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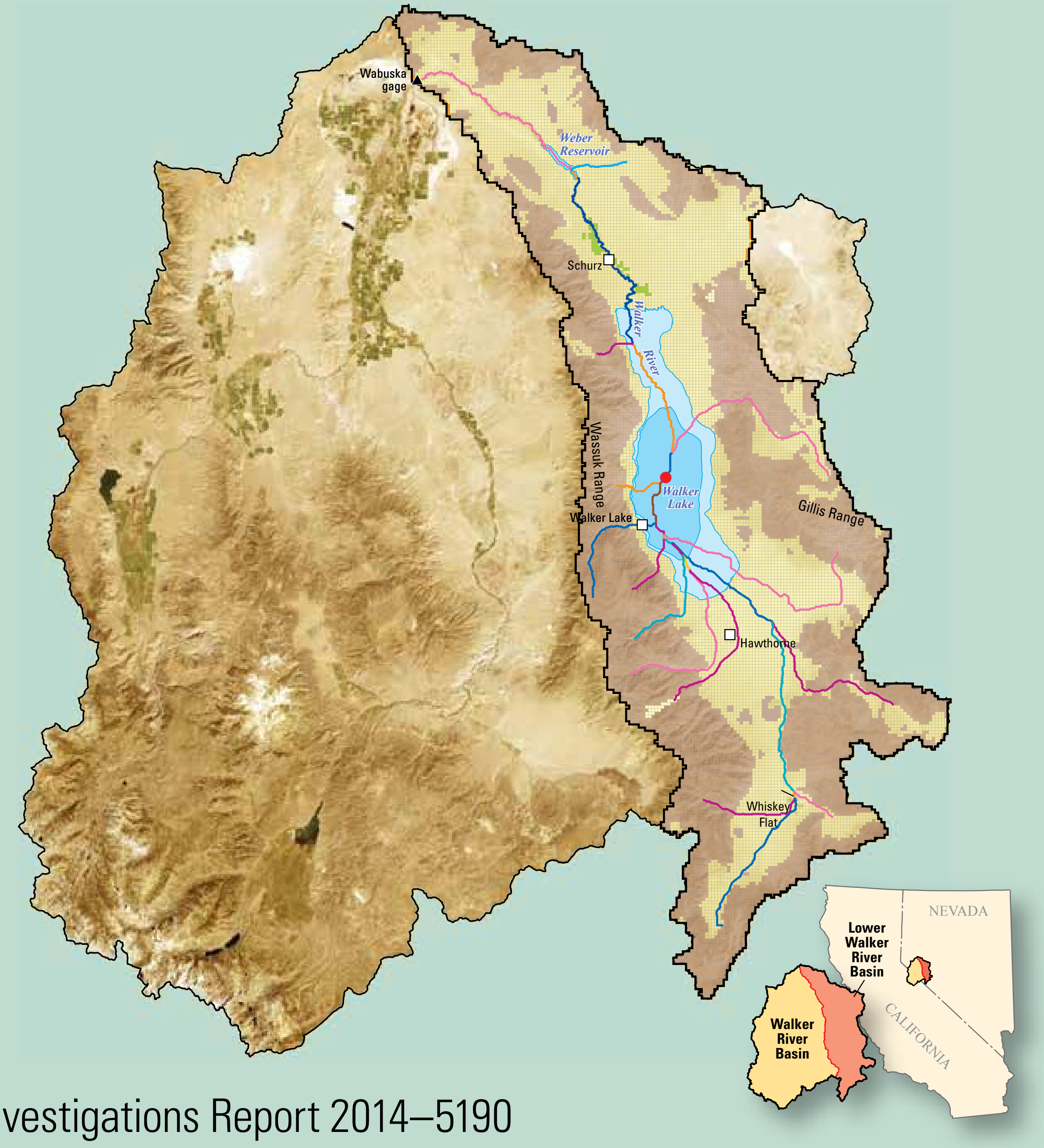
Simulation of the Lower Walker River Basin Hydrologic System, West-Central Nevada, Using PRMS and MODFLOW Models



Scientific Investigations Report 2014–5190

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

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By Kip K. Allander, Richard G. Niswonger, and Anne E. Jeton

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
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)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
ton, short (2,000 lb)	0.9072	metric ton
	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×°C)+32

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

°C=(°F-32)/1.8

The PRMS model uses Inch/Pound units and results and discussions of PRMS model are also presented using Inch/Pound units. The MODFLOW model uses units of meters and days, but results and discussions are presented using Inch/Pound units. Specific model input variables or parameters are presented in Inch/Pound units followed by equivalent SI unit (in parenthesis) used in model.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), unless otherwise noted. When vertical datum is specified as local datum, it is referring to either the local datum for the Walker Lake gage or Weber Reservoir gage. The local datums for these two gages are tied to reference points surveyed to the National Geodetic Vertical Datum of 1929 (NGVD 29). In this report, the conversion of Walker Lake level in NGVD 29 datum to North American Vertical Datum of 1988 (NAVD 88) is +3.48 feet, and the conversion of Weber Reservoir level in NGVD 29 to NAVD 1988 is +3.40 feet.

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

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

Simulation of the Lower Walker River Basin Hydrologic System, West-Central Nevada, Using PRMS and MODFLOW Models

By Kip K. Allander, Richard G. Niswonger, and Anne E. Jeton

Abstract

Walker Lake is a terminal lake in west-central Nevada with almost all outflow occurring through evaporation. Diversions from Walker River since the early 1900s have contributed to a substantial reduction in flow entering Walker Lake. As a result, the lake is receding, and salt concentrations have increased to a level in which *Oncorhynchus clarkii henshawi* (Lahontan Cutthroat trout) are no longer present, and the lake ecosystem is threatened. Consequently, there is a concerted effort to restore the Walker Lake ecosystem and fishery to a level that is more sustainable. However, Walker Lake is interlinked with the lower Walker River and adjacent groundwater system which makes it difficult to understand the full effect of upstream water-management actions on the overall hydrologic system including the lake level, volume, and dissolved-solids concentrations of Walker Lake. To understand the effects of water-management actions on the lower Walker River Basin hydrologic system, a watershed model and groundwater flow model have been developed by the U.S. Geological Survey in cooperation with the Bureau of Reclamation and the National Fish and Wildlife Foundation.

The watershed model was developed using the precipitation runoff modeling system (PRMS) and the groundwater flow model was constructed using the MODular groundwater FLOW model (MODFLOW) and both were calibrated for the lower Walker River Basin. These models can be incorporated in an integrated Groundwater and Surface-water FLOW (GSFLOW) model of the lower Walker River Basin. Additionally, the MODFLOW model developed for this study is useful for efficiently simulating long-term and large-scale effects of water-management actions on groundwater hydrology, streamflow, and Walker Lake level, volume, and dissolved-solids concentrations.

The lower Walker River Basin PRMS model (LWR_PRMS) was constructed using a subbasin approach to aid in development and calibration, and simulates a 30-year period from 1978 to 2007 using daily time steps. The LWR_PRMS was used to estimate the distribution of groundwater recharge specified in the MODFLOW model. The highest rates of groundwater recharge occur in the Wassuk Range beneath perennial and ephemeral stream channels, whereas lower rates of recharge occur beneath alluvial fans along mountain fronts. The total groundwater recharge estimated using PRMS was about 25,000 acre-feet per year.

The lower Walker River Basin MODFLOW (LWR_MF) model simulates an 89-year period using monthly time steps. The LWR_MF was constructed with an initial steady-state simulation to represent dynamic equilibrium conditions from 1908 to 1918 and then a transient simulation representing the period 1919–2007. The model was calibrated using a combination of manual and automated methods of adjusting model parameters to minimize errors between model simulated results and weighted observations of groundwater levels, streamflows, and lake level. Hydrologic conditions simulated with the LWR_MF include the movement and change in storage of groundwater, and the water budgets for Walker River, Walker Lake, and the groundwater system. The LWR_MF computed dissolved-solids concentrations for Walker Lake using simulated lake volume and an assumed constant internal salt mass of 37.2 million tons.

Effects of potential changes in water management on future conditions (scenarios) of the lower Walker River Basin hydrologic system and Walker Lake from 2011 to 2070 were evaluated. Several water-management scenarios were considered, including a baseline scenario that represents no changes in system management, improved irrigation efficiencies for the Walker River Indian Irrigation Project (WRIIP), a range of increased streamflows entering the lower Walker River Basin, and, the fallowing of fields on the WRIIP.

For the baseline scenario, it was assumed that streamflow conditions from 1981 to 2010 will be repeated in the future. Results indicate that Walker Lake level and volume continue to decline but at a slower rate as the surface area of the lake becomes smaller and lake evaporation decreases. Dissolved-solids concentrations in Walker Lake continue to increase and increase much more rapidly during periods when minimal flows reach the lake due to a diminished lake volume. Alternatively, in years with high runoff, lake level increases are greater and dissolved-solids decreases are greater, compared with equivalent runoffs experienced during 1981–2010.

The simulated effects of improving WRIIP efficiencies on Walker River streamflows, Walker Lake inflow, level, and dissolved-solids concentrations, and crop consumptive use, are compared with the baseline reference scenario for a range of irrigation efficiency improvements from 0 to 25 percent over 60 years. Results indicate that water is conserved through a reduction in irrigation-induced groundwater recharge and subsequent groundwater discharge through evapotranspiration. The conserved water mostly goes to increased streamflow to Walker Lake, followed by increased crop consumptive use, then increased evaporation from Weber Reservoir.

The simulated effects of increased streamflows at Walker River at Wabuska streamgage (10301500) on Walker Lake inflow, level, and dissolved-solids concentrations, and crop consumptive use, are compared with the baseline scenario after 60 years under two different management methods for Weber Reservoir. Results indicate Walker Lake level and dissolved-solids concentrations stabilized with increased irrigation-season streamflow of about 40,000 acre-feet per year at the Walker River at Wabuska streamgage. Walker Lake level increased, and dissolved-solids concentration decreased, with increased flows of 50,000 acre-feet per year or more. After 60 years with additional irrigation-season streamflows of 50,000 acre-feet per year, Walker Lake level increased by about 48 feet, and lake dissolved-solids concentrations decreased by about 3,000 milligrams per liter (mg/L). With 75,000 acre-feet per year of additional streamflow, Walker Lake level increased by 70 feet, and dissolved-solids concentration decreased by 7,600 milligrams per liter.

The effects of fallowing of Walker River Indian Irrigation Project fields from 2007 to 2010 on Walker Lake inflow, level, and dissolved solids were evaluated. Fallowing resulted in a near doubling of Walker River inflow to Walker Lake during this period, an increase in Walker Lake level of about 1.4 feet, and a decrease in dissolved-solids concentration of about 540 mg/L.

Introduction

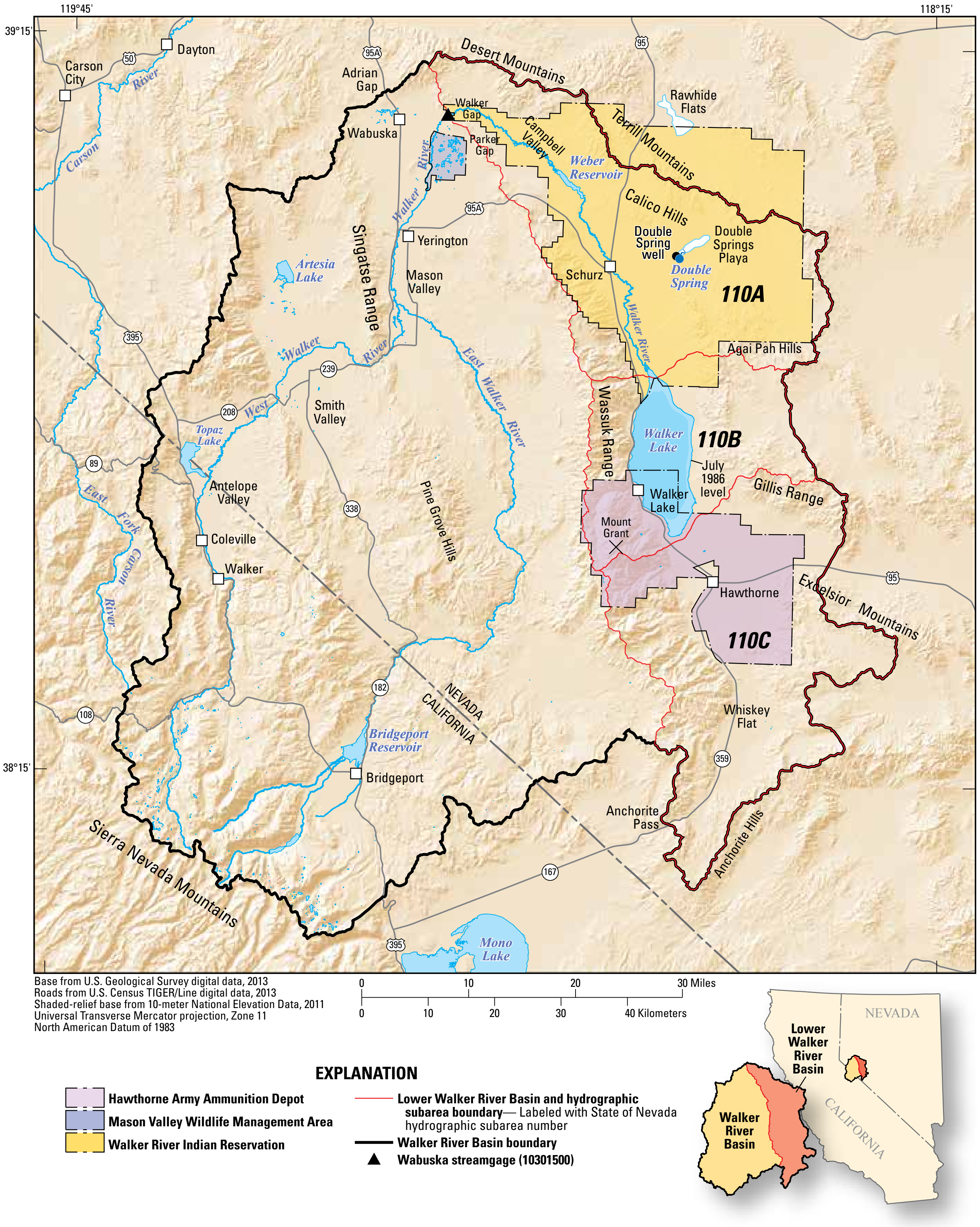
Walker Lake is a terminal lake in west-central Nevada (fig. 1). The main outflow from the lake is by evaporation and the main inflow to the lake is the Walker River. Since the late 19th century, diversions from Walker River have decreased inflow to Walker Lake. Evaporation from the lake is greater than the inflow during most years, resulting in a lake water budget that can only be balanced by a reduction in storage. Consequently, there has been a fairly steady decline in the level of Walker Lake of about 1.6 feet per year (ft/yr) since 1918. Because nearly the entire outflow from Walker Lake is by evaporation, salts that enter the lake remain there and become concentrated in lake water. Evaporative losses and diminished inflows from Walker River have caused concentrations of dissolved solids in the lake to increase from 4,000 to nearly 20,000 milligrams per liter (mg/L) from 1930 to 2011 (fig. 2).

Dissolved-solids concentrations in Walker Lake have increased to levels where only 3 of 17 fish species that historically lived in the lake were still present in 1979 (Koch and others, 1979). The *Oncorhynchus clarkii henshawi* (Lahontan Cutthroat trout), a species listed as threatened under the Endangered Species Act, was regularly stocked through 2008, but a very low harvest rate indicated a low survival rate, and the last Lahontan Cutthroat Trout capture was reported May 2009. The ecologic health of Walker Lake is of great concern to local communities that rely on the fishery for economic and spiritual reasons. Additionally, Walker Lake is a stopover point on the Pacific Flyway for migratory birds from within and outside the United States. There are international treaties in place that attempt to protect the integrity and success of the migratory flyways. This puts additional pressure on the users of Walker River to help maintain Walker Lake as a viable fishery.

In the spring of 2004, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Bureau of Reclamation to improve hydrologic understanding and knowledge of the Walker River Basin hydrology (Lopes, 2005). The major objectives of that study were to

1. Quantify the amount of streamflow in the Walker River Basin and determine the percentage of that streamflow by hydrographic area,
2. Determine evapotranspiration losses from natural riparian and non-riparian phreatophytic vegetation and the lake surface,
3. Develop an improved water budget for Walker Lake, and
4. Develop the capability to predict how changes in streamflow deliveries that pass the Wabuska streamgage will affect water levels and dissolved-solids concentrations in Walker Lake.

This project addresses objective four above. Groundwater discharge from storage in the aquifers adjacent to Walker Lake contributes water to the lake as the level declines. The quantity of groundwater discharge to Walker Lake is required to estimate the volume of water from upstream sources necessary to reduce dissolved-solids concentrations in Walker Lake to a predetermined level. A long-term mean dissolved-solids concentration of 12,000 mg/L has been established by the State of Nevada as a Total Maximum Daily Load (TMDL) for Walker Lake (Nevada Division of Environmental Protection, 2005). If Walker Lake were maintained at a constant level, groundwater discharge to Walker Lake would decrease over time, decreasing a component of inflow to Walker Lake. On the other hand, increased streamflow to Walker Lake will cause both the storage within the lake and surrounding aquifers to increase as the lake level rises. Thus, the relation between stream inflows to the lake and the corresponding changes in the lake level and dissolved-solids concentration are dependent, in part, on the hydrogeology of the surrounding groundwater system. An integrated groundwater/surface-water model is needed to predict the effects of management actions on Walker Lake



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 1. Location and general features of the Walker River Basin and lower Walker River Basin, west-central Nevada.

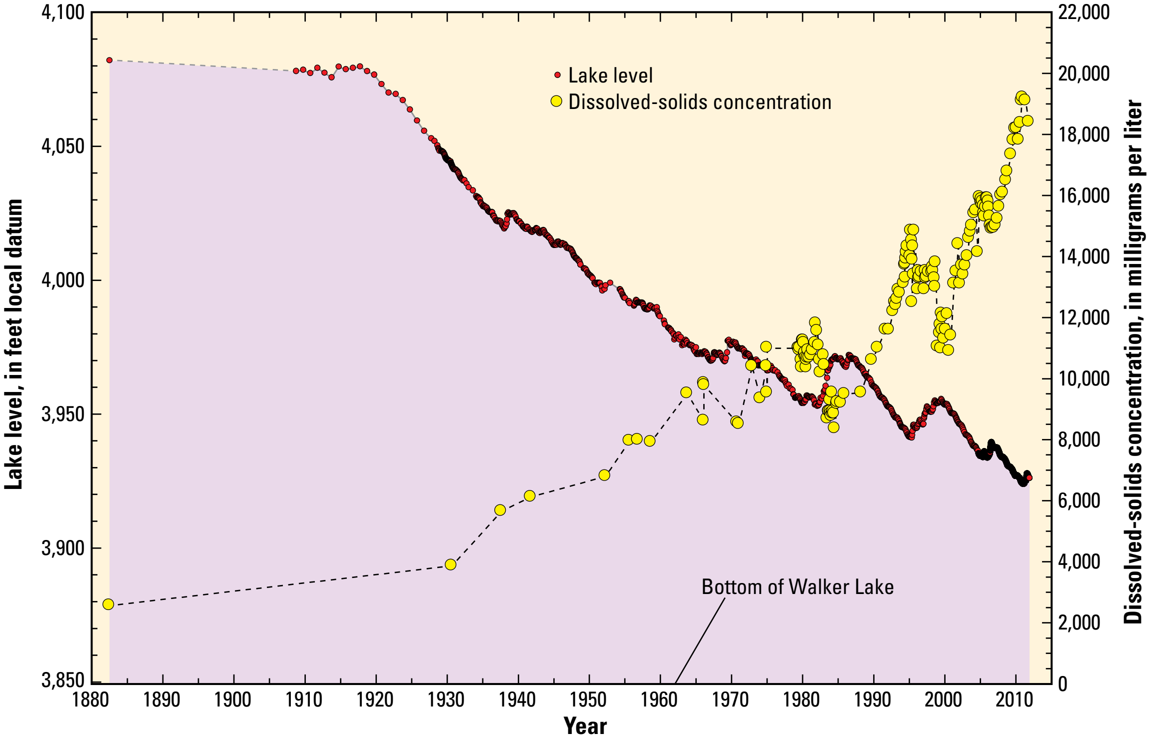


Figure 2. Time series of lake levels and dissolved-solids concentrations for Walker Lake, west-central Nevada, 1882–2011.

because the interactions among Walker Lake, Walker River, and the adjacent groundwater system are complex and vary with time and Walker Lake level. This model can be used to gain a better understanding of how upstream water management actions affect the lake levels and dissolved-solids concentrations in Walker Lake and support the selection of optimized actions that benefit the water users in the basin.

The USGS, in cooperation with the Bureau of Reclamation and the National Fish and Wildlife Foundation, undertook the work described in this report to develop this model. The main objective of the study was to relate streamflow in the Walker River at Wabuska streamgage with groundwater conditions in the lower Walker River basin and Walker Lake level, volume, and dissolved-solids concentrations. The specific objectives were to

1. Refine the hydrogeologic understanding of the aquifers surrounding Walker Lake and the manner in which Walker Lake and Walker River interact with these aquifers for various lake-level conditions;
2. Estimate the groundwater component of Walker Lake water budget for current, historical, and potential future lake conditions; and
3. Estimate how changes to water deliveries at the Walker River at Wabuska streamgage, Weber Reservoir operation, and project irrigation efficiencies affect the lake-level and dissolved-solids concentrations in Walker Lake.

Purpose and Scope

The purpose of this report is to describe the development, calibration, and use of the watershed precipitation runoff modeling system watershed model (PRMS) and the MODular groundwater FLOW model (MODFLOW) for the lower Walker River Basin. This report presents a description of the hydrologic system being simulated and estimates of groundwater recharge used to calibrate the PRMS model. The report describes the PRMS model used to simulate surface-water processes and estimate distribution of groundwater recharge for use with MODFLOW model. The report then presents the MODFLOW model used to simulate groundwater hydrology, river flow, and lake level. Finally, the report presents results of four predictive simulations. The first predictive simulation is a baseline simulation in which no water-management action is implemented, and the results are used for evaluating the effects of management actions. The second predictive simulation evaluates the response of Walker Lake level and dissolved-solids concentrations, as well as crop consumptive use over a 60-year period, to varying improvements of irrigation efficiency on the Walker River Indian Irrigation Project. The third predictive simulation evaluates the response of Walker Lake level and dissolved-solids concentrations to an increase in streamflow at the Walker River at Wabuska streamgage. The fourth predictive simulation estimates the benefit of the Walker River Indian Irrigation Project fallowing program between water years[1] 2007 and 2010 to Walker Lake level and dissolved-solids concentrations.

Previous Simulations of Hydrologic System

There has been no previous effort to simulate the hydrologic system of the entire lower Walker River Basin. However, there have been several models produced to simulate parts of the hydrologic system.

The first known numeric simulation within the lower Walker River Basin was constructed to test assumptions for groundwater recharge and discharge rates as part of investigations of the water resources of the Walker River Indian Reservation (Schaefer, 1980). The flow model was a two-dimensional (2D) finite element model with a total of 130 elements. Schaefer (1980) used the model to demonstrate that estimates of groundwater recharge from the Walker River and discharge through the playas at Double Springs and Rawhide Flats were reasonable for a given set of transmissivity estimates. Schaefer (1980) used hydraulic conductivities ranging from 15 to 130 feet per day (ft/d) to estimate a range of groundwater recharge from Walker River of 3,000 to 65,000 acre-feet per year (acre-ft/yr) and a range of groundwater discharge from Double Springs and Rawhide Flats discharge areas of 2,500 to 40,000 acre-ft/yr.

The next numeric simulation in the study area was a simple water-balance model created by Milne (1987) to simulate the level of Walker Lake. Milne (1987) reconstructed lake levels for four Great Basin terminal lakes (Walker, Pyramid, Winnemucca, and Owens) to study the response of present-day (1986) closed-basin lakes to historical climate variability. In order to simulate Walker Lake level, observed inflows were used along with known lake level/volume/area relations and estimated evaporation and groundwater inflows in order to match the historical lake-level record. Milne then used the best water-balance model to estimate “pristine” lake-level conditions by rerunning the model using an estimated flow record for Walker River with the effects of diversions removed. Milne concluded that Walker Lake would have risen above the historical highstand during the 1980s had there been no human-initiated diversions from Walker River.

Concurrent with this study, the University of Nevada Reno and Desert Research Institute are developing an integrated surface-water, groundwater, water rights distribution model for the area upstream from the lower Walker River Basin called the Decision Support Tool (DST). The models presented in this report were designed to work in conjunction with the upstream DST models in order to simulate how water-management activities upstream from the lower Walker River Basin affect the lower Walker River Basin hydrology, especially Walker Lake levels and dissolved-solids concentrations.

Description of Hydrologic System

The Walker River Basin encompasses a drainage area of about 3,950 square miles (mi^2) in west-central Nevada and eastern California (fig. 1). The study area, which is the watershed area downstream from the Walker River at Wabuska streamflow-gaging station in northern Mason Valley, is referred to as the lower Walker River Basin (LWR) throughout this report (fig. 3). The lower Walker River Basin also includes the areas of Whiskey Flat and Hawthorne, south of Walker Lake. The study area boundary (red line in fig. 3) generally follows the topographic divide that isolates surface drainage of the lower Walker River Basin from that of the middle Walker River Basin. The boundary follows the mountain crests adjacent to Walker Lake, except in the Double Springs area (fig. 3) where the boundary is drawn across the valley floor. The study area encompasses about 1,240 mi^2 and represents about 31 percent of the entire Walker River Basin.

The following sections provide a generalized summary of the lower Walker River Basin hydrologic system. These sections summarize the hydrologic elements and processes that are incorporated into and simulated by the models.

Physiography

The study area is coincident with Hydrographic Area[2] 110, which is defined by the Nevada State Engineer (Cardinalli and others, 1968; Rush, 1968). Hydrographic Area 110 is divided into 3 subareas: 110A, 110B, and 110C (fig. 1). Hydrographic subarea 110A is the area of the lower Walker River Basin downstream from the Wabuska gaging station (where the Walker River exits Mason Valley) to the north side of the 1968 shoreline of Walker Lake. Most of the Walker River Indian Reservation lies within hydrographic subarea 110A. Hydrographic subarea 110B includes Walker Lake, the surrounding watershed that drains directly to the lake, and some of the area south of Walker Lake between the lake and the Hawthorne Army Ammunition Depot (Army Depot; fig. 3). Hydrographic subarea 110B also includes drainages from the east along the Gillis Range and from the west along the Wassuk Range. Hydrographic area 110C is the lower Walker River Basin south of Walker Lake and includes Whiskey Flat, Hawthorne, and the Army Depot.

Major geographic features of the lower Walker River Basin include the lower Walker River, Weber Reservoir, Walker Lake, Whiskey Flat, Wassuk Range, Mount Grant, and Gillis Range (fig. 3). Communities in the study area include the towns of Schurz, Hawthorne, and Walker Lake, and the Army Depot. The town of Schurz is near the middle of the Walker

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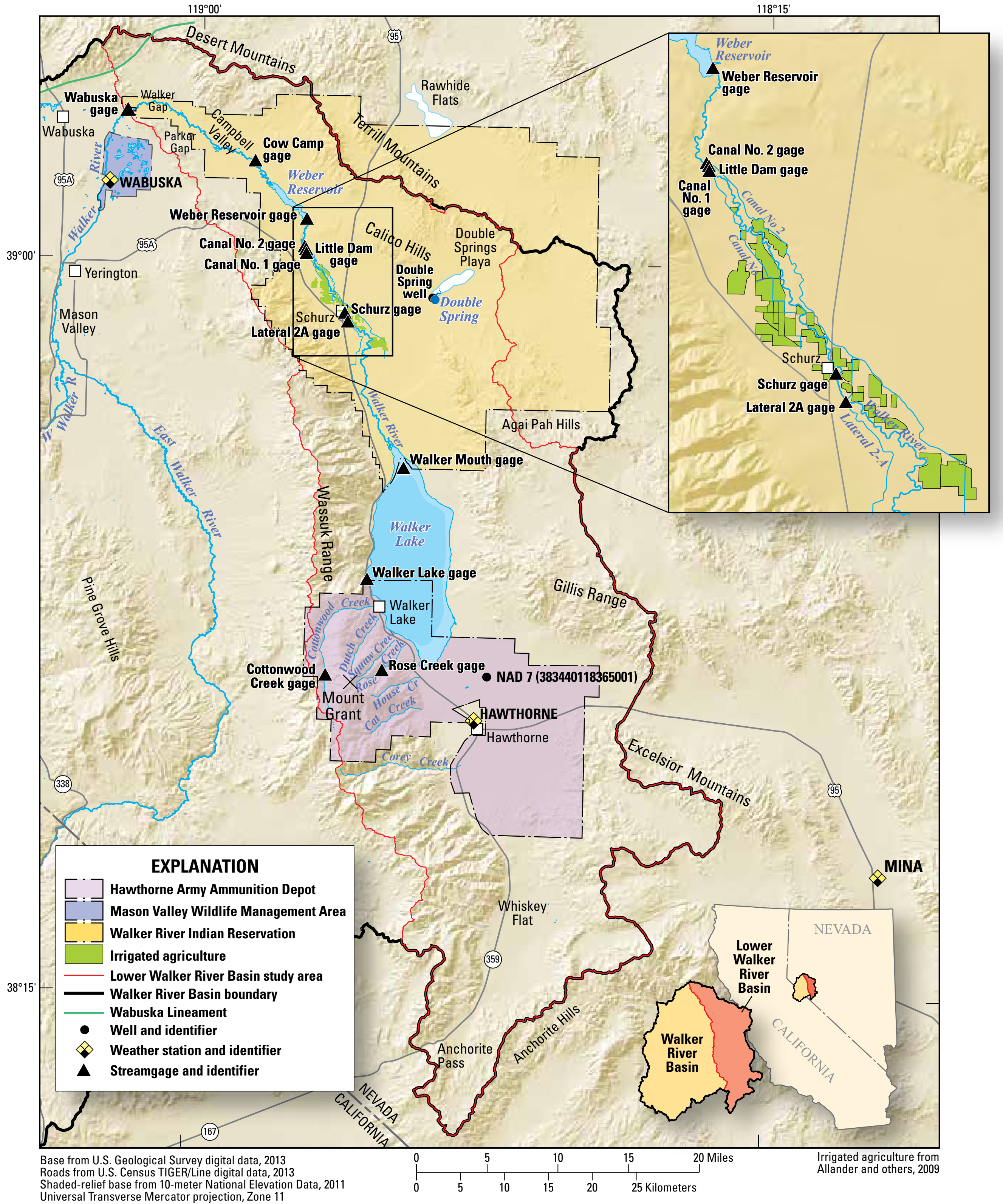
[1] A water year is the period from October 1 to September 30; it is designated by the year in which it ends. Water year is used almost exclusively throughout this report. In order to reduce confusion between calendar years and water years in this report, all reference to years and periods is to water years unless specifically referred to as calendar year.

[2] Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960s for scientific and administrative purposes (Cardinalli and others, 1968; Rush, 1968). The official hydrographic-area names, numbers, and geographic boundaries continue to be used in U.S. Geological Survey information products and Nevada Division of Water Resources administrative activities.



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Irrigated agriculture from Allander and others, 2009

Figure 3. Major hydrologic features, streamflow and lake gages, and weather stations of the lower Walker River Basin study area, west-central Nevada.

Table 1. Stream, lake, and weather station information for sites in and near the lower Walker River Basin, west-central Nevada.

[Sites shown in Figure 3. Sites are listed in clockwise and downstream order starting with Walker River; Latitude and Longitude are in decimal degrees, North American Datum of 1983 (NAD 83); Altitude is feet National Geodetic Vertical Datum of 1929 (NGVD 29), Altitude accuracy is 10 to 20 feet]

Station name	Site identification number	Short name	Latitude	Longitude	Altitude of gage datum	Period of record
Stream						
Walker River near Wabuska	10301500	Wabuska gage	39.1524611	-119.0988889	4,300	1/15/1920–9/30/1935; Nearly continuous since 1/1/1939
Walker River above Weber Reservoir	10301600	Cow Camp gage	39.1032533	-118.929317	4,215	6/13/1977–9/30/1982; Continuous since 6/1/1994
Canal No. 1 at Little Dam near Schurz, NV	10301755	Canal No. 1	39.01242024	-118.861258	4,160	Nearly continuous since 4/21/1995
Canal No. 2 at Little Dam near Schurz, NV	10301742	Canal No. 2	39.0140869	-118.8609803	4,160	Nearly continuous since 4/19/1995
Walker River above Little Dam above Schurz, NV	10301745	Little Dam gage	39.01353135	-118.8609803	4,160	4/19/1995–4/11/2001; Continuous since 10/1/2004
Walker River at Schurz, NV	10302000	Schurz gage	38.94908679	-118.8079225	4,120	7/1/1913-9/30/1933
Walker River at Lateral 2A Siphon near Schurz, NV	10302002	Lateral 2A gage	38.94019785	-118.8037557	4,105	Continuous since 10/1/1994
Walker River nr Mouth at Walker Lake, NV	10302025	Walker Mouth gage	38.79103038	-118.727085	3,940	10/1/2004-5/16/2006; Continuous since 7/24/2010
Rose Creek near Walker Lake, NV	10302145	Rose Creek	38.58353236	-118.750416	6,460	5/5/2005-9/30/2008
Cottonwood Creek near Walker Lake, NV	10302160	Cottonwood Creek	38.5779755	-118.8243069	7,940	5/5/2005–9/30/2008
Lake						
Weber Reservoir near Schurz, NV	10301700	Weber Reservoir	39.04464245	-118.8601474	4,218	Nearly continuous since 4/28/1995
Walker Lake near Hawthorne, NV	10288500	Walker Lake	38.67658636	-118.7720849	3,900	Monthly 8/1928–9/2004; Continuous since 10/1/2004
Weather station						
Wabuska 5 SE, Nevada	268822	Wabuska	39.0833	-119.1167	4,300	Daily since 10/1971
Hawthorne, Nevada	263512	Hawthorne	38.55	-118.6667	4,275	Daily since prior to 10/1971
Mina, Nevada	265168	Mina	38.3833	-118.1	4,550	Daily since 7/1948

River Indian Reservation. The highest point in the study area is Mount Grant, at 11,239 feet (ft; NGVD 29), and the lowest point is the surface of Walker Lake, which had an altitude of 3,934.8 ft (NGVD 29) in October 2007. Although the overall length of the study area is approximately 90 miles (mi), the distance between the highest and lowest points (Mount Grant and Walker Lake, respectively) is only about 5 mi, resulting in a dramatic vertical topographic gradient of about 1,460 feet per mile (ft/mi) along the west side of Walker lake.

Walker River, Weber Reservoir, and Walker River Indian Irrigation Project

The headwaters of the Walker River originate in the eastern Sierra Nevada Mountains in California and collect in the West and East Walker Rivers (fig. 1). The West and East Walker Rivers join in the southern end of Mason Valley to form the main stem Walker River, which then flows about 70 mi to its terminus at Walker Lake, Nevada. The Walker River is the largest and most important tributary to Walker Lake.

Walker River enters the study area at the Wabuska streamgage (Wabuska gage, 10301500), which is at the far downstream edge of Mason Valley and is conterminous with the gap in the hills between Mason Valley and Campbell Valley (fig. 3; table 1). There is a long and nearly complete streamflow record for the Wabuska gage beginning January 1, 1939 (table 1). Downstream from the Wabuska gage the river meanders through a well-developed flood plain for about 12 linear miles before it enters Weber Reservoir. The Walker River above Weber Reservoir streamgage (Cow Camp gage, 10301600; table 1) is located approximately 2 mi upstream from Weber Reservoir. The Cow Camp gage monitors streamflow that enters Weber Reservoir and the Walker River Indian Irrigation Project (WRIIP). However, because of the presence of many naturally abandoned river channels within the flood plain away from the main channel, backwater conditions created by beaver dams and natural vegetation debris in the channel, streamflow can bypass this streamgage, especially during high flows.

The WRIIP is the system of canals and irrigation ditches and includes Weber Reservoir and related infrastructure that supports the agricultural operation of the Walker River Paiute Tribe. The WRIIP is maintained and operated by the Bureau of Indian Affairs.

Construction of Weber Reservoir was completed in 1935, but the reservoir began filling prior to its completion on July 27, 1934 (Katzer and Harmsen, 1973). The reservoir is about 4 mi long by less than 0.5 mi wide and stores about 10,700 acre-feet (acre-ft) of water at its maximum operating level of 4,208 ft (local datum; Katzer and Harmsen, 1973). The reservoir begins to spill over its radial gates at a level of 4,210 ft (local datum; Katzer and Harmsen, 1973). Stage is monitored from the gate house (Weber Reservoir, 10301700; table 1).The minimum operating level for Weber Reservoir is 4,194 ft (local datum) with storage of 1,500 acre-ft to provide the minimum pool for fish (Stephen Brown, Bureau of Indian Affairs, oral commun., September 2010). However, the minimum operating level was adjusted to 4,187 ft (local datum) for a brief period from 2000 to 2003. Water is released from Weber Reservoir back into the main channel of Walker River as needed to provide for irrigation demand when water levels are above minimum pool level. When reservoir levels are at or below minimum pool level, flow releases from Weber Reservoir are at or below the rate of Walker River inflow. When Walker River inflows are greater than irrigation demand and will cause the maximum operating level in Weber Reservoir to be exceeded, flow is released into the main channel and allowed to move downstream from diversion structures toward Walker Lake. This approach to reservoir management is referred to as the no-pass-through approach in this report and is discussed in later sections describing hypothetical management scenarios.

The operational guidelines for Weber Reservoir were modified several times from 2000 through 2008 in response to an evaluation of dam safety for earthquake readiness (Stephen Brown, Bureau of Indian Affairs, oral commun., September 2010). In June 2000, the maximum operating level of Weber Reservoir was lowered to 4,196.5 ft (local datum). Then in early 2004, the lake level criteria were reevaluated, and maximum operating level was increased to 4,200 ft (local datum) at which it was operated until dam improvements were completed in 2010. For the 2011 irrigation season, maximum operating level was restored to original operating level of 4,208 ft (local datum).

Approximately 2 miles downstream from Weber Reservoir is a small diversion structure locally referred to as Little Dam (which is located at the Little Dam gage; fig. 3). This diversion structure is a simple low-head concrete weir in the stream channel and provides sufficient head in the river to divert flow through two diversion canals on either side. Diversions into the canals are monitored using two streamgages: Canal No. 1 at Little Dam near Schurz, NV (Canal No. 1, 10301755; table 1) and Canal No. 2 at Little Dam near Schurz, NV (Canal No. 2, 10301742; table 1). Streamflow that is not diverted passes over Little Dam to the main channel of Walker River and is monitored using the streamgage Walker River above Little Dam (Little Dam gage, 1030745; table 1). As a result of an unfortunate naming mishap, there is often general confusion understanding which flows are represented by these three streamgages. Regardless of what the full streamgage names imply, the flows represented by these streamgages are the actual diversions into Canal No. 1 and Canal No. 2, and the flow downstream from Little Dam after the diversions are removed is measured by the Little Dam gage.

Both canals are lined with concrete along much of their lengths and deliver irrigation water to downstream fields on respective sides of the river. Canal No. 1 delivers water along the right side of the river, and Canal No. 2 delivers water mainly along the left side of the river (looking downstream). Downstream from where Walker River crosses Highway 95, Canal No. 2 has a right lateral extension that crosses over Walker River to deliver irrigation water to some fields along the right side of the river. Beyond the irrigated fields, the main canals are not lined. The canals do not return flow directly to the main stem of the river. On occasion, flows in Canal No. 2 were allowed to pass out the end of the irrigation network into a natural abandoned river channel, which brought water to some natural grassland areas where it helped to support seasonal rangeland for cattle.

The area of the WRIIP irrigated with Walker River water was decreed to be 2,100 acres in 1939 (Horton, 1996). There are no records of actual year-to-year irrigated acreage available. The maximum irrigated acreage is assumed to be 2,100 acres every year, but that is likely to be less in years with limited water. Irrigated acreage of the WRIIP was also estimated by Allander and others (2009) from landsat data collected in 2000, a near normal irrigation year, and was very close to 2,100 acres after removal of fields watered only with groundwater. Alfalfa is the principal crop irrigated on the WRIIP.

Below the Little Dam diversion structure, flow remaining in Walker River follows the natural channel down through the town of Schurz and approximately 1 mi past Schurz where it reaches the Walker River at Lateral 2A streamgage (Lateral 2A gage, 10302002; table 1). The Walker River at Schurz streamgage (Schurz gage, 10302000; table 1) was located just upstream from this location between 1913 and 1933. Below the Lateral 2A gage, Walker River follows its natural and increasingly incised channel until it reaches Walker Lake. Streamflow entering Walker Lake has not been continuously monitored, except for a brief period from October 2004 to May 2006, and more recently since July 2010, when the Walker River near mouth at Walker Lake streamgage began operation (Walker Mouth gage, 10302025; table 1).

The flow of Walker River generally decreases as it traverses the study area toward Walker Lake. For the 30-year period 1971–2000, the mean discharge of the river as it entered the study area at the Wabuska gaging station was 138,000 acre-ft/yr (Lopes and Allander, 2009b). To compare streamflows at other streamgages along the Walker River over a common period, Lopes and Allander (2009b) used statistical methods to normalize the available streamflow record for each site to the 1971–2000 period. The 1971–2000 streamflow normal for the Lateral 2A gage was 108,000 acre-ft/yr. This indicates an average reduction in streamflow along this reach of about 30,000 acre-ft/yr over this period. This loss is attributed to a combination of processes: recharge to the groundwater system from infiltrating stream water and irrigation water, evapotranspiration from natural and agricultural vegetation, and open-water evaporation from Weber Reservoir (Lopes and Allander, 2009b; Allander and others, 2009). For 11 years from 1995 to 2006 (not including 1996), the mean diversion from Walker River through Canal No. 1 and Canal No. 2 was about 16,700 acre-ft/yr. Adjustment of this figure to the 30-year normal period resulted in an estimated diversion rate of about 16,200 acre-ft/yr (Lopes and Allander, 2009b). Although historically there were no permanent gaging stations downstream from the Lateral 2A gage on the Walker River, miscellaneous discharge measurements and data from short-term, temporary gaging stations, indicate that the 30-year mean streamflow entering Walker Lake is about 105,000 acre-ft/yr (Lopes and Allander, 2009b). This would indicate a general loss of flow between Lateral 2A gage and Walker Lake of about 3,000 acre-ft/yr. This loss is attributed to a combination of seepage loss to the groundwater system and evapotranspiration from natural vegetation and shallow groundwater. Following extended periods when the lowest reach of Walker River below Lateral 2A is dry, substantial losses of streamflow can occur as the channel is rewetted and recharges the local groundwater system. Lopes and Allander (2009a) estimated a net loss of 8,000 acre-ft along this reach in 2005 after flows rewetted this reach of the river following a drought period of about 5 years.

Other Tributaries

Although the Walker River is the biggest and most significant tributary to Walker Lake, there are other streams that intermittently contribute water to the lake. The only perennial stream reaches within the study area besides Walker River are in the Wassuk Range, but these streams become dry prior to reaching Walker Lake, except under exceptionally rare high runoff events. The following streams have perennial reaches in the Wassuk Range: Cottonwood Creek, Dutch Creek, Squaw Creek, Rose Creek, House Creek, Cat Creek, and Corey Creek (Boyle Engineering Corp, 1976; fig. 3). There are many ephemeral stream channels in the Wassuk Range and Gillis Range that can, on rare occasions, flow to Walker Lake under exceptionally high runoff conditions, mainly following strong summer thunderstorms.

Under natural conditions, perennial streamflow from the Wassuk Range infiltrates to the large alluvial fans the streams traverse. Alluvial fans typically have relatively permeable deposits and fairly deep unsaturated zones that allow efficient infiltration of flow from small mountain tributaries (Maurer and others, 2004; Prudic and others, 2007). Some of the perennial flows in the Wassuk Range are captured and diverted to supply water to the Army Depot. This water is conveyed through pipes and is used for municipal, industrial, and recreational purposes. The town of Walker Lake relies on fresh groundwater supply from the Cottonwood Creek canyon alluvial fan aquifer.

Within the mountains, tributaries frequently have steep and incised channels. Typically the incised channels are filled to some degree with fluvial deposits. Fluvial deposit thicknesses can range from non-existent (bedrock channel) to a few tens of feet thick or greater, and fluvial deposits can act as a pathway for groundwater movement from the mountains beneath the stream channels. Generally the cross-sectional area of alluvial channels within the mountains is fairly small, and only a small amount of groundwater flows beneath the stream channels in comparison with occasional surface flows in the channels and groundwater that recharges as mountain front recharge.

Streamflow entering Walker Lake from other tributaries has not been monitored, and direct measurements are not available. However, there are two estimates of tributary discharge to Walker Lake. Everett and Rush (1967, p. 10) estimated average annual surface-water runoff (not including Walker River) to be 3,000 acre-ft/yr. Lopes and Allander (2009b; p. 38) reevaluated the Everett and Rush (1967) estimate and determined a net tributary inflow of 1,000 acre-ft/yr by subtracting the estimated tributary diversion (2,000 acre-ft/yr) by the Army Depot from the original Everett and Rush (1967) estimate of 3,000 acre-ft/yr. However, this analysis was incorrect as Everett and Rush had already accounted for this diversion in their estimate; therefore, Lopes and Allander (2009b) effectively double counted the diversion in their estimate. However, the effect of this error on the overall water budget estimate of Walker Lake is small because the uncertainty of tributary inflow is likely less than the uncertainty of estimated inflows from Walker River.

Walker Lake

Walker Lake is the terminus of the Walker River and is the lowest point in the basin. Walker Lake is a remnant of ancient Lake Lahontan, a large pluvial lake that occupied a large part of the Great Basin, most recently during the late Pleistocene epoch (Russell, 1885; Benson, 1988).

Walker Lake depth was first documented in 1882 by Russell (1885), and estimated lake level from this date is 4,082 ft (Lopes and Smith, 2007). Routine monthly monitoring of Walker Lake level began in 1928. Annual lake level reconstruction for the period 1909 through 1928 was done by Rush (1970). Over the 90-year period from October 1918 to October 2007, the Walker Lake level declined 143 ft from 4,078 ft to 3,934.8 ft (fig. 2; local datum). In October 2007, the surface area was 32,100 acres; total water volume, 1.75 million acre-ft; mean depth, 54.5 ft; and maximum depth about 85 ft. The minimum altitude of the lake bottom is 3,849.3 ft and is near the center of the lake (Lopes and Smith, 2007).

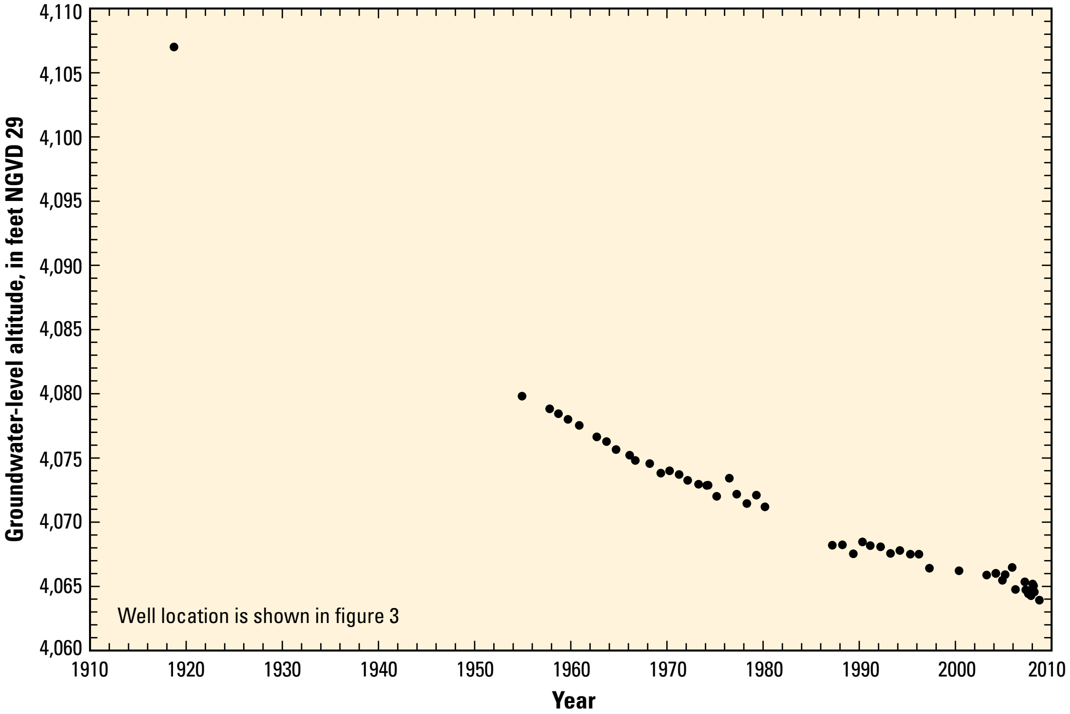


Figure 4. Groundwater-level hydrograph for a well, NAD 7, (site identifier 383440118365001) located south of Walker Lake on the Hawthorne Army Ammunition Depot, west-central Nevada.

Dissolved-solids concentration data for Walker Lake (fig. 2) have historically been measured using two different methods and estimated using a third method. The first measurement method is laboratory analysis of samples taken from Walker Lake for weight of dry residue remaining after evaporation of the volatile portion of an aliquot of the water sample (Hem, 1992). The second measurement method is summing of the concentrations of dissolved constituents (Hem, 1992). The third method is estimation from in-situ measurements of specific conductance and conversion to dissolved-solids concentration by means of a regression relation (Hem, 1992). For this report, dissolved-solids concentrations based on the first and second measurement methods are considered "measured" dissolved-solids concentrations, whereas dissolved-solids concentrations estimated from measurements of specific conductance are considered "estimated." Measured dissolved-solids concentration data for Walker Lake were obtained from the USGS National Water Information System (NWIS), from two reports (Rush, 1970, and Benson and Spencer, 1983), the Nevada Department of Wildlife, and the Nevada Division of Environmental Protection. Estimated dissolved-solids concentration data were obtained or calculated from Koch and others (1979), Nevada Department of Wildlife, Nevada Division of Environmental Protection, and NWIS.

The first two dissolved-solids samples were collected in 1882 by Russell (1885) and were analyzed and reported by Clarke and Chatard (1884, p. 22), and concentrations were 2,516 and 2,488 mg/L (average, 2,502 mg/L). The dissolved-solids concentration from these two samples were re-estimated by Rush (1970) to be 2,560 mg/L (fig. 2). The next known measurement was made by the U.S. Navy in November 1952, 6,790 mg/L (Benson and Spencer, 1983). The three dissolved-solids concentration values for 1882 to 1952 are estimates from Benson and Spencer (1983) and may be based on measured lake water electrical conductance reported in Miller and others (1953). The source of the Walker Lake measurements reported in Miller and others (1953) is unknown. After 1952, dissolved-solids concentrations were measured more frequently, at least every 5 years through 1970 and even more frequently since. Estimates of the net salt flux to Walker Lake range from 56,000 to 66,000 tons per year (ton/yr) (Thomas, 1995; Nevada Division of Environmental Protection, 2005).

Groundwater altitudes adjacent to Walker Lake are higher than the lake level (Lopes and Allander, 2009a), which indicates that the general direction of groundwater flow is towards Walker Lake and that groundwater generally discharges to the lake. When Walker Lake level rapidly rises, which occurs with large inflows from the Walker River, the hydraulic gradient likely reverses, so that lake water flows outward into the groundwater system. However, given the long-term, relatively continuous decline in Walker Lake level, this outflow from Walker Lake to the groundwater system occurs infrequently and only for periods of a few weeks to a few months.

Because of the relatively continuous decline in the Walker Lake level since 1919, the general trend in groundwater altitudes adjacent to Walker Lake has also been declining (fig. 4). The earliest point in figure 4 was estimated from the bathymetry of Walker Lake (which indicates the lake shore in 1919 was near well NAD7; fig. 3) and the assumption that groundwater levels near the shoreline were conterminous with the lake level. This groundwater level hydrograph illustrates the decline of the groundwater altitude and storage adjacent to Walker Lake that has occurred during declining lake conditions.

Groundwater

Groundwater recharge, by definition, is the accretion of water to the water table (Winter and others, 1998). Groundwater enters the lower Walker River Basin as direct groundwater inflow at basin boundaries, recharge from precipitation and runoff originating within the study area, or leakage from streams and lakes. Groundwater generally flows toward Walker Lake and discharges mainly as evapotranspiration and inflow to Walker Lake. Some groundwater is lost through outflow through the basin boundary near Double Springs, is pumped, or discharges to streams. The movement of groundwater in the lower Walker River Basin is described in detail by Lopes and Allander (2009a).

Subsurface flow of groundwater from Mason Valley beneath the Parker and Walker Gaps is estimated to be about 700 and 100 acre-ft/yr, respectively, by Lopes and Allander (2009b). There are no other known sources of subsurface inflow to the lower Walker River Basin.

Groundwater recharge originating from precipitation and runoff originating from within the lower Walker River Basin is referred to as “recharge” in this report. Groundwater recharge occurs from infiltration of precipitation, leakage from perennial and ephemeral tributary streams in the mountains and across alluvial fans, and occasionally along ephemeral channels that cross the alluvial basins. Subsurface flow and groundwater recharge also occur where mountains intersect the alluvial system.

The only known estimate of recharge in the lower Walker River Basin is by Everett and Rush (12,500 acre-ft/yr; 1967) and was made using the Maxey-Eakin method (Maxey and Eakin, 1949; Eakin and others, 1951). The Maxey-Eakin method of estimating recharge is based on an empirical relation between precipitation and groundwater recharge developed by Maxey and Eakin (1949). However, Everett and Rush (1967) assumed there was no recharge in the Wassuk Range adjacent to Walker Lake. Lopes and Allander (2009a,b) did not estimate recharge as part of their work, except in areas draining to Walker River. Estimates of recharge were needed in this study to constrain the calibrations and results of the PRMS and MODFLOW models and are presented further on in the report in “Estimates of Groundwater Recharge” section.

Groundwater recharge also originates as leakage from Walker River, Weber Reservoir, and Walker Lake during periods of rising lake level. Groundwater recharge that originates from these sources is referred to as Walker recharge in this report. Walker recharge is the net sum of seepage losses from Walker River that reach the water table, seepage losses from Weber Reservoir, occasional seepage losses from Walker Lake when its lake level rises, and infiltration of applied irrigation water.

Groundwater flows toward Walker Lake, with the exception of about 100 acre-ft that flows northward toward Wabuska Lineament, which is northeast of Wabuska gage, and about 2,700 acre-ft/yr that flows east from the lower Walker River Basin and discharges through Double Springs and as subsurface outflow (Lopes and Allander, 2009b). Most of the groundwater outflow discharges to the atmosphere as evapotranspiration from riparian and phreatophytic vegetation and shallow groundwater (Allander and others, 2009; Lopes and Allander, 2009b). Lopes and Allander (2009b) estimated groundwater discharge through evapotranspiration along the lower Walker River corridor as 17,700 acre-ft/yr, or 61 percent of the total groundwater outflow of about 29,000 acre-ft/yr. Groundwater that discharges directly to Walker Lake was estimated by Lopes and Allander (2009b) as 8,500 acre-ft/yr for lake conditions from 2004 to 2007.

Groundwater is pumped for domestic, agriculture, and municipal use in the lower Walker River Basin and is estimated to be between 200 and 321 acre-ft/yr north of Walker Lake and between 440 and 2,900 acre-ft/yr south of Walker Lake (Everett and Rush, 1967; Boyle Engineering Corp., 1976; Schaefer, 1980; Huffman and Carpenter, Inc., 2001; and Lopes and Allander, 2009b).

Climate

The climate in the study area is typical of the semi-arid great basin desert regime and is classified as mid-latitude desert because of its cold winters and hot summers (Houghton and others, 1975, p. 3). For the 1971–2000 climate summary period at the three weather stations listed in table 1, the average maximum daily temperature was 68.7 degrees Fahrenheit (˚F), and the average minimum daily temperature was 36.4 ˚F (Allander and others, 2009). Small amounts of precipitation fall year round on the valley floor, with a slightly uneven monthly distribution (Allander and others, 2009). In the valleys, most annual precipitation occurs as rain, and occasionally snow, during winter and spring storms. During summer, infrequent but sometimes powerful convective storms can produce destructive flash floods (Hess and Glancy, 2000). Precipitation in the mountains is greater and has a more seasonal distribution with orographic enhancement of winter storm systems; snow pack is present in the Wassuk Range during most winters. Using the 1971–2000 annual normal precipitation relation for the Walker precipitation zone derived by Lopes and Medina (2007) and an average valley bottom altitude of 4,055 ft results in an estimated annual precipitation of 4.5 inches (in.), which is similar to 1971–2000 precipitation normal for the Hawthorne weather station (4.5 in.; Western Regional Climate Center, 2013a). The maximum 1971–2000 annual normal precipitation on Mount Grant was estimated to be 16.5 in. at an altitude of about 11,250 ft. There are no high-altitude precipitation gages near the study area for verification of that value.

Vegetation Communities

Natural vegetation in the study area can be characterized by three main vegetation zones: (1) a riparian zone that extends along nearly the entire reach of the lower Walker River and adjacent to the south side of Walker Lake in an area of groundwater discharge, and along small perennial reaches of local streams within the Wassuk Mountains; (2) a scrubbrush zone that dominates the valley floors of the study area outside of the riparian zone (generally below an altitude of 5,500 ft); and (3) a pinyon-juniper woodland zone that dominates areas at altitudes ranging from about 5,500 to 9,000 ft in the Wassuk and Gillis Ranges.

The riparian community persists in areas with an abundance of available water from streams, shallow groundwater, or both. Vegetation in the riparian zone can be dense and lush, including trees such as *Populus fremontii* (Fremont cottonwood) and *Elaegnus angustifolia* (Russian olive). The dominant types of shrubs and grasses include *Salix* spp. (willow), *Chrysothamnus* spp. (rabbitbrush), *Sarcobatus vermiculatus* (greasewood), and *Distichlis spicata* (saltgrass).

Along the lower part of the Walker River between Schurz and Walker Lake at about the altitude of the 1882 shoreline (4,082 ft, local datum; Lopes and Smith, 2007), the soils become more alkaline, and the riparian vegetation abruptly transitions to *Tamarix ramosissima* Ledeb (saltcedar). Saltcedar, also known as tamarisk, is listed by the State of Nevada as a noxious and invasive weed (Nevada Department of Agriculture, 2005; Natural Resources Conservation Service, 2008) because it is non-native and difficult to control. The health and vigor of the saltcedar community has declined substantially as a result of the introduction of the saltcedar leaf beetle as a biological control agent. Adjacent to the saltcedar are large areas of greasewood, rabbitbrush, and saltgrass.

The scrubbrush zone persists in areas in which little or no water is available from either streams or groundwater. This community relies mostly on soil moisture from direct precipitation for its water needs, but in some areas groundwater can be used if depths to water are within reach of the plants root system. The vegetation in the scrubbrush zone can be characterized as moderate to very sparse density of predominately greasewood, *Artemisia tridentata* (big sagebrush), and rabbitbrush.

The pinyon-juniper woodland vegetation grows at moderate altitudes (5,500 to 9,000 ft) within the study area, where precipitation ranges from about 10 to 15 in/yr (Houghton and others, 1975). This vegetation community is dominated by *Pinus monophylla* (pinyon pine trees) and *Juniperus* spp. (juniper trees), as well as sagebrush in open areas and between the trees. Vegetation in the pinyon-juniper woodland community mainly relies on precipitation for its water needs.

Agricultural vegetation in the study area is dominated by flood- and sprinkler-irrigated alfalfa and, to a much lesser extent, irrigated turf. Most of the irrigated crops in the study area are on the Walker River Indian Reservation; the remainder is in the Whiskey Flat area. During the 2007 growing season (May–October), the Walker River Paiute Tribe began reconstructing the Weber Reservoir dam and, as a consequence, fallowed their fields until the construction was completed and irrigation resumed in 2011. Most of the irrigated turf is a small 9-hole golf course adjacent to the Hawthorne Army Depot near Hawthorne. Smaller areas of turf are in Hawthorne at schools, government facilities, and private residences.

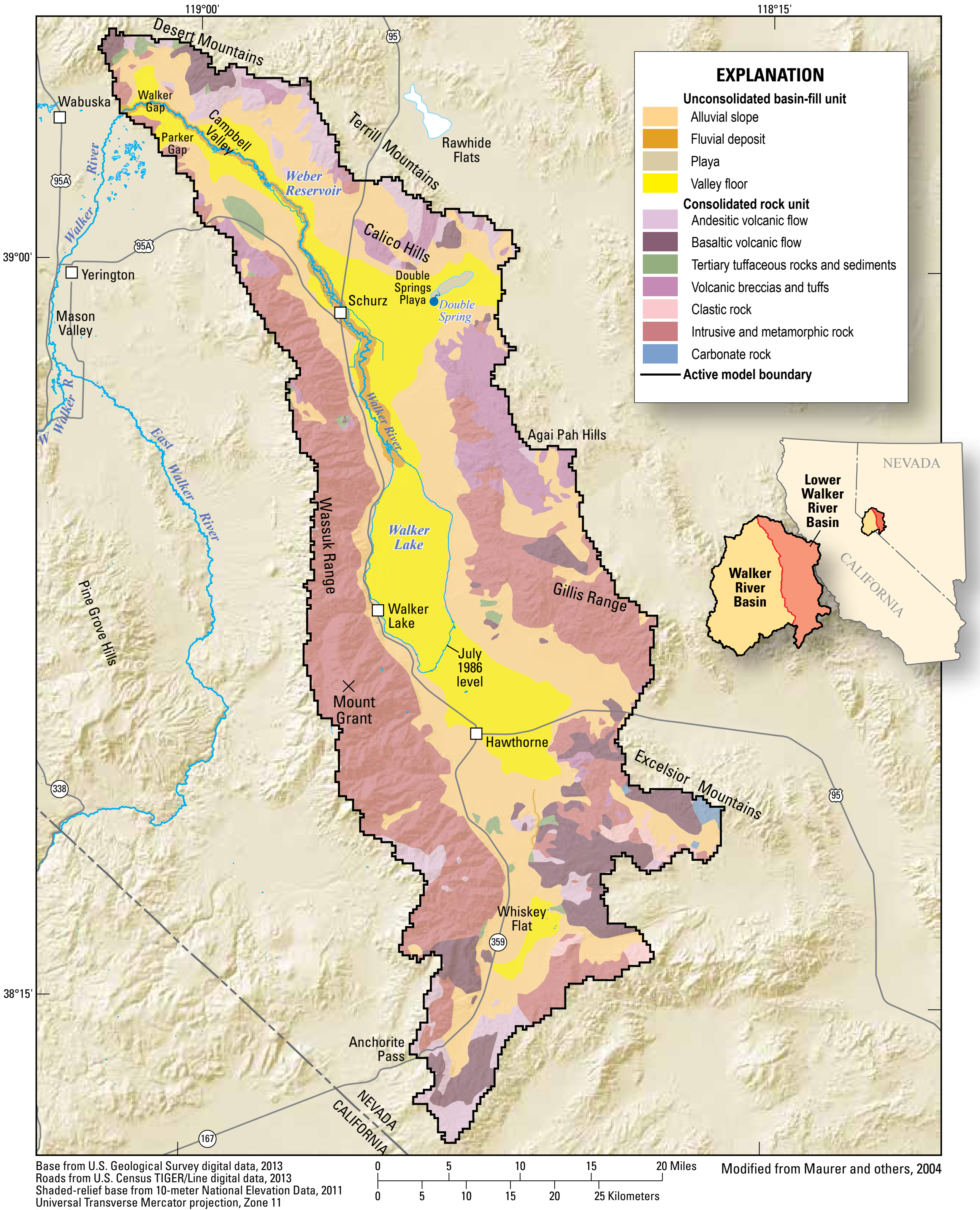
Hydrogeology

The hydrogeology of the lower Walker River Basin is fairly typical of perennial river basins within the Basin and Range Physiographic Province and is characterized by Maurer and others (2004). However, not much is known about the geometry and thicknesses of the hydrogeologic units, and development of a detailed hydrogeologic model of the lower Walker River Basin was beyond the scope of this project. A summary of the hydrogeology of the lower Walker River Basin is provided by Lopes and Allander (2009a). The discussion that follows is a brief summary of the “Hydrogeologic Units” section from Lopes and Allander (2009a) but modified to pertain specifically to this work.

The work of Maurer and others (2004) is used to characterize the hydrogeologic units in the study area. The hydrogeologic units are divided into two main units: consolidated rocks and unconsolidated sediments. Consolidated rocks form the mountains that separate basins where unconsolidated sediments are deposited. Maurer and others (2004) further subclassified consolidated rock units into eight hydrogeologic units and unconsolidated sediments into four hydrogeologic units. The distribution of the hydrogeologic units in the lower Walker River Basin is shown in figure 5.

Consolidated rock hydrogeologic units present in the lower Walker River Basin include carbonate rocks, Quaternary- to Tertiary-aged basalt, Quaternary- to Tertiary-aged andesite, volcanic breccias and tuffs, intrusive and metamorphic rocks, Tertiary tuffaceous rocks and sediments, and clastic rocks. Andesite, volcanic breccias and tuffs, intrusive and metamorphic rocks, Tertiary tuffaceous rocks and sediments, and clastic rock units are all considered to have very low horizontal hydraulic conductivities (Maurer and others, 2004). Carbonate rocks, basaltic flows, and highly fractured rocks are considered to have low horizontal hydraulic conductivities.

Almost the entire Wassuk Range and the southern half of the Gillis Range are composed of intrusive and metamorphic rocks (Maurer and others, 2004). The northern one-half of the Gillis Range, parts of the Calico Hills, and the northern end of the Wassuk Range consist of volcanic breccias, welded tuffs, and volcanic rocks older than Tertiary age. Andesitic and basaltic volcanic flows compose most of the Excelsior and Desert Mountains, Anchorite Hills, parts of the Calico Hills, and Parker Butte south of the Wabuska streamgage. Minor amounts of carbonate rocks occur along the southeastern edge of the basin. Tertiary tuffacious rocks crop out in alluvial fans in the north, south, and eastern parts of the alluvial basin. Clastic rocks crop out in a few locations in the Excelsior Mountains.



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Modified from Maurer and others, 2004

Figure 5. Hydrogeologic units in the lower Walker River Basin, west-central Nevada.

All four of the unconsolidated sediment types differentiated by Maurer and others (2004) are present in the lower Walker River Basin. These include alluvial slope sediments, fluvial deposits, valley floor sediments, and playas (fig. 5).

Alluvial slope sediments are unconsolidated with a slope greater than 3 percent deposited along the flanks of mountain ranges adjacent to valley floors (Maurer and others, 2004). The regions where alluvial slope sediments accumulate are commonly referred to as alluvial fans or piedmont slopes. The depositional environment where alluvial slope sediments accumulate is the area of transition from high energy mountain streams to lower energy as water spreads toward the valley bottoms. Sediment textures that form alluvial slopes transition from coarse deposits near the apex to finer deposits near the base. Textural sorting increases from the apex to the base with little stratification. In general, alluvial slopes are an area of aggradation, which, over time, causes the stream to wander and deposit sediments across the slope, giving them their characteristic “fan” shape. Alluvial slope sediments have a relatively high vertical hydraulic conductivity, compared to valley floor sediments (Maurer and others, 2004). Alluvial slopes can be an area of relatively high groundwater recharge, depending on the magnitudes and durations of intermittent flows that cross them (Prudic and others, 2007). In the lower Walker River Basin, alluvial slopes extend from the eastern flank of the Wassuk Range to valley floors or fluvial deposits along the Walker River and from the Wassuk and Gillis Ranges into the western and eastern sides of Walker Lake (fig. 5).

Fluvial deposits are sediments that have been deposited by flowing water and generally have a higher degree of sorting and coarser texture. Fluvial deposits generally have greater horizontal hydraulic conductivities than those of the other unconsolidated sediments. Fluvial deposits in the lower Walker River Basin generally occur along the valley bottom adjacent to and beneath Walker River.

Valley floor sediments are unconsolidated with a slope of less than 3 percent, except where intersected by fluvial deposits and playas (Maurer and others, 2004). Valley floor sediments generally consist of interbedded layers of fine-grained and coarse-grained sediments (Lopes and Allander, 2009a). Coarse sediments likely were deposited by Walker River, beach deposits by Walker Lake, and dune deposits by eolian processes downwind from dry lake beds. Fine-grained deposits are likely lacustrine deposits from Walker Lake and ancient Lake Lahontan. Fine-grained deposits are probably horizontally continuous throughout the valley floor sediments, except where strata have been eroded by the Walker River and except for valley floor sediments above the historical high stand of ancient Lake Lahontan. Valley floor sediments generally have relatively high horizontal hydraulic conductivities that are an order of magnitude greater than hydraulic conductivities in the vertical direction. The high degree of anisotropy is due in large part to the interbedded layering of lacustrine deposits from the ancient lakes. Valley floor sediments in the lower Walker River Basin occur along the valley adjacent to Walker River, in the Double Spring area east of Schurz, Nev., southeast of Walker Lake, and in Whiskey Flat (fig. 5).

Playas are relatively flat surfaces, commonly void of vegetation, that occupy valley floors that originate from repeated desiccation of ephemerally pooled water bodies. A playa is generally a flat surface of clay or very fine sediment with very high salt content. Horizontal hydraulic conductivities of playas are extremely low, restricting exchange of water between the surface and the ground, except through transpiration by phreatophytic vegetation along their peripheries. The only playa in the lower Walker River Basin is at Double Spring, 6 mi. east of Schurz, Nev. (figs. 3 and 5). The Double Springs playa is a flat surface of clay with a thin salt crust and salt grass growing near Double Springs and Double Springs well, both on the west side of the playa. Surface runoff from the northern Agai Pah Hills and southern Terrill Mountains runs onto the playa and evaporates.

The depth to basement and thickness of unconsolidated sediments in the lower Walker River Basin are largely unknown. Drillers’ reports available from the Nevada State Engineers office were examined for holes drilled through basin fill into basement rock. There is only one known well that penetrates through the basin fill into basement rock, and that is located fairly close to the boundary with consolidated rock. There have been many wells drilled to 500 ft that do not penetrate basement, which indicates basin-fill thickness is greater than 500 ft at these locations. Additional work has been conducted to estimate basin-fill thickness using surface geophysical methods at selected locations. Schaefer (1980) used seismic reflection to estimate the thickness of basin fill at various locations on Walker River Indian Reservation. Lopes and Allander (2009a) used seismic refraction to estimate the thickness of basin fill near Double Springs and south of Walker Lake on the Army Depot. These data, as well as a single depth estimate from a cross section by Blair and McPherson (1994), are summarized in table 2. The estimated basin-fill thickness ranged from 600 to 2,000 ft with an average of 1,180 ft.

Hydraulic Properties

Hydraulic properties of the unconsolidated sediments have been estimated in a number of previous studies. In 1967, Everett and Rush (1967) estimated specific yield of the unconsolidated sediments to range from 0.10 to 0.15. Schaefer (1980) estimated specific yield of the unconsolidated sediments north of Walker Lake on the Walker River Indian Reservation to range from 0.06 to 0.25 with a mean of about 0.14 and estimated horizontal hydraulic conductivity to range from 1 to 92 ft/d with an average of 34 ft/d. Lopes and Allander (2009a) used slug tests from observation wells to estimate the horizontal hydraulic conductivity of unconsolidated sediments. Slug tests yielded a range of horizontal hydraulic conductivity estimates at the Army Depot of 2 to 100 ft/d with a mean of 30 ft/d; north of Walker Lake and outside of the Walker River floodplain, 0.2 to 30 ft/d with a mean of 7 ft/d; and along the Walker River flood plain, 1 to 200 ft/d with a mean of 70 ft/d. Lopes and Allander (2009a) used a single-well aquifer test to estimate a horizontal hydraulic conductivity of 8 ft/d

Table 2. Estimates of basin-fill thickness with approximate locations and reference source, lower Walker River Basin, west-central Nevada.

[UTM, Universal Transverse Mercator projection]

Site or other identifier	Basin-fill thickness (feet)	Basin-fill thickness (meter)	Approximate location of depth estimates		Reference
			UTM easting	UTM northing	
WR-11	1,020	310	349200	4317400	Schaefer, 1980
WR-2	1,420	430	335200	4329900	Schaefer, 1980
WR-10	900	270	357000	4319800	Schaefer, 1980
DS Line3	890	270	352500	4310800	Lopes and Allander, 2009a
WR-3	1,300	400	341800	4325100	Schaefer, 1980
DS Line1	1,025	310	350200	4315500	Lopes and Allander, 2009a
WR-9	1,150	350	363000	4314000	Schaefer, 1980
Figure 3 cross section	2,000	610	347900	4301200	Blair, 1994
WR-1	1,150	350	331800	4331500	Schaefer, 1980
WR-8	600	180	355700	4314600	Schaefer, 1980
HAAD Line1	1,500	460	356900	4273900	Lopes and Allander, 2009a
WR-4	830	250	338100	4322900	Schaefer, 1980
DS Line4	1,600	490	352900	4313800	Lopes and Allander, 2009a
Average	1,180	360			
Minimum	600	180			
Maximum	2,000	610			
Median	1,150	350			

at the Double Springs well and a multiple-well aquifer test at an irrigation supply well 4 mi. south of Schurz to estimate a horizontal hydraulic conductivity of 50 ft/d with a vertical anisotropy (horizontal hydraulic conductivity/vertical hydraulic conductivity) of about 5.

Estimates of Groundwater Recharge

Groundwater recharge derived from precipitation in the lower Walker River Basin was estimated to provide constraints for the watershed and groundwater flow model calibrations. These estimates, made for the six subbasins of the lower Walker River Basin, were needed to calibrate and constrain the PRMS model (discussed in section “Simulation of Runoff and Groundwater Recharge”). Five estimates of recharge were made using a variety of methods and the 1971–2000 Precipitation-elevation Regressions on Independent Slopes Model precipitation distribution (PRISM; Daly and others, 1994) and are summarized in table 3. The five estimates are precipitation threshold estimate, minimum estimate, reasonable estimate, maximum estimate, and a modified Maxey-Eakin estimate. Table 3 also includes simulated recharge from the PRMS model for comparison.

The precipitation threshold estimate is a simple estimation that relates overall recharge to the volume of precipitation in excess of a threshold value and is analogous to the method used by Halford and Plume (2011). For this method, a threshold precipitation rate of 12 inches per year (in/yr) was used. This threshold was arbitrarily chosen on the basis of an estimated annual evapotranspiration of 12 in/yr (rounded) for a pinion and juniper vegetation zone when sufficient water is available (Thodal and Tumbusch, 2006). It was assumed that, in areas with annual precipitation of less than 12 in., the entire quantity of precipitation is lost through evapotranspiration in any given year. This method provides a very quick general estimate of the magnitude of recharge for a given area but is likely highly inaccurate with no associated estimates of uncertainties. This method yielded an overall recharge estimate for the lower Walker River Basin of about 21,000 acre-ft/yr.

The “minimum,” “reasonable,” and “maximum” estimates in table 3 are based on the range of annual recharge rates reported for other hydrographic basins in the Great Basin (Berger, 2000; Nichols, 2000) with perceived similarities to the subbasins described in this report. The minimum rates selected ranged between 0.12 to 0.60 in/yr. The minimum recharge estimate for the lower Walker River Basin was about 11,000 acre-ft/yr. The maximum rates, used as an upper bound for an acceptable recharge estimate, ranged from 0.48 to 1.8 in/yr. The maximum recharge estimate for the lower Walker River Basin was about 53,000 acre-ft/yr. The “reasonable” estimates, which are considered to be mid-range estimates, ranged from 0.24 to 1.2 in/yr. The “reasonable” recharge estimate for the lower Walker River Basin was about 29,000 acre-ft/yr at a rate of 0.36 in/yr.

The modified Maxey–Eakin estimate is based on a method described by Nichols (2000). This method is based on the same concept as the original method (Maxey and Eakin, 1949; Eakin and others, 1951), using the premise that the percentage of precipitation that goes to groundwater recharge increases

Table 3. Estimated recharge and Precipitation-Runoff Modeling System (PRMS) simulated recharge for the lower Walker River Basin and subbasins, west-central Nevada.

[All recharge estimates are in acre-feet per year; Except for simulated value, total recharge estimates for lower Walker River basin are the sum of subbasin recharge estimates and are rounded to nearest thousand acre-feet per year]

Subbasin name	Precipitation threshold estimate	Minimum estimate	Reasonable estimate	Maximum estimate	Modified Maxey-Eakin estimate	PRMS simulated recharge
Cottonwood Creek	4,200	430	1,000	1,700	1,700	701
Rose Creek	1,600	270	540	810	620	66
Hawthorne	4,000	3,600	11,000	18,000	4,300	9,049
Wildhorse Canyon	200	420	850	1,700	770	1,041
Wassuk	11,000	2,300	7,000	14,000	6,200	8,214
Gillis	190	4,400	8,700	17,000	790	6,054
Total						
Lower Walker River Basin	21,000	11,000	29,000	53,000	14,000	25,125

as a function of altitude. The original and modified Maxey–Eakin methods derive recharge estimates by accumulating precipitation over precipitation zones and then multiplying by a recharge coefficient for each of the zones. The recharge coefficients derived for the Maxey–Eakin method were originally developed using precipitation estimates derived from the Hardman (1936) precipitation map. Nichols (2000) revised the recharge coefficients using precipitation estimates derived from the PRISM map (Daly and others, 1994). The recharge estimate for the lower Walker River Basin made using the modified Maxey–Eakin method is about 14,000 acre-ft/yr. Recent evaluations of empirical methods used to estimate recharge in Nevada desert basins (Epstein and others, 2010) indicate the modified Maxey–Eakin method tends to estimate greater recharge than the original Maxey–Eakin method and the bootstrap brute-force recharge model (BBRM). The BBRM is an alternative method for estimating recharge that is similar in application to the original and modified Maxey–Eakin methods (Epstein and others, 2010). The estimated recharge for the lower Walker River Basin from Epstein and others (2010; hydrographic areas (HA's) 110A, 110B, and 110C) using the BRRM was 26,400 acre-ft/yr, which is nearly double the estimate from the modified Maxey–Eakin method (14,000 acre-ft/yr).

Each of these methods yielded a disparity of recharge estimates. This is the nature of using simplified empirical approaches for estimating recharge.

Simulation of Runoff and Groundwater Recharge (PRMS Model)

The lower Walker River hydrologic system can be conceptualized as the integration of climate, surface-water, and groundwater processes. The development of the PRMS watershed model is discussed in this section and is shown in context with the overall modeling strategy in figure 6.

Runoff and groundwater recharge in the lower Walker River Basin was estimated using PRMS (Leavesley and others, 1983; Leavesley and others, 2005; Markstrom and others, 2008) to simulate interactions among temperature, precipitation, evapotranspiration, and land use. PRMS is a process-based, distributed-parameter modeling system that simulates streamflow hydrographs and hydrologic water budgets at the watershed and subwatershed (referred to as "subbasins" in this report) scale. The streamflow hydrograph conceptually is composed of three principle components: a rapid response from surface runoff to the stream, a delayed and somewhat prolonged response from shallow subsurface interflow to a stream (sometimes referred to as interflow), and a very delayed and seasonal base flow as a result of groundwater discharge to the stream. Additional information on PRMS is available from Markstrom and others (2008) and *http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html* (accessed February 1, 2013).

The lower Walker River Basin PRMS (LWR_PRMS) model provides the atmospheric and land-surface hydrologic components for the GSFLOW model and groundwater recharge estimates for the MODFLOW model. The PRMS model is run in two different modes, depending on whether it is being run by itself (PRMS-only mode) or along with MODFLOW using GSFLOW (integrated mode).

PRMS simulates subsurface processes in a simplistic manner using conceptual reservoirs to represent water storage in soil, subsurface, and groundwater in what are called the preferential-flow, gravity, capillary, and groundwater reservoirs (fig. 13, Markstrom and others, 2008). The LWR_PRMS simulates runoff across the landscape and shallow subsurface interflow using a cascade routing procedure. The cascade

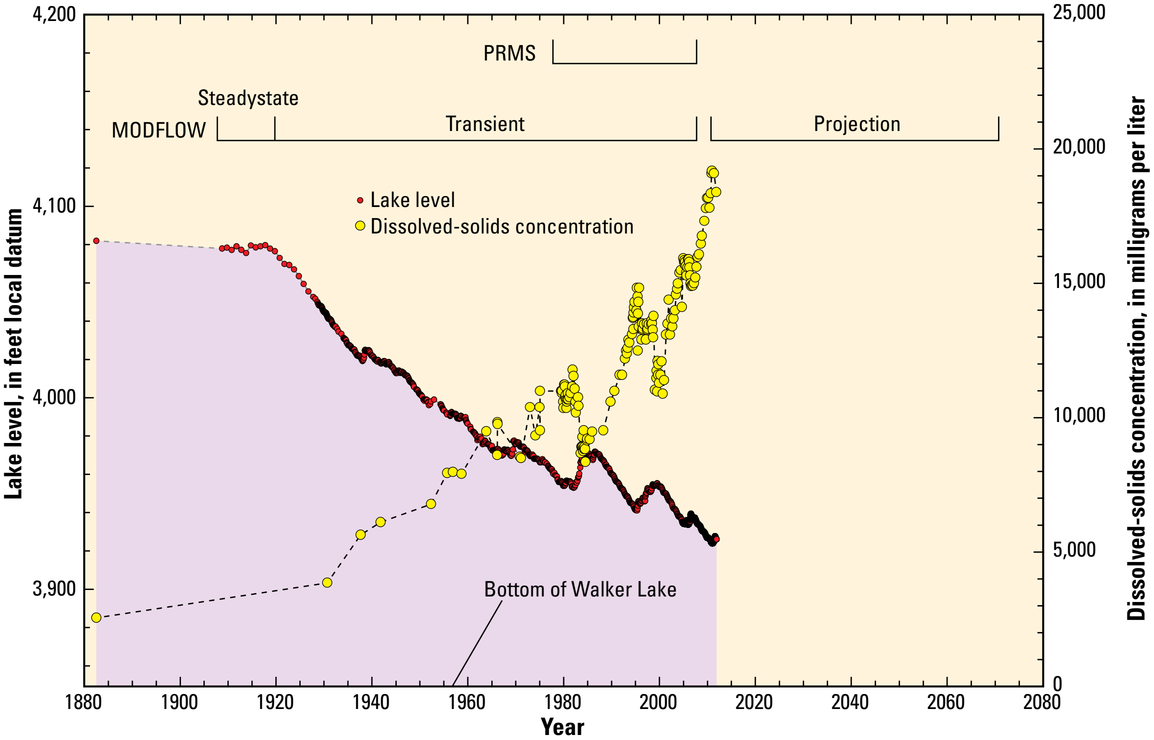


Figure 6. Simulation periods of stand-alone PRMS and MODFLOW models and lake levels with dissolved-solids concentrations for Walker Lake, west-central Nevada.

routing procedure defines the flow paths between the hydrologic response units of the PRMS model and is discussed in Henson and others (2013). The cascading procedure requires a stream network (which is consistent with stream network used in MODFLOW model) to collect cascading flows and route them through the drainages. A major limitation of PRMS is that once cascading flows are collected in the stream segments, the flow cannot subsequently infiltrate to groundwater and is routed directly to the end of each segment. Therefore, once flow reaches a stream segment, it accumulates (increases) as it moves downstream, resulting in unrealistically high runoff from the drainages. The runoff computed by PRMS approximates the quantity of runoff that originates from the respective drainage areas and does not consider losses that occur as water moves through ephemeral channels.

The PRMS model uses basin-wide parameters (nondistributed parameters) to specify constant numeric values used in hydrologic process calculations and uses hydrologic response unit (HRU)-dependent parameters (distributed parameters) to represent spatially varying hydrologic characteristics that are defined for individual HRUs. HRUs are model areas with similar physiographic properties, such as altitude, slope, aspect, vegetation, soil, geology, and climate that affect hydrologic responses.

The LWR_PRMS includes six subbasins that compose the lower Walker River Basin. Each individual subbasin model was developed and calibrated prior to being combined into the full LWR_PRMS. Most HRU-dependent parameters were independently determined and computed from digital datasets, whereas some were determined through model calibration. Climate data were compiled from nearby weather stations. Limited streamflow data were compiled along with groundwater recharge estimates and idealized ephemeral hydrographs to calibrate the subbasin models. Idealized ephemeral hydrographs are conceptualized hydrographs from ungaged basins, in which only anecdotal evidence of flow is available, characterized by virtually no base flow and little to no flow most of the time, except during infrequent flow events associated with individual large storms or rapid snowmelt. Model parameters were initially assigned using parameters from similar characteristic watersheds but were revised through calibration.

The LWR_PRMS was used to estimate overall water-budget components for each of the subbasins and the lower Walker River Basin and to develop a representative distribution of mean annual recharge for later use and rescaling with the MODFLOW model. Although recharge could be estimated on a monthly or seasonal time scale using the PRMS model, the PRMS model does not simulate the same period as the MODFLOW model (fig. 6). It is assumed that the mean annual recharge for the 30-year period of the PRMS model is representative of the mean annual recharge for the 89-year period of the transient MODFLOW model.

Model Design

The LWR_PRMS uses the same basin delineation of the lower Walker River Basin as the MODFLOW model (fig. 3), except Weber Reservoir and Walker Lake were omitted from the PRMS model domain. The Walker Lake area omitted is based on the July 1986 extent (fig. 7), which was the greatest extent of the lake between 1978 and 2007. The HRUs were delineated as 400-x-400-meter (m) grid units that coincided with the MODFLOW grid. The LWR_PRMS represents the 30-year period of 1978 through 2007 (fig. 6). However, the model begins simulation 5 years prior to 1978 (1973 through 1977) to “condition” the simulation by providing a period of time to adjust antecedent hydrologic conditions at the start of the calibration and simulation period, 1978. The LWR_PRMS required delineation of a stream network to route flow, delineation of subbasins to assist with determination of model parameters through calibration, and assembly of climate data needed to drive the model.

Stream Network

A stream network was used with the PRMS model to help define subbasins and provide a destination for cascading flows from the subbasins (fig. 7). The stream network represented the main-stem of the Walker River and significant tributary drainages and was generated from a composite 40-m digital elevation model (DEM) using a geographic information system (GIS).

The composite 40-m DEM was developed from a 10-m DEM of the area obtained from the National Elevation Dataset (NED; U.S. Geological Survey, 1999), a 5-m DEM of Walker Lake bathymetry from Smith (2008), and a DEM of Weber Bathymetry derived from Katzer and Harmsen (1973). The 5-m DEM was resampled to 10-m DEM, coinciding with the NED DEM, and then merged with the NED DEM. This DEM was then resampled to develop the composite 40-m DEM. The composite 40-m DEM was modified so there were no local depressions, except the broad topographic depressions that are occupied by Walker Lake and Double Springs playa.

The stream network was derived from the composite 40-m DEM using flow direction and flow accumulation grids. The flow direction from each cell was determined by finding the adjacent or diagonal cell with steepest descent downgradient. These flow directions were combined into the flow direction grid. The flow direction grid was then used to determine the number of upstream cells that were contributing to each cell. The number of cells contributing flow to each cell was combined into the flow accumulation grid.

The flow accumulation grid was used along with selective delineation of some tributary streams to derive the stream network. Initially, a relatively dense stream network was defined on the basis of a minimum of 4,000 contributing cells. This dense network was then simplified by selectively removing less important tributaries until the network represented the more important tributary drainages of the lower Walker River Basin. Additionally, main tributary channels were shortened so they extended only about three-quarters up their respective drainages into the mountains. In order to accurately delineate the upstream part of Walker River within the lower Walker River Basin, the same general procedure discussed above was used with a DEM for the entire Walker River Basin rather than just the lower Walker River Basin.

Subbasins

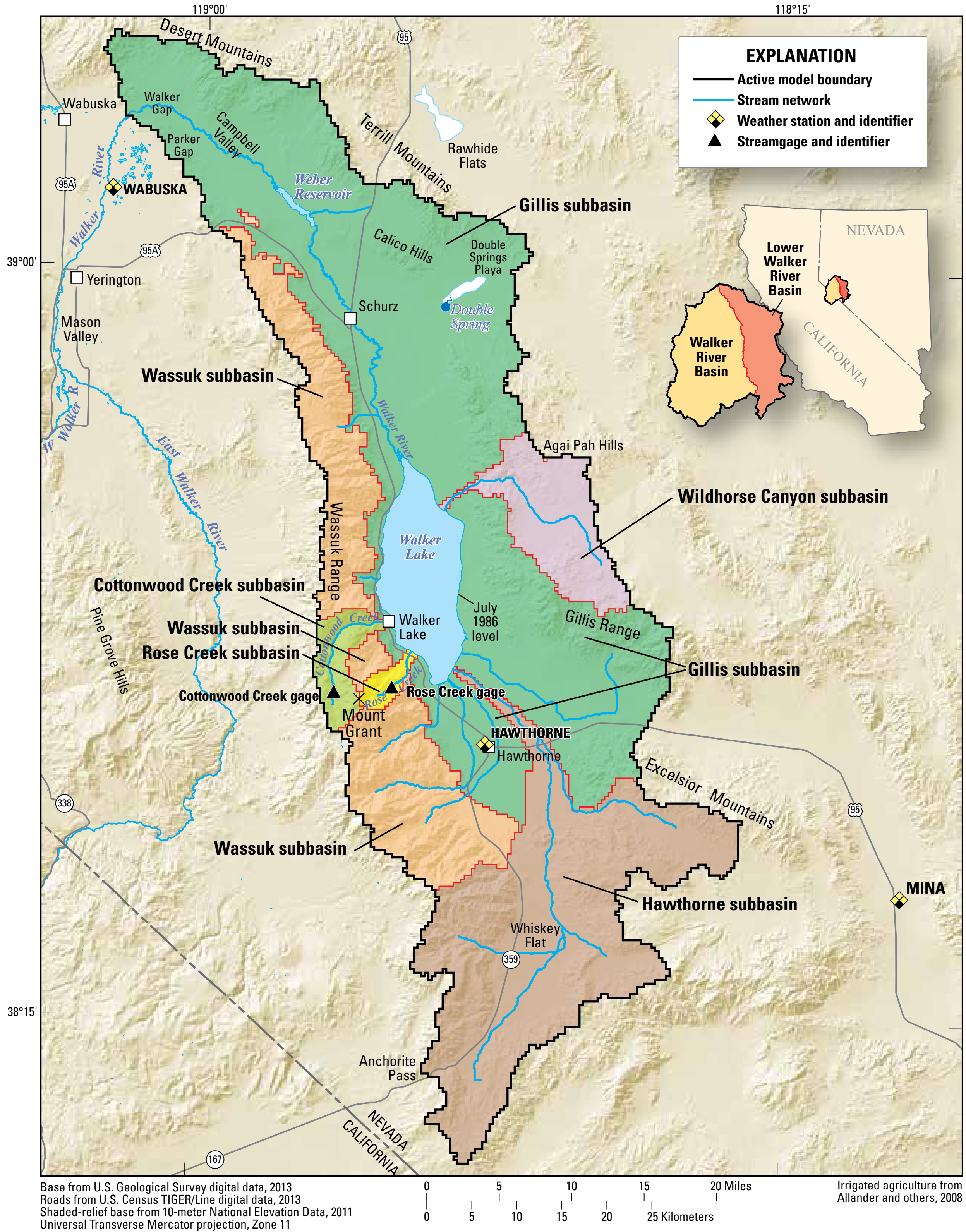
The LWR_PRMS includes six subbasins that compose the lower Walker River Basin, excluding the July 1986 extent of Walker Lake (fig. 7, table 4). Two of the subbasins are gaged perennial-stream subbasins (Cottonwood Creek and Rose Creek), and the other four are ungaged ephemeral-stream subbasins. The four ungaged ephemeral-stream subbasin models represent a large area in the southern part of the lower Walker Basin referred to here as the Hawthorne subbasin, Wildhorse Canyon subbasin, a large area representing the eastern side of the Wassuk Range that is referred to as the Wassuk subbasin, and another large area representing the valley floor and western side of Gillis Range referred to as the Gillis subbasin.

The subbasins Cottonwood Creek, Rose Creek, Hawthorne, and Wildhorse Canyon were delineated as the topographic basins that drain to downstream points where their respective drainages intersect with the July 1986 surface of Walker Lake. The Wassuk subbasin was delineated as the consolidated rock area of the Wassuk Range with Cottonwood Creek, Rose Creek, and Hawthorne subbasins removed. The Gillis subbasin area was the area of the lower Walker River Basin not occupied by the other subbasins or Walker Lake. The composite 40-m DEM was used to delineate the subbasins (fig. 7).

The Cottonwood Creek subbasin (14,550 acres; table 4) is in the Wassuk Range and contains one of the few perennial tributaries in the study area (fig. 7). The bedrock of this subbasin is considered to have mostly very low permeability because of the presence of primarily intrusive or metamorphic rock, except along stream channels where fluvial deposits are present. Altitude ranges from around 4,000 ft near the watershed outlet at Walker Lake to greater than 11,000 ft on Mount Grant. Although Cottonwood Creek is gaged (USGS streamgage 10302160; table 1), the location of the streamgage is roughly two-thirds of the way upstream from the channel outlet at Walker Lake, and the streamflow record is very limited (May 2005 through September 2007). Runoff was generally less than 1 cubic feet per second (ft^3/s) with spring flows around 2–3 ft^3/s. Precipitation from PRISM (Daly and others, 1994) ranges between 5.3 and 23.3 in/yr (table 4).

Rose Creek subbasin (5,061 acres) shares the Mount Grant boundary with Cottonwood Creek and has similar bedrock geology (fig. 7). The gaging station for Rose Creek (USGS streamgage 10302145; table 1) is also about two-thirds of the way upstream from the watershed outlet to Walker Lake, and the streamflow record is also very limited (May 2005 to September 2007). Similar to Cottonwood Creek subbasin, runoff is generally less than 1 ft^3/s with higher spring runoff flows between 2 and 3 ft^3/s. Precipitation from PRISM ranges between 4.9 and 23.2 in/yr (table 4).

Hawthorne subbasin (179,299 acres) is an ephemeral system in the southern part of the lower Walker River Basin that drains the southern end of the Wassuk Range to the west and the low highlands to the east (fig. 7). Altitudes range from around 4,000 ft to 10,000 ft with a few peaks near 11,000 ft, though most of the basin lies well below 7,000 ft. Precipitation



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Irrigated agriculture from Allander and others, 2008

Figure 7. Location of the modeled subbasins, weather stations, streamgages and selected geographic features, lower Walker River Basin, west-central Nevada.

Table 4. Lower Walker River Basin and subbasin designations, dominant recharge zone, range in precipitation, and indexed weather stations used for distributing climate data, lower Walker River Basin, west-central Nevada.

[PRISM, Precipitation-elevation Regressions on Independent Slopes Model (Daly and others, 1994)]

Subbasin name (figure 7)	Area (acres)	Gaged or ungaged subbasin	Perennial or ephemeral subbasin	PRISM estimated precipitation range (inches per year)	Indexed weather stations (figure 8)
Cottonwood Creek	14,550	Gaged	Perennial	5.3–23.3	Hawthorne
Rose Creek	5,061	Gaged	Perennial	4.9–23.2	Hawthorne
Hawthorne	179,299	Ungaged	Ephemeral	4.5–17.6	Hawthorne and Mina
Wildhorse Canyon	41,909	Ungaged	Ephemeral	4.8–13.7	Hawthorne
Wassuk	116,870	Ungaged	Ephemeral	5.9–22.9	Hawthorne and Wabuska
Gillis	400,665	Ungaged	Ephemeral	4.3–13.7	Hawthorne and Wabuska
Total					
Lower Walker River Basin	758,353	Mostly Ungaged	Mostly Ephemeral	4.3–23.3	Hawthorne, Wabuska, and Mina

from PRISM ranges from 4.5 to 17.6 in/yr (table 4) with most of the subbasin receiving between 7 and 10 in/yr.

The Wildhorse Canyon subbasin (41,909 acres) represents a single ephemeral drainage basin in the Gillis Range (fig. 7). Altitudes range from 4,000 ft to 7,600 ft. This subbasin is much drier than Cottonwood Creek and Rose Creek subbasins but does occasionally generate substantial flows during infrequent large rain events. Precipitation from PRISM ranges from 4.8 to 13.7 in/yr. PRMS parameters for the Wildhorse Canyon and Gillis Subbasins are similar.

The Wassuk subbasin (116,870 acres) is the remainder of the Wassuk Range with Cottonwood Creek, Rose Creek, and Hawthorne subbasins removed and contains both ephemeral and perennial drainage basins (fig. 7). Altitudes range from 4,000 ft to around 11,000 ft. Precipitation from PRISM ranges from 5.9 to 22.9 in/yr.

The Gillis subbasin (400,665 acres) is the remainder of the lower Walker River Basin with all other subbasins and the July 1986 extent Walker Lake removed. It includes most of the Gillis Range and most of the valley floors, and contains only ephemeral drainage basins (fig. 7). Altitudes range from near 4,000 ft to almost 8,000 ft. Precipitation from PRISM (Daly and others, 1994) ranges from 4.3 to 13.7 in/yr. Although the Gillis subbasin contains the Walker River, flow in the river was not simulated, except for flows originating from runoff and precipitation within the lower Walker River Basin.

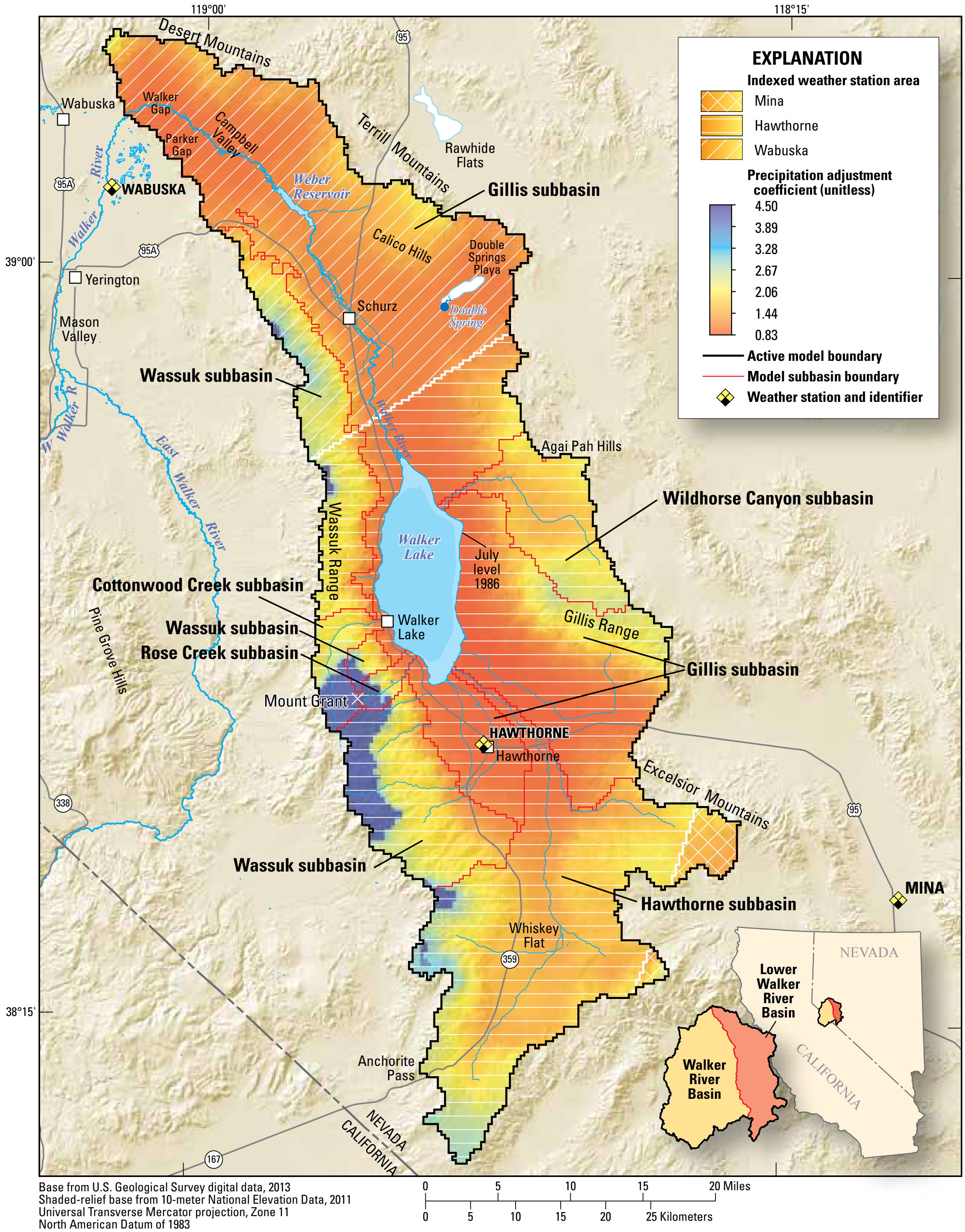
Determination of HRU-Dependent and Basin-Wide Parameters

HRU-dependent parameters are used for distributing climate data to the watershed and characterizing watershed and soil properties that affect the routing of water over land or through the soil zone, subsurface, and groundwater reservoirs. For a full list of HRU-dependent parameters and source of values, see table 4 in Jeton (2000); for a detailed description of the parameters, see Markstrom and others (2008).

Daily climate data, including minimum and maximum air temperature, precipitation, and potential evapotranspiration (PET), were distributed from weather stations to individual HRUs using HRU-dependent parameters referred to as "adjustment coefficients." The distribution of temperature adjustment coefficients was based on vertical lapse rates that correspond to cooling of air temperature for every 1,000-ft increase of altitude (2.9–4.4˚F, depending on month). The mean altitude of each HRU was used to calculate an adjustment of the HRU's temperature relative to the altitude of the weather station indexed to the HRU. Minimum and maximum air temperatures for each HRU were calculated by adding the adjustment coefficient to the temperature observed at the indexed weather station. If the altitude of the HRU was greater than that of the indexed weather station, then the temperature adjustment coefficient for the HRU was negative (resulting in cooler temperature); if the altitude of the HRU was less than that of the indexed weather station, the temperature adjustment coefficient for the HRU was positive (resulting in a warmer temperature).

Precipitation adjustment coefficients were determined for each HRU using PRISM (Daly and others, 1994) and are shown in figure 8. Jeton and others (2005) indicated that PRISM overestimates measured precipitation by about 5 percent for the lower Walker River Basin. The mean annual precipitation adjustment coefficient for each HRU was calculated by dividing the estimated mean annual precipitation from PRISM for each HRU by the 30-year (1971–2000) mean annual precipitation for the weather station indexed to that HRU and then decreased by 5 percent to correct for the indicated PRISM bias. The 1971–2000 mean annual precipitation for the reference weather stations was 6.1 for Mina, 4.5 in. for Hawthorne, and 4.8 in. for Wabuska. Daily precipitation was distributed to each HRU by multiplying the precipitation observed at the indexed weather station by the precipitation adjustment coefficient for the HRU.

The distribution of PET adjustment coefficients was determined using Jensen–Haise air-temperature coefficients (Jensen and Haise, 1963; Leavesley and others, 1983). The Jensen–Haise air temperature coefficient was calculated for each HRU using the altitude of the HRU and a regionally estimated minimum and maximum monthly temperature for the warmest



Base from U.S. Geological Survey digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 8. Distribution of precipitation adjustment coefficients used in the LWR_PRMS and areas of weather stations indexed to each hydrologic response unit, lower Walker River Basin, west-central Nevada.

month of the year. The PET for each HRU is calculated using a modified Jensen–Haise formula, which is based on air temperature and is described in Marskstrom and others (2008) and Leavesley and others (1983).

HRU-dependent parameters used for characterizing watershed and soil properties include HRU type, slope, aspect, altitude, soil types, soil water-holding capacity, vegetation types, vegetation canopy densities, and percentage of impervious surface. HRU type defines the HRU as land, lake, swale, or inactive, if outside of the model domain. Slope, aspect, and altitude were derived from the 40-m DEM. Soil types and soil water-holding capacity were derived from the 1:250,000 State Soil Geographic database (STATSGO; U.S. Department of Agriculture, 1991). Vegetation type, canopy densities, and percentage of impervious cover were derived from the 2001 40-m National Land Cover Data (NLCD) database (*http://www.epa.gov/mrlc/nlcd-2001.html*, accessed February 1, 2013). The land cover data reflect 1998–2000 conditions, which are assumed to be constant over the entire simulation period.

HRU-dependent parameters that determine the lateral routing (cascading) of runoff across the surface and interflow through the subsurface are pre-defined flow routes between adjacent HRUs. The cascades procedure used requires HRU altitudes and the stream network. The numerical procedure for calculating cascades was developed as part of this work and is described and documented in Henson and others (2013).

Two HRU-dependent parameters affect the distribution of water within the soil zone reservoirs and groundwater reservoir (*ssr2gw_rate* and *soil2gw_max*) and therefore affect groundwater recharge (see Markstrom and others, 2008, for detailed descriptions). These parameters were adjusted through model calibration, as discussed in more detail later in the "Model Calibration" section.

PRMS simulates runoff as the combination of precipitation rejected from the soil zone and discharge from subsurface and groundwater reservoirs to the streams (see Markstrom and others, 2008, for detailed descriptions). The duration and magnitude of base flow, or for ephemeral subbasins the absence of base flow, and routing of groundwater depends on HRU-dependent parameters *gwsink_coef* and *gwflow_coef,* which were applied by subbasin. The *gwsink_coef* parameter defines the volume of water that infiltrates to groundwater that does not discharge to streams as base flow. This parameter was adjusted for each subbasin to adjust the base-flow component of runoff. The *gwflow_coef* parameter defines the proportion of groundwater in the groundwater reservoir allowed to discharge to streams. The combination of the groundwater that goes to stream base flow and that which is removed from the model using *gwsink_coef* is groundwater recharge (conceptually becoming groundwater outflow from the watershed either by underflow or groundwater evapotranspiration).

Basin-wide parameters were specified as numeric values used in hydrologic process calculations that are constant across HRUs within a subbasin. For a list of basin-wide parameters and source of values, see table 4 in Jeton (2000); for a detailed description of these parameters, see Markstrom and others (2008).

Climate Data

PRMS requires daily precipitation and maximum and minimum air temperature data to distribute temperature, precipitation, and PET to the HRUs. Western Regional Climate Center data were obtained for three weather stations that are in or near the lower Walker River Basin (fig. 3, table 1; Western Regional Climate Center, 2013b). The three weather stations are Wabuska (4,300 ft), Hawthorne (4,275 ft), and Mina (4,550 ft). The weather stations are located near the valley bottom. No high-altitude weather data were available in or near the study area. The common period of available record used from these weather stations is a 35-year period from 1973 to 2007, which coincides with the model simulation period plus the prior 5 years used to establish antecedent hydrologic conditions.

Climate data were processed to address common problems, such as missing data and poor or outlier data. Missing or unreliable data were replaced by estimated data necessary to address measurement and quality flags set by the source agencies, and the data were reformatted to a consistent format needed for analysis and input. Three percent of precipitation and temperature data were missing. Standard linear regression techniques (Helsel and Hirsch, 1995) were used to correlate data between each of the weather stations using monthly regressions for precipitation and temperature time-series data and were used to estimate missing data. Annual precipitation for the three weather stations used in the LWR_PRMS for the model pre-conditioning period (1973–1977) and model calibration period (1978–2007) and the mean annual precipitation for the three weather stations for the model calibration period 1978–2007 are shown in figure 9.

Daily climate data from the three weather stations were distributed to each HRU on the basis of proximity of HRU to nearest weather station and precipitation and temperature adjustment coefficients. Only a single weather station was indexed to each HRU. The weather station indexed to each of the HRUs is shown in figure 8.

Model Calibration

Calibration of the LWR_PRMS was an iterative process of adjusting HRU-dependent and basin-wide parameters, computing simulated runoff and water budgets, and comparing simulation results with estimated water budgets and hydrographs. This procedure was repeated for each subbasin as well as the entire lower Walker River Basin, excluding Walker Lake. The simulations were conducted using daily time steps, but groundwater recharge was computed on a mean annual basis (over the entire simulation period) to compare it with the estimates of annual groundwater recharge in table 3. Accurate simulation of runoff timing was considered less important than the annual water-budget components for this study. Assuming the dominant inflows (precipitation) and outflows (evapotranspiration) from the system are adequately modeled and the net inflows are properly partitioned through the soil

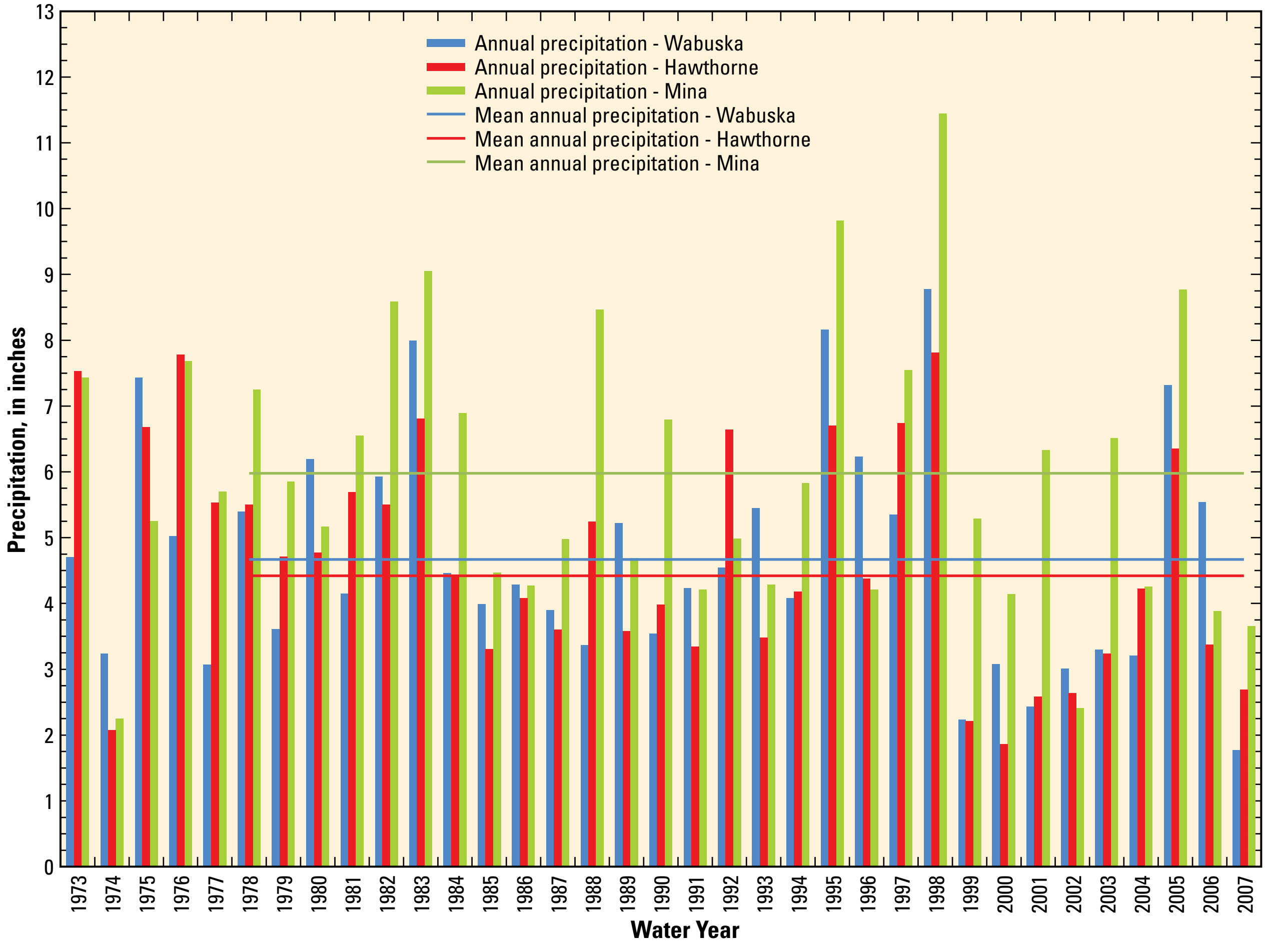


Figure 9. Annual precipitation at the three index weather stations Wabuska, Hawthorne, and Mina, lower Walker River Basin, west-central Nevada, water years 1973–2007, used in LWR_PRMS and mean annual precipitation over the model simulation period water years 1978–2007.

zone, subsurface, and groundwater reservoirs; the simulated hydrograph will have characteristics similar to those of the hydrograph from observed data or an idealized hydrograph, and estimates of groundwater recharge will be reasonable.

Initial HRU-dependent and basin-wide PRMS parameters were based on calibrated parameters for hydrologically similar perennial and ephemeral subbasins in the middle Carson River Basin (Jeton and Maurer, 2011). These parameters were modified as necessary to improve the LWR_PRMS and subbasin PRMS model simulation fits to hydrographs from observed data or idealized hydrographs, water budgets, and groundwater-recharge estimates.

Calibration of the perennial subbasin models (Cottonwood Creek and Rose Creek) was constrained by streamflow data from Cottonwood Creek and Rose Creek streamgages (fig. 7) and estimates of groundwater recharge (table 3). However, the streamflow data were limited to two stations near the middle of the two subbasin drainage areas with a period of record less than 2 years, which is not ideal for model calibration. Additionally, use of stream segments in PRMS limits the ability of PRMS to appropriately simulate runoff because PRMS does not allow stream losses to groundwater; therefore, streamflows only accumulate as they move downstream, which provides an unrealistic representation of runoff from drainages. The runoff simulated within the stream segments by the PRMS model is more appropriately conceptualized as the quantity of runoff originating from the respective drainage areas. Data from streamgages along the Walker River were not used for calibration because the LWR_PRMS only simulates runoff originating within the lower Walker River Basin.

Calibration of the ephemeral subbasin models (Hawthorne, Wildhorse Canyon, Wassuk, and Gillis) was constrained by idealized ephemeral hydrographs and estimates of groundwater recharge (table 3). Once precipitation and PET were adequately represented in the subbasin models, the parameters that control how water is partitioned between the soil zone, subsurface, and groundwater reservoirs were adjusted to simulate the idealized ephemeral hydrographs. The base flow and subsurface interflow hydrograph components were controlled by adjusting the parameter “*gwsink_coef*” individually for each of the six subbasins.

Delineation of Recharge Zones

The distribution of groundwater recharge is an important input to the MODFLOW model. Recharge for each HRU is calculated as the portion of precipitation that infiltrates to the groundwater reservoir and does not reach the stream channel or evaporate. To help guide the distribution of recharge, the potential areas of the lower Walker River Basin to receive groundwater recharge were identified and used to zone the distribution of the HRU-dependent parameters related to groundwater recharge (*soil2gw_max* and *ssr2gw_rate*). To generate a realistic distribution, *soil2gw_max* and *ssr2gw_rate* were adjusted to represent five different recharge zones that are based on the underlying geology (fig. 10). The actual simulated groundwater recharge using PRMS was thus informed by the five recharge zones. The five zones were classified as consolidated rock, fractured rock, alluvium, mountain stream channels, or alluvial channels, which correspond to the following potentials for groundwater recharge: very low, low, moderate, high, or very high, respectively. The potential groundwater recharge zones were developed using the stream network, the regional hydrogeology by Maurer and others (2004) that is summarized in figure 5, and used to develop hydrogeology-based groundwater recharge areas.

The consolidated rock recharge zone corresponds to areas of clastic, intrusive, and metamorphic rocks (fig. 5) and is consistent with the very low permeability consolidated rock unit in the MODFLOW model. The consolidated rock recharge zone occurs mainly in the mountainous areas of the lower Walker River Basin, where precipitation is generally greater than in the valleys, and contributes mainly to surface runoff with very little groundwater recharge.

The fractured rock recharge zone corresponds to areas of Quaternary- and Tertiary-age volcanic flows, breccias, tuffs, tuffacious rocks, and carbonate rocks (fig. 5) and is consistent with the low permeability consolidated rock units in the MODFLOW model. The fractured rock recharge zone has a greater potential for groundwater recharge than the consolidated-rock recharge zone but lower potential than other recharge zones and mainly occurs in the mountainous areas where precipitation is greater than in the valleys.

The alluvium recharge zone corresponds to alluvial slopes and valley floors, and has a moderate potential for groundwater recharge. This recharge zone comprises all four unconsolidated sediment units (fig. 5), which are categorized as basin fill for the MODFLOW model. Precipitation is generally much less than evapotranspiration in these areas, so the likelihood of groundwater recharge is low.

The mountain stream channel recharge zone corresponds to mountain drainage areas with relatively thin fluvial deposits that underlie perennial or ephemeral stream channels. These fluvial deposits result from episodic fluvial erosion and deposition, have a relatively high potential for groundwater recharge, overlie consolidated rock units, and are consistent with the stream network used in both models (fig. 5 and fig. 7). The mountain stream-channel recharge zone has a relatively high potential for groundwater recharge that is limited by the thickness of the stream channel deposits. However, this recharge zone occurs in the mountains where runoff and subsurface interflows concentrate flows along the channels and therefore have a relatively high potential for groundwater recharge.

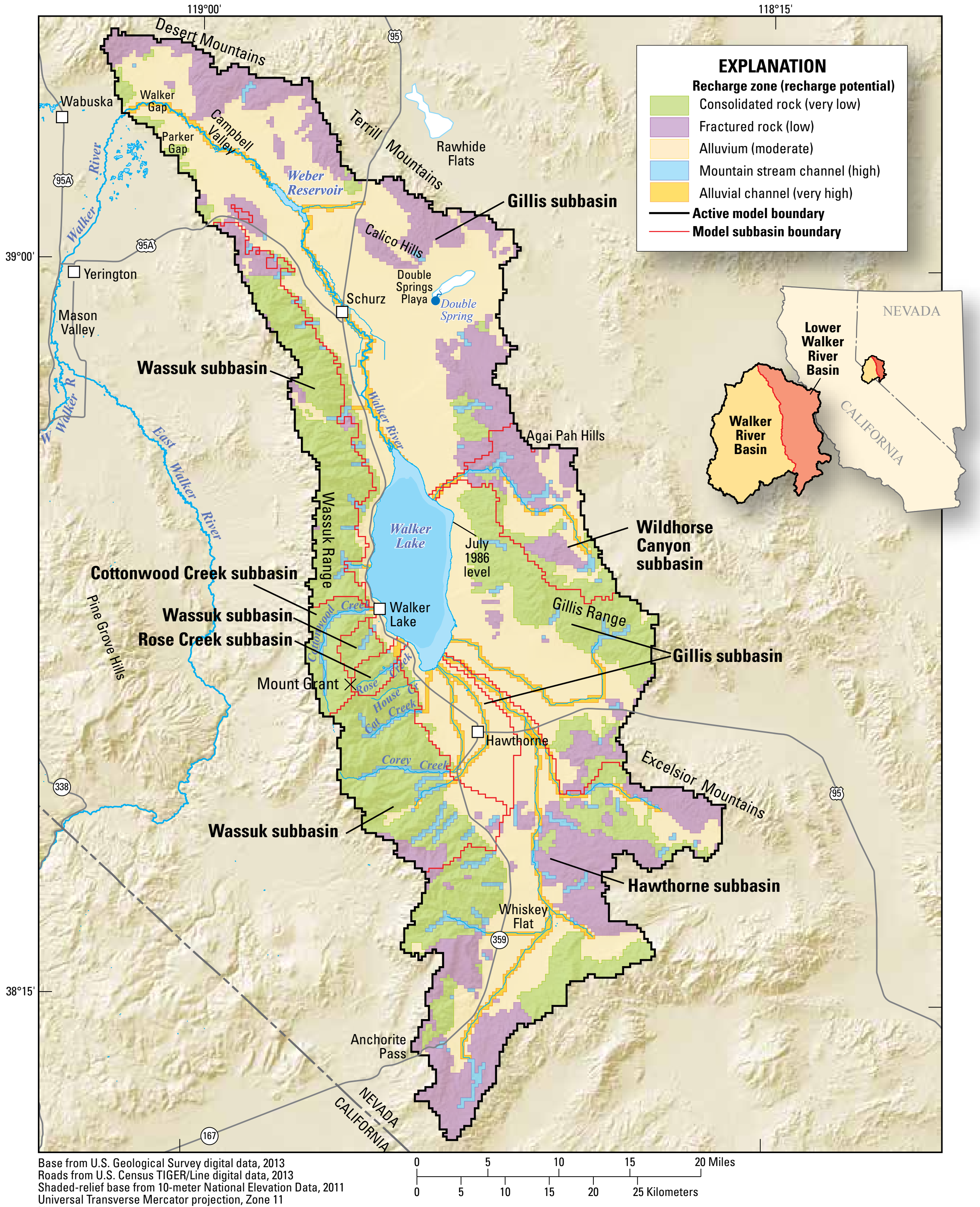
Finally, the alluvial-channel recharge corresponds to ephemeral stream channels that overlie alluvium. The deposits along these channels are generally well-sorted sand and gravel with minimal silt and clay and have a very high potential for groundwater recharge. The alluvial channels in the lower Walker River Basin are generally dry. Walker River is represented as an ephemeral channel in the PRMS model because inflows upstream from the lower Walker River Basin are not simulated. Alluvial channels are those areas in which the stream network intersects unconsolidated sediments (figs. 5, 7). Although alluvial channels have a high potential for groundwater recharge, because PRMS does not allow flow in the stream channels to reinfiltrate, the actual source of groundwater recharge within this zone is limited to cascading flows prior to discharge to stream network.

Demonstration of PRMS Model Fit—Hawthorne Subbasin

The results of calibration of the subbasin PRMS models are demonstrated here by describing the calibration of the Hawthorne subbasin model. The Hawthorne subbasin is ungaged and ephemeral; it represents areas of the southern Wassuk Range and Excelsior Mountains and the alluvial valley between them (fig. 7). There is very little to no streamflow data for the drainages within the Hawthorne subbasin, so an idealized hydrographic approach was used to calibrate the model.

The Hawthorne subbasin model consists of 4,538 HRUs and is shown in figure 11. Surface runoff and subsurface interflow are routed between HRUs using a cascading procedure (shown in inset of fig. 11). Flow paths begin at the HRUs corresponding to topographic peaks and continue downslope until reaching a stream segment. The thickest arrows represent 100 percent of the flow from one HRU to a single adjacent HRU, whereas the thinnest arrows indicate flow is divided with 25 percent of the flow going to each of four adjacent HRUs. The flow from one HRU to an adjacent HRU(s) always totals 100 percent. The cells with stream segments (blue cells in fig. 11) correspond to the stream channel where surface and subsurface interflow is eventually routed. Cells adjacent to the stream channel contribute 100 percent of the surface runoff and subsurface interflow to the stream segment.

There are seven stream segments in the Hawthorne subbasin (9 through 15; fig. 11). Simulated runoff originating from the drainage area and contributing to each stream segment is quantified by the Hawthorne subbasin model. Flow in each stream segment represents the runoff generated from the area cascading to the stream plus the inflow from upstream segments (recall that PRMS does not allow for stream channel



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
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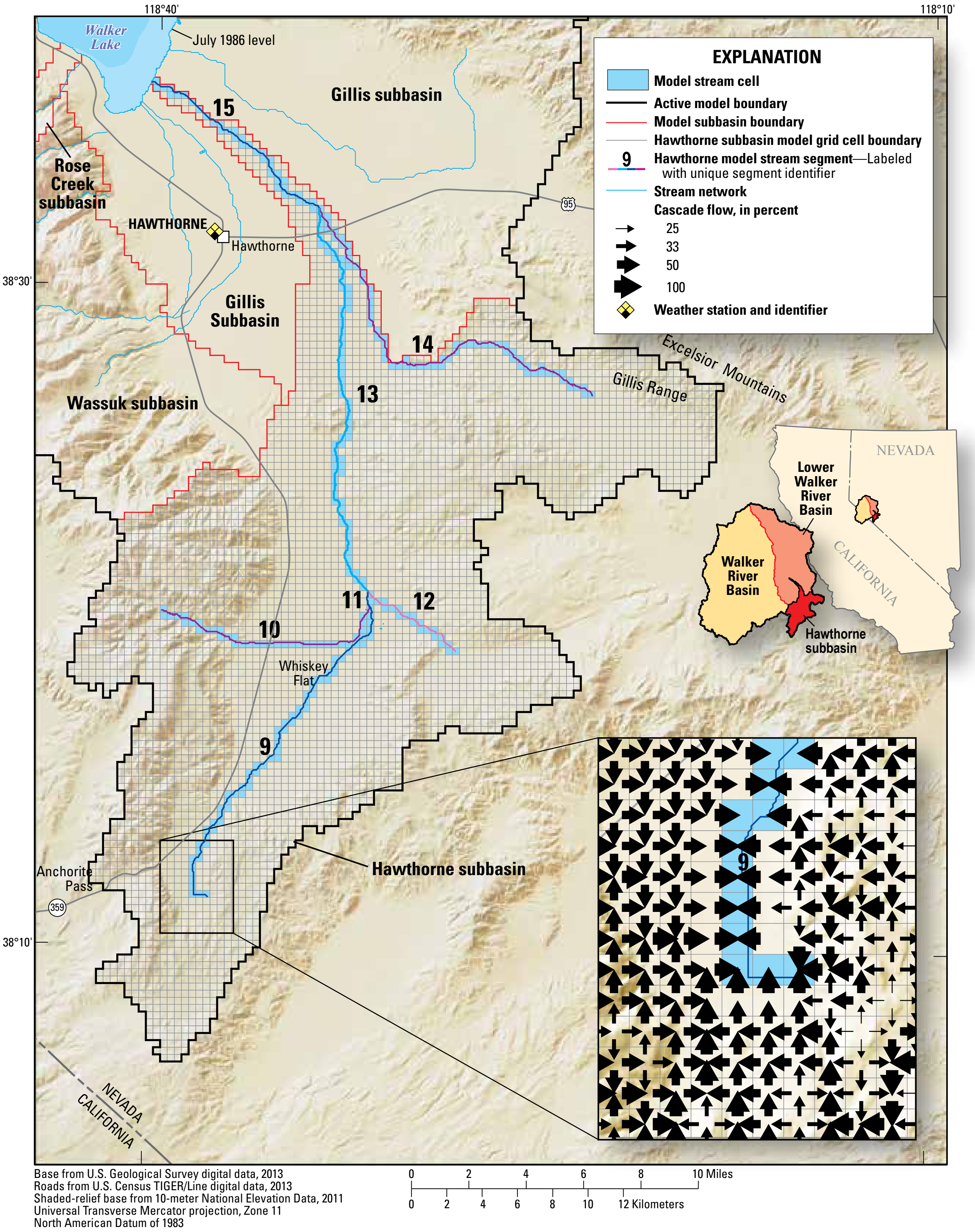
Figure 10. Delineated recharge zones in the lower Walker River Basin, west-central Nevada, with relative potential for groundwater recharge.



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Roads from U.S. Census TIGER/Line digital data, 2013
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Figure 11. Hawthorne subbasin model grid with stream segments and inset showing the cascading procedure.

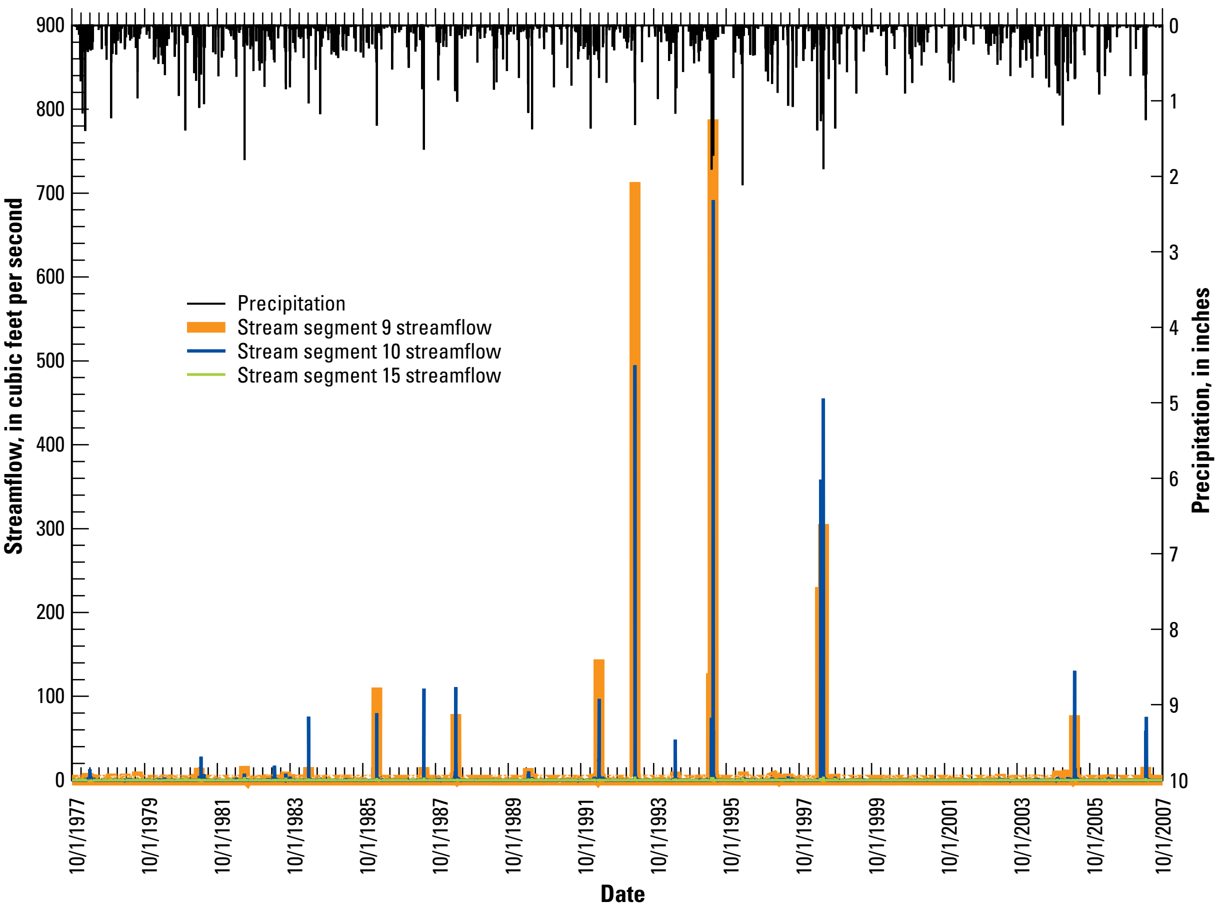


Figure 12. Hydrographs of simulated runoff for stream segments 9 and 10 that drain the southern Wassuk Range and stream segment 15 that drains to Walker Lake, with daily precipitation, Hawthorne subbasin, west-central Nevada, water years 1977–2007.

losses and only accumulates flow in stream network). The flows originating from an individual stream segment drainage area are determined by subtracting the total flow of the stream segment of interest from the combined inflow entering from upstream segments. Figure 12 shows hydrographs of simulated runoff for flow originating from drainage areas and contributing to stream segments 9 and 10, which represent two upper watershed segments draining from the southern Wassuk range, and stream segment 15, which represents the area contributing to the final stream segment prior to reaching Walker Lake. Stream segment 10 drains the area of the Hawthorne subbasin that has the greatest precipitation (fig. 8); segment 9 drains the area with the next greatest precipitation. The HRUs cascading into stream segments 9 and 10 have precipitation adjustment coefficients that simulate precipitation at a rate of 2.5–3 times the precipitation at the indexed weather station Hawthorne (fig. 8). After refinement of calibration parameters, simulated mean-annual runoff originating from the drainage areas and contributing to stream segments 9 and 10 was 645 acre-ft/yr. Segment 9 contributed 307 acre-ft/yr (48 percent of combined flow), and segment 10 contributed 338 acre-ft/yr (52 percent of combined flow). The mean annual runoff originating from the drainage area of stream segment 15 was only 19 acre-ft/yr. This demonstrates that the model simulates occasional flows coming out of the mountains that are substantial in comparison to smaller flows originating lower in the drainage along the valley floor bottom. The runoff originating from these drainages is consistent with the idealized hydrograph and anecdotal evidence.

The combined hydrograph (fig. 13) for the seven stream segments in the Hawthorne subbasin model (fig. 11) is separated into the hydrograph components surface runoff, subsurface interflow, and base flow. After refinement of calibration parameters, the runoff event in May 1995 was the peak event simulated for the Hawthorne subbasin, consisting of 79 percent surface runoff, 18 percent subsurface interflow, and 4 percent base flow (rounded values). This demonstrates that the model is simulating runoff from rain events with most of the water originating from surface runoff, some water from subsurface interflow, and a very small amount from base flow, which is consistent with the idealized hydrograph. For the Hawthorne subbasin simulation, runoff primarily occurred during events with simulated basin daily precipitation that exceeded 1 inch (fig. 12). The combined mean annual runoff originating from the seven stream segment drainage areas was 1,080 acre-ft/yr (1.5 ft^3/s) with the source drainage stream segments (segments 9, 10, 12, and 14) accounting for 915 acre-ft/yr (1.3 ft^3/s). The combined median annual runoff

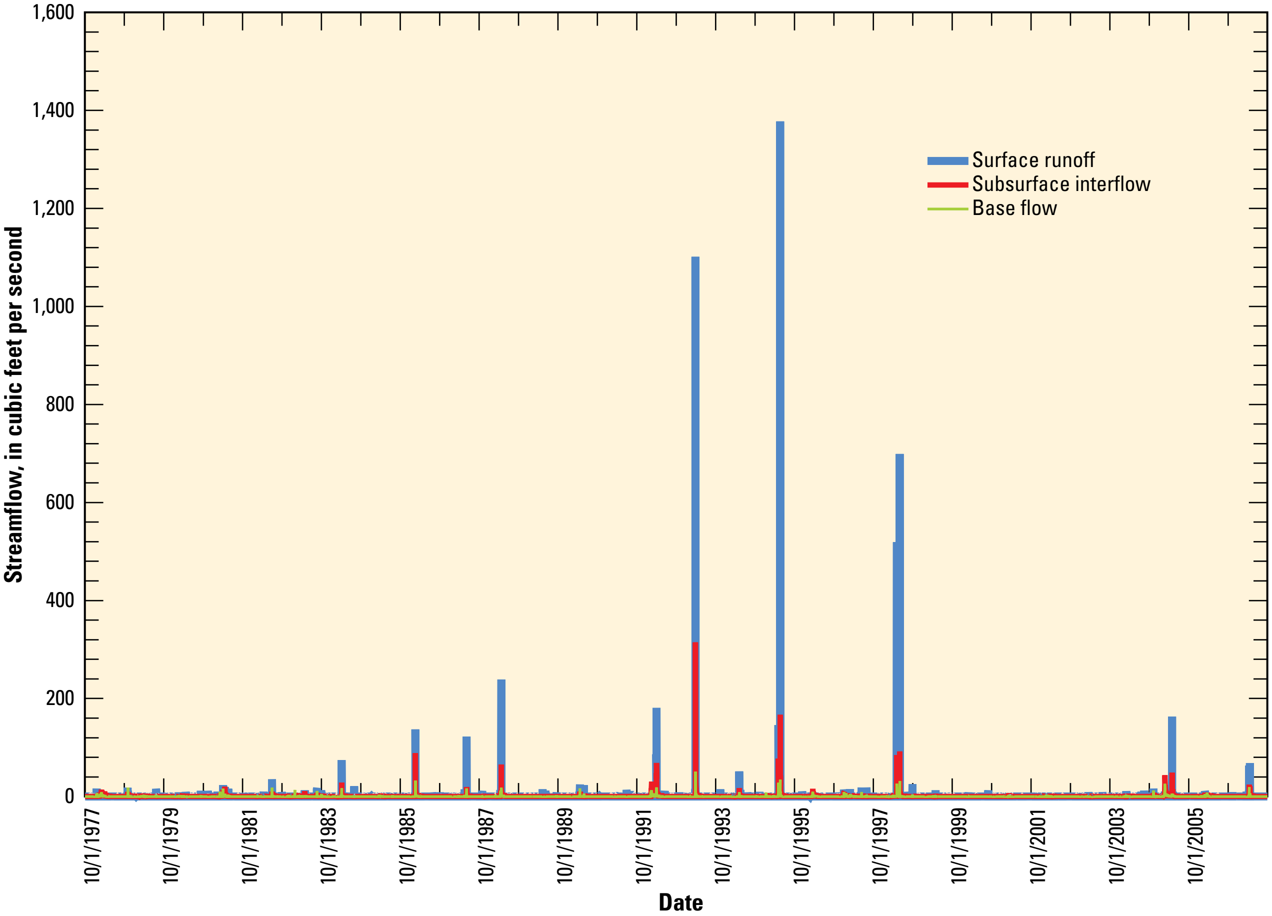


Figure 13. PRMS runoff components surface runoff, subsurface interflow, and base flow, Hawthorne subbasin, west-central Nevada, water years 1977–2007.

was 52 acre-ft/yr (0.07 ft^3/s) with the source drainage stream segments accounting for 33 acre-ft/yr (0.05 ft^3/s), indicating that the lower stream segment drainage areas are generating virtually no flow almost all of the time, which is also consistent with the idealized hydrograph.

The spatial distribution of mean annual groundwater recharge (fig. 14) generally resembles the hydrogeologic recharge zone distribution for this area (fig. 10). Very high recharge rates are localized in the mountain stream channels (for example the upper reach of segment 10) with some rates greater than (>) 14.4 in/yr (0.001 m/d). Very low recharge rates, generally less than 0.14 in/yr (0.00001 m/d), are associated with consolidated rock, and a moderate to high recharge rate of 1.4 in/yr (0.0001 m/d) is associated with alluvium. The groundwater recharge estimate for the entire Hawthorne subbasin is 9,049 acre-ft/yr (0.61 in/yr; 0.000042 m/d) and accounts for 7.4 percent of total precipitation (table 5).

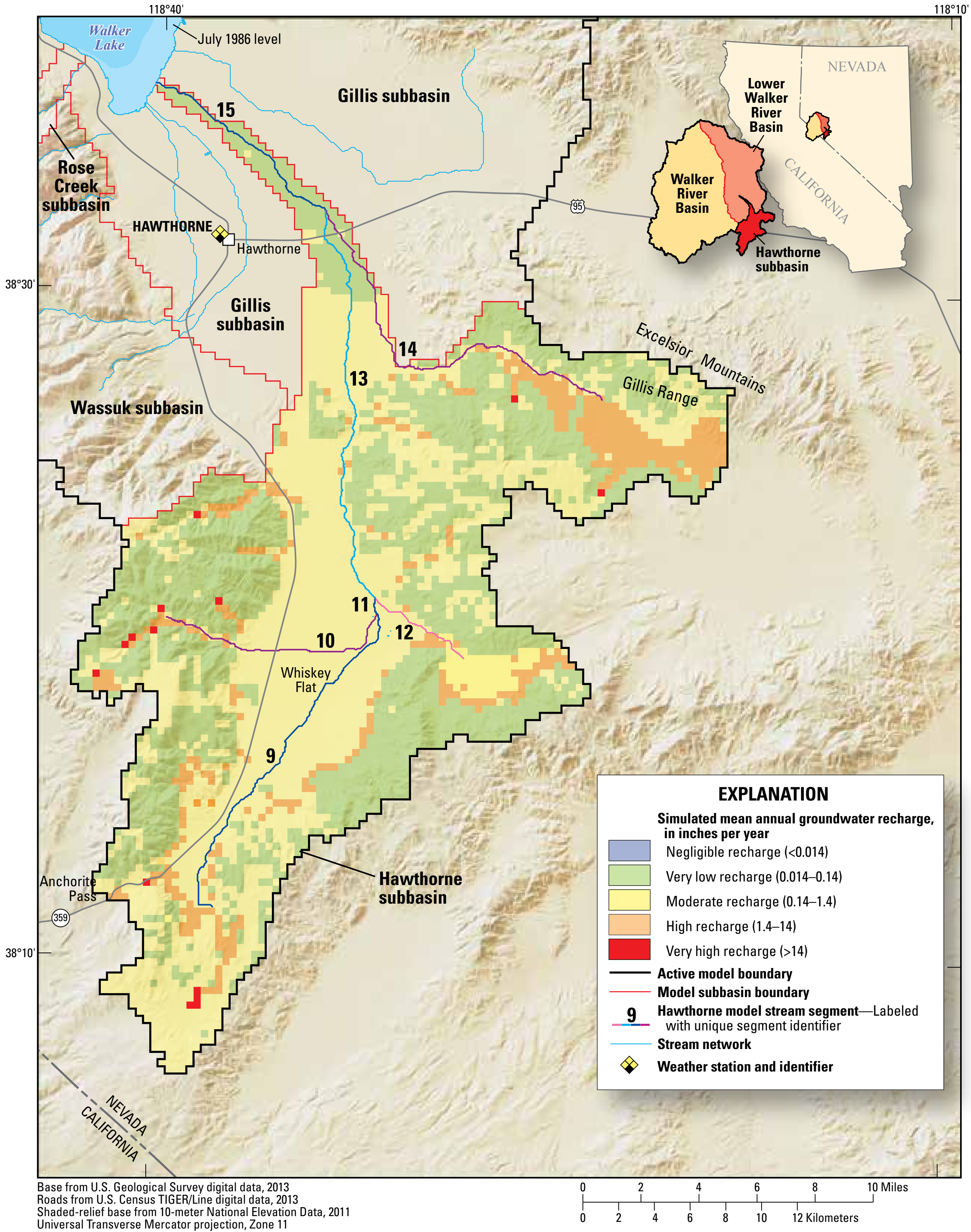
The Hawthorne subbasin PRMS model adequately simulated an ephemeral distribution of flow with the lower stream segments generating almost no flow most of the time. Runoff was less than (<) 1 percent of precipitation, evapotranspiration was 92 percent of precipitation, and recharge was 7.4 percent of precipitation (table 5).

Model Results

Water budgets are summarized in terms of precipitation, evapotranspiration, runoff, and groundwater recharge for the area of the lower Walker River Basin and for each of the subbasins in table 5. Because the amount of water in soil zone storage is cyclical on an annual basis, the long-term change in soil water storage over the 30-year simulation averages zero and is not discussed as part of simulated water budgets. Groundwater recharge is estimated for each active HRU of the model, and the distribution is presented and summarized by subbasin as well as by recharge zone.

Water Budgets

Mean annual water-budget components for the six subbasin models and the LWR_PRMS show the distribution of precipitation into evapotranspiration, runoff, and recharge for the 1978–2007 simulation period (table 5). Mean annual precipitation for the subbasin models ranges from 5.8 in. for the Gillis subbasin to just under 13 in. for Cottonwood Creek and Rose Creek subbasins. Precipitation for the lower Walker River Basin averaged 7.3 in/yr.



Base from U.S. Geological Survey digital data, 2013
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Figure 14. PRMS simulated mean annual groundwater recharge rates for Hawthorne subbasin, west-central Nevada, water years 1978–2007.

Table 5. Mean annual water budgets for the lower Walker River Basin and subbasins, west-central Nevada, as simulated by the LWR_PRMS model, water years 1978–2007.

[Unless otherwise specified, units are in inches and (acre-feet); LWR, lower Walker River; PRMS, Precipitation-Runoff Modeling System; ET, evapotranspiration; ppt, precipitation]

Subbasin model	Precipitation	ET	ET (percent of ppt)	Runoff	Runoff (percent of ppt)	Recharge	Recharge (percent of ppt)
Cottonwood Creek	12.8 (15,460)	10.9 (13,171)	85	1.3 (1,623)	10.5	0.58 (701)	4.5
Rose Creek	12.3 (5,170)	10.1 (4,240)	82	2.2 (928)	18.0	0.16 (66)	1.3
Hawthorne	8.1 (121,754)	7.5 (111,752)	92	0.07 (1,112)	0.9	0.61 (9,049)	7.4
Wildhorse Canyon	8.0 (28,106)	7.7 (26,980)	96	0.03 (119)	0.4	0.30 (1,041)	3.7
Wassuk	10.1 (98,395)	9.1 (88,197)	90	0.62 (6,045)	6.1	0.84 (8,214)	8.3
Gillis	5.8 (193,508)	5.6 (187,026)	97	0.02 (714)	0.4	0.18 (6,054)	3.1
LWR PRMS Model	7.3 (462,685)	6.8 (431,643)	93	0.17 (10,542)	2.3	0.40 (25,125)	5.4

The mean annual evapotranspiration for the subbasin models ranged from 5.6 in. for the Gillis subbasin to 10.9 in. for the Cottonwood Creek subbasin (table 5). Mean annual evapotranspiration for the lower Walker River Basin averaged 6.8 in. Mean annual evapotranspiration as a percentage of precipitation ranged from 82 percent for the Rose Creek subbasin to 97 percent for the Gillis subbasin. The mean annual evapotranspiration for the lower Walker River Basin was 93 percent of precipitation.

As previously stated, simulated runoff from the subbasins is not representative of actual streamflow to Walker Lake, but rather is representative of the total runoff generated within the subbasins without consideration of channel losses. Mean annual runoff generated from within the subbasins ranged from 0.02 in. in the Gillis subbasin to 2.2 in. in Rose Creek subbasin (table 5). The mean annual runoff generated from the lower Walker River Basin averaged 0.17 in. Runoff as a percentage of precipitation was small for all of the subbasins, ranging from less than 1 percent for Gillis, Wildhorse Canyon, and Hawthorne subbasins to a high of 18 percent for the Rose Creek subbasin. Runoff accounted for 2.3 percent of precipitation in the lower Walker River Basin.

Distribution of Groundwater Recharge

The LWR_PRMS was used to estimate the magnitude and distribution of groundwater recharge, which was needed for the MODFLOW model. The recharge discussed in this section represents only recharge originating from precipitation within the lower Walker River Basin. Groundwater recharge from Walker River is simulated within the MODFLOW model.

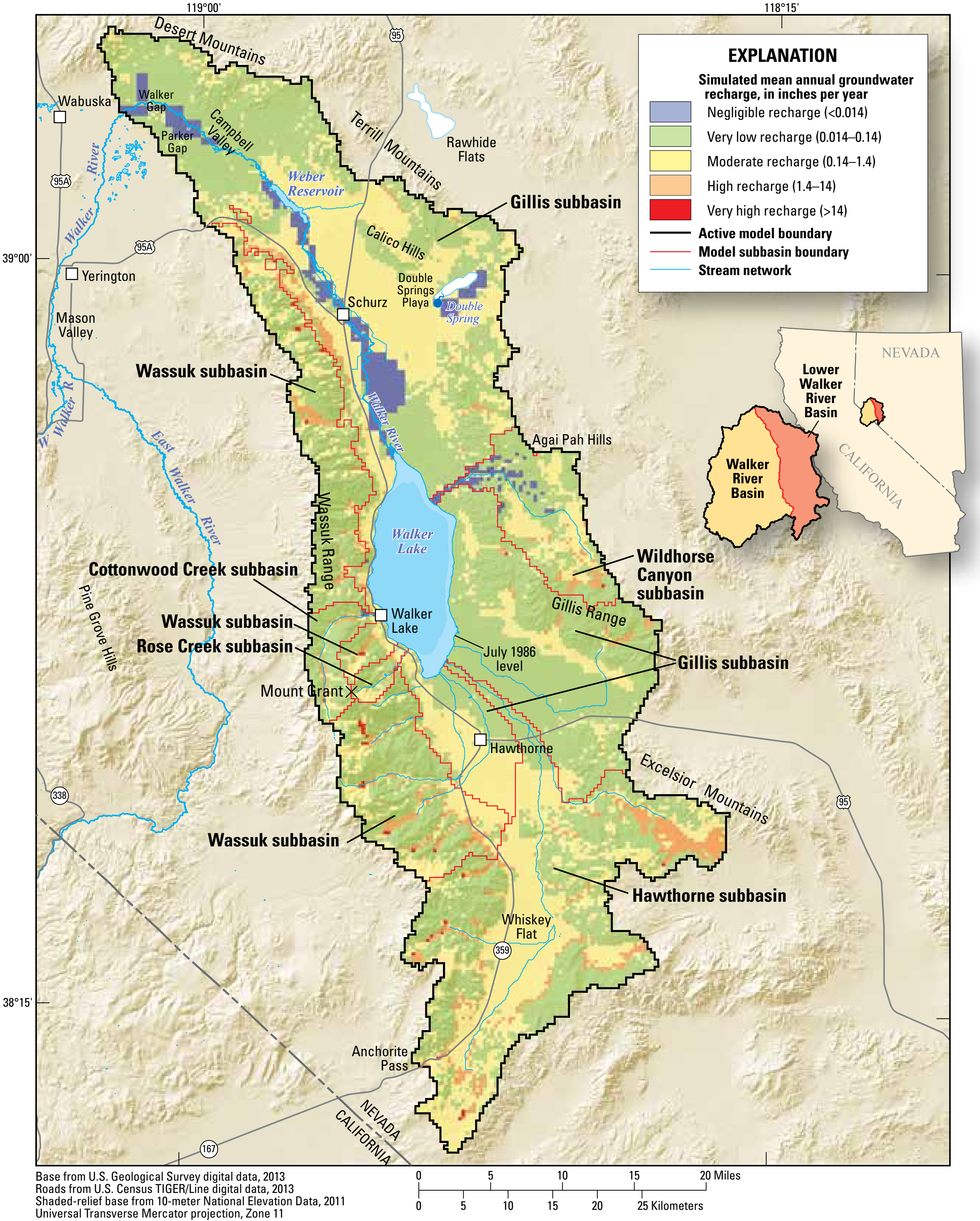
The recharge rate for each HRU represents the mean annual rate over the full 30-year simulation period; the rates are summarized for each subbasin and the overall lower Walker River Basin in table 5. Recharge rates are multiplied by areas and time periods and appropriate conversion factors to compute recharge volumes.

The PRMS simulated distribution of groundwater recharge for the lower Walker River Basin is shown in figure 15. Mean daily groundwater recharge rates are classified into five order-of-magnitude classes: negligible recharge (<0.014 in/yr; <10^{-6} m/d), very low recharge (0.014–0.14 in/yr; 10^{-6}–10^{-5} m/d), moderate recharge (0.14–1.4 in/yr; 10^{-5}–10^{-4} m/d), high recharge (1.4–14 in/yr; 10^{-4}–10^{-3} m/d), and very high recharge (>14 in/yr; >10^{-3} m/d). Very high recharge rates were simulated along the mountain stream channels predominantly in the Wassuk Range to the west and south. High recharge rates were simulated (1) in mountain stream channels, (2) along contacts between the consolidated rock units of the mountains and alluvial basins in the eastern part of the Hawthorne subbasin adjacent to the southern Gillis Range, and (3) along the base of the Wassuk mountain front north of Walker Lake. Moderate recharge rates were simulated in the upper parts of the alluvial basins and alluvial slopes. Very little to no recharge was simulated within alluvial valley bottoms and in the consolidated rock units of the mountains. Areas with negligible recharge were simulated along the Walker River upstream of Walker Lake, localized areas in the Wildhorse subbasin and Gillis Range, and along very steep consolidated rock slopes of the Wassuk Range (fig. 15).

Mean annual recharge for the subbasin models ranged from 0.16 in. for the Rose Creek subbasin to 0.84 in. for the Wassuk subbasin (table 5). The lower Walker River Basin had an average recharge rate of 0.40 in/yr. Recharge as percent of precipitation was calculated as the difference between precipitation and the sum of evapotranspiration and surface runoff and shallow subsurface interflow divided by precipitation. Recharge percent of precipitation ranged from a high of 8.3 percent in the Wassuk subbasin to 1.3 percent in the Rose Creek subbasin. The lower Walker River Basin had an overall recharge percent of precipitation of 5.4 percent.

The annual volume of simulated groundwater recharge ranged from just 9,049 acre-ft/yr for the Hawthorne subbasin to 66 acre-ft/yr for the Rose Creek subbasin. The overall recharge volume for the lower Walker River Basin was simulated to be 25,125 acre-ft/yr.

In addition to being used to assign recharge related parameters in the PRMS model, the recharge zones in figure 10 were used to aggregate and summarize groundwater recharge (table 6). More than 80 percent of total recharge occurs in the alluvium and mountain stream channel recharge zones,



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
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Figure 15. Distribution of simulated groundwater recharge rates for the lower Walker River Basin, west-central Nevada, water years 1978–2007, using the LWR_PRMS model.

Table 6. Groundwater recharge and recharge parameter values for the lower Walker River Basin, west-central Nevada, summarized by recharge zone, LWR_PRMS model, water years 1978–2007.

[LWR, lower Walker River; PRMS, Precipitation-Runoff Modeling System; *ssr2gw_rate*, PRMS parameter that computes gravity drainage to the PRMS groundwater reservoir; *soil2gw_max*, PRMS parameter that represents the maximum value of soil-water excess routed directly to the PRMS groundwater reservoir]

Recharge zone[1]	Area (acres)	Fraction of total area (percent)	Recharge potential	Mean Recharge rate (inches per year)	Recharge volume (acre-feet per year)	Fraction of total recharge (percent)	*ssr2gw_ rate*	*soil2gw_ max*
Consolidated Rock	219,310	28	Very Low	0.060	1,097	4	0.001	0.001
Fractured Rock	152,098	19	Low	0.14	1,730	7	0.002	0.01
Alluvium	361,880	46	Moderate	0.44	13,186	53	0.15	1.0
Mountain Channels	24,710	3	High	4.01	8,256	33	0.5	2.0
Alluvial Channels	37,006	5	Very High	0.22	677	3	1.0	5.0

[1] Recharge zones are shown in figure 10.

although the two zones account for only 50 percent of the basin area. More than 30 percent of the total recharge is from mountain stream channels, even though this zone only accounts for 3 percent of the basin area. Alluvial channels, which have the highest potential for groundwater recharge, contribute only about 3 percent of the total recharge as a result of low precipitation and high evapotranspiration rates on the valley floor. The consolidated and fractured rock recharge zones contribute just over 10 percent of the recharge, which is higher than might be expected because of the very low to low potential for recharge. However, these zones occur in the higher precipitation areas in the mountains and therefore have a greater source of water available for recharge.

The calibration determined values for the *ssr2gw_rate* and *soil2gw_max* HRU-dependent parameters discussed earlier are also summarized in table 6. The parameter *ssr2gw_rate* (unitless) ranged from 0.001and 0.002 for the consolidated rock and fractured rock recharge zones, respectively, to a maximum of 1.0 for the alluvial channels recharge zone. The parameter *soil2gw_max* ranged from 0.001 for the consolidated rock recharge zone to 5.0 for the alluvial channels recharge zone.

The LWR_PRMS simulated recharge distribution is compared with groundwater recharge estimates made using other methods (table 3). The quantity of simulated LWR_PRMS recharge for the individual subbasins is generally between the minimum and reasonable estimates or a little greater than the reasonable estimate with the exception of the Rose Creek subbasin, which is substantially less than the minimum estimated recharge. The LWR_PRMS simulated 25,125 acre-ft/yr of groundwater recharge for the lower Walker River Basin, which is a little less than the reasonable estimate of 29,000 acre-ft/yr. Simulated recharge for the lower Walker River Basin is about 65 percent greater than the Modified Maxey–Eakin method estimate. Though recharge estimates from the different methods vary widely, the PRMS estimates provide an adequate initial estimation of magnitude and distribution of groundwater recharge for the lower Walker River Basin. However, as will be discussed later in section “Groundwater Recharge”, the mean annual recharge was reduced to calibrate the MODFLOW model.

Model Limitations

The purpose of the LWR_PRMS is to simulate the atmospheric and land-surface hydrologic components for the future GSFLOW model and calculate groundwater recharge and distribution for use with the MODFLOW model. Very little streamflow data were available for detailed calibration of the LWR_PRMS, and the available streamflow data were measurements made near the middle of the subbasin drainage areas rather than at outflow locations of the subbasins. Furthermore, because a stream network is needed for integration with MODFLOW, one of the major limitations of the PRMS modeling framework is that once cascading flows are collected in the stream segments, the flow is no longer available for interactions with other hydrologic processes and is directly routed to the end of the stream segments. The obvious limitation of this is that once flows are in a stream segment, they only accumulate as they move downstream, resulting in unrealistic over-estimation of runoff from the subbasins. The runoff simulated by this model is more appropriately conceptualized as the quantity of runoff originating from the respective subbasins rather than streamflow, which would also consider in-stream losses to groundwater that generally occur as water moves along ephemeral channels. The model was designed and calibrated to provide a reasonable approximation of the large scale watershed characteristics of the lower Walker River Basin. The LWR_PRMS does not accurately represent individual tributary streamflows.

Uncertainty in the distribution of precipitation is partly attributed to the lack of high-altitude weather stations. The absence of measurements for the PRISM regression analyses in the region lends additional uncertainty to those estimates, particularly for the Wassuk Range where precipitation rates are relatively high compared with the rest of the study area. A mean annual lapse rate adjustment distribution was used for the LWR_PRMS to distribute climate data to HRUs from weather station data, rather than more accurate monthly adjustment coefficients. The LWR_PRMS distributed climate data to individual HRUs using data from the nearest weather station rather than compositing climate data from multiple weather stations prior to distribution. This links the climate data from large portions of the watershed to single weather stations;

therefore, any data errors from a single weather station will be distributed to HRUs indexed to the station. Additionally, localized precipitation variability, such as summer convective storms, is simulated as widely distributed precipitation events, which is not always representative of the distribution of precipitation. However, it is assumed that the probability of occurrence of summer rain events at the weather stations is the same as that for indexed HRUs, giving an overall realistic distribution of precipitation over time.

The LWR_PRMS estimated recharge distribution was developed without interaction or feedback of the groundwater system. This likely affects the overall pattern and distribution of recharge. However, with appropriate scaling of the recharge, it is assumed that the recharge distribution simulated by the LWR_PRMS is adequate for calibration of the MODFLOW model.

Simulation of Walker River, Walker Lake, and Groundwater Flow (MODFLOW Model)

The development of the MODFLOW groundwater flow model is discussed in this section and is shown in context with the overall modeling strategy in figure 6. Groundwater flow, changes in water levels, groundwater interactions with Walker River and Walker Lake, and water budgets in the lower Walker River Basin were simulated using the Newton formulation of the 2005 MODular groundwater FLOW model (MODFLOW-NWT; Harbaugh, 2005; Niswonger and others, 2011). MODFLOW is a FORTRAN compiled program that uses a finite-difference numerical approach to solve the three-dimensional groundwater flow equation (Harbaugh, 2005). MODFLOW takes advantage of a modular type construction (modules are also known as packages) that enables developers to simulate effects of specific hydrologic processes, such as evaporation, recharge, pumping, streamflow routing, and lakes, on groundwater levels and flows. MODFLOW discretizes the groundwater flow system using a rectilinear grid composed of columns, rows, and layers. Hydraulic properties, initial specified water levels, boundary conditions, and external stresses are distributed to the model grid to form a system of finite-difference equations for unknown heads (equivalent groundwater levels in open wells penetrating, and screened only in, the simulated depth interval of the particular model cell) using an iterative process until the maximum successive change in water levels is less than user specified convergence criteria.

The lower Walker River Basin MODFLOW model (LWR_MF) simulates the groundwater system, lakes, and streams of the lower Walker River Basin. The model simulates steady-state conditions in the lower Walker River Basin before lake-level declines began in 1919 and transient conditions from 1919 through 2007 (fig. 6). A post-processing routine was used to compute simulated dissolved-solids concentrations in Walker Lake.

Model Design

The model domain covers 1,242 square miles (mi^2) and represents the entire study area, including the mountains and basin sediments. The model domain follows the topographic divide of the mountains surrounding the lower Walker River Basin, except along the northeastern boundary where the domain cuts through the alluvial basin east of Double Springs (fig. 16). The northwestern boundary, where Walker River enters the study area, coincides with the location of the Walker River at the Wabuska streamgage. The model represents the exchange of groundwater with surface water of Walker River, Walker Lake, tributaries to Walker Lake, and an approximation of the Walker River Indian Irrigation Project (WRIIP).

Development of the LWR_MF required horizontal and vertical discretization of the lower Walker River Basin, temporal discretization of the simulation period, specification of boundary and initial conditions, and specification of aquifer hydraulic properties for model cells. Land-surface altitudes and the stream network were derived from the composite 40-meter (m) DEM.

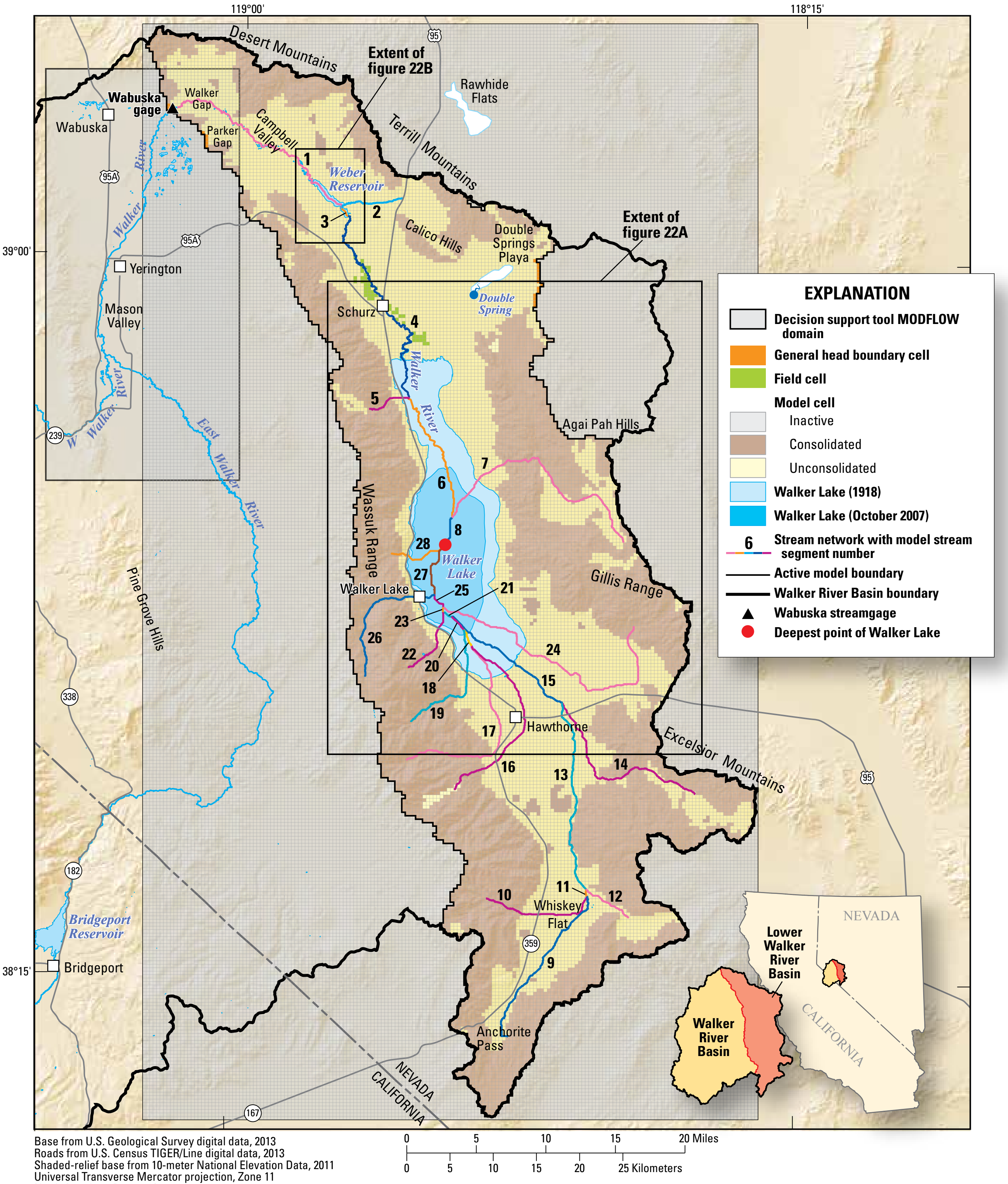
Discretization

The hydrologic system is discretized with a horizontal grid of 178 columns and 317 rows and is vertically discretized into 6 layers, resulting in a total of 338,556 cells (fig. 16). Each cell is 400 m (1,312 ft) square on the horizontal and has variable thickness. The grid is aligned north–south. The northwest corner of the grid is located at Universal Transverse Mercator (UTM) Zone 11 coordinate 315,228 m east and 4,345,446 m north.

The LWR_MF grid overlaps part of the Decision Support Tool (DST) model grid constructed by the University of Nevada Reno and Desert Research Institute along the northwestern boundary (fig. 16; Boyle and others, 2010). This was done so that groundwater flow across the shared boundary of the two models could be linked in the future if needed.

Land-surface altitude for each of the lower Walker River Basin model cells was determined by overlaying the LWR_MF grid on the composite 40-m DEM and taking the mean altitude over the area of respective grid cells. Some altitudes along streams were adjusted to ensure that streams were below land surface and stream slopes were positive.

The geometry and depths of the hydrogeologic units are largely unknown. Therefore a simplified approach was used to vertically discretize the hydrogeologic units in this model. In general, basin-fill sediments compose the primary aquifer in the lower Walker River Basin aquifer system. The consolidated rock units that make up the mountains and underlie basin-fill sediments do not constitute an aquifer, but are represented in the model as units with very low horizontal hydraulic conductivity. The bottom model boundary is set at an arbitrary altitude of -1 m.



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
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Figure 16. Extent of LWR_MF grid and major conceptualized features of the lower Walker River Basin, west-central Nevada.

The four unconsolidated basin-fill units identified in the lower Walker River Basin (fig. 5) are represented individually in the model and collectively represent the basin-fill aquifer. The seven consolidated rock units identified in the lower Walker River Basin are aggregated into three consolidated rock units in the model and are represented in one model layer. Quaternary- to Tertiary-age volcanic basalt and andesite, volcanic breccias and tuffs, carbonate rocks, and Tertiary tuffacious rocks and sediments were grouped into a single low horizontal hydraulic conductivity consolidated rock unit. Clastic rocks and intrusive and metamorphic rock types were grouped into a single very low horizontal hydraulic conductivity consolidated rock unit. Undetermined basement rocks that underlie the basin-fill sediments were grouped into an undifferentiated consolidated rock unit also with low horizontal hydraulic conductivity.

A simplified approach was used to define the geometry and thickness of the basin-fill units in the model. The maximum total thickness of the basin-fill unit was set at the average depth of 1,180 ft (360 m; table 2). The total thickness of the basin-fill unit was tapered near its edges as it approaches the contact with consolidated rock unit at land surface to make the basin fill thinner near edges and improve the numerical stability of the model.

Conceptually, the LWR_MF is vertically discretized into three units, but functionally it is discretized into six model layers. Conceptually, the three main units represented are (1) Walker Lake and Weber Reservoir, (2) basin-fill aquifer, and (3) consolidated rock. The six model layers are discussed below.

Layer 1 represents Walker Lake and Weber Reservoir with assigned maximum altitudes of 4,097.5 ft (1,249 m) and 4,219 ft (1,286 m), respectively (fig. 17*A*). These altitudes allow model simulated lake levels to vary above the 1882 highstand for Walker Lake by about 15 feet (4,082 ft, local datum; fig. 2) and up to the spillway of Weber Reservoir (4,210 ft, local datum). Model cells in this layer were active only when simulated lake levels in Walker Lake or Weber Reservoir were above land surface in lake cells and were inactive when simulated lake levels were below land surface in lake cells. The bottom of layer 1 corresponds to land surface and the bottom bathymetries of Walker Lake and Weber Reservoir.

The basin-fill aquifer is discretized into four progressively thicker layers with depth, with thinner layers near land surface to better simulate groundwater/surface-water interactions. Layers 2 through 5 represent the basin-fill sediments that compose the principle aquifer. Most groundwater/surface-water interactions take place in layer 2 and are simulated as vertical exchanges. This is reasonable because the lake bottoms are mostly gently sloping. The bottom of layer 5 represents the bottom of basin-fill sediments in the basin.

Layer 2 is a thin layer with the lateral extent originally defined using the valley floor, playas, and fluvial deposit designations from Maurer and others (2004; fig. 17*B*). Layer 2 also includes alluvial areas intersected by Walker River and the extent of Walker Lake from 1908 to 1918. Layer 2 is generally 23 ft (7 m) thick or less to optimize simulations of groundwater/surface-water interactions while allowing evapotranspiration processes to occur to an adequate depth. Thicknesses of model cells at some locations were increased to prevent a stream reach from penetrating through the bottom of the layer.

Layers 3 and 4 underlie layer 2 and together represent a single basin-fill unit in the model beneath layer 2. Layers 3 and 4 are active only where layer 2 is active (fig. 17*C*). The aquifer properties for layers 3 and 4 are constant vertically and vary horizontally. Layers 3 and 4 mainly represent valley floor sediments (Maurer and others, 2004) but also represent alluvial slope sediments in areas intersected by Walker River (Maurer and others, 2004).

Layers 3 and 4 are progressively thicker than layer 2, except where underlain by consolidated rock units. The thickness of layer 3 varies from 3 to 26 ft (1 and 8 m), depending on the distance of the model-cell center from the nearest surface contact of consolidated rock with basin fill. An exponential relation was used to assign thickness. At the consolidated rock-basin fill contact (0 distance), thickness was 3 ft (1 m) and doubled every 328 ft (100 m) away from the consolidated rock unit until the maximum thickness of 26 ft (8 m) was achieved. The maximum thickness of 26 ft (8 m) for layer 3 was realized at a distance of 984 ft (300 m) from nearest consolidated rock-basin fill contact. The same procedure was used to determine thicknesses of layer 4, except that maximum thickness was 67 ft (20 m) and was realized at a distance of 1,417 ft (432 m) from nearest consolidated rock-basin fill contact. The maximum thickness of layers 3 and 4 combined is 92 ft (28 m).

Layer 5 extends across the entire basin-fill sediment region and also represents thin fingering aquifers in mountain drainages (fig. 17*D*). Layer 5 horizontally extends beyond the active domain of layers 2–4. Within the extent of layer 4, layer 5 represents the same hydrogeologic unit as layer 4. Beyond the extent of layer 4, layer 5 represents alluvial slope sediments, except beneath perennial and ephemeral streams in the mountain drainages where layer 5 represents fluvial deposits. Layer 5 also represents fluvial deposits underlying the tributary streams, which are assigned a thickness of 23 ft (7 m) to improve simulation of perennial and ephemeral mountain stream groundwater/surface-water interactions. Layer 5 is generally thicker than layers 2–4 and ranges from 23 to 1,066 ft (7 and 325 m), depending on the distance of the model-cell center from the consolidated rock unit. Similar to layers 3 and 4, an exponential relation was used to assign thickness. At the consolidated rock/basin-fill contact, thickness is equal to 23 ft (7 m) and doubles every 1,312 ft (400 m) away from consolidated rock unit up to the designated thickness of 1,066 ft (325 m). The 1,066 ft (325 m) thickness was achieved at a distance of 7,093 ft (2,162 m) from the nearest consolidated rock unit.

Layer 6 represents the consolidated rock groups that compose the mountains and underlie the basin-fill sediments (fig. 17*E*). In most of the valley, the consolidated rock

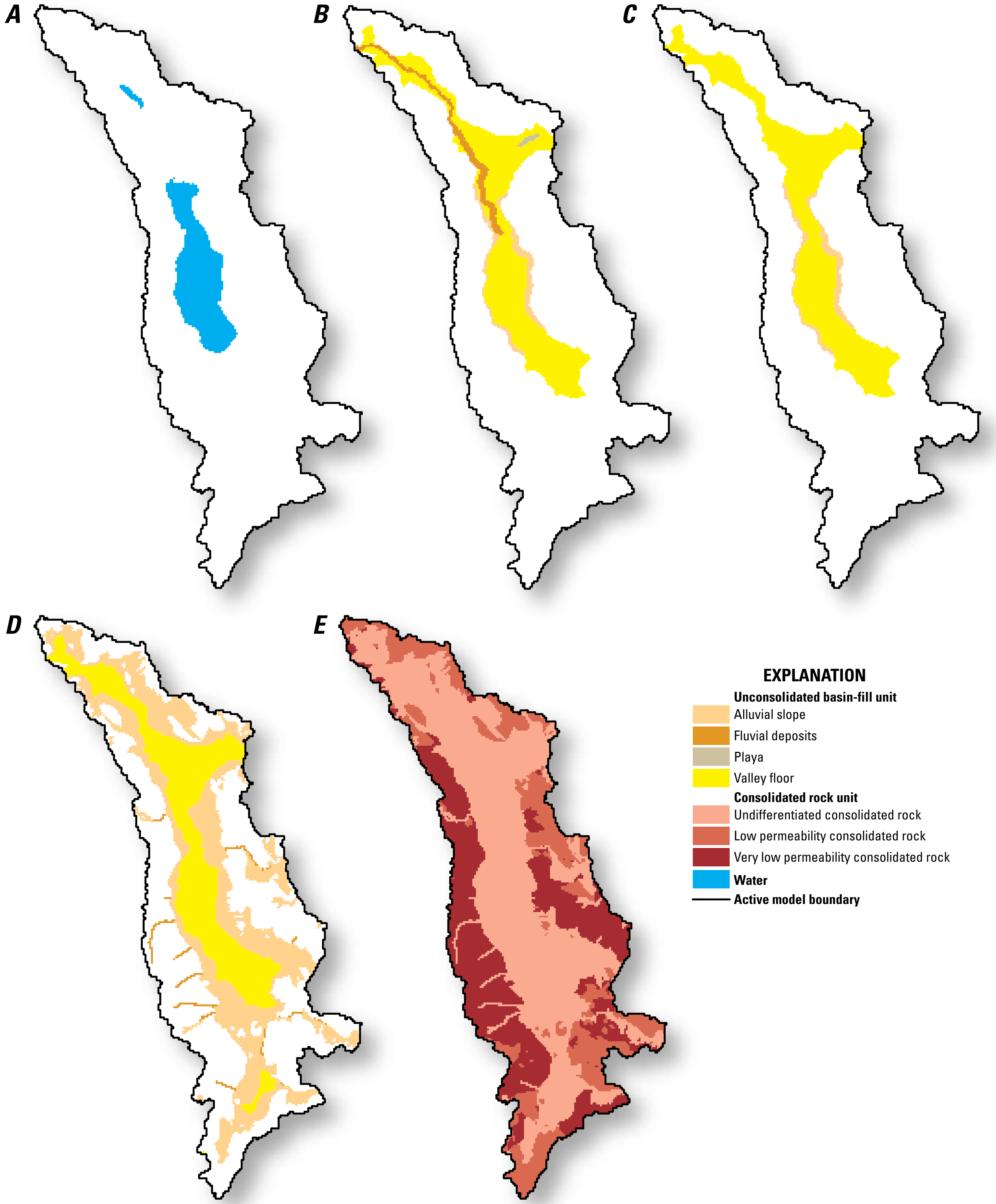


Figure 17. Extent and hydrogeology of layers discretized in LWR_MF groundwater flow model: *A*, Layer 1; *B*, Layer 2; *C*, Layers 3 and 4; *D*, Layer 5; and *E*, Layer 6.

is concealed by basin-fill sediment. However, in the Wassuk Range and some of the Gillis Range, consolidated rock crops out at the surface, and the top of layer 6 is specified at land-surface altitude. In these areas, the thickness of layers 1 through 5 is zero. The altitude of bottom of layer 6 is arbitrarily chosen as -3 ft (-1 m). This results in a layer thickness ranging from 2,679 to 11,025 ft.

The difference in altitude between the top of layer 2 and the bottom of layer 5 represents the overall thickness of the basin-fill aquifer (fig. 18). The basin fill is fairly thin near its edges at the contacts with consolidated rocks. At a distance of 5,250–6,562 ft (1,600–2,000 m) from the consolidated rock/basin-fill contact, the depth of the basin fill increases until it reaches a maximum thickness of 1,180 ft (360 m) at a distance 7,094 ft (2,162 m) from the contact with consolidated rocks.

Temporally, the model simulates 63 stress periods. Each stress period is further discretized into approximate monthly time steps. The first stress period represents dynamic equilibrium (steady-state) conditions of the basin from 1908 to 1918 (fig. 6) and establishes the initial hydrologic conditions for the transient simulation, which uses the remaining 62 transient stress periods. The transient simulation stress periods were discretized into varying numbers of monthly time steps. Monthly time steps were equivalent to 30.44 days and were determined by dividing the average number of days in a year (365.25 days) by 12 months. The LWR_MF uses time units of days.

The second stress period represents the 15.8-year period beginning when steady declines of Walker Lake began October 1, 1918, and extending to the time when storage of Walker River water in Weber Reservoir began in July 31, 1934. During this stress period, water was diverted directly from Walker River to supply irrigation demand. The second stress period had 190 monthly time steps.

The third stress period represents the 43.2-year period from the beginning of storage in Weber Reservoir August 1, 1934, and extending to September 30, 1977. During this stress period, water was diverted from Weber Reservoir to supply irrigation demand rather than from Walker River. The third stress period had 518 monthly time steps.

The 4th to the 47th stress periods represent the 22.1-year period from October 1, 1977, to the time when operation rules and criteria for Weber Reservoir were adjusted to account for new earthquake safety protocols on October 31, 1999. Each year during this period was divided into two seasonal stress periods, a dormant season (Nov. 1–Apr. 30) and an irrigation season (May 1–Oct. 31), and each year contained six time steps per stress period.

The 48th to the 55th stress periods represent the 4-year period from November 1, 1999, to October 31, 2003, when the earthquake operation rules for Weber Reservoir were readjusted. In February 2000, the U.S. Bureau of Indian Affairs lowered the maximum operating lake level of Weber Reservoir to increase dam safety in case of an earthquake. During this stress period, the maximum operating lake level of Weber Reservoir was lowered from 4,208 ft to a new operational level of 4,196.5 ft (local datum).

The 56th to the 62d stress periods represent the 3.5-year period from November 1, 2003, to April 30, 2007, when reconstruction of Weber dam and fallowing of fields began. In early 2004, the U.S. Bureau of Indian Affairs readjusted the maximum operating lake level of Weber Reservoir slightly upward to increase useable storage in the reservoir. During this stress period, the maximum operating lake level of Weber Reservoir was raised to 4,200 ft (local datum) to be consistent with the revised operation criteria.

The 63d and final stress period represents the 0.4-year period from May 1, 2007, to the end of the model simulation on September 30, 2007. In 2007, the U.S. Bureau of Indian affairs implemented a fallowing program during the reconstruction of the Weber dam. During this time, water was not diverted from Walker River or Weber Reservoir. This was simulated by specifying a zero irrigation demand in the model. This stress period contained only five time steps.

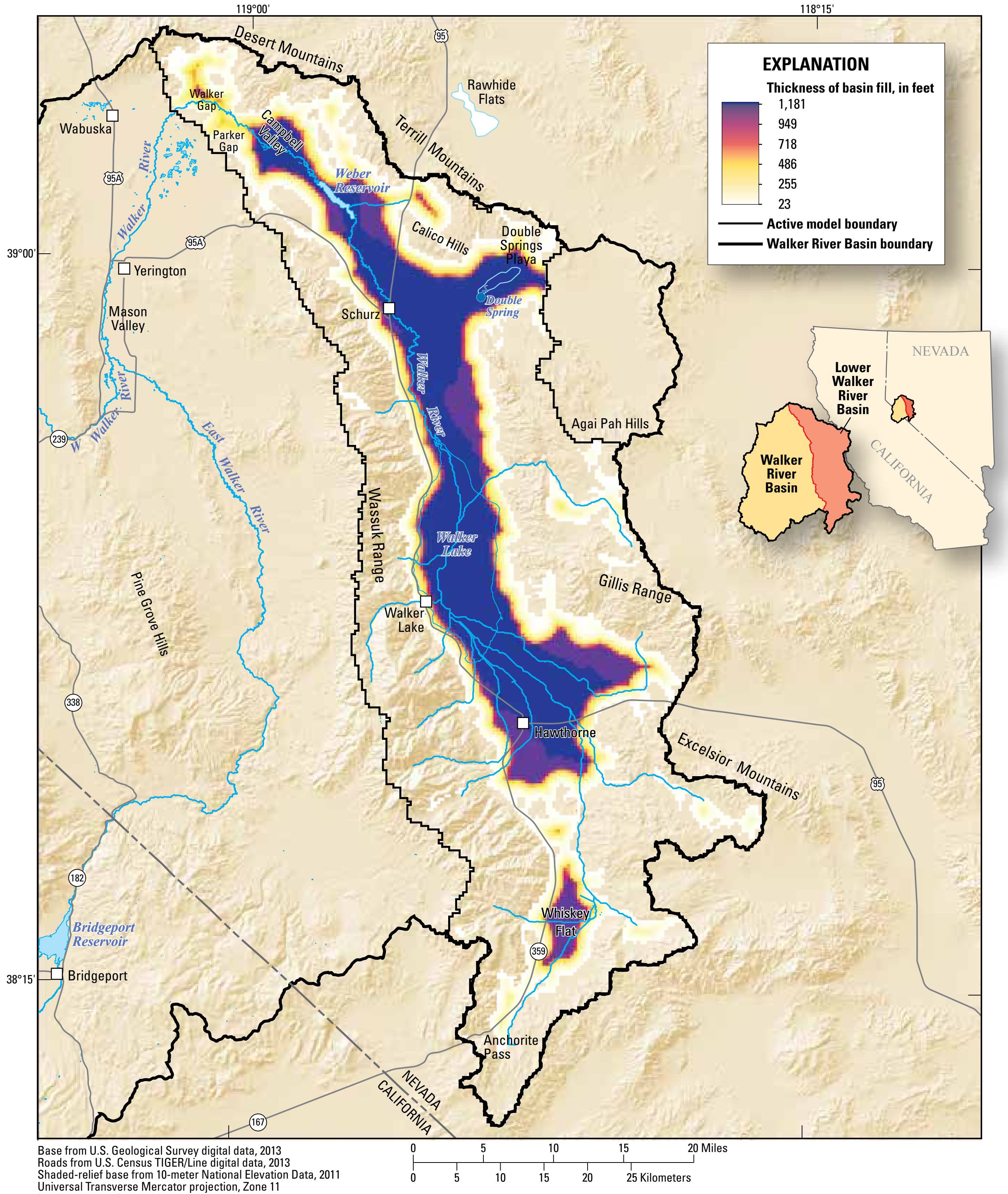
Boundary Conditions and Processes

Boundary conditions specify where water enters and exits the model domain. In the LWR_MF, boundary conditions were specified where the model boundary corresponds to natural physical boundaries of the system, except where the domain cuts through the alluvial basin east of Double Springs (fig. 16). This section discusses the boundary conditions and processes used by this model.

Streamflow Routing

The LWR_MF routes streamflow through the same stream network described earlier in the Stream Network section. The stream network provides a pathway for surface water to move from upland areas to areas of discharge in the lowlands, especially the Walker River where it enters the model domain at the Wabuska streamgage and discharges to Walker Lake (fig. 16). Surface water in streams can originate from upstream sources, groundwater discharge, or as specified diversions from Weber Reservoir. Streamflow routing enables the model to move surface water from these sources to either Walker Lake or agricultural fields while allowing exchanges with groundwater.

The Walker River and its tributaries and diversions are simulated in the model using the Streamflow Routing package (SFR2) in MODFLOW (Prudic and others, 2004; Niswonger and Prudic, 2005). Streamflow routing within the SFR2, as implemented in the LWR_MF, assumes that volumetric inflows and outflows are equal (Prudic and others, 2004). SFR2 is designed to route streamflow one way through the stream network while allowing the stream water to exchange with groundwater through the streambed. The interactions between the stream and groundwater are based on properties specified for the streambed and aquifer and on the calculated stream level and groundwater level. The difference in altitude between the stream level and the groundwater level governs the direction of water movement between the stream and



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 18. Thickness of basin-fill unit in the lower Walker River Basin, west-central Nevada, as discretized in the LWR_MF.

aquifer, whereas the magnitude of that difference, as well as streambed properties, governs how much water transfers between the two. SFR2 defines streams using stream segments and stream reaches. Stream reaches are individually defined for each model cell with a river or tributary channel (fig. 1, Prudic and others, 2004). Stream reaches are grouped into stream segments between tributary stream or lake junctions. For each segment of the stream network, stream depth is calculated using Manning's equation (Prudic and others, 2004), which requires stream slope, streambed roughness coefficient, and stream-channel geometry (Barnes, 1967). Stream depth is added to the altitude of the streambed to simulate stream level. Stream channel geometry was defined using a wide rectangular channel with specified width for tributaries and using a specified eight-point channel cross section for the Walker River.

For the Walker River below Weber Reservoir, as well as most of the tributaries, the water in the stream may not be in hydraulic connection with the groundwater because an unsaturated zone underlies the stream channel (see Winter and others, 1998, for explanations of groundwater/surface-water interactions and unsaturated zones beneath streams). SFR2 also simulates one-dimensional vertical flow between streams and aquifer through the unsaturated zone, where it is present (Niswonger and Prudic, 2005).

The stream network was intersected with the model grid to determine lengths, slopes, and altitudes of individual stream reaches within each model cell. For stream reaches with calculated slopes of zero, slopes were set to 0.0001 (dimensionless).

The altitudes of the stream reaches were determined using the composite 40-m DEM, which has higher resolution than the LWR-MF model grid (400 m), so some stream reaches had altitudes above land surface of the associated model cell (elevated stream reach) or below the bottom of the associated cell (penetrating stream reach). Elevated stream reaches were rectified by adjusting the land-surface altitudes of associated model cells upwards so that the stream reach was incised by 1 or 2 m. In contrast, the penetrating stream reaches were rectified by increasing the thickness of associated model cells so the stream reach did not penetrate through the bottom of these cells.

All streams in the lower Walker River Basin were simulated in the LWR_MF to discharge to Walker Lake at its deepest point near its center (fig. 16). This simplified framework was used rather than the more complex specification of discharge to a changing shoreline of Walker Lake at all times during the simulated period. To prevent the streams from interacting with the groundwater system beneath the lake surface, whenever the simulated stream level was beneath the simulated lake level, streambed hydraulic conductivity was set to zero, and alternatively, when the simulated stream level was above the simulated lake level, the streambed hydraulic conductivity was set to its calibrated value. This approach conceptually routes flow directly from the shoreline to the bottom of the lake. This approach also was used for Walker River flows entering Weber Reservoir.

Walker River Inflow

The largest flow of water entering the model domain was at the Wabuska gage (stream segment 1; fig. 16). The streamflows entering the model during the steady-state simulation were determined through calibration and during the transient simulation were specified on the basis of available streamflow data. The Wabuska streamgage has the second longest and most complete streamflow record in the Walker River Basin (fig. 19*A*) with data available beginning in 1903. There are two periods with missing streamflow data: 1905–1920 and 1935–1939. The streamflow for Wabuska gage was estimated for these missing periods so that long-term streamflow could be compared with the calibration-determined steady-state stress period inflow and to specify inflow for missing portions of the transient simulation period.

Missing periods of streamflow for the Wabuska gage were estimated using six methods (fig. 19*B*, table 7). Four of the estimation procedures were simple linear regressions between streamflow at Wabuska gage and streamflow at other sites on Walker River (methods 1–4, table 7). The other two methods were based on observed flows at Wabuska gage (methods 5–6, table 7). In general, the methods are listed in order of preference for their use. For example, method 1 was the first method applied and was applied to all missing records where possible (for all missing days at Wabuska in which Walker River at Schurz had data). If data needed for method 1 were not available, then method 2 was used, and so on.

The average annual streamflow estimated at the Wabuska gage for 1908 to 1918 was 253,000 acre-ft/yr. This is about 24,000 acre-ft/yr less than the 277,000 acre-ft/yr estimated by Everett and Rush (1967) for nearly the same period (1909–18).

Walker River

Streamflow that enters the model through the boundary at the Wabuska gage is routed downstream along the main stem of the Walker River where it is subjected to a variety of potential losses and gains, and storage in Weber Reservoir; then the remaining flow discharges into Walker Lake. This section discusses how these processes in the Walker River are simulated in the model and how the main stem of Walker River is specified in the model. Some of the important stream properties related to controlling the level, water budget, and streamflow of Walker River are inflows from upstream, direct surface runoff, direct precipitation, and tributaries; outflows from downstream, diversions, and evaporation; and Manning's roughness coefficient.

The streambed is the zone between the stream and aquifer where properties can be adjusted to control simulated interactions between the stream and groundwater. Some of the important streambed properties related to controlling the interactions of Walker River with the groundwater system are streambed thickness, streambed hydraulic conductivity, saturated and initial volumetric water content of unsaturated zones beneath the river, if present, and the Brooks–Corey exponent.

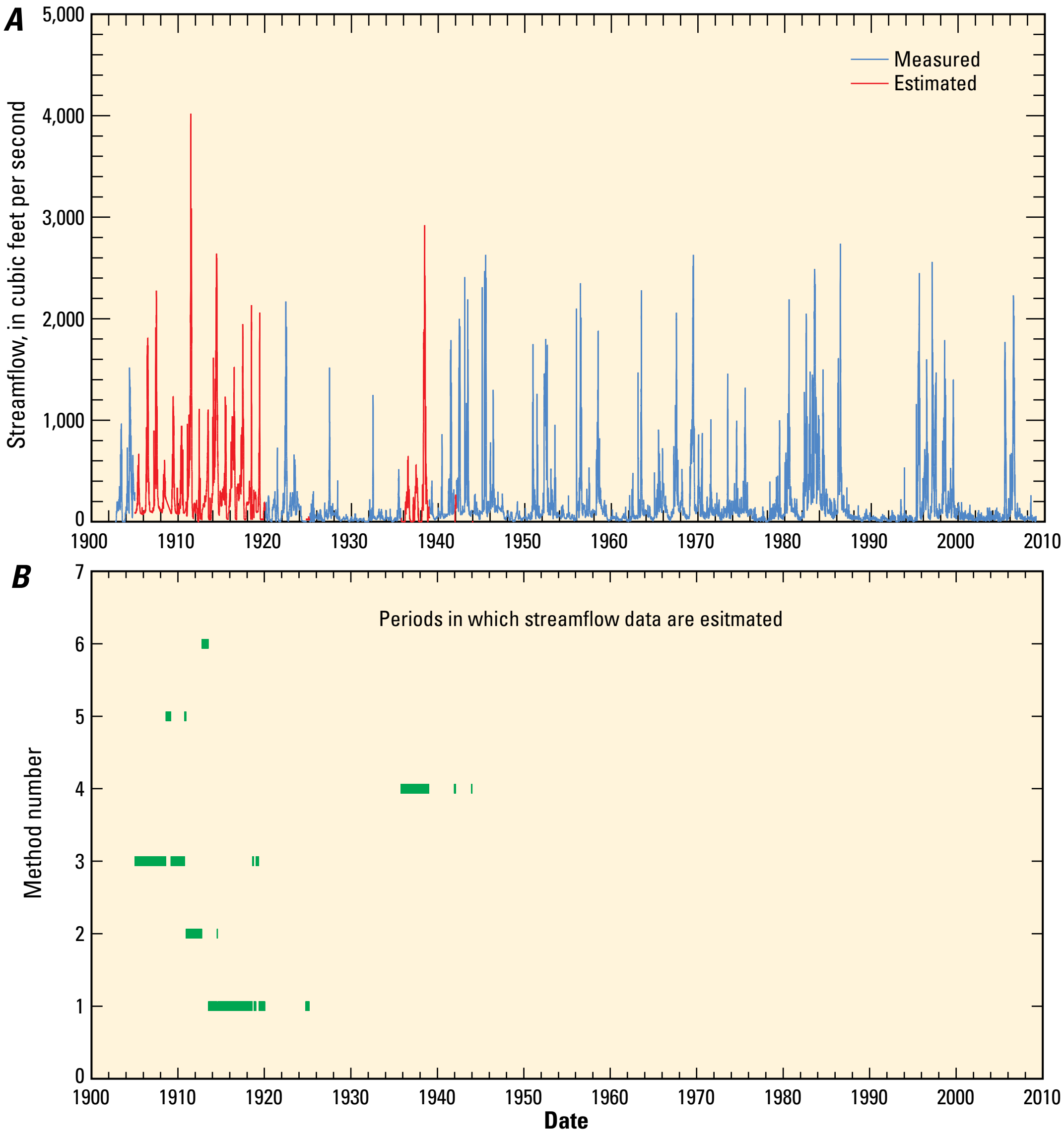


Figure 19. *A*, hydrograph for Walker River at Wabuska (10301500), west-central Nevada, and *B*, periods of record that were estimated and method used for estimating streamflow. Methods are defined in table 7.

Table 7. Methods and relations used for estimating missing streamflow data for Walker River near Wabuska streamgage, west-central Nevada.

[Periods over which these relations were applied are shown in figure 19B. Schurz, Walker River at Schurz, Nevada, 10302000; WAB, Walker River near Wabuska, Nevada, 10301500; ft^3/s, cubic feet per second; Mason, Walker River at Mason, Nevada, 10301000; WWCole, West Walker River near Coleville, California, 10296500; EWBrid, East Walker River near Bridgeport, California, 10293000; NA, not applicable]

Method	WAB=	R^2	Condition	Period of relation
1	1.035Schurz+22.9	0.95	For all paired data	1/15/1920–9/30/1930
2	0.866Mason-56.3	0.94	For all paired data; Minimum allowed for WAB is 1 ft^3/s	6/1/1921–11/1/1922
3	0.535WWCole+48.1	0.53	For all paired data prior to 6/30/1922	10/1/1902–6/29/1922
4	$0.022EWBrid^{1.66}$	0.63	For all paired data with EWBrid between 6 and 1220 ft^3/s	10/1/1921–1/1/2009
5	Linear interpolation	NA	Only used for periods of up to a few months during non-irrigation season	NA
6	Mean daily flow at WAB	NA	Mean daily flows calculated from all available dates with measured or estimated flows prior to 6/30/1923	NA

In situations when an unsaturated zone is present between the stream and groundwater, the property of saturated volumetric water content controls the rate of infiltration through the unsaturated zone. Saturated volumetric water content is generally equivalent to the specific yield plus specific retention of sediments beneath the stream (Niswonger and Prudic, 2005). The Brooks–Corey exponent is a parameter used in mathematical expressions that relate hydraulic conductivity to water content within the unsaturated zone.

In the first part of the simulation (stress periods 1 and 2; October 1918 through July 1934), Walker River was simulated as a river channel through the location of Weber Reservoir. Diversions from the Walker River by the Walker River Paiute Tribe for irrigation were simulated at a specified rate and were made at what later becomes the outlet location for Weber Reservoir. Beginning in stress period 3 (August 1934), when the newly constructed reservoir began filling, flow was specified to enter and exit the reservoir rather than remaining as a river. Beginning with stress period 3, reservoir operation rules were established dictating that streamflow is released only back into the main stem of Walker River downstream from the reservoir after storage in the reservoir exceeds spillway heights (discussed later in the "Walker Lake and Weber Reservoir" section).

The channel geometry of the main stem of Walker River was defined using measured cross sections surveyed between April 2008 and October 2010. Cross sections were surveyed at each streamgage site (Wabuska, Cow Camp, Little Dam, and Lateral 2A; fig. 3) and at one additional location midway between Lateral 2A gage and Walker Lake. Each measured cross section consisted of 10 to 24 points. Only a single cross section can be specified for each stream segment in the SFR2, and a single cross section is restricted to only 8 points. Therefore, measured cross sections were grouped for the stream segments they represented and were generalized using an 8-point definition (fig. 20) and a total bank height of 13.1 ft (4.0 m) to ensure that simulated flows remained within the channel and could not spill onto the floodplain. This was done by averaging the generalized cross sections within a stream segment and adjusting single points of the generalized cross section to ensure that the height of stream channel bottom was 0 at the deepest part of the stream (thalweg) and the total cross-sectional area was equal to the average of the measured cross-sectional areas.

The Walker River stream segments from Wabuska streamgage to the south end of Weber Reservoir (stream segments 1 and 3) were defined by the average of the Wabuska and Cow Camp streamgage cross sections (fig. 20). The Walker River stream segments from the Weber Reservoir spillway to the deepest point of Walker Lake (stream segments 4, 6, 8) were defined by the average of the Little Dam, Lateral 2A, and the additional cross section (fig. 20).

Stream properties related to controlling the level, water budget, and streamflow of Walker River were specified. The only inflows for Walker River were inflows to the model at Wabuska gage; thus, direct surface runoff and precipitation contributions to Walker River were assumed to be negligible and were specified as zero. The only outflows specified for Walker River were diversions to meet irrigation demand prior to construction of Weber Reservoir. Direct evaporation from Walker River was assumed to be negligible and was also specified as zero. Manning's roughness coefficient was assumed to be 0.030 (unitless) for the entire length of the Walker River.

Streambed properties were specified or determined through calibration for two main river reaches. An upstream reach represented the stream segments upstream from Weber Dam (upstream reach), and a downstream reach represented the stream segments downstream from Weber Dam (downstream reach). For both main river reaches, the streambed thickness was arbitrarily chosen to be 3.3 ft (1 m) thick. The hydraulic conductivity of the streambed, which controls how readily water can move through the streambed under saturated conditions, was parameterized for the upstream and downstream reach (*StrBedKus* and *StrBedKds,* respectively). Additionally, the hydraulic conductivity of the streambed was automatically set to zero anytime the model simulates the stream levels beneath a lake level to prevent spurious interactions with the groundwater system. The model calibration (discussed later in "Model Calibration" section) resulted in upstream hydraulic conductivity of 0.23 ft/d (0.07 m/d) and downstream hydraulic conductivity of 0.016 ft/d (0.005 m/d).

Saturated volumetric water content was assigned a constant value of 0.30 (unitless) to correspond to the combined storage of specific yield (0.15) and specific retention (0.15) (both unitless values are assumed) for both main river reaches. The Brooks–Corey exponent was specified as a constant 4.0 (unitless) for the entire length of Walker River (Niswonger and others, 2006).

Tributaries

Tributaries were defined in the model as all stream segments in the lower Walker River Basin that are not the main stem of the Walker River (fig. 16) and were primarily included to collect groundwater discharge. Tributaries originate within the model domain from areas of higher altitude in the Terrill Mountains, Gillis Range, Excelsior Mountains, Anchorite Hills, and Wassuk Range (fig. 3) and discharge to Walker River or to Walker Lake. Most of the tributaries drain the southern half of the lower Walker River Basin and are ephemeral along their entire lengths; however some tributary reaches are perennial.

No inflows to the tributaries were specified. Direct surface runoff and precipitation contributions to the tributaries were assumed to be negligible and were specified as zero. There were no diversions specified for the tributaries. Direct evaporation from the tributaries was assumed to be negligible and was specified as zero. Manning's roughness coefficient was assumed to be 0.030 (unitless) for the entire tributary network. The channel geometries of the tributaries were generalized using conceptually wide rectangular channels of 10.0 ft (3.05 m) width.

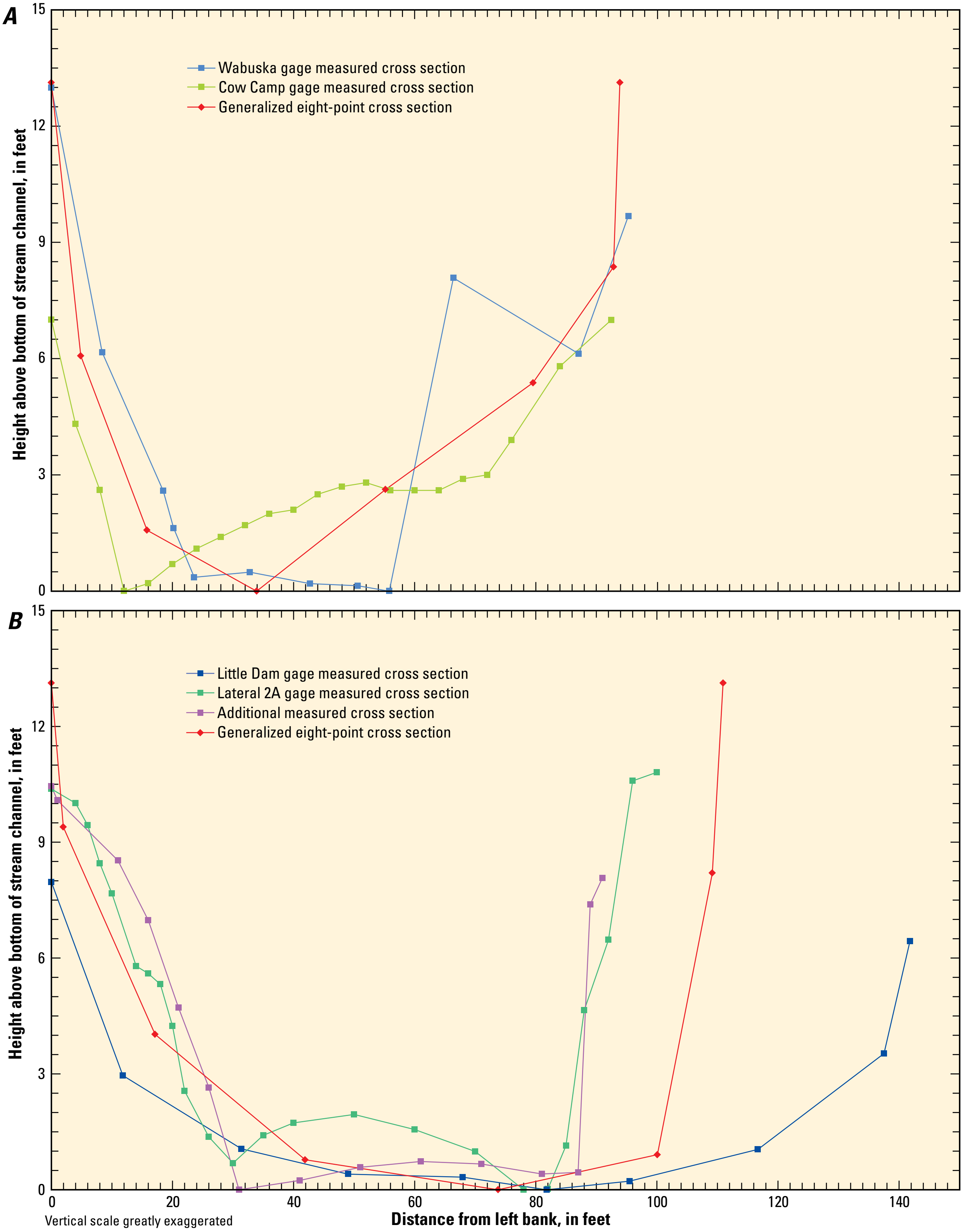


Figure 20. Measured and generalized cross sections used to define *A*, stream segments 1 and 3 and *B*, stream segments 4, 6, and 8.

Table 8. Annual diversion and irrigation season data and computed irrigation efficiencies for Walker River Indian Irrigation Project, in west-central Nevada, for available record, irrigation seasons 1995–2007.

[No., number; WRIIP, Walker River Indian Irrigation Project; nm, not measured, assumed negligible except during 1997; —, insufficient data for computation]

Calendar year	Irrigation season flow (acre-feet)					Irrigation season				
	Canal No. 1	Canal No. 2	Total WRIIP diversion	Flow out of WRIIP[1]	Net WRIIP diversion[2]	Start date	End date	Season length (days)	Full irrigation season	Irrigation project efficiency[3]
1995	7,059	11,990	19,050	nm	19,050	4/21/1995	10/31/1995	193	Yes	0.39
1996	—	—	—	—	—	—	—	—	—	—
1997	9,619	15,417	25,036	nm	25,376	4/21/1997	10/26/1997	188	Yes	[4]0.29
1998	7,886	14,980	22,866	4521	18,345	4/20/1998	10/20/1998	183	Yes	0.40
1999	8,415	15,135	23,551	4760	18,791	4/19/1999	10/25/1999	189	Yes	0.39
2000	5,531	7,999	13,530	563	12,967	4/24/2000	11/1/2000	191	No	
2001	4,449	6,346	10,794	nm	10,794	4/18/2001	10/23/2001	188	No	
2002	3,662	5,699	9,360	nm	9,360	4/29/2002	10/19/2002	173	No	
2003	5,222	7,603	12,825	nm	12,825	4/24/2003	10/30/2003	189	No	
2004	4,431	6,512	10,943	nm	10,943	5/4/2004	9/12/2004	131	No	
2005	6,504	9,473	15,977	nm	15,977	5/2/2005	10/18/2005	169	No	
2006	6,824	11,436	18,260	nm	18,260	5/3/2006	10/17/2006	167	Yes	0.40
[5]2007	0	0	0	nm	0			0	No	
Mean	6,328	10,236	16,563	—	15,699	Apr 23	Oct 21	178.3		0.40

[1] Flow out of WRIIP was gaged for 3-year period. Stream site is U.S. Geological Survey 10301900 Canal 2 at end of lined ditch below Schurz, Nevada.

[2] WRIIP diversion is calculated as total of Canal 1 and Canal 2 diversions less flow out of the WRIIP.

[3] Irrigation project efficiency was only computed for full irrigation years and is computed as the ratio of water consumed by crops (7,350 acre-feet) to the Net WRIIP diversion.

[4] Irrigation project efficiency in 1997 is considered to be an anomaly and was not included in calculation of mean irrigation project efficiency. This is due to very high WRIIP diversion for the season which is assumed to be a result of unmeasured flow out of WRIIP.

[5] Fields were fallowed in 2007 for beginning of Weber Dam reconstruction project. No diversions were made.

Diversions

There are two main diversions of surface water in this hydