-1935	0	09-01-1935	243	243
3	09-01-1935	243	08-01-1937	943	700
4	08-01-1937	943	07-01-1938	1,277	334
5	07-01-1938	1,277	04-01-1941	2,282	1,005
6	04-01-1941	2,282	12-01-1941	2,526	244
7	12-01-1941	2,526	10-01-1946	4,291	1,765
8	10-01-1946	4,291	01-01-1948	4,748	457
9	01-01-1948	4,748	06-01-1953	6,726	1,978
10	06-01-1953	6,726	09-01-1955	7,548	822
11	09-01-1955	7,548	03-01-1957	8,095	547
12	03-01-1957	8,095	06-01-1958	8,552	457
13	06-01-1958	8,552	03-01-1962	9,921	1,369
14	03-01-1962	9,921	07-01-1962	10,043	122
15	07-01-1962	10,043	01-01-1964	10,592	549
16	01-01-1964	10,592	11-01-1964	10,897	305
17	11-01-1964	10,897	06-01-1965	11,109	212
18	06-01-1965	11,109	01-01-1968	12,053	944
19	01-01-1968	12,053	01-01-1973	13,880	1,827
20	01-01-1973	13,880	01-01-1975	14,610	730
21	01-01-1975	14,610	01-01-1978	15,706	1,096
22	01-01-1978	15,706	12-01-1982	17,501	1,795
23	12-01-1982	17,501	12-01-1987	19,327	1,826
24	12-01-1987	19,327	10-01-1991	20,727	1,400
25	10-01-1991	20,727	01-01-1994	21,550	823
26	01-01-1994	21,550	11-01-1994	21,854	304
27	11-01-1994	21,854	09-01-1998	23,254	1,400
28	09-01-1998	23,254	01-01-1999	23,376	122
29	01-01-1999	23,376	06-01-2004	25,354	1,978
30	06-01-2004	25,354	03-01-2005	25,627	273
31	03-01-2005	25,627	12-31-2010	27,758	2,131

Colorado River elevations from USGS surveys in the 1920s compiled by Robert Webb of the USGS National Research Program were used (Birdseye and Burchard, 1924; Burchard, 1927). River elevations between sites from these pre-dam surveys were linearly interpolated to obtain elevations for all model boundary cells along the Colorado River. For the transient model, water-elevation data from gages on the Colorado River and associated reservoirs (fig. 7) were spatially and temporally interpolated to obtain the time-variant river and reservoir boundary conditions (fig. 8). Colorado River elevation immediately downstream of Lake Mead was estimated using digital elevation models (DEMs). For discontinued gages and gages with limited periods of record, data were extrapolated in time. Lake Mead and Lake Mohave elevations were applied to the groundwater-flow model in all model cells within the full-pool area of these lakes for periods after the construction of Hoover and Davis Dams, respectively. This simplification has minor implications for the simulated groundwater-flow system. The elevation of Lake Mead reaches the full-pool model cell at the lake's widest section by May 1938 and never retreats more than one model cell from the full-pool area throughout the simulations.

Recharge

Natural aquifer recharge from precipitation and underflow plus ephemeral flow at Truxton Wash was simulated in steady-state and transient models. For the transient-conditions simulation only, incidental aquifer recharge from leaking water distribution lines, wastewater from septic systems, and effluent from wastewater-treatment systems was included in the model.

Natural Recharge

Results from the Basin Characterization Model (BCM; Flint and Flint, 2007b) were used to determine locations and rates of natural aquifer recharge from precipitation

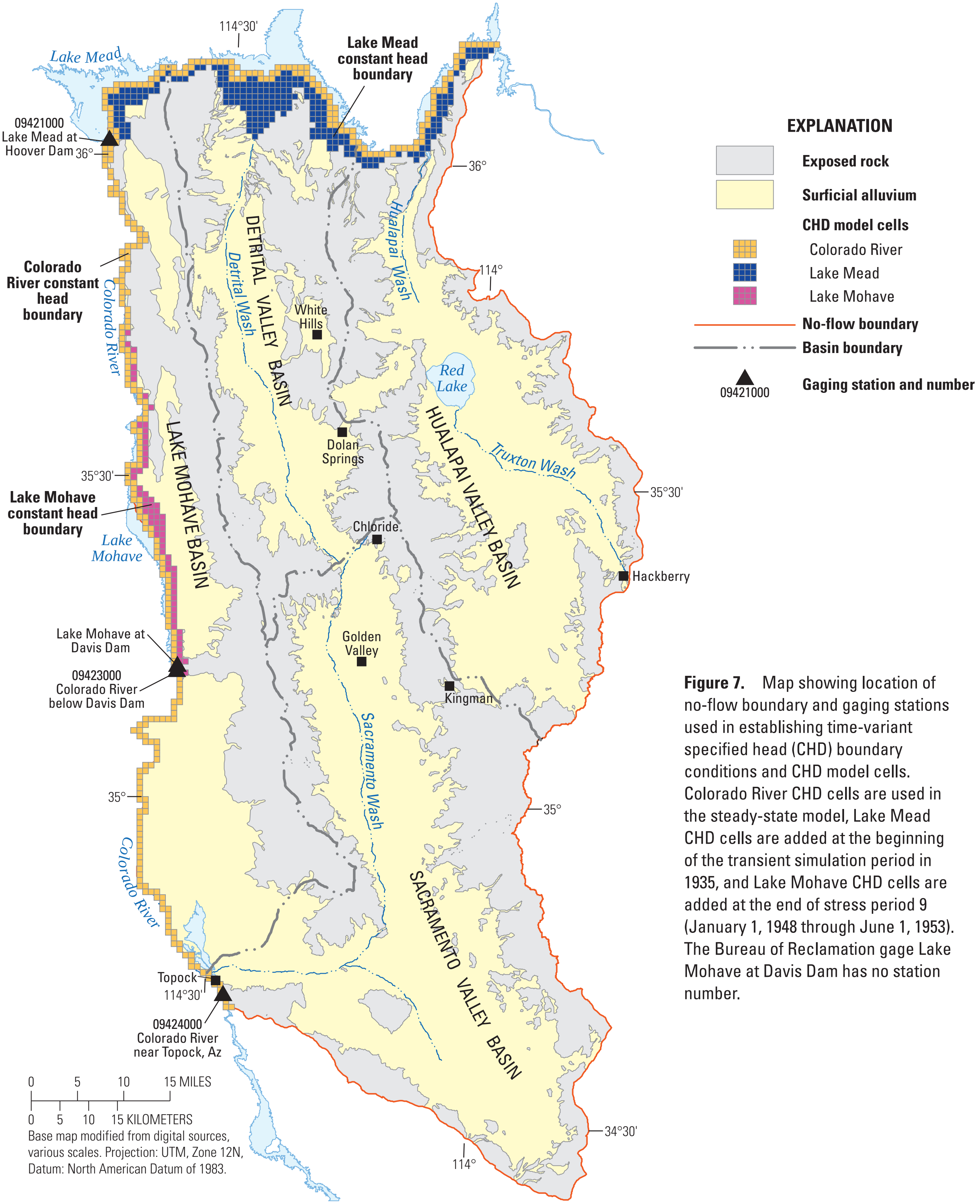


Figure 7. Map showing location of no-flow boundary and gaging stations used in establishing time-variant specified head (CHD) boundary conditions and CHD model cells. Colorado River CHD cells are used in the steady-state model, Lake Mead CHD cells are added at the beginning of the transient simulation period in 1935, and Lake Mohave CHD cells are added at the end of stress period 9 (January 1, 1948 through June 1, 1953). The Bureau of Reclamation gage Lake Mohave at Davis Dam has no station number.

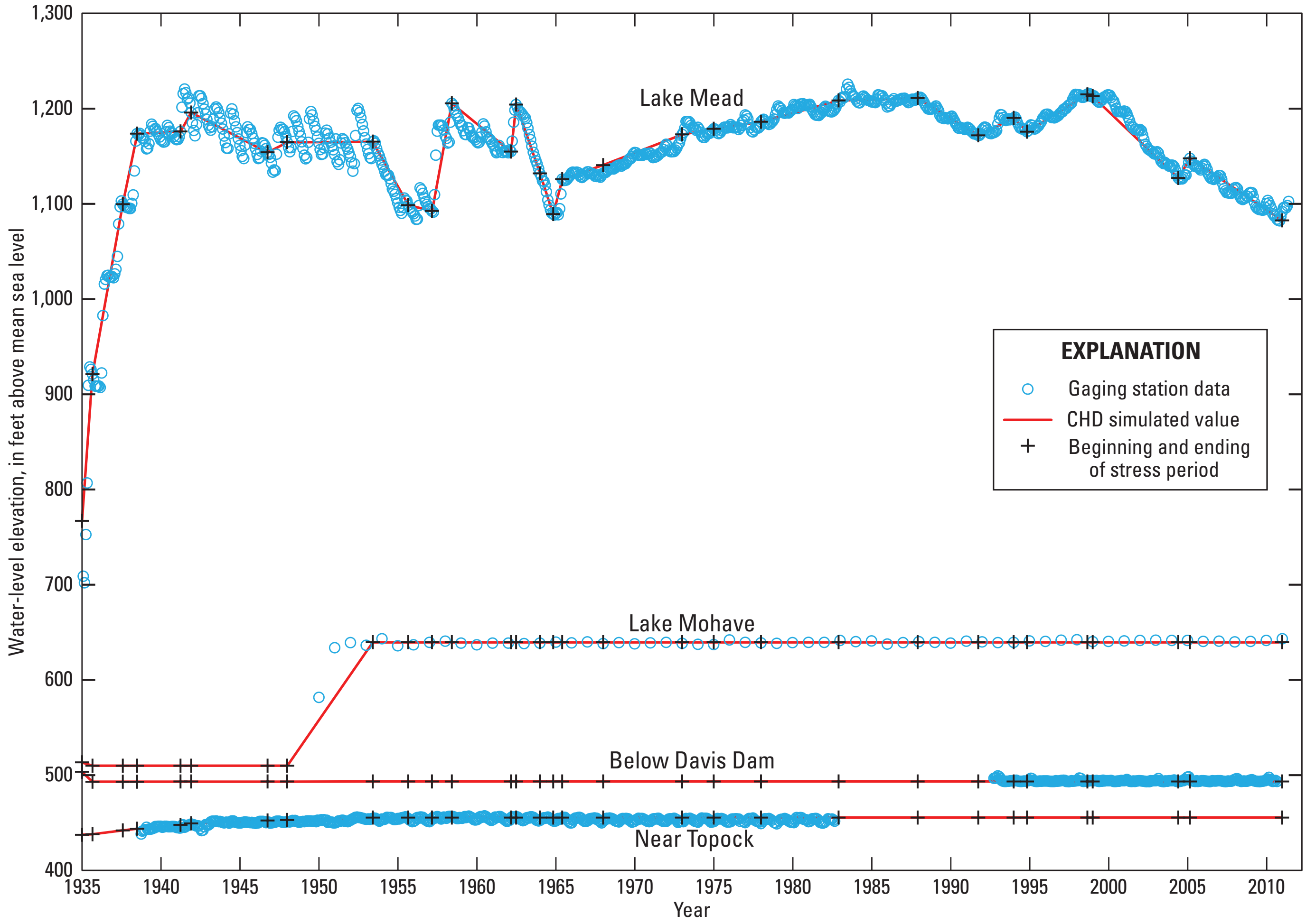


Figure 8. Graph showing gage data used for simulating time-variant specified-head (CHD) boundary conditions along the Colorado River and associated reservoirs in the study area.

for both steady state and transient conditions models. The BCM estimates runoff and in-place recharge using a distributed-parameter water-balance model. The BCM water balance was calculated for 885×885-ft (270×270-m) cells throughout the model area for the period 1940 through 2006. For each cell, monthly values of precipitation, maximum and minimum air temperatures, and potential evapotranspiration were used to calculate monthly volumes of water potentially available for runoff and in-place recharge, together known as available water. The BCM water-balance equation (Flint and Flint, 2007a, 2007b) includes available water (AW), precipitation (P), snowmelt (Sm), potential evapotranspiration (PET), snow accumulation (Sa), and soil-water storage (Ss):

$$AW = P + Sm - PET - Sa + Ss \qquad (1)$$

In-place recharge is calculated in the BCM as the volume of water for a given time that can drain from the soil zone directly into consolidated bedrock or unconsolidated deposits (Flint and Flint, 2007b). Runoff is calculated as available water in excess of the total soil-water storage capacity (soil porosity multiplied by soil depth). Total natural aquifer recharge from precipitation is the sum of in-place recharge and some portion of runoff that becomes recharge, either in the cell in which it is produced, or in other cells down slope. Although the BCM calculates both in-place recharge and runoff separately, it does not estimate how much of the runoff ultimately becomes recharge. Temperature and precipitation estimates required by the BCM were obtained using data from the PRISM Climate Group (PRISM Climate Group, 2008). Potential evapotranspiration was estimated with latitude, topographic shading, and air temperature using the Priestley-Taylor equation corrected for vegetated and bare-soil areas (Flint and Flint, 2007a). Estimates of the storage capacity of a soil were based on soil-texture data from the State Soil Geographic Database (STATSGO; U.S. Department of Agriculture, 1994). The spatial distribution of saturated hydraulic conductivity in bedrock and alluvium was determined from geologic maps. When air temperature was at or below freezing, snow depth was calculated for areas where precipitation occurs. Sublimation of snow was calculated as a percentage of evapotranspiration, and snowmelt was based on net radiation when air temperatures are above freezing (Flint and others, 2004).

The total amount of natural aquifer recharge estimated from BCM results includes in-place recharge plus some percentage of runoff that becomes recharge. For the steady-state model, two scenarios of natural aquifer recharge from precipitation were investigated to determine the effect of different recharge sites on the resulting calibrated groundwater-flow models. BCM results averaged over the period 1940 through 2006 were used to estimate natural aquifer recharge from precipitation for both scenarios. For the first scenario (subsequently referred to as the “in-place-recharge scenario”), natural aquifer recharge from precipitation was assumed to occur only at sites of BCM-calculated in-place recharge, which is almost exclusively in the mountainous areas of the model domain (fig. 9). To account for the percentage of BCM-calculated runoff that becomes recharge, the in-place-recharge values in each model cell were scaled by a factor of 1.39 to obtain a total volume of natural aquifer recharge from precipitation similar in magnitude to those reported by Garner and Truini (2011) for the Detrital, Hualapai, and Sacramento Valley Basins. Total natural aquifer recharge from precipitation in the three basins of the study area for the in-place-recharge scenario is 12,369 acre-ft/yr, comparable to the 12,300 acre-ft/yr reported by Garner and Truini (2011), excluding 500 acre-ft/yr of infiltrating flow at Truxton Wash (accounted as natural aquifer recharge from underflow using the WEL package in the models).

For the second recharge scenario (subsequently referred to as the “runoff-recharge scenario”), natural aquifer recharge from precipitation was assumed to occur almost exclusively in alluvial model cells. BCM-calculated runoff was routed from mountainous areas down elevation to alluvial model cells in ArcGIS using National Hydrography Dataset (NHD) flowlines (see http://nhd.usgs.gov/tools.html) and a groundwater-flow-model recharge input file was created using these alluvial-cell locations (fig. 10). The magnitude of recharge in each model cell from this routed runoff was scaled by a factor of 1.15 to obtain a total natural aquifer recharge from precipitation similar to that in the in-place recharge scenario. A small amount of aquifer recharge (112 acre-ft/yr in the Detrital, Hualapai, and Sacramento Valley Basins) was placed in bedrock model cells to stabilize the numerical solution and prevent model cells from becoming dry. The amount of recharge located in bedrock cells was 1 percent of the BCM-calculated in-place recharge for bedrock areas, but the sites were spread evenly over all bedrock model cells. Total natural aquifer recharge from precipitation in the runoff-recharge scenario was 12,271 acre-ft/yr, similar to that in the in-place recharge scenario and Garner and Truini’s (2011) reported values.

For the transient model, natural aquifer recharge from precipitation was modeled using scaled values and locations from average BCM-calculated annual in-place recharge results. As in the in-place-recharge scenario for the steady-state model, recharge values for all model cells for the transient model were scaled by a factor of 1.39. For periods outside of the 1940–2006 BCM-calculated results, averages for the periods of record were used. Discretization of the transient-conditions simulation into 31 stress periods captured periods of high and low scaled BCM-calculated recharge results during the model period but does not attempt to match all individual annual results (fig. 11). Total natural aquifer recharge from precipitation for the Detrital, Hualapai, and Sacramento Valley Basins in the transient model for the period 1935 through 2010 from the discretized MODFLOW input was 919,465 acre-ft, compared with 931,333 acre-ft for scaled BCM-calculated in-place recharge.

Groundwater inflow into the Hualapai Valley Basin through the Truxton Wash channel and infiltration of ephemeral runoff in the channel was simulated in both the steady-state and transient models using the WEL package. Based on estimates in Garner and Truini (2011), 800 acre-ft/yr was inputted into the first model cell in Hualapai Valley where Truxton Wash enters the basin (fig. 1). The rate of natural aquifer recharge from underflow from Truxton Wash was kept constant for the transient model.

Incidental Recharge

In a process known as incidental recharge, a portion of water that is not consumed during its use reenters the groundwater system. Incidental recharge in the study area was assumed to occur from leaks in water-supply lines, from septic-system drain fields, and from wastewater-treatment-plant discharge. Changes in the rates of incidental recharge from these sources were assumed to occur in proportion to changes in the rates of water delivered to the sources. No direct measurements of incidental recharge were available for the study area, but estimates developed in Garner and Truini (2011) were used to define the rate of simulated incidental recharge. No incidental recharge for Detrital Valley was reported by Garner and Truini (2011) owing to slight water use in this basin. Estimates of total incidental recharge for the 2007–08 period include about 2,100 acre-ft/yr for Sacramento Valley and about 4,300 acre-ft/yr for Hualapai Valley (Garner and Truini, 2011). Of these total rates of incidental recharge, the greatest portion is from septic-system drain fields (1,700 acre-ft/yr in Sacramento Valley and 3,000 acre-ft/yr in Hualapai Valley). These estimates of incidental recharge were scaled backward in time proportional to estimated municipal pumping (for leaks in water-supply lines and discharge from wastewater-treatment plants) and estimated self-supplied domestic pumping (for septic-system drain fields) to obtain incidental recharge rates for the 31 stress periods in the transient model (table 4). Incidental recharge from septic-system drain fields was distributed in the model domain on the basis of population density of rural census blocks with at least 10 people from the 2000 census (U.S. Census Bureau, 2010; fig. 12). It was assumed that current and historical populated areas were

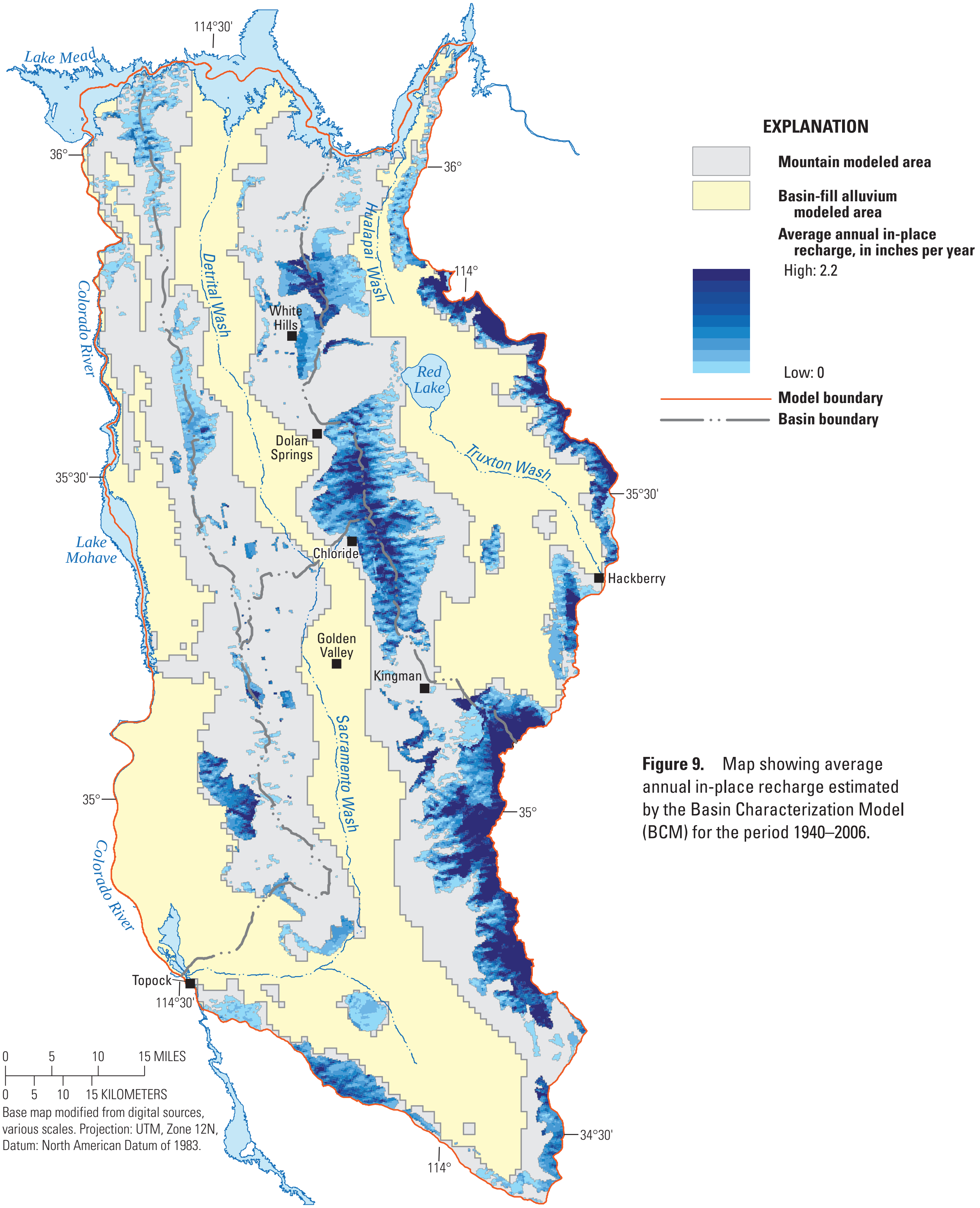
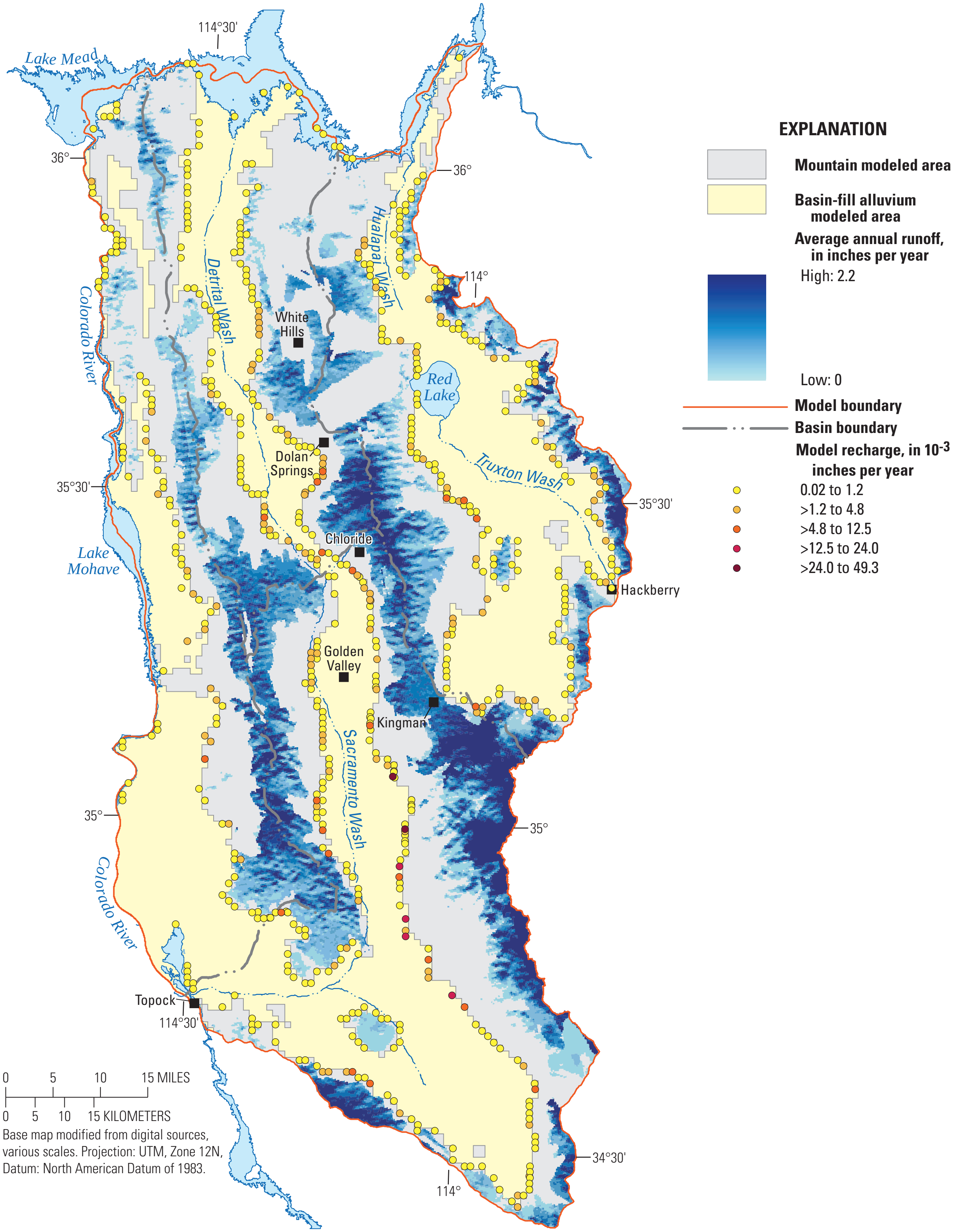


Figure 9. Map showing average annual in-place recharge estimated by the Basin Characterization Model (BCM) for the period 1940–2006.



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983.

Figure 10. Map showing average annual runoff estimated by the Basin Characterization Model (BCM) for the period 1940–2006, and model cells where the runoff was applied as recharge.

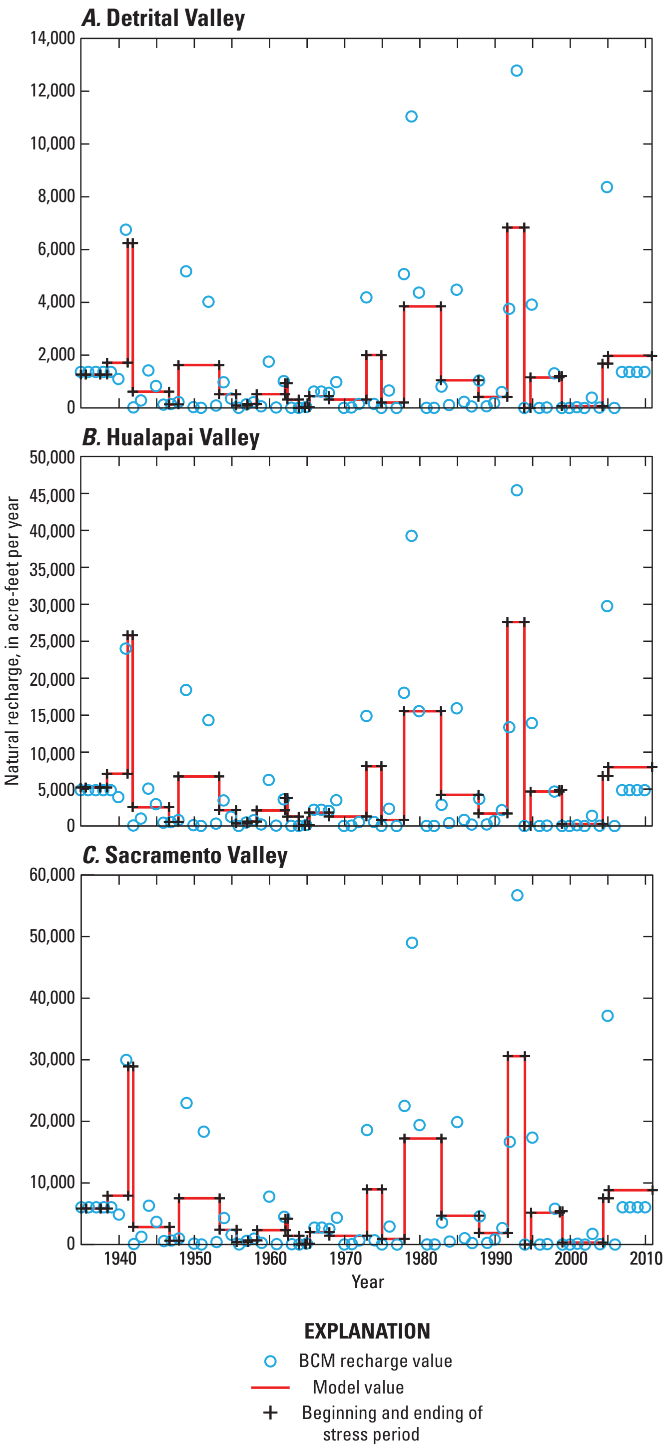


Figure 11. Plots showing natural recharge model input and scaled Basin Characterization Model (BCM) in-place-recharge values for *A* , Detrital; *B*, Hualapai; and *C*, Sacramento Valleys.

in the same locations, although both population and water use have increased through time. Incidental recharge from leaking water-supply lines was also distributed based on population density from 2000 census records (U.S. Census Bureau, 2010), but only within the Kingman urban-census blocks (fig. 12). Point locations for wastewater-treatment plant discharge (B.D. Garner, U.S. Geological Survey, written commun., 2011) were used for the location of incidental recharge from this source (fig. 12). Incidental recharge was simulated using the WEL package.

Groundwater Withdrawals

Groundwater is withdrawn in the study area for domestic, municipal, and industrial uses. Because groundwater supplies nearly all water needs in the study area, numerous wells have been drilled, including more than 3,300 wells within the Detrital, Hualapai, and Sacramento Valley Basins registered with the ADWR as of 2009 (Arizona Department of Water Resources, 2009b). Records for the amount and locations of groundwater withdrawals, however, are very limited for current conditions, and even more so for historical withdrawals. Simulated groundwater withdrawals in the transient model were based on historical groundwater withdrawals estimated by Garner and Truini (2011) and further details provided by B.D. Garner (U.S. Geological Survey, written commun., 2011). Municipal withdrawals for the City of Kingman occurred at Hackberry, near the City of Kingman in the Sacramento Valley, and near the City of Kingman in Hualapai Valley during different periods (figs. 13 and 14; table 5). Model-cell locations for these municipal withdrawals were estimated using well records from the ADWR Wells-55 database (Arizona Department of Water Resources, 2009b). Self-supplied domestic withdrawals were located in model cells on the basis of population density information from 2000 census blocks (U.S. Census Bureau, 2010; fig. 13). As with incidental recharge distribution, it was assumed that populated areas during current and historical periods were the same. Industrial withdrawals for Griffith Energy power production in Sacramento Valley were located on the basis of the ADWR Wells-55 database information (Arizona Department of Water Resources, 2009b; fig. 13). Groundwater withdrawals from Mineral Park Mine in Sacramento Valley, just southeast of Chloride (fig. 1), were not included in the transient simulations because accurate information was unavailable on the location or rate of withdrawals from this facility. According to the feasibility study for the mine, a new mill that began operation in late 2008 has a water demand of 16,000 acre-ft/yr and five wells were permitted and drilled in the vicinity of Mineral Park Mine with design pump capacities from 1,600 to 2,400 acre-ft/yr (H.R. Guenther, written commun., 2008). Information gathered recently by the USGS Arizona Water Science Center Water-Use Program, however, indicates that mine water needs are being met by Valley Pioneers Water Company at a rate around 5,000 acre-ft/yr (S. Tadayon, oral commun., 2012). Results from further investigation of the location and rate of water supply for the mine, if available, should be incorporated into future transient-model simulations.

Table 4. Incidental recharge for each stress period by source for the transient simulation model.

[Values are in acre-feet per year]

Stress period	Start/end dates	Hualapai Valley			Sacramento Valley		
		Wastewater-treatment plant	Leaking water-supply pipes	Septic-system discharge	Wastewater-treatment plant	Leaking water-supply pipes	Septic-system discharge
1	pre-dam to 01-01-1935	0	0	0	0	0	0
2	01-01-1935 to 09-01-1935	25	16	0	6	6	210
3	09-01-1935 to 08-01-1937	25	16	0	6	6	210
4	08-01-1937 to 07-01-1938	25	16	0	6	6	210
5	07-01-1938 to 04-01-1941	25	16	0	6	6	210
6	04-01-1941 to 12-01-1941	25	16	0	6	6	210
7	12-01-1941 to 10-01-1946	55	35	0	14	14	210
8	10-01-1946 to 01-01-1948	42	27	0	11	11	175
9	01-01-1948 to 06-01-1953	42	27	0	11	11	175
10	06-01-1953 to 09-01-1955	42	27	0	11	11	175
11	09-01-1955 to 03-01-1957	42	27	0	11	11	175
12	03-01-1957 to 06-01-1958	42	27	0	11	11	175
13	06-01-1958 to 03-01-1962	59	37	1,020	15	15	175
14	03-01-1962 to 07-01-1962	59	37	1,020	15	15	175
15	07-01-1962 to 01-01-1964	85	53	3,401	21	21	175
16	01-01-1964 to 11-01-1964	85	53	3,401	21	21	175
17	11-01-1964 to 06-01-1965	433	271	5,102	108	108	280
18	06-01-1965 to 01-01-1968	476	297	6,803	119	119	280
19	01-01-1968 to 01-01-1973	527	329	6,803	132	132	560
20	01-01-1973 to 01-01-1975	527	329	6,803	132	132	560
21	01-01-1975 to 01-01-1978	705	440	6,803	176	176	777
22	01-01-1978 to 12-01-1982	727	454	9,259	182	182	810
23	12-01-1982 to 12-01-1987	331	207	5,102	83	83	1,119
24	12-01-1987 to 10-01-1991	358	224	5,400	90	90	1,119
25	10-01-1991 to 01-01-1994	358	224	5,400	90	90	1,119
26	01-01-1994 to 11-01-1994	553	346	286	138	138	1,124
27	11-01-1994 to 09-01-1998	637	398	0	159	159	1,124
28	09-01-1998 to 01-01-1999	722	451	340	180	180	1,124
29	01-01-1999 to 06-01-2004	764	478	0	191	191	1,473
30	06-01-2004 to 03-01-2005	816	510	310	204	204	1,616
31	03-01-2005 to 12-31-2010	800	500	3,000	200	200	1,700

Groundwater withdrawals in the study area, reported by Garner and Truini (2011), were discretized into the 31 transient stress periods (table 5, fig. 14). The total simulated volume of groundwater withdrawal in Detrital, Hualapai, and Sacramento Valleys between 1935 and the end of 2010 was about 507,000 acre-ft.

Groundwater Observations Used in Model Calibration

Modeled hydraulic heads were compared with water-level observations in wells to evaluate the ability of the models to simulate historical groundwater conditions. Well and water-level data for the model area were obtained from the ADWR Groundwater Site Information (GWSI) database (Arizona Department of Water Resources, 2007). Spreadsheet tools developed by Tillman (2009) were employed to investigate water-level data, select wells for use in model calibration, and export water-level data in a GIS-compatible format. For steady-state predevelopment conditions, wells located within general areas of significant water-level change as presented in Anning and others (2007) were not used for calibration. Clusters of wells with similar water levels were also thinned (one or more wells removed) to facilitate parameter estimation in the UCODE program (Hill and Tiedeman, 2007). The resulting set of wells was then divided into three geographic areas: one for wells in basin-fill alluvium, one for wells in high-elevation-alluvium areas, and one for wells in mountainous areas. This process

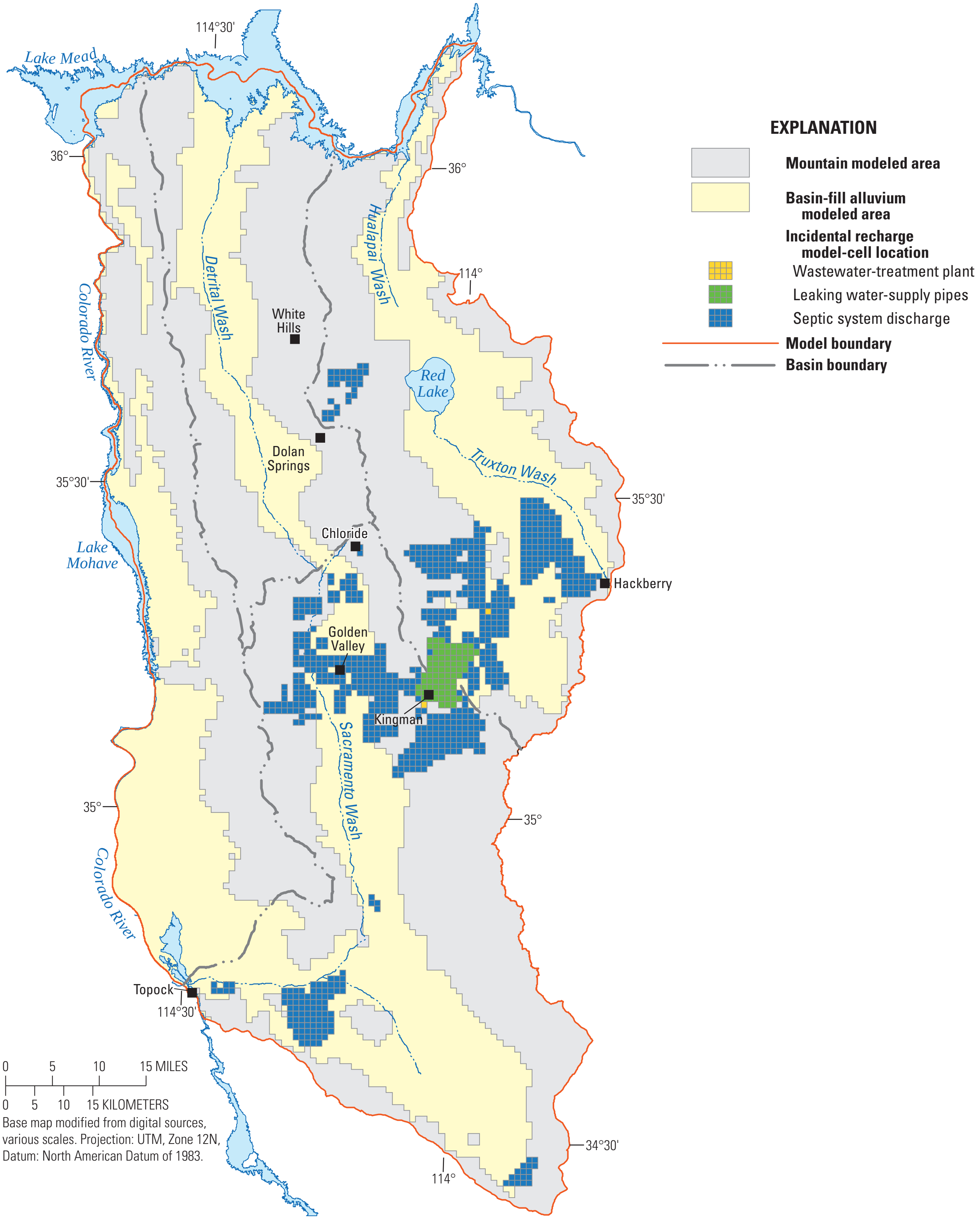


Figure 12. Map showing locations of model cells having incidental recharge in transient simulations. See table 4 for recharge rates by source for all stress periods.

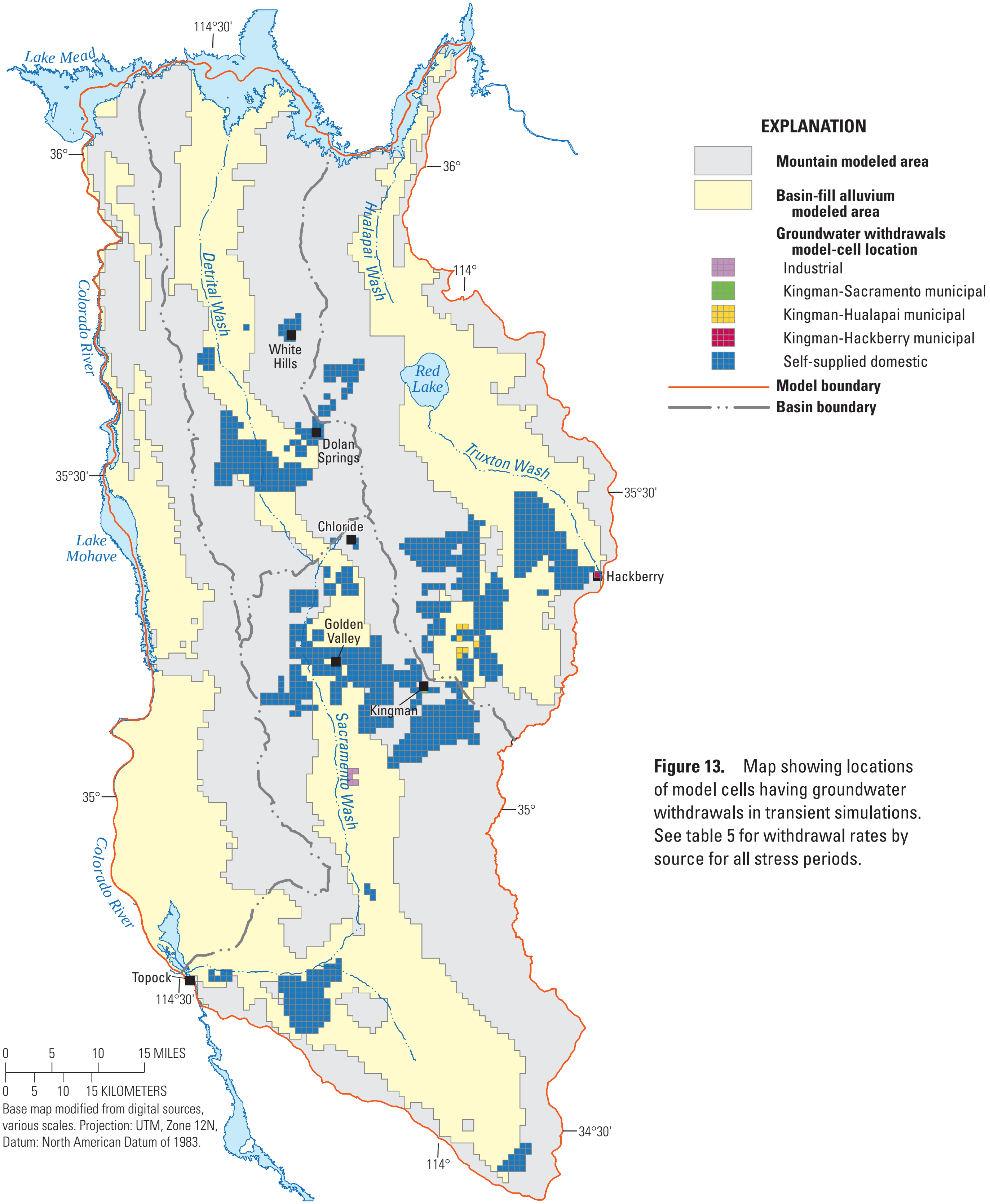


Figure 13. Map showing locations of model cells having groundwater withdrawals in transient simulations. See table 5 for withdrawal rates by source for all stress periods.

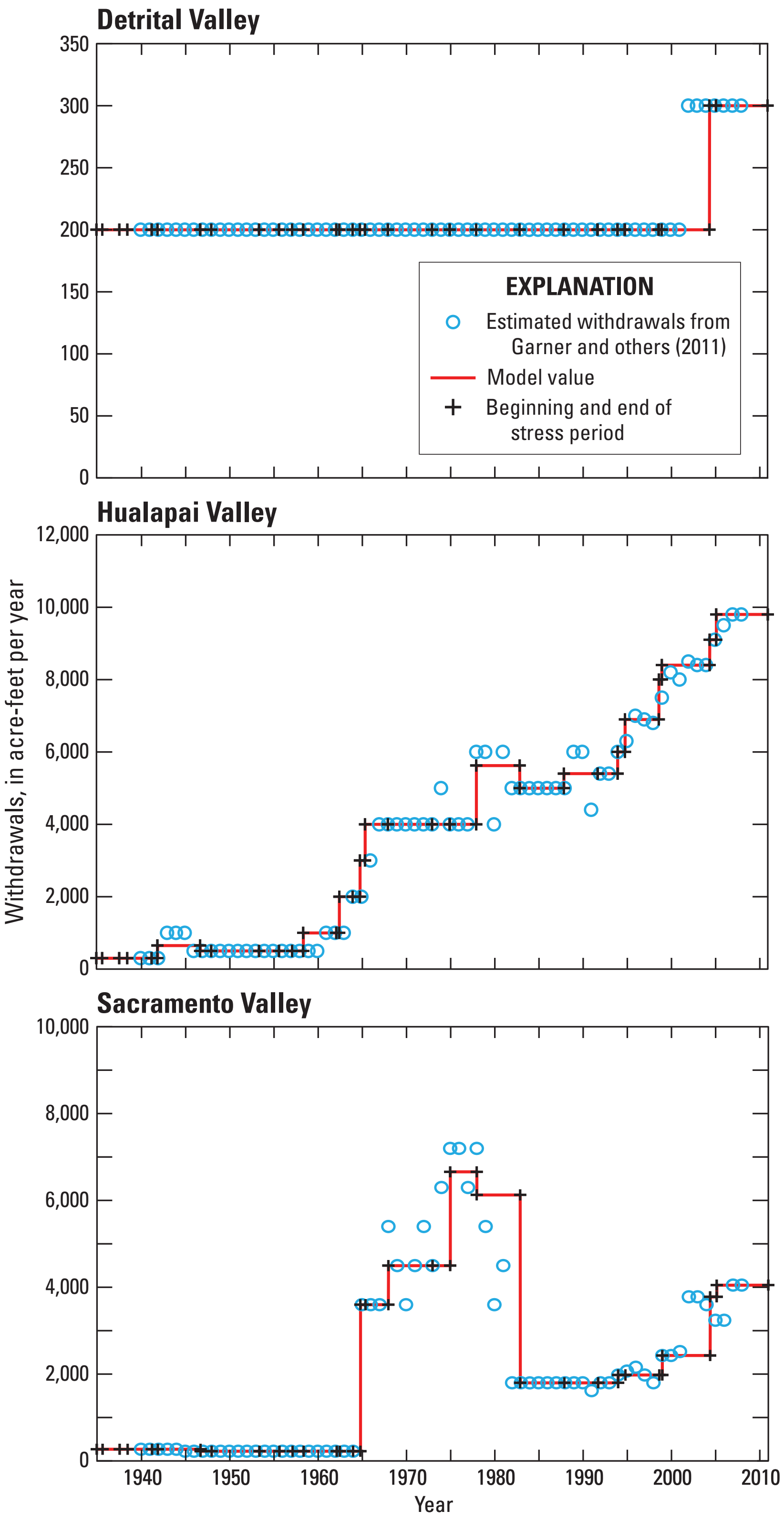


Figure 14. Plots showing simulated total groundwater withdrawals and values estimated by Garner and Truini (2011) for the study area.

resulted in 175 basin-fill alluvium water levels, 35 high-elevation-alluvium water levels, and 177 mountainous-area water levels (fig. 15). The earliest recorded observation for each of the basin-fill wells was used for model calibration. Because the range of earliest water-level observations spans many decades (fig. 16), these water levels may be expected to deviate from average conditions to varying degrees depending on when they were measured. Owing to concerns about the effect of the creation of Lake Mead on the single well with water-level observations available in northern Detrital Valley, water levels at locations called "control points" were used in this area instead (fig. 15). Water levels at these six control points were determined from predevelopment water-level contours published by Freethey and Anderson (1986). Because the locations were in areas outside the scope of this work, minimal effort was made to calibrate the steady-state models to high-elevation-alluvium and mountainous-area well data, and further work would be required to accurately model groundwater flow in these systems.

Records were analyzed for suitable wells in basin-fill alluvium with which to calibrate the transient model. Hydrographs from all wells in the ADWR's GWSI with at least four water-level observations were created and analyzed for dates of earliest and latest observation and number of observations in the period of record, among other criteria. The qualitative assessment of the hydrographs resulted in the selection of 32 basin-fill-alluvium wells in the study area with which to compare transient-model results (fig. 17).

Model Calibration

Simulated groundwater flow through a steady-state groundwater system is evaluated by comparing simulated hydraulic heads with water-level observations from wells and by comparing simulated aquifer discharge with known discharge. Because little is known about aquifer discharge from the model area to the Colorado River, and because no other significant natural-discharge sites exist, flows were not used to calibrate the groundwater-flow model; matching of water-level observations was the only criterion used. Calibration of the steady-state models to water-level observations was performed using a combination of trial and error (hand calibration) and UCODE_2005 (Poeter and others, 2005) within the ModelMate (Banta, 2011) interface. UCODE_2005 performs

Table 5. Groundwater withdrawals used in transient simulations, by source, for each stress period.

[Values are in acre-feet per year]

Stress period	Start/end dates	Detrital Valley	Hualapai Valley			Sacramento Valley		
		Self-supplied domestic	Self-supplied domestic	Kingman-Hackberry municipal	Kingman-Hualapai municipal	Self-supplied domestic	Kingman-Sacramento municipal	Industrial
1	pre-dam to 01-01-1935	0	0	0	0	0	0	0
2	01-01-1935 to 09-01-1935	200	0	300	0	300	0	0
3	09-01-1935 to 08-01-1937	200	0	300	0	300	0	0
4	08-01-1937 to 07-01-1938	200	0	300	0	300	0	0
5	07-01-1938 to 04-01-1941	200	0	300	0	300	0	0
6	04-01-1941 to 12-01-1941	200	0	300	0	300	0	0
7	12-01-1941 to 10-01-1946	200	0	650	0	300	0	0
8	10-01-1946 to 01-01-1948	200	0	500	0	250	0	0
9	01-01-1948 to 06-01-1953	200	0	500	0	250	0	0
10	06-01-1953 to 09-01-1955	200	0	500	0	250	0	0
11	09-01-1955 to 03-01-1957	200	0	500	0	250	0	0
12	03-01-1957 to 06-01-1958	200	0	500	0	250	0	0
13	06-01-1958 to 03-01-1962	200	300	700	0	250	0	0
14	03-01-1962 to 07-01-1962	200	300	700	0	250	0	0
15	07-01-1962 to 01-01-1964	200	1,000	1,000	0	250	0	0
16	01-01-1964 to 11-01-1964	200	1,000	1,000	0	250	0	0
17	11-01-1964 to 06-01-1965	200	1,500	1,500	0	400	3,600	0
18	06-01-1965 to 01-01-1968	200	2,000	2,000	0	400	3,600	0
19	01-01-1968 to 01-01-1973	200	2,000	2,000	0	800	4,200	0
20	01-01-1973 to 01-01-1975	200	2,000	2,000	0	800	4,200	0
21	01-01-1975 to 01-01-1978	200	2,000	2,000	0	1,110	6,290	0
22	01-01-1978 to 12-01-1982	200	2,720	90	2,810	1,160	5,650	0
23	12-01-1982 to 12-01-1987	200	1,500	100	3,400	1,600	400	0
24	12-01-1987 to 10-01-1991	200	1,590	90	3,730	1,600	400	0
25	10-01-1991 to 01-01-1994	200	1,590	90	3,730	1,600	400	0
26	01-01-1994 to 11-01-1994	200	80	100	5,820	1,610	590	0
27	11-01-1994 to 09-01-1998	200	0	100	6,800	1,610	590	0
28	09-01-1998 to 01-01-1999	200	100	100	7,800	1,610	590	0
29	01-01-1999 to 06-01-2004	200	0	80	8,320	2,110	590	0
30	06-01-2004 to 03-01-2005	300	90	90	8,920	2,310	590	1,300
31	03-01-2005 to 12-31-2010	300	880	100	8,820	2,430	500	1,580

parameter estimation by repeatedly running the groundwater-flow model, using adjusted parameter values for each run, and comparing model simulated output to observed values. The UCODE_2005 algorithm seeks to minimize the sum-of-squared-weighted residuals between observed and simulated values. UCODE_2005 was also used to investigate parameter sensitivity using composite scaled sensitivities (Hill, 1998). Composite scaled sensitivities incorporate the total amount of information obtained from observations for the estimation of a single parameter (Hill and Tiedeman, 2007). Composite scaled sensitivities of parameters can be compared relative to one another to indicate for which parameters the observations provide more information. The two steady-state models were calibrated for the study area investigating two scenarios of natural aquifer recharge from precipitation: scaled BCM-calculated in-place recharge, simulating mountain-block recharge; and scaled BCM-calculated runoff routed to basin-fill alluvium model cells, simulating mountain-front recharge. The transient groundwater-flow model used the hydraulic conductivities and hydraulic-head results from the calibrated steady-state, in-place recharge scenario model as conductivities and initial head conditions, respectively, although some adjustment of hydraulic conductivities was required for the transient model as discussed below. For the transient model, specific yields within hydraulic-conductivity parameter zones were adjusted using trial and error, and simulated water-level trends were compared with transient water-level observations.

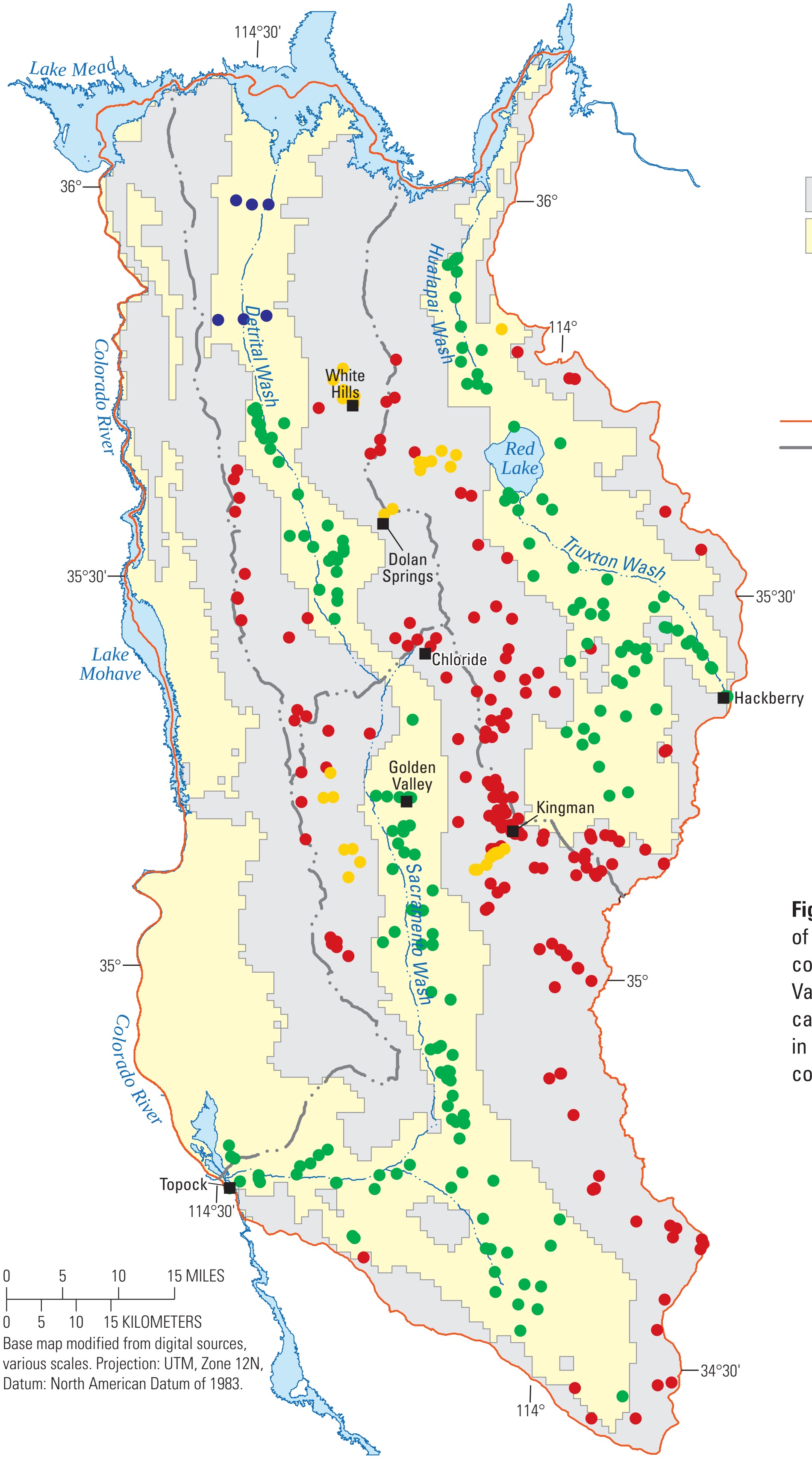


Figure 15. Map showing locations of wells in basin-fill alluvium and control points in northern Detrital Valley used for steady-state model calibration. Water levels in wells in other areas area shown for comparison.

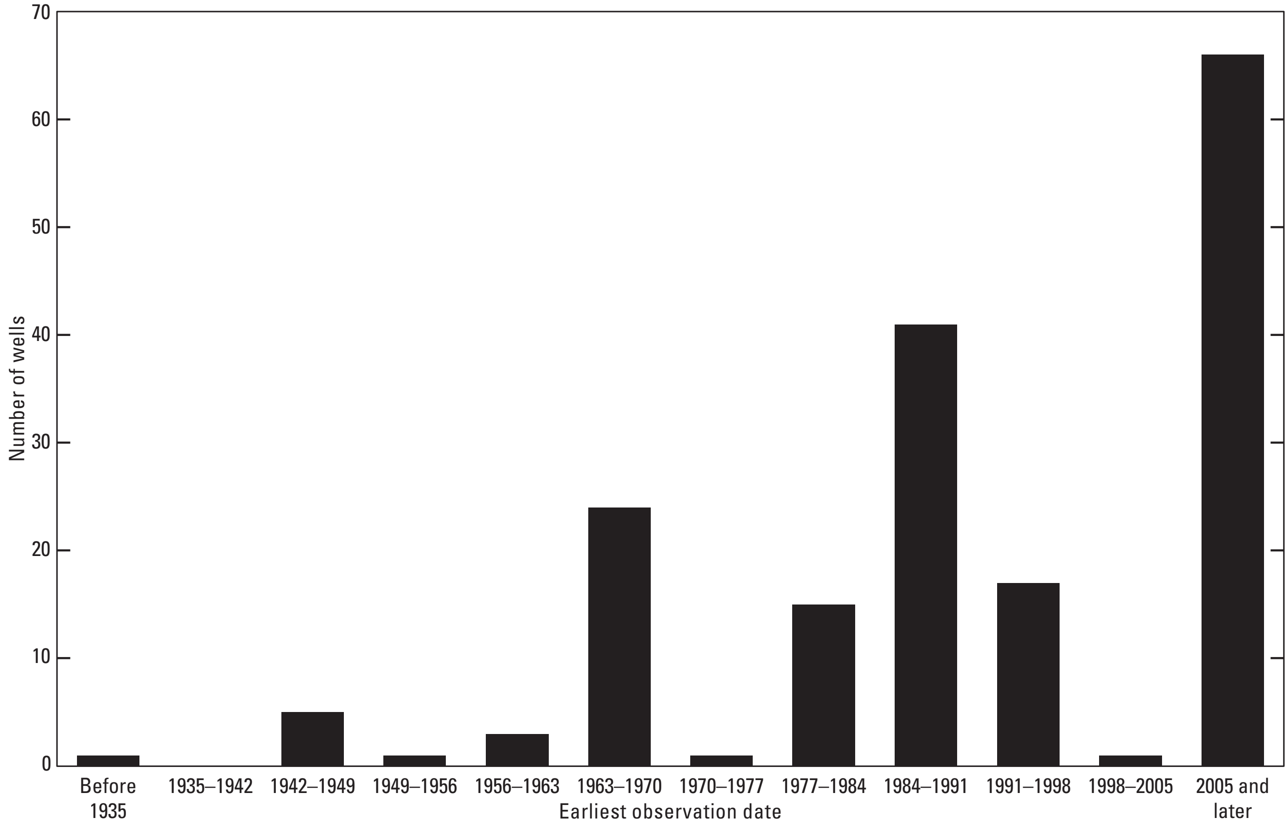


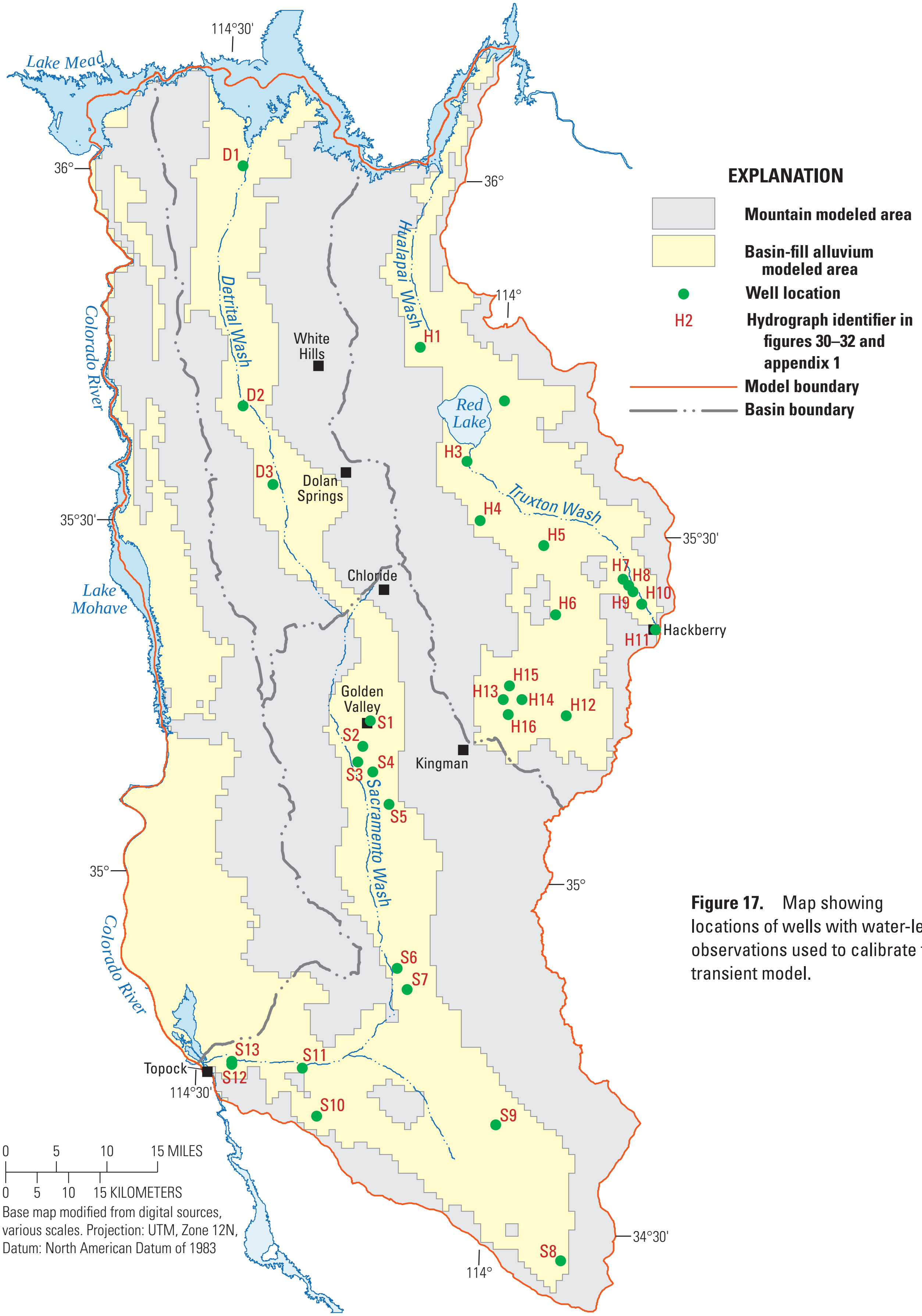
Figure 16. Bar graph showing dates of earliest water-level observation in basin-fill-alluvium wells used for calibrating the steady-state groundwater-flow models.

Aquifer Hydraulic Properties

Modeling groundwater flow in a steady-state groundwater system involves balancing inputs to the system (for example, natural recharge) and outputs from the system (for example, discharge) with flow through the system. The internal-flow packages of MODFLOW use a finite-difference numerical scheme to solve the groundwater-flow equation for hydraulic head at each model cell. As an interim step in this scheme, MODFLOW calculates hydraulic conductance (or just conductance) using transmissivities, which are themselves calculated as the product of hydraulic conductivity and saturated thickness (Harbaugh, 2005). The hydraulic conductivity of a porous media is its capacity to transmit water through a unit cross-sectional area (Heath, 1983), and transmissivity is the rate at which groundwater is transmitted through a unit width of aquifer under a unit hydraulic gradient. Because little is known about the depth of the groundwater-flow system in the basin-fill aquifers of the study area, an arbitrary elevation of -1,148 ft (-350 m) from mean sea level was used to define the bottom of the single-layer model. Hydraulic conductivity parameters in a single-layer, arbitrary-bottom model incorporate both the capacity of the media to transmit water and the thickness of the saturated deposits. Values that are seemingly low or high for a particular deposit or rock type also reflect the actual saturated depth at that location. For example, a hydraulic conductivity of 0.1 ft/d in a 1,000-ft saturated-depth area of a basin would yield a transmissivity equal to a hydraulic conductivity of 1 ft/d in a 100-ft saturated-depth area of a basin for the same simulated water level and sediment type.

For the transient model, aquifer storage properties must be defined to simulate the movement of water into and out of storage in pore spaces with variation in hydraulic head. The single-layer model presented here simulates a water-table aquifer using the MODFLOW “convertible layer” option; therefore specific yields are used in the model. A convertible layer in MODFLOW may become a confined layer if simulated water levels rise above the bottom of the layer above it, although this is not possible in the single-layer model described in this study.

Parameter zones were created in the model area within which hydraulic conductivities are assumed to be the same (fig. 18). The locations and dimensions of these zones were initially based on rock type in the mountainous areas of the model domain (Richard and others, 2000; Beard and others, 2011) and on lithologic information from saturated sediments in the basin-fill aquifers (fig. 5). The alluvial zones were subsequently subdivided as necessary to improve model fit, generally on the basis of depth to bedrock information (fig. 5) indicating a likely change in transmissivity. Mountainous



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983

Figure 17. Map showing locations of wells with water-level observations used to calibrate the transient model.

zones were also subdivided in places to achieve better qualitative match with known water levels, but additional information on fractures, faults, weathering, and saturated thickness of these rocks is required to effectively model groundwater flow in these areas. Parameter zones for mountainous areas were extended into basin-fill areas to include outcropping bedrock areas, high-elevation-alluvium areas, and thin alluvium (fig. 18). In northern Detrital Valley near Lake Mead, some alluvium zones incorporate areas of recent sedimentary rocks (figs. 3 and 5). No horizontal anisotropy was simulated throughout the model.

Simulation of Steady-State Conditions

As described in detail above, predevelopment steady-state groundwater-flow models were calibrated for two natural-recharge scenarios. In the first scenario, scaled BCM-calculated in-place recharge was the only natural aquifer recharge from precipitation simulated. BCM-calculated in-place recharge occurs almost exclusively in the high-elevation mountainous model cells (fig. 9). In scenario two, scaled BCM-calculated runoff was routed to basin-fill model cells where aquifer recharge occurs (fig. 10). A very small amount (about 100 acre-ft/yr) of in-place recharge was also applied to mountainous cells for model stability in the second recharge scenario.

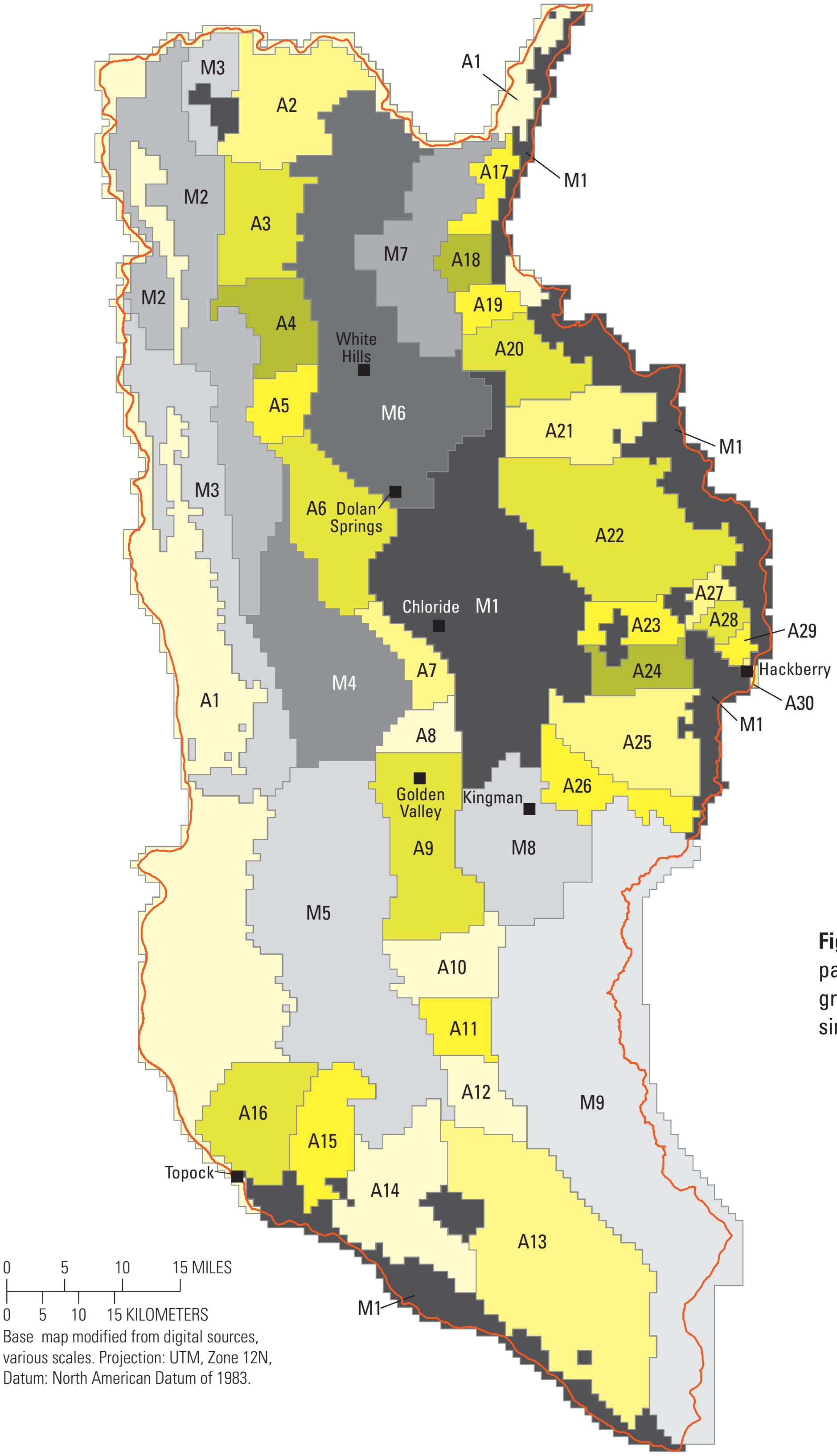
Steady-State Model with In-Place Recharge

Calibrated hydraulic conductivities for basin-fill alluvium parameter zones (fig. 18) in the in-place recharge model range from 0.02 to 13.1 ft/d (table 6). Hydraulic conductivities were low in zones covering areas of thin basin-fill including

Table 6. Basin-fill parameter zones for steady-state groundwater-flow simulations with calibrated hydraulic conductivity values.

[Parameter zone locations are shown in figure 18. Range of transmissivity values within each zone are computed as the product of saturated thickness and hydraulic conductivity; ft/d, feet per day; ft^2/d, square feet per day]

Parameter zone identifier	Steady-state model, recharge scenario 1				Steady-state model, recharge scenario 2			
	Hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)			Hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)		
		Minimum	Average	Maximum		Minimum	Average	Maximum
A1	2.62	4,145	4,662	9,133	4.10	6,476	7,185	14,226
A2	0.43	792	844	914	0.56	1,036	1,104	1,199
A3	0.19	399	451	512	0.26	562	635	721
A4	0.16	416	453	493	0.23	610	665	722
A5	0.26	814	835	858	1.57	4,933	4,974	5,015
A6	0.49	1,607	1,661	1,684	0.49	1,567	1,653	1,690
A7	0.02	60	69	75	0.02	58	69	78
A8	2.13	6,420	6,436	6,468	1.64	4,783	4,790	4,812
A9	0.49	1,400	1,442	1,484	1.64	4,662	4,731	4,784
A10	5.74	16,288	16,321	16,362	5.74	16,236	16,287	16,334
A11	0.49	1,301	1,355	1,394	0.66	1,712	1,795	1,855
A12	13.12	34,420	34,549	34,662	13.12	33,960	34,124	34,298
A13	0.33	788	850	879	0.52	1,264	1,316	1,359
A14	2.62	5,768	6,155	6,347	2.62	5,725	6,154	6,328
A15	0.49	816	919	1,103	0.59	982	1,104	1,317
A16	7.22	11,537	11,752	11,908	7.22	11,525	11,764	11,953
A17	1.89	4,020	5,234	5,844	1.38	2,852	3,797	4,269
A18	0.72	2,227	2,349	2,465	0.54	1,669	1,763	1,851
A19	2.95	10,120	10,225	10,288	2.95	10,130	10,210	10,257
A20	3.77	13,139	13,287	13,431	3.94	13,672	13,784	13,893
A21	0.82	2,912	2,961	2,998	0.54	1,908	1,945	1,977
A22	9.84	35,924	36,030	36,108	21.33	77,889	77,984	78,053
A23	9.84	36,086	36,121	36,159	2.30	8,404	8,424	8,451
A24	0.12	459	476	488	0.08	302	314	323
A25	1.31	5,135	5,163	5,187	0.66	2,571	2,593	2,602
A26	0.02	65	68	75	0.05	195	198	212
A27	0.98	3,611	3,623	3,636	0.13	481	493	505
A28	0.05	182	191	200	0.08	309	323	334
A29	0.66	2,671	2,688	2,702	0.98	4,013	4,030	4,046
A30	0.08	343	369	381	0.08	343	373	386



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983.

Figure 18. Map showing parameter zones for groundwater-flow-model simulations.

just east of Kingman (zone A26), the groundwater divide between Detrital and Sacramento Valleys near Chloride (zone A7) and along the Truxton Wash channel downgradient from Hackberry (zones A28 and A30; fig. 18). Conductivities were highest just upgradient of the western bend in basin fill in Sacramento Valley (zone A12) and in the parameter zones overlying the 2.7-mi-deep parts of the Hualapai Valley near Red Lake (zones A22 and A23; fig. 5). Mountainous-area parameter zones have hydraulic conductivities that are mostly an order of magnitude lower than the lowest basin-fill value (table 7). The lowest conductivities for mountainous areas are in the Black Mountain crystalline and volcanic rock (table 7; figs. 2 and 3). High relative conductivity is found in sedimentary and volcanic rocks of White Hills and in the crystalline rocks of the Hualapai Mountains (table 7; figs. 2 and 3).

The direction of simulated groundwater flow is from high-elevation recharge areas toward valley floors (figs. 19 and 20). Simulated groundwater flow then moves northward to the Colorado River in both Detrital and Hualapai Valleys, and southward/southwestward toward the Colorado River in Sacramento Valley, similar to the conceptual model described in Anning and others (2007). In nearly all areas, simulated groundwater recharge mounds occur in mountainous regions, indicating that little interbasin groundwater flows across bedrock areas. The only exception occurs in the area just to the west of the 1,500-ft control points in Detrital Valley (fig. 19), where a simulated hydraulic gradient between Detrital Valley and the Lake Mohave Basin is evident. For groundwater to flow from Detrital Valley Basin to the Lake Mohave Basin, however, a connected hydraulic pathway must also exist, and no data at present indicate whether or not such a pathway exists. Simulated groundwater levels in basin-fill alluvium fit observed groundwater levels in wells with a mean absolute error of 32 ft (fig. 21*A*). Mean absolute error of model fit for individual basins was 15 ft for Detrital Valley, 36 ft for Hualapai Valley, and 36 ft for Sacramento Valley. The residuals, calculated as the measured groundwater level minus the simulated water level, appear to be fairly normally distributed for most wells in all three basins (fig. 21*B*). Most of the larger residuals are located in the upgradient end of Hualapai Valley Basin near Hackberry in a narrow area of steep hydraulic-head gradient, and in the downgradient area of Sacramento Valley (fig. 22). As described above, minimal effort was made to calibrate the high-elevation-alluvium and mountainous-area parameter zones (fig. 23), and so further work would be required to accurately simulate groundwater flow in these areas.

Table 7. Parameter zones in mountainous areas for steady-state groundwater-flow simulations and calibrated hydraulic conductivity values.

[Parameter zone locations are shown in figure 18; ft/d, feet per day]

Parameter zone identifier	Hydraulic conductivity (ft/d)	
	Steady-state model recharge scenario 1	Steady-state model recharge scenario 2
M1	2.95E-03	1.82E-05
M2	1.64E-04	9.84E-06
M3	3.28E-04	6.56E-06
M4	1.64E-04	6.56E-07
M5	8.20E-04	4.92E-06
M6	1.64E-03	4.92E-06
M7	6.56E-04	2.62E-06
M8	8.20E-04	3.28E-06
M9	1.31E-02	6.56E-05

Composite scaled sensitivities of basin-fill alluvial parameter zones to alluvium water levels computed by UCODE indicate that the most sensitive hydraulic conductivity zone for the in-place-recharge scenario final values is parameter zone A17, which delineates the fairly shallow discharge area of Hualapai Valley Basin (table 8; fig. 18). Zone A15 near the outflow of Sacramento Valley was also relatively sensitive to basin-fill alluvium water-level observations (table 8). Relatively insensitive zones include A8 and A10 near the upgradient end of Sacramento Valley Basin, A23 in Hualapai Valley near Long Mountain (fig. 2), and A27 and A29 along Truxton Wash (table 8; fig. 18).

Simulated groundwater-budget components for the steady-state model include inflow to the groundwater system from natural recharge, flow from adjacent basins, and inflow at Truxton Wash (for Hualapai Valley). Groundwater outflows occur to adjacent valleys and to the Colorado River. The most natural recharge occurs in Hualapai and Sacramento Valleys, both receiving more than 5,000 acre-ft/yr (table 9).

Steady-State Model with Runoff as Recharge

For the runoff-recharge scenario, with mountain-generated runoff routed to alluvium model cells, calibrated hydraulic conductivities for basin-fill alluvium parameter zones (fig. 18) range from 0.02 to 21.3 ft/d (table 6). Hydraulic conductivities were low in zones covering areas of thin basin-fill, including the groundwater divide between Detrital and Sacramento Valleys near Chloride (zone A7), just east of Kingman (zones A26 and A24), and the Truxton Wash channel downgradient from Hackberry (zones A27, A28, and A30; fig. 18). Conductivities were highest near the 2.7 mi-deep part of the Hualapai Valley near Red Lake (zone A22), just upstream of Dutch Flat in Sacramento Valley (zone A12), and at the outflow of Sacramento Valley Basin (zone A16; table 6). Calibrated hydraulic conductivities for basin-fill-alluvium parameter zones for both recharge scenarios were similar; all but six conductivities were within a factor of 2 or less (table 6). The greatest percentage differences in calibrated conductivities between the in-place and runoff-recharge scenarios occurred

Table 8. Composite scaled sensitivities for basin-fill alluvium parameter zones to alluvium water levels for steady-state groundwater-flow simulations.

[Parameter zone locations are shown in figure 18]

Parameter zone identifier	Steady-state model, recharge scenario 1		Steady-state model, recharge scenario 2	
	Composite scaled sensitivity	Ratio to maximum	Composite scaled sensitivity	Ratio to maximum
A1	11.54	0.111	11.76	0.086
A2	13.53	0.131	21.23	0.155
A3	29.46	0.284	43.50	0.317
A4	27.39	0.264	45.26	0.330
A5	8.28	0.080	2.85	0.021
A6	6.02	0.058	18.23	0.133
A7	10.96	0.106	13.59	0.099
A8	0.31	0.003	9.28	0.068
A9	9.52	0.092	7.77	0.057
A10	0.72	0.007	3.06	0.022
A11	16.82	0.162	23.15	0.169
A12	1.50	0.014	9.96	0.073
A13	28.17	0.272	32.93	0.240
A14	19.41	0.187	37.41	0.273
A15	65.41	0.631	89.43	0.653
A16	4.29	0.041	18.89	0.138
A17	103.63	1.000	137.03	1.000
A18	43.66	0.421	54.43	0.397
A19	7.05	0.068	11.37	0.083
A20	8.79	0.085	10.59	0.077
A21	12.38	0.119	19.74	0.144
A22	1.82	0.018	8.37	0.061
A23	0.46	0.004	3.87	0.028
A24	19.99	0.193	17.10	0.125
A25	2.12	0.020	9.62	0.070
A26	26.30	0.254	6.04	0.044
A27	0.83	0.008	13.98	0.102
A28	11.93	0.115	14.24	0.104
A29	1.16	0.011	7.14	0.052
A30	9.81	0.095	20.90	0.153

Table 9. Simulated predevelopment groundwater budget for in-place-recharge scenario.

[Values are in acre-feet per year; –, no data]

Water-budget component	Detrital Valley	Hualapai Valley	Sacramento Valley
Inflow from natural recharge	1,270	5,230	5,870
Inflow from adjacent valleys	500	640	1,640
Inflow at Truxton Wash (Hualapai Valley only)	–	800	–
Net outflow to Colorado River	1,400	5,940	2,130
Outflow to adjacent valleys	370	740	[1]5,380

[1] Outflow from Sacramento Valley to Lake Mohave Basin discharges to Topock Marsh and the Colorado River near Topock.

in zone A27 along Truxton Wash in Hualapai Valley, where the in-place recharge value of 0.98 ft/d was larger than the 0.13 ft/d value for the runoff-recharge model, and in zone A5 in Detrital Valley, where the runoff-recharge value of 1.57 ft/d is larger than the in-place recharge value of 0.26 ft/d.

Mountainous-area parameter zones were initially assigned hydraulic conductivities two orders of magnitude lower than those for the in-place recharge model. This reduction in mountain conductivities was required because very little recharge occurs in mountainous areas in the second recharge scenario (about 100 acre-ft/yr total in all three basins), and nearly all recharge is routed to alluvium model cells. Some minor adjustments in mountainous-area parameter zone values were made during calibration to qualitatively improve model fit in mountainous areas (table 7; fig. 2).

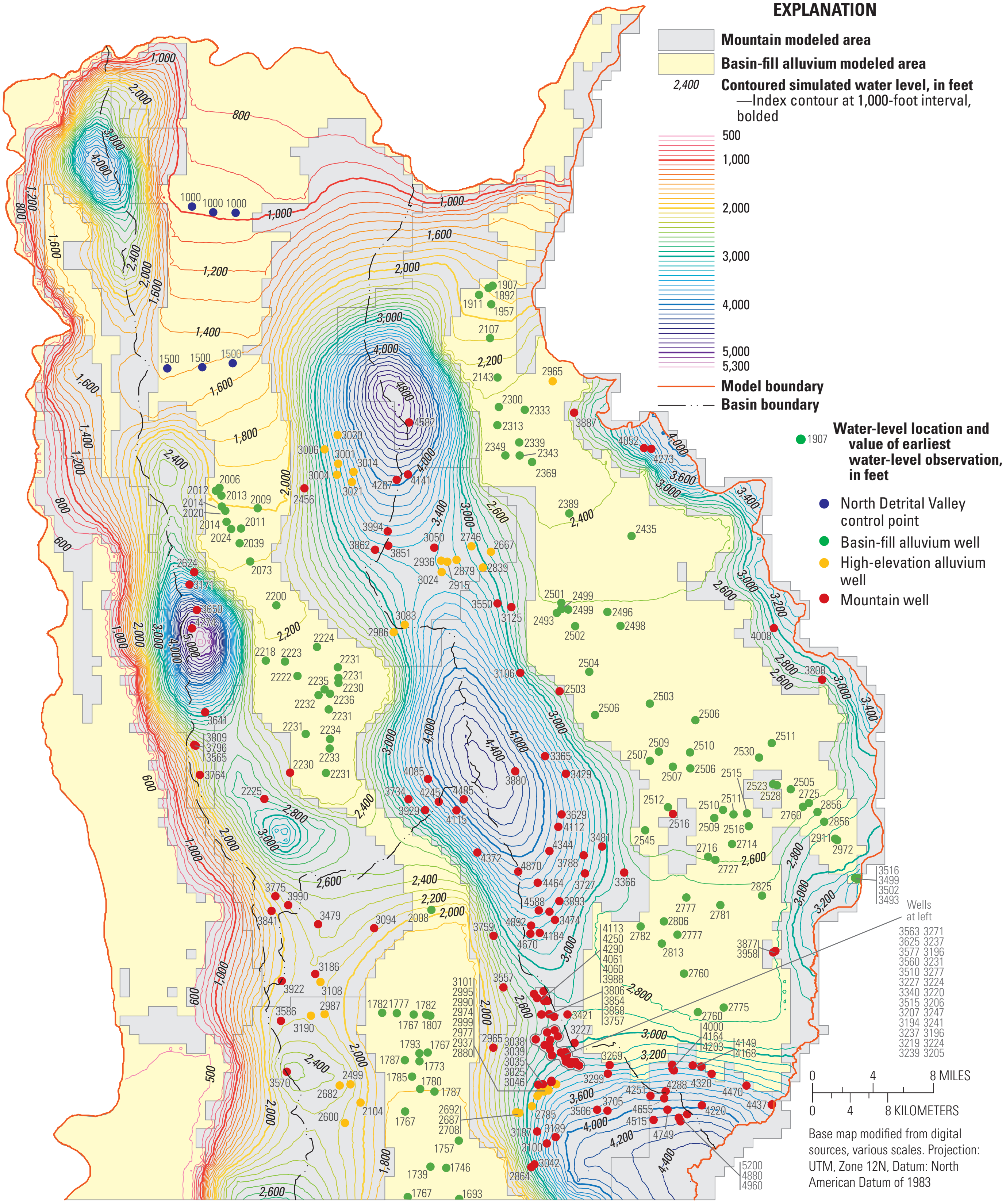


Figure 19. Map showing detail of northern part of study area showing steady-state model results for in-place-recharge scenario and earliest water-level observations for wells in the Detrital and Hualapai Valley Basins.

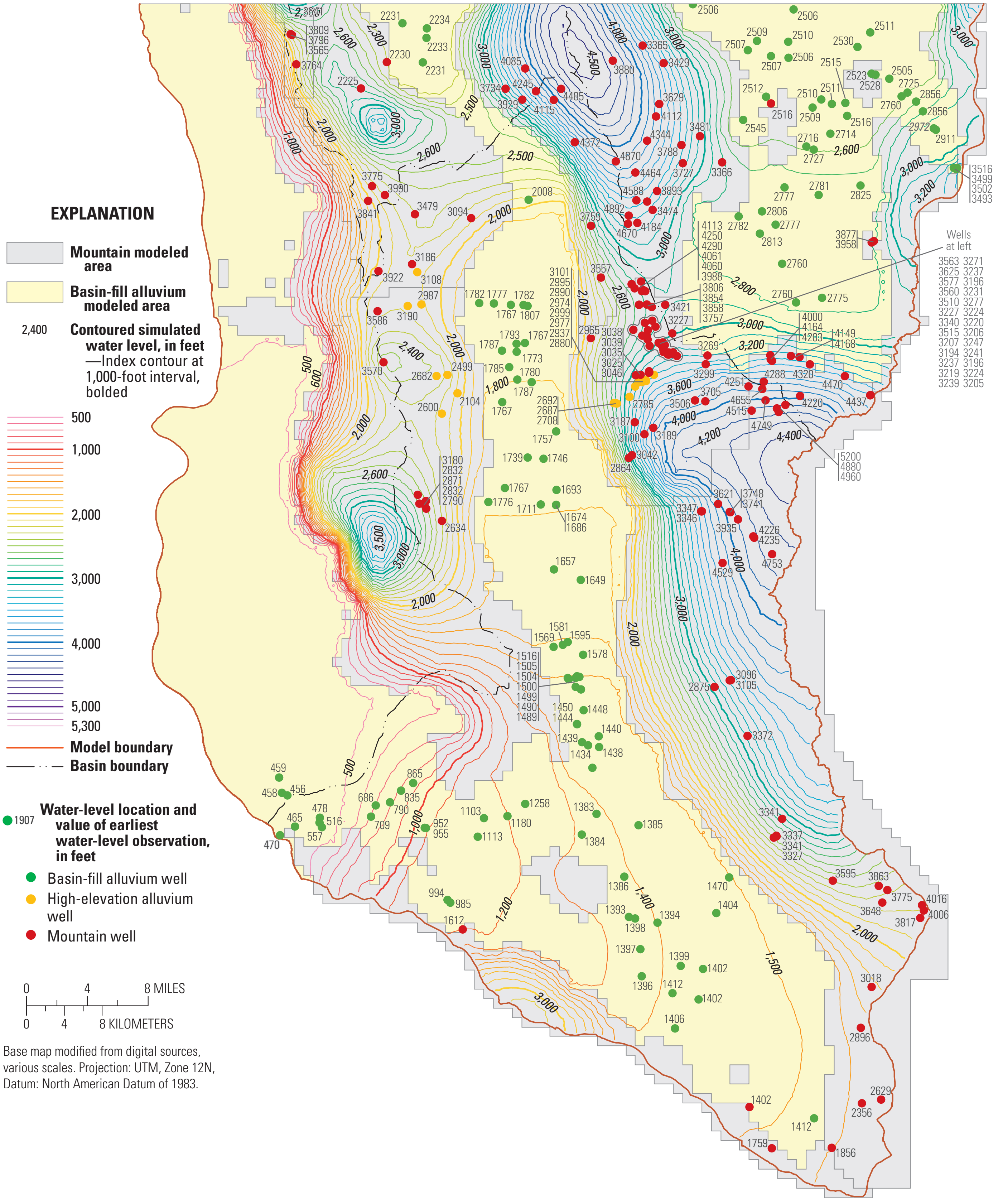


Figure 20. Map showing detail of southern part of study area showing steady-state model results for in-place-recharge scenario and earliest water-level observations for wells in the Sacramento Valley Basin.

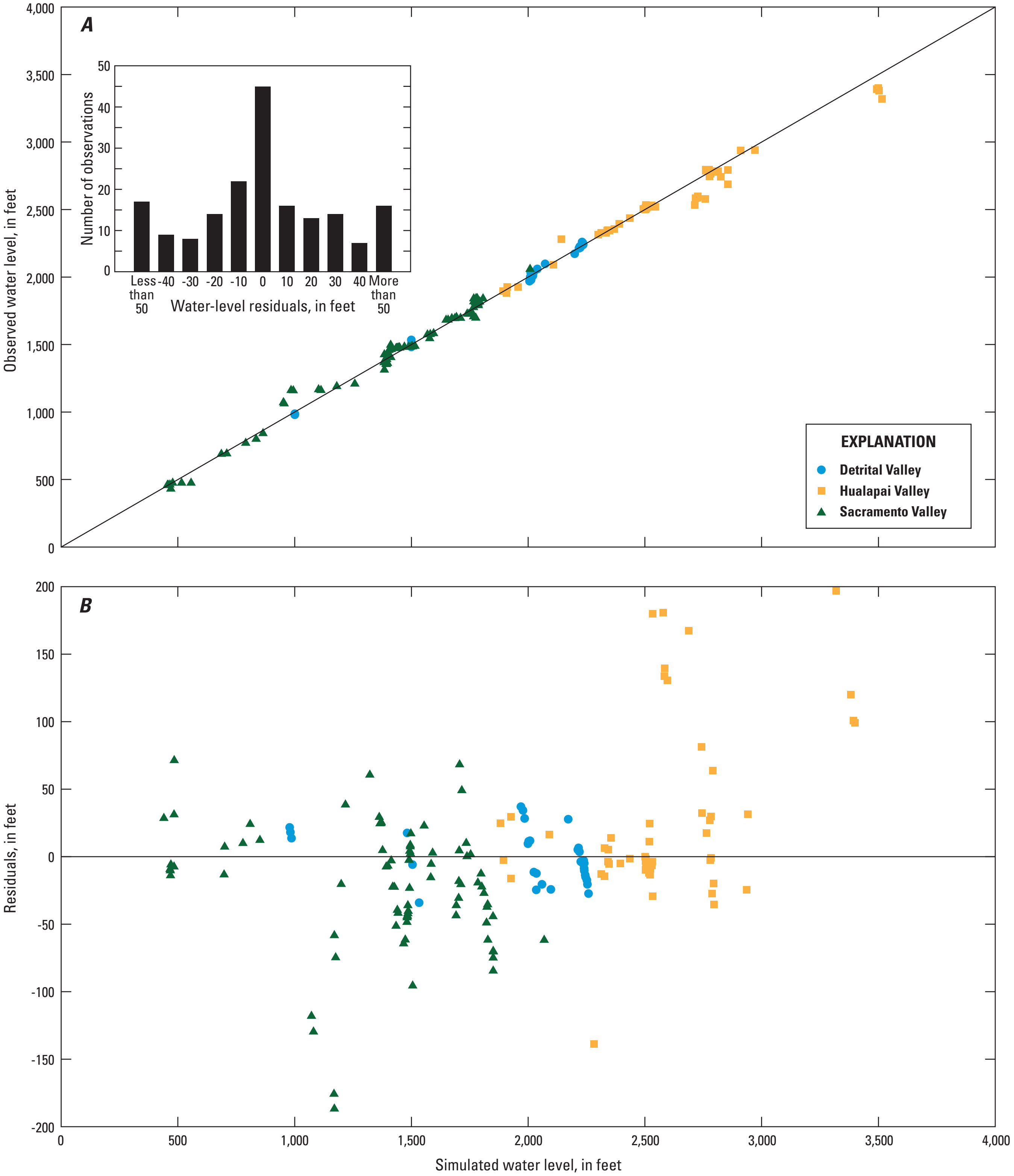
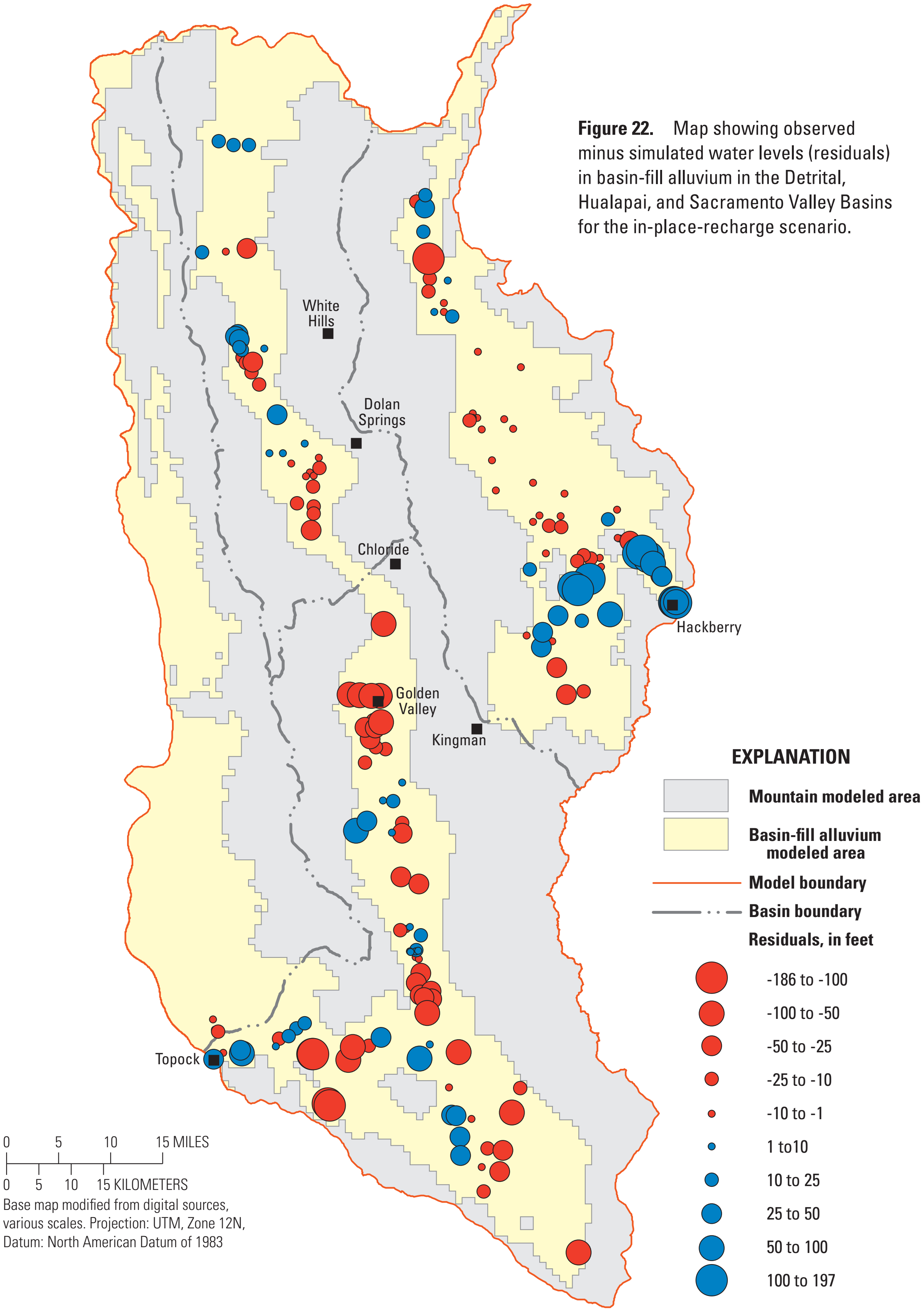


Figure 21. Scatter plots showing observed against simulated water levels (*A*) with bar graph showing distribution of the magnitude of water-level residuals (*A*, inset) and scatter plot showing water-level residuals against simulated water levels (*B*) for basin-fill alluvium in the Detrital, Hualapai, and Sacramento Valley Basins for in-place-recharge scenario.

Figure 22. Map showing observed minus simulated water levels (residuals) in basin-fill alluvium in the Detrital, Hualapai, and Sacramento Valley Basins for the in-place-recharge scenario.



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983

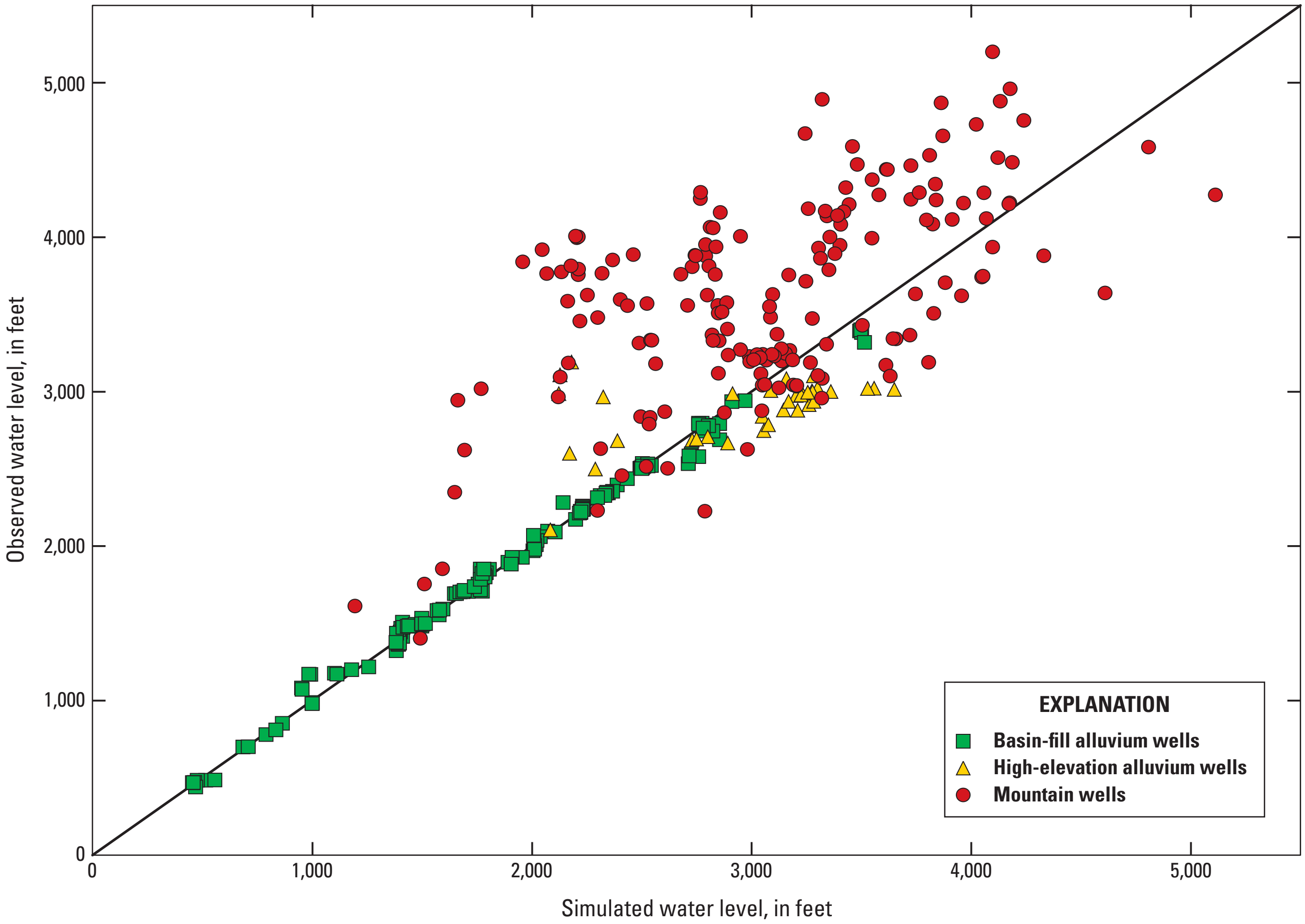


Figure 23. Scatter plot showing observed against simulated water levels for all areas in the Detrital, Hualapai, and Sacramento Valley Basins for in-place-recharge scenario.

The direction of simulated groundwater flow in the runoff-recharge scenario is the same as for the in-place recharge model: from recharge areas (along basin-fill margins for the second scenario) toward valley floors, and then along valley floors to discharge areas along the Colorado River (figs. 24 and 25). As with the in-place recharge model, simulated groundwater recharge mounds occur in most of the mountainous regions, indicating a limited potential for interbasin groundwater flow across bedrock areas. The area of western Detrital Valley where groundwater gradients may permit flow to Lake Mohave Basin is even larger in the runoff-recharge scenario than in the in-place recharge scenario, existing along much of the length of the Black Mountains (fig. 24). Simulated groundwater levels in basin-fill alluvium fit observed groundwater levels in wells with a mean absolute error of 32 ft (fig. 26*A*). Mean absolute error of model fit for individual basins was 18 ft for Detrital Valley, 32 ft for Hualapai Valley, and 38 ft for Sacramento Valley. Residuals appear to be somewhat less normally distributed than for the in-place recharge scenario for all three basins (fig. 26*B*), with a slight negative skew. As with the in-place recharge scenario, most of the larger residuals are located in the upgradient end of Hualapai Valley basin in the steep hydraulic-gradient area near Hackberry, and near the discharge of Sacramento Valley (fig. 27). Similar to the in-place-recharge scenario, additional work would be required to accurately simulate groundwater flow in mountainous areas (fig. 28).

Composite scaled sensitivities of basin-fill alluvial parameter zones to alluvium water levels computed by UCODE indicate that the most sensitive hydraulic conductivity zones for the runoff-recharge scenario final values are the same as for the in-place recharge scenario, and have similar sensitivities relative to the maximum (table 8). The most sensitive parameter zones for both scenarios are A17, which delineates the fairly shallow discharge area of Hualapai Valley Basin, and A15 near the outflow of Sacramento Valley (table 8; fig. 18). Hydraulic conductivity in parameter zones at discharge locations controls the hydraulic head in all upgradient areas that flow through their location. The relatively insensitive zones for the runoff-recharge scenario were significantly more sensitive than those in the in-place recharge scenario (table 8), probably owing to the greater areal distribution of recharge in the second scenario than in the first scenario (fig. 10).

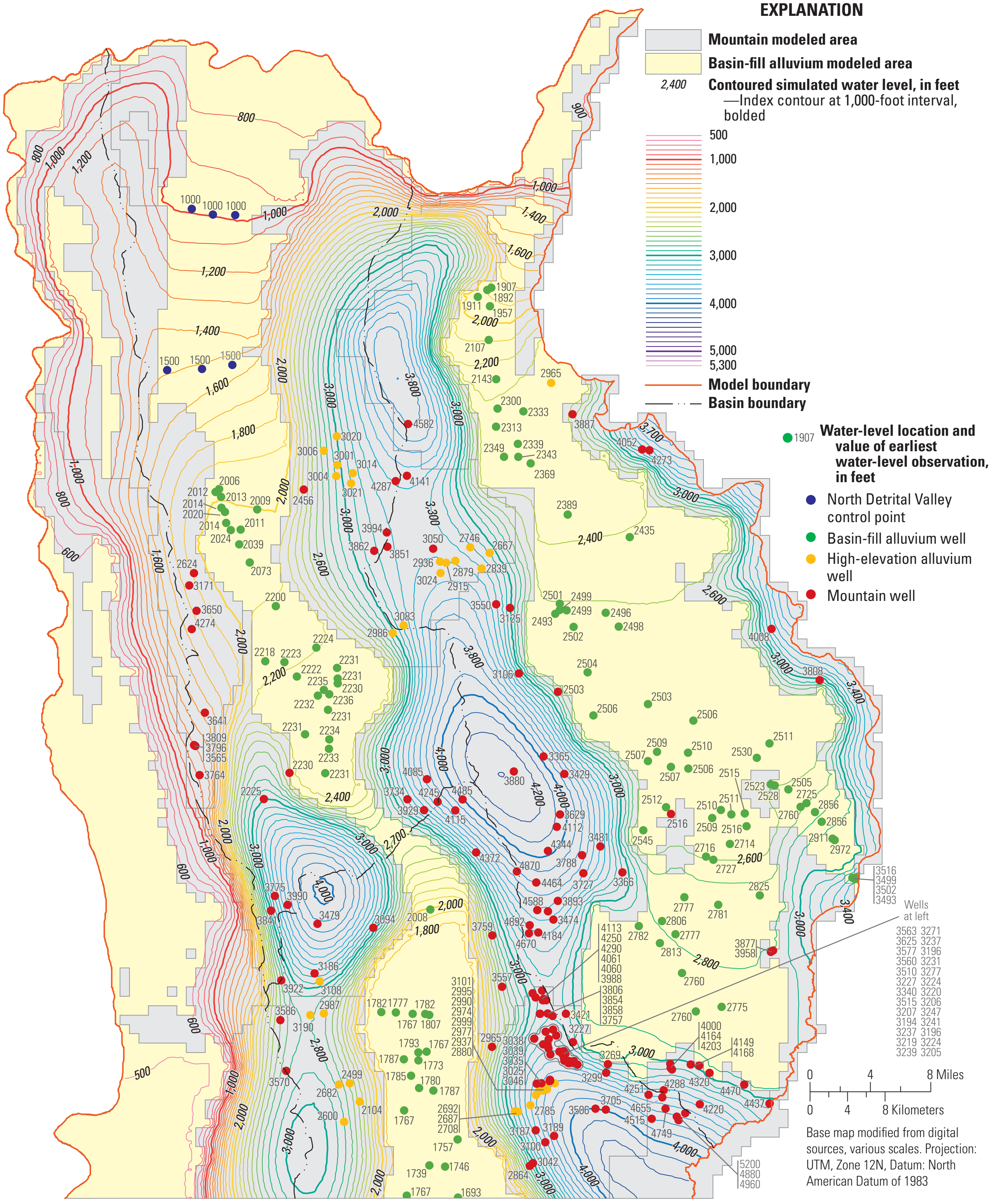
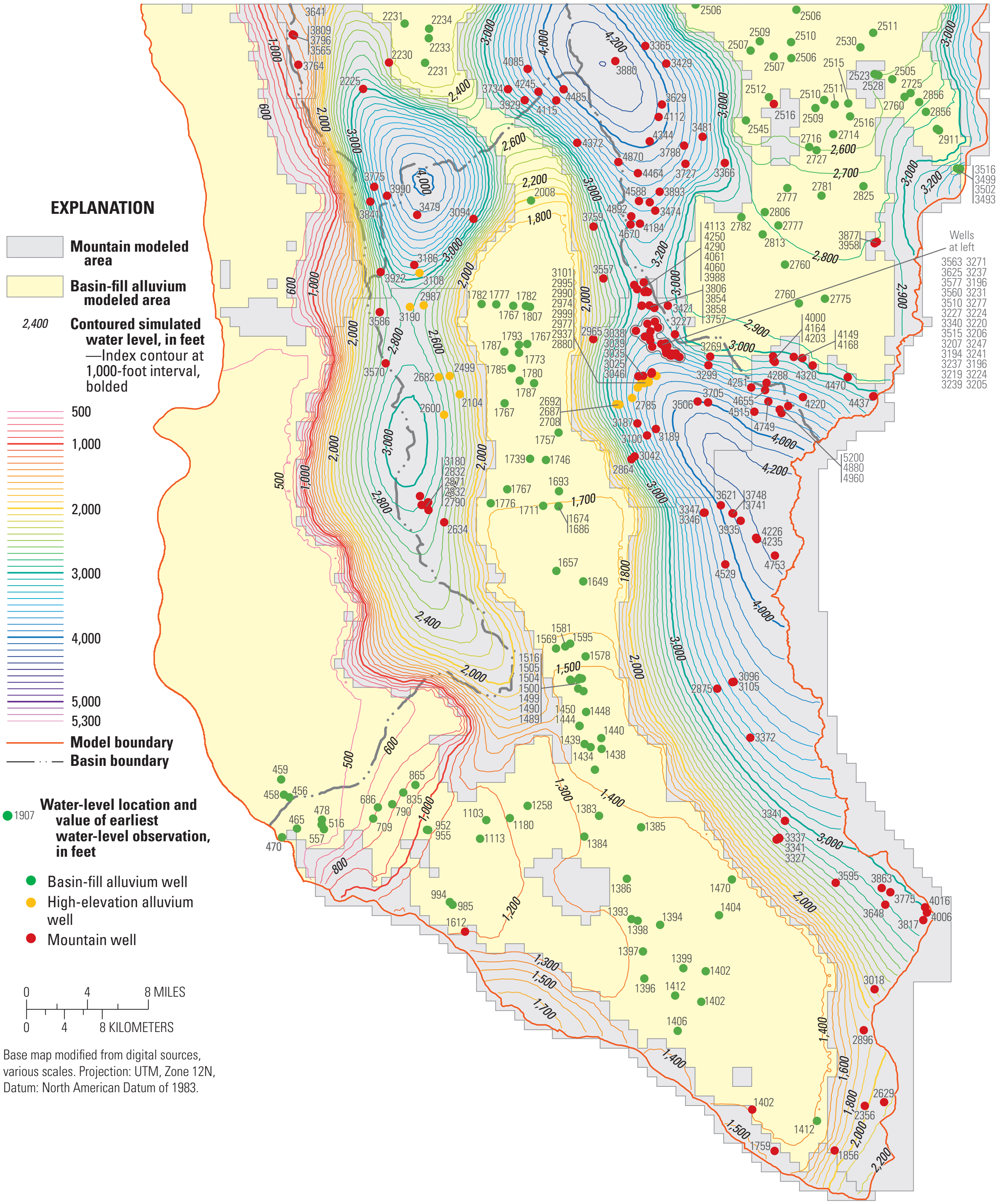


Figure 24. Map showing detail of northern part of study area showing steady-state model results for runoff-recharge scenario and earliest water-level observations for wells in the Detrital and Hualapai Valley Basins.



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983.

Figure 25. Map showing detail of southern part of study area showing steady-state model results for runoff-recharge scenario and earliest water-level observations for wells for Sacramento Valley Basin.

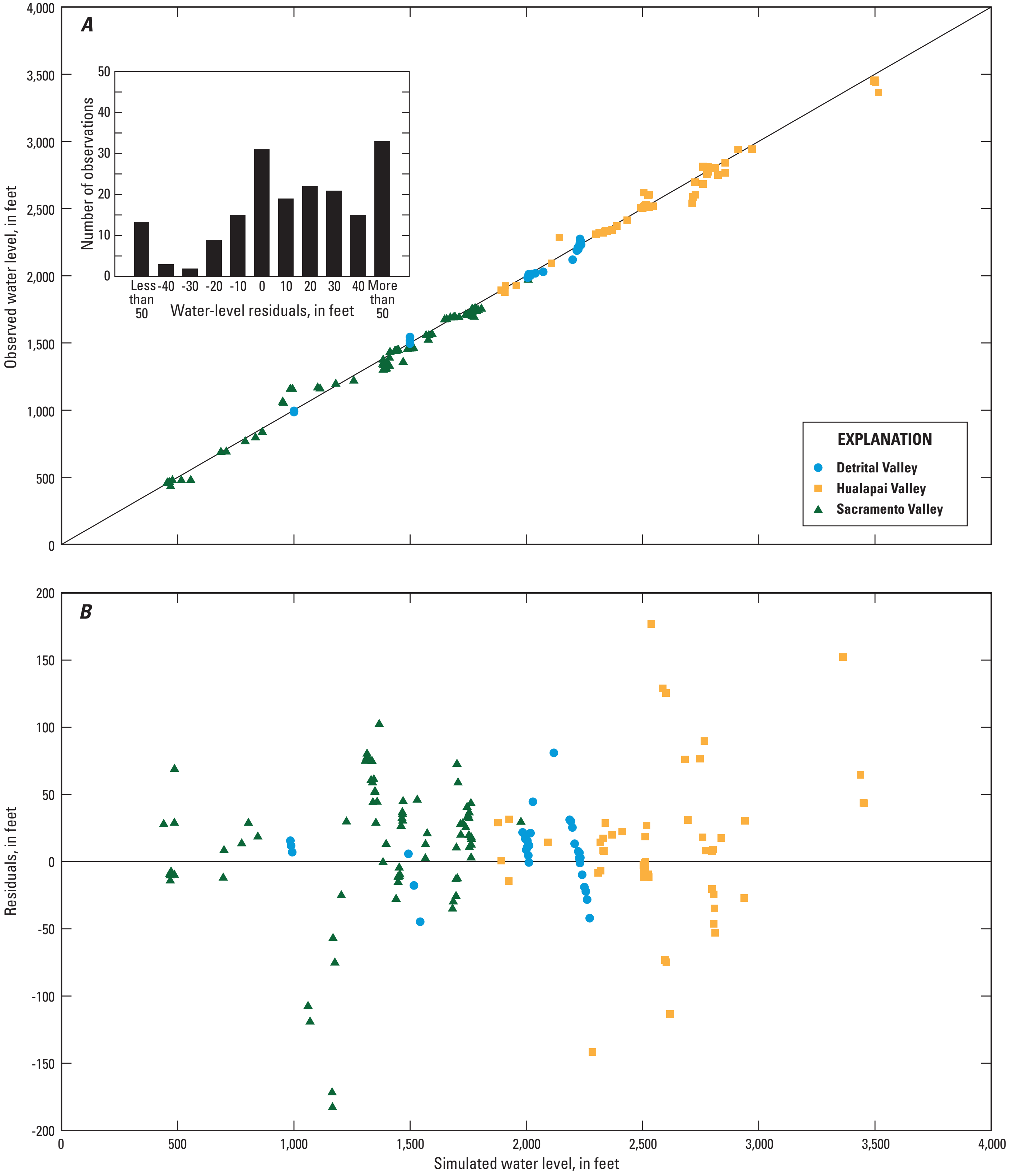
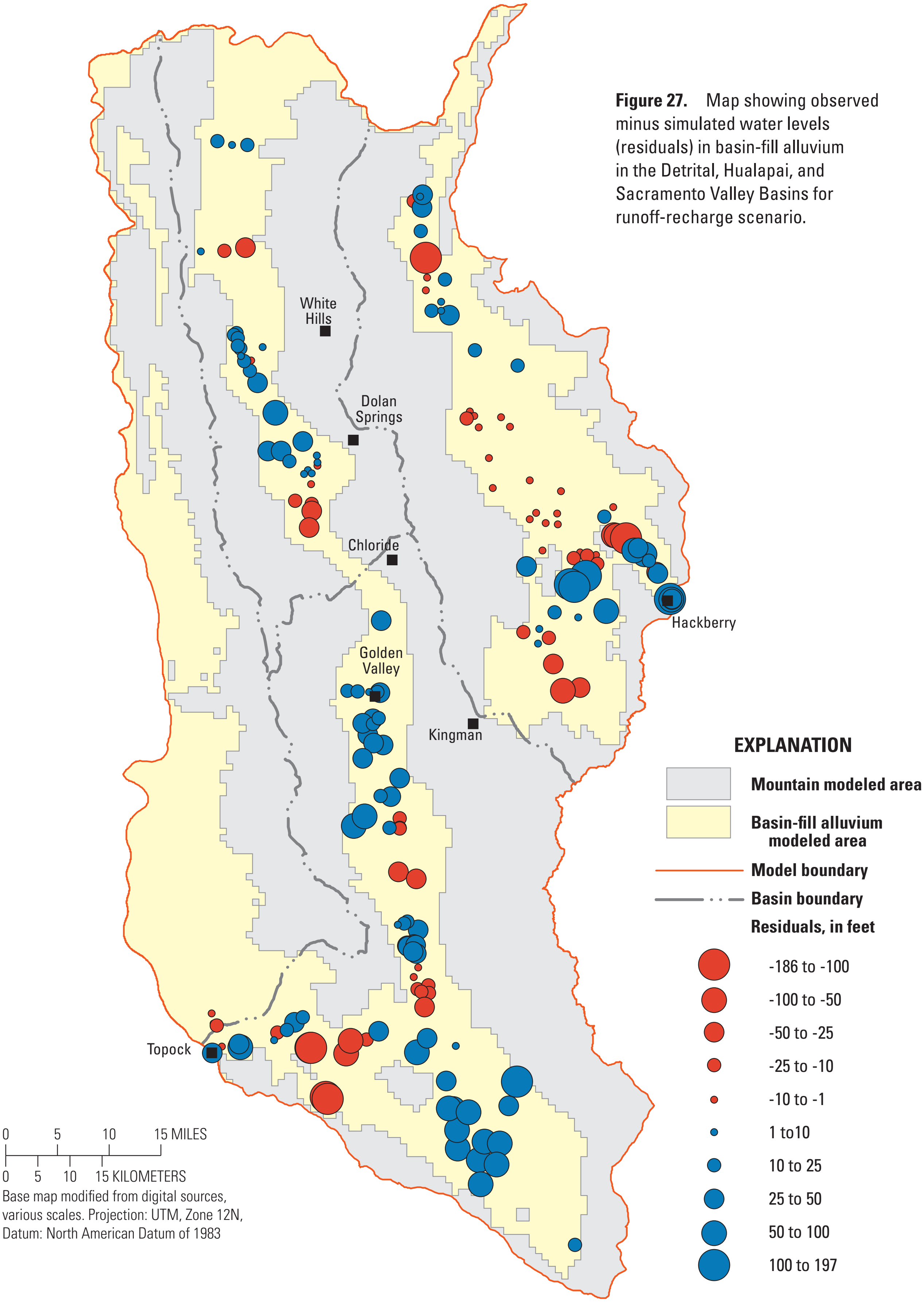


Figure 26. Scatter plots showing observed against simulated water levels (*A*) with bar graph showing distribution of the magnitude of water-level residuals (*A*, inset) and scatter plot showing water-level residuals against simulated water levels (*B*) for basin-fill alluvium in the Detrital, Hualapai, and Sacramento Valley Basins for runoff-recharge scenario.

Figure 27. Map showing observed minus simulated water levels (residuals) in basin-fill alluvium in the Detrital, Hualapai, and Sacramento Valley Basins for runoff-recharge scenario.



Base map modified from digital sources, various scales. Projection: UTM, Zone 12N, Datum: North American Datum of 1983

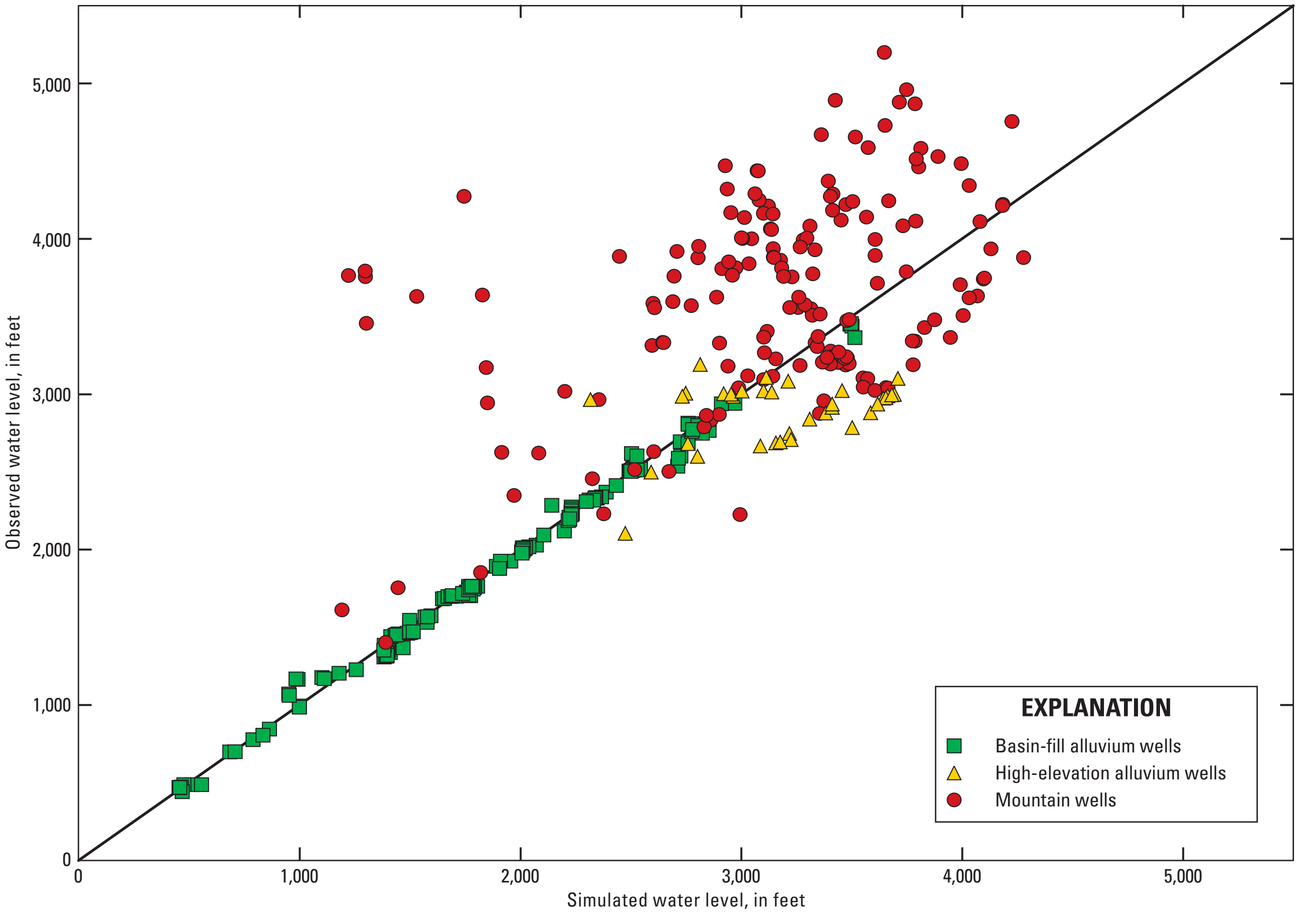


Figure 28. Scatter plot showing observed against simulated water levels for all areas in the Detrital, Hualapai, and Sacramento Valley Basins for runoff-recharge scenario.

Values of simulated groundwater budget components in the runoff-recharge scenario were similar to those in the in-place-recharge scenario, with notable exceptions in the distribution of recharge and, subsequently, outflow (table 10). Hualapai Valley Basin received 30 percent less recharge from runoff than from the in-place recharge scenario, with about 39 percent of this difference in recharge going to Detrital Valley and 55 percent going to Sacramento Valley.

Simulation of Transient Conditions

Groundwater flow during transient conditions was simulated for the period 1935 through 2010. Groundwater stresses simulated in the transient model include changing lake and river boundary conditions (figs. 7 and 8); scaled BCM-calculated in-place recharge (fig. 11); incidental recharge from wastewater-treatment-plant return flow, leaking water-supply pipes, and septic system discharge (fig. 12; table 4); and groundwater withdrawals for municipal, domestic, and limited industrial uses (figs. 13 and 14; table 5). Results of the in-place-recharge steady-state model were used as initial conditions for the transient model and simulated water levels were compared with water-level observations in 32 basin-fill wells with temporal data spanning several decades (fig. 17). During calibration, some adjustments were made in hydraulic conductivities in the original in-place recharge steady-state model to better simulate transient well data (table 11), because the original steady-state model was developed using average natural recharge conditions and fixed Colorado River levels, and was calibrated to earliest water-level observations that were as many as several decades apart (fig. 16). Groundwater levels in the study area may change through time even in the absence of pumping in response to changes in natural recharge and changes in water levels in the Colorado River and Lake Mead. Adjustment of hydraulic conductivity values for the transient model for some parameter zones was required to better fit data from some transient wells where observations began many years after steady-state conditions had ceased. The adjusted hydraulic conductivities result in a mean absolute error of 45 ft (fig. 29*A*) for the same basin-fill wells that were used to calibrate the steady-state model (fig. 15). Mean absolute error of the hydraulic head initial conditions of the transient model for individual basins was 86 ft for Detrital Valley, 49 ft for Hualapai Valley, and 27 ft for Sacramento Valley. Residuals appear to be fairly normally distributed for all three

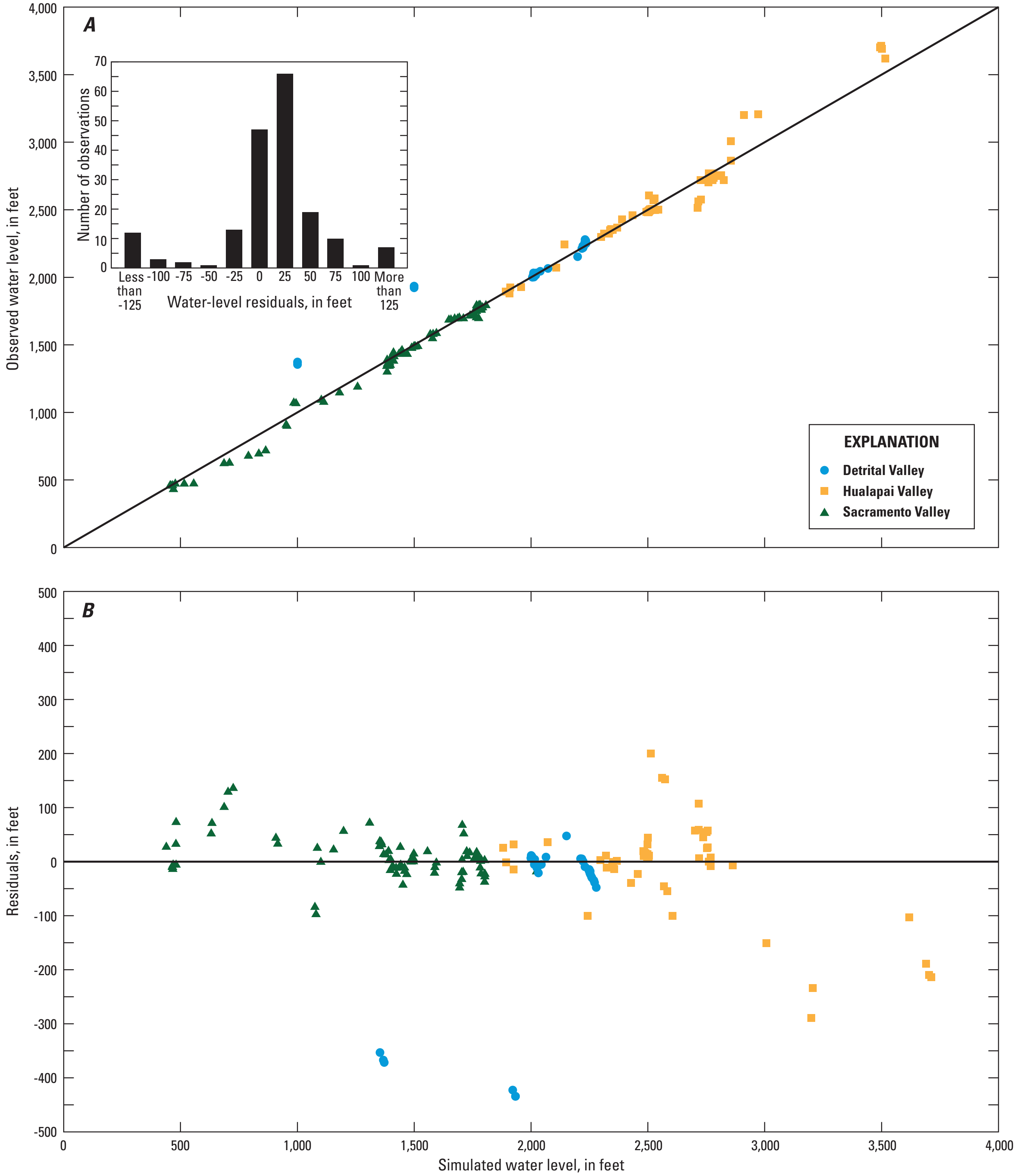


Figure 29. Scatter plots showing observed against simulated water levels (*A*) with bar graph showing distribution of the magnitude of water-level residuals (*A*, inset) and water-level residuals against simulated water levels (*B*) for basin-fill alluvium in the Detrital, Hualapai, and Sacramento Valley Basins for recalibrated initial conditions of transient model.

Table 10. Simulated predevelopment groundwater budget for runoff-recharge scenario.

[Values are in acre-feet per year; –, no data]

Water-budget component	Detrital Valley	Hualapai Valley	Sacramento Valley
Inflow from natural recharge	1,870	3,680	6,720
Inflow from adjacent valleys	0	50	1,310
Inflow at Truxton Wash (Hualapai Valley only)	–	800	–
Net outflow to Colorado River	1,780	4,500	2,440
Outflow to adjacent valleys	95	40	[1]5,600

[1] Outflow from Sacramento Valley to Lake Mohave Basin discharges to Topock Marsh and the Colorado River near Topock.

Table 11. Parameter zones for transient groundwater-flow simulations with calibrated hydraulic conductivity and specific yield values.

[Zone identifiers beginning with "A" denote basin-fill areas and zones beginning with "M" denote mountainous zones. Parameter zone locations are shown in figure 18; ft/d, feet per day]

Parameter zone identifier	Hydraulic conductivity (ft/d)	Specific yield (percent)
A1	2.62	5
A2	0.15	2
A3	0.15	5
A4	1.15	10
A5	0.49	10
A6	0.33	10
A7	0.02	1
A8	2.13	1
A9	0.75	0.5
A10	6.56	5
A11	0.49	5
A12	2.62	5
A13	0.49	5
A14	1.15	1
A15	0.75	5
A16	8.20	5
A17	1.89	5
A18	0.82	5
A19	1.64	10
A20	2.46	10
A21	1.97	5
A22	9.84	8
A23	9.84	5
A24	0.13	5
A25	1.31	7
A26	0.02	15
A27	0.10	1
A28	0.03	3
A29	0.82	10
A30	0.07	1
M1	2.95E-03	5
M2	1.64E-04	5
M3	3.28E-04	5
M4	1.64E-04	5
M5	8.20E-04	5
M6	1.64E-03	5
M7	6.56E-04	5
M8	8.20E-04	5
M9	1.41E-02	5

basins (fig. 29*B*). The significantly higher mean absolute error for Detrital Valley is owing to the much poorer fit of the predevelopment control points created from water-level contours in Freethey and Anderson (1986; fig. 15). Low hydraulic conductivities were required in northern Detrital Valley (table 11) to raise water levels to match observations beginning in 1985 at well D1 (fig. 17), resulting in simulated water levels that were higher than the control points for pre-1935 conditions.

Specific yields in basin-fill alluvium areas for the transient simulation were adjusted to qualitatively match trends in water levels for parameter zones containing wells with transient water-level data (fig. 17). Nearby basin-fill parameter zones with no transient water-level data were assigned specific yields of adjacent zones. The parameter zones used for hydraulic conductivity calibration were also used for specific yield calibration (fig. 18). Gaps in the water-level record and little change in water levels with time for several wells resulted in nonunique specific yields that could range significantly and still result in a similar qualitative fit to the data. All mountainous-area and high-elevation-alluvium parameter zones were assigned a specific yield of 5 percent. Specific yields in basin-fill parameter zones with transient water-level observations range from a low of 0.5 percent in parameter zone A9 to a high of 15 percent in zone A26, with most zones having a specific yields of 5 percent (table 11). Lower specific yields occur in upgradient zones of Sacramento Valley with evaporite deposits, and in shallow zones along Truxton Wash in Hualapai Valley (table 11; fig. 18). Higher specific yields are located in upgradient areas of Detrital Valley, in deeper areas north of Red Lake in Hualapai Valley, and in upgradient areas east of Kingman (table 11; fig. 18).

Few wells in Detrital Valley had data with which to calibrate the transient model (fig. 30). Transient water-level results for well D1, less than 2 mi from the full-pool Lake Mead shoreline (fig. 17), show the effect of filling the reservoir and changing lake levels over time. Water-level observations in all three transient wells in Detrital Valley do not change much during their 1984–2008 period of record (fig. 30). In Hualapai Valley, observed and simulated water levels show decreasing temporal trends in water levels at wells H13

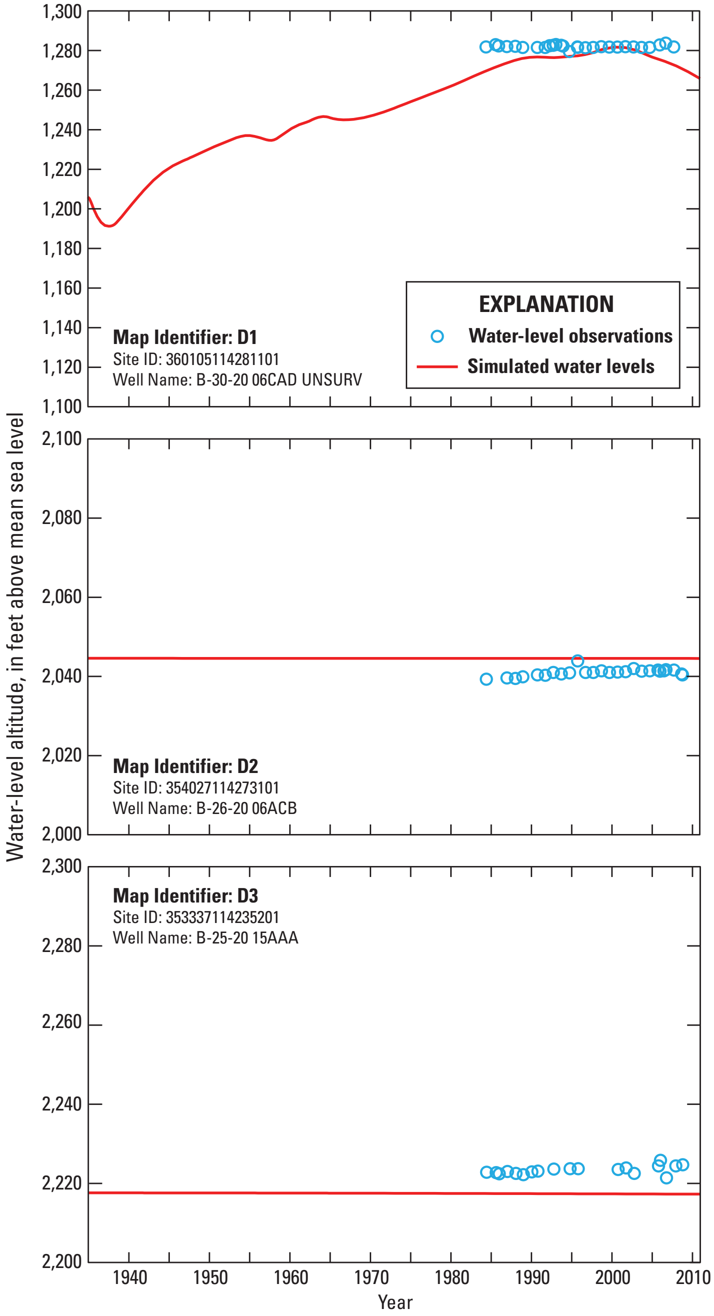


Figure 30. Plots showing observed and transient-model simulated water levels for Detrital Valley. Map identifiers refer to numbering system in figure 17. Vertical axes have different ranges but same scale increment between the tick marks.

through H16 near the Kingman-Hualapai municipal pumping center (fig. 31; appendix 1). Trends in water-level observations in wells H7 through H10 along Truxton Wash (figs. 17 and 31; appendix 1) are poorly matched by the transient simulation, possibly owing to variation in recharge from ephemeral flow in the wash that was not modeled. Simulated water-level drawdown at well H11 caused by Kingman-Hackberry municipal pumping (fig. 17; appendix 1) is not evident in available water-level observations. The low specific yields in this and other parameter zones along Truxton Wash may not be warranted, and changes in observed water levels in this area may be responding to changes in recharge from intermittent flow in Truxton Wash. Trends in water-level observations and simulated water levels in wells S1 through S5 in upgradient areas of Sacramento Valley (figs. 17 and 32; appendix 1) are all declining, although the recent rise in water-level observations in well S1 is not simulated by the model. Simulated and observed water levels in other parts of Sacramento Valley are fairly stable, except at wells S11 and S13 near the outflow of the basin (figs. 17 and 32; appendix 1). The transient model does not simulate the declining trends seen in these wells, possibly owing to an unidentified stress in the flow system.

Model Limitations and Areas for Improvement

The preliminary single-layer groundwater-flow models presented here, like all models, are approximations of complex physical systems. Sparse data for much of the study area required generalization of hydraulic parameters and simplification of physical processes. Additionally, limitations in the availability of groundwater-withdrawal and water-level data, and imprecisely (or omitted) modeled aquifer stresses result in inaccuracies in simulated groundwater levels in some parts of the model domain. One of the most valuable outcomes of developing a model, including the current effort, is identification of the types and locations of data most needed to improve future models. That knowledge can direct future data collection efforts to collect the most important information and greatly improve cost effectiveness.

Although the groundwater-flow models described in this report were shown to accurately simulate direction of groundwater flow in the study area and generally simulate water-level observations and trends in most areas, a more accurate model may be developed through a number of improvements. A re-evaluation of parameter zones for both hydraulic conductivity and specific yield could improve the calibration of water levels and trends in the narrow alluvial area along Truxton Wash near Hackberry. Similarly, model performance at the outflow of Sacramento Valley near Topock could be improved with different parameter zones and, possibly, by the inclusion of area lake levels in the transient model (fig. 1). Simulation of the groundwater system in the Truxton Wash area may also be improved by using the Streamflow-Routing package (Prudic and others, 2004) with flow data from the USGS gage Truxton Wash near Valentine, Ariz. (site identifier

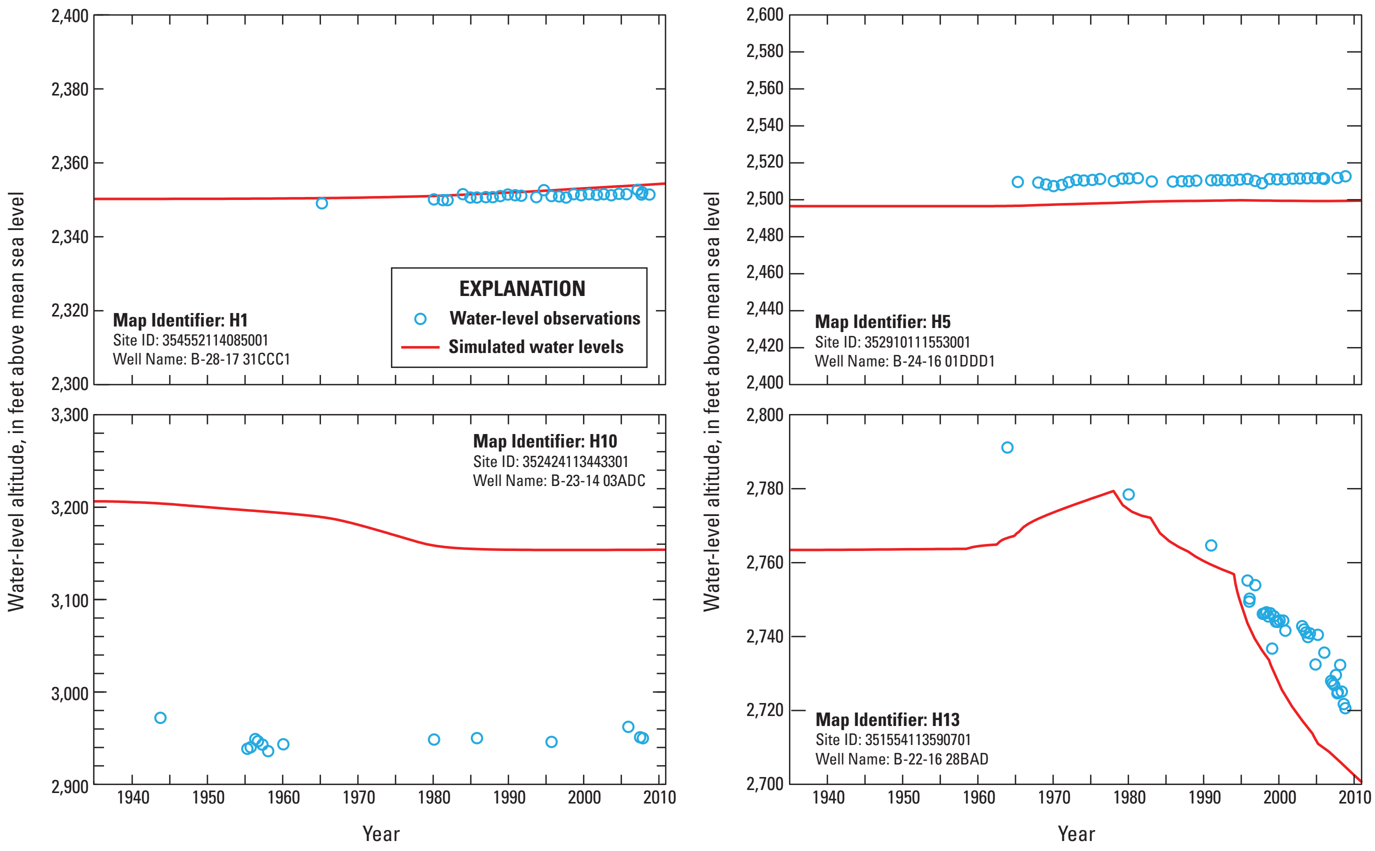


Figure 31. Plots showing observed and transient-model-simulated water levels for selected wells in Hualapai Valley. Map identifiers refer to numbering system in figure 17. See appendix 1 for all transient-model hydrographs. Vertical axes have different ranges but same scale increment between the tick marks.

09404343), which is located just over 4 miles upstream of where Truxton Wash enters the model area near Hackberry. Water levels were simulated in high elevation alluvium and mountainous areas on the basis of parameter zones created around generalized rock types (for example, crystalline, volcanic, or sedimentary). This effort could be improved with zonation based on additional information such as fractures, faults, and weathering of these rocks. Additional water-level information would aid in calibrating the transient-conditions model in areas where data are currently lacking, particularly ongoing water-level monitoring in northern Detrital Valley. Some additional transient-water-level data may be obtained by piecing together hydrographs from nearby wells, each with limited time-series data. Additional information on the location and rate of groundwater withdrawals for the Mineral Park Mine in Sacramento Valley also should be incorporated into future transient models. Finally, additional calibration of the groundwater-flow model to independent estimates of groundwater discharge to Lake Mead and the Colorado River would help reduce model uncertainty. Maximum and minimum discharges can be estimated using a Darcy's law approach if additional data on observed hydraulic gradient near locations of groundwater discharge were collected.

Summary and Conclusions

Numerical groundwater-flow models for steady-state and transient conditions were developed for the basin-fill aquifers of the Detrital, Hualapai, and Sacramento Valleys. The goals of this preliminary modeling exercise were to gather and evaluate existing data, to test aquifer-recharge concepts, to establish initial distribution of aquifer parameter values, and to indicate directions for improvement for future regional groundwater models for the area. A single layer with vertically averaged aquifer properties was used to model basin-fill aquifers in the study area. The steady-state models investigated two recharge scenarios for pre-dam (pre-1935) conditions, including in-place recharge and runoff as recharge. The steady-state models were able to approximate the direction of groundwater flow and simulate water-level observations in most areas, with poorer model fit in areas with steep hydraulic head gradients. Water levels in mountainous areas were not extensively calibrated and model fit in these areas could be improved with additional hydraulic conductivity parameter zones. The transient-conditions model simulated 1935 through 2010 conditions with 31 stress periods that ranged in length from 122 days to 5.8 years and were

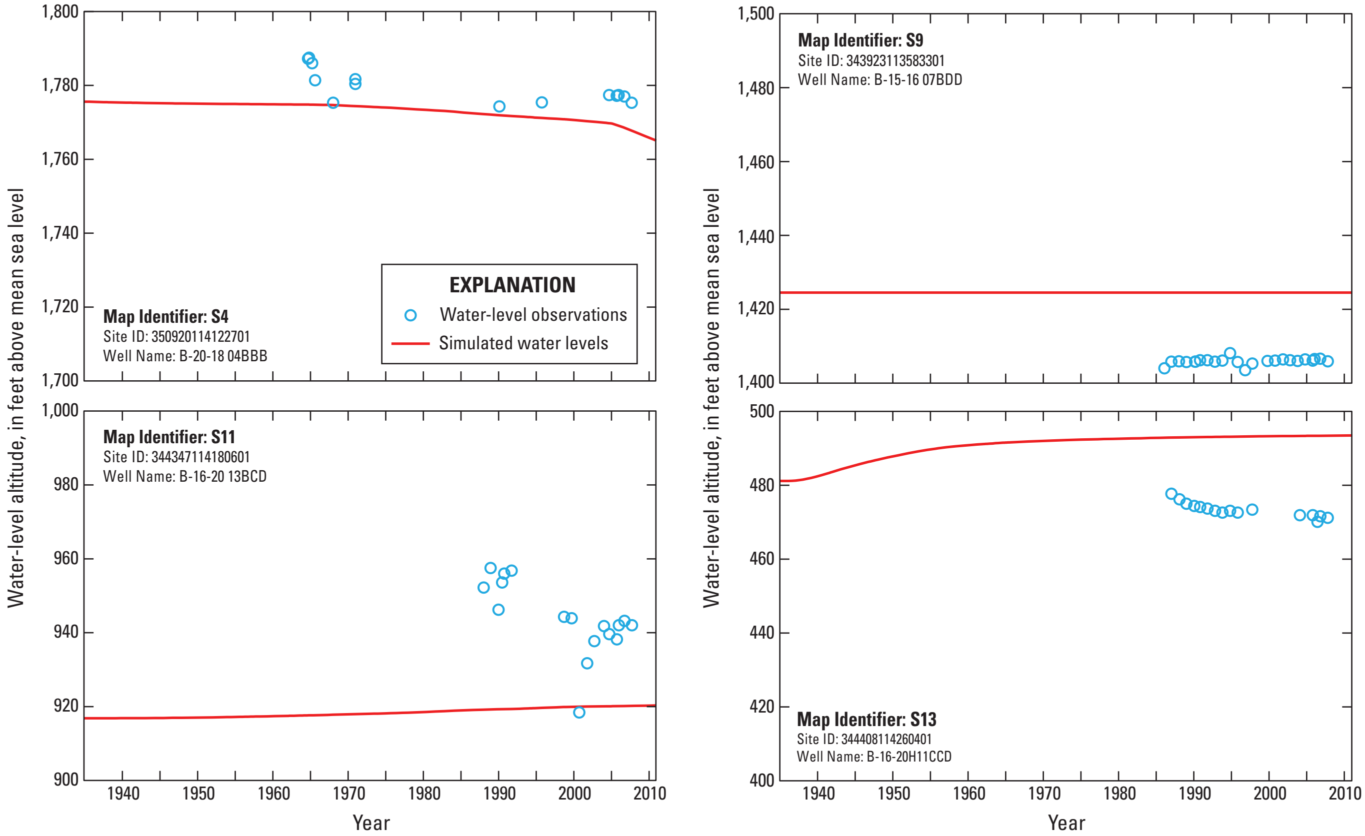


Figure 32. Plots showing observed and transient-model-simulated water levels for selected wells in Sacramento Valley. Map identifiers refer to numbering system in figure 17. See appendix 1 for all transient-model hydrographs. Vertical axes have different ranges but same scale increment between the tick marks.

chosen to capture the many important changes in groundwater system stresses. Model stresses simulated in the transient model include changing Colorado River and associated reservoir levels; municipal, self-supplied domestic, and limited industrial groundwater withdrawals; natural recharge from precipitation; and incidental recharge from leaks in water-supply lines, septic-system drain fields, and discharge from wastewater-treatment plants. The transient model was able to approximate observed water-level trends throughout most of the model area where transient data were available. All models are archived in accordance with USGS policies, and data files are available upon request.

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Appendix 1. Simulated Transient Water Levels and Observed Water Levels in Wells in Detrital, Hualapai, and Sacramento Valley Basins.

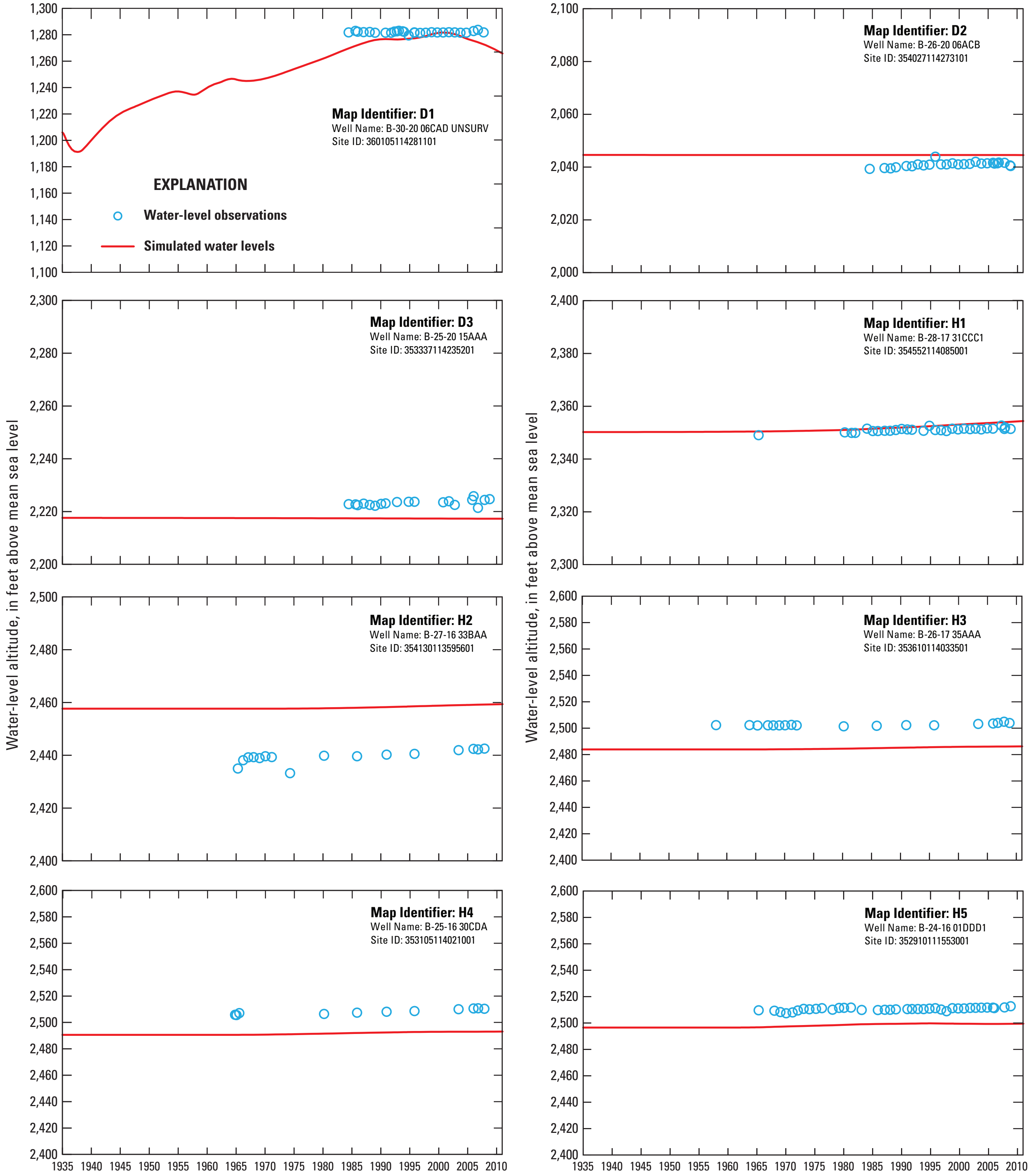

Figure A1. Plots of observed and transient-model simulated water levels for wells used in calibrating transient model. Map identifier refers to numbering system in figure 17. Vertical axes have different ranges but same scale increment.

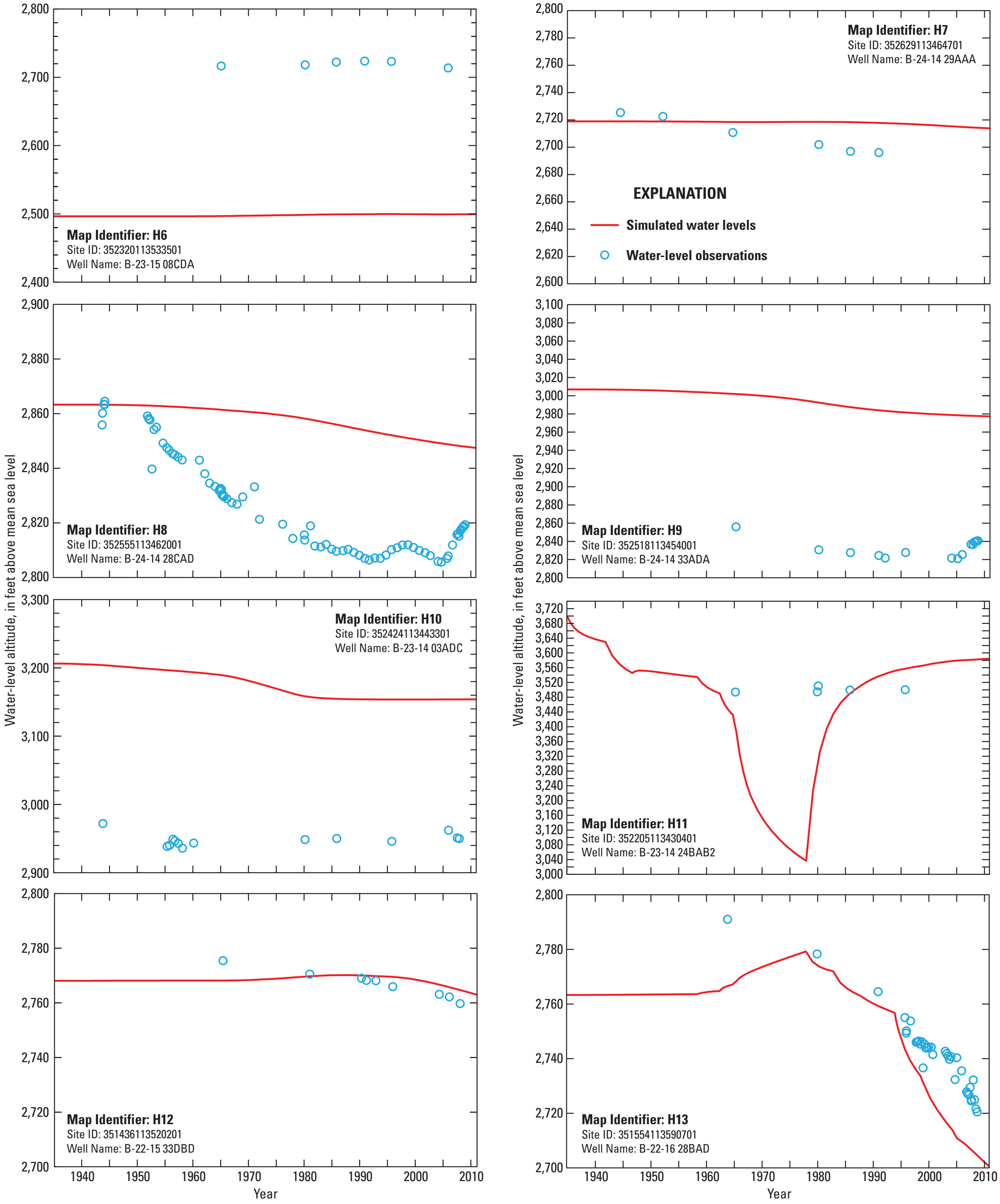

Figure A1.—Continued

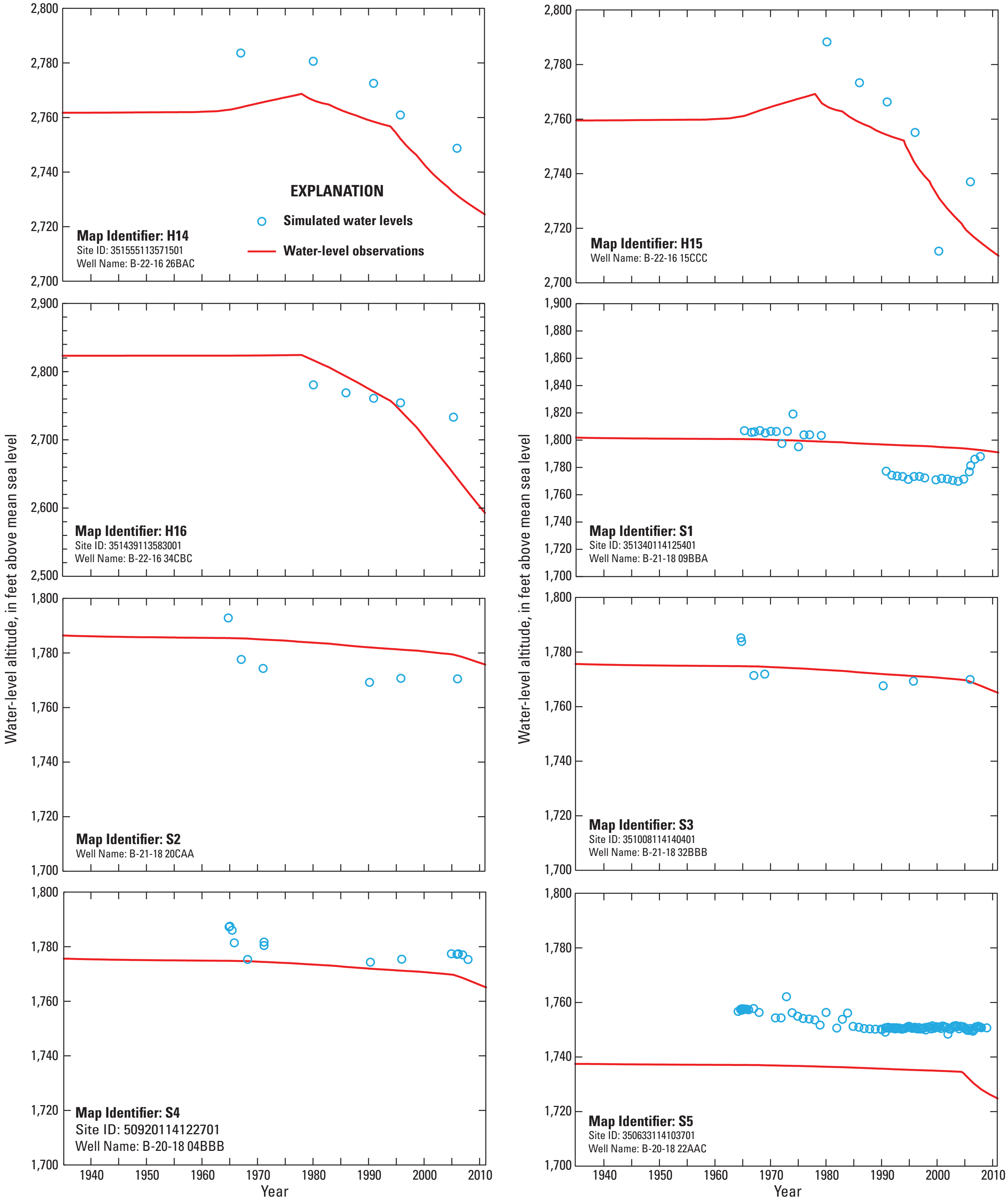

Figure A1.—Continued

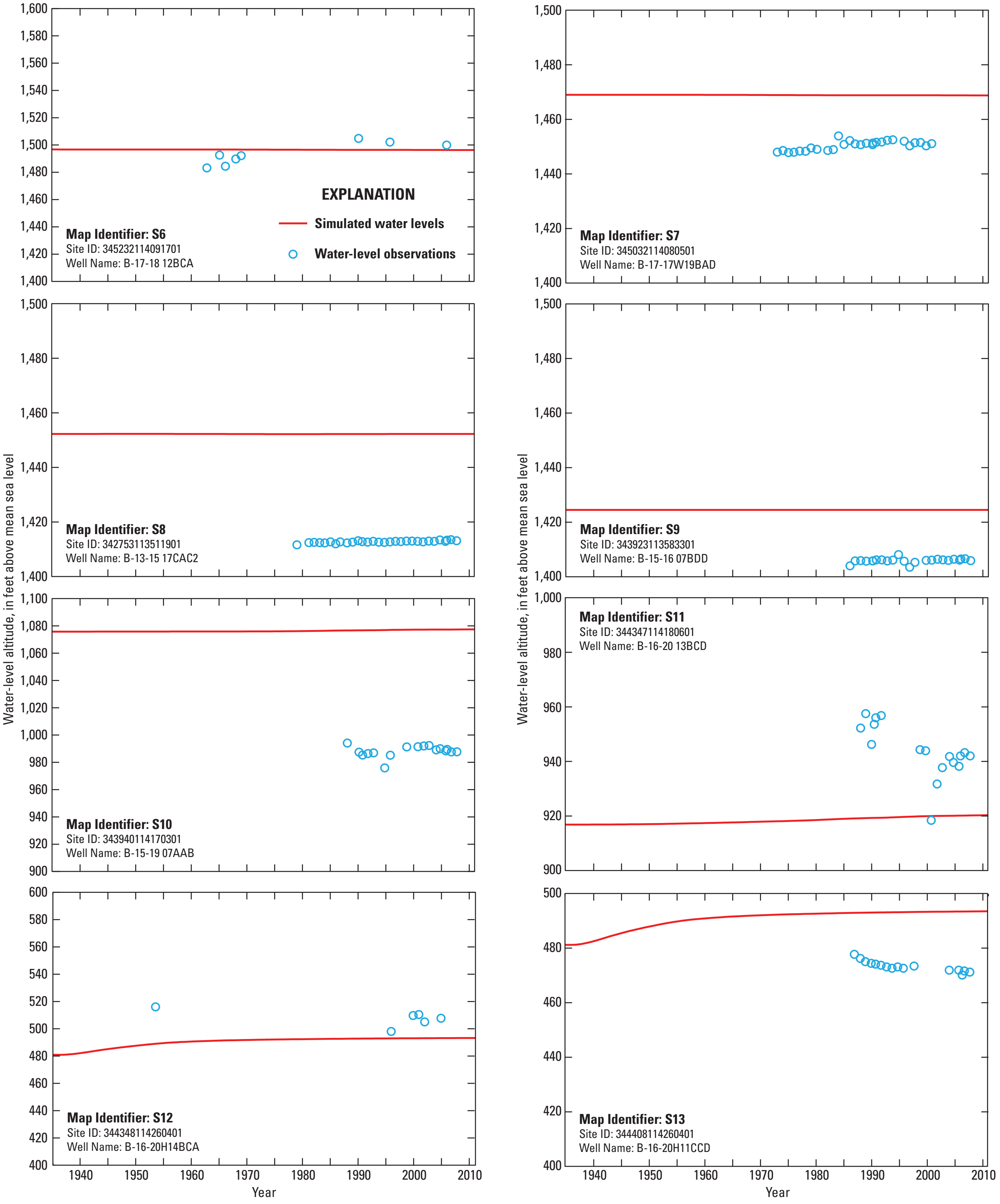

Figure A1.—Continued

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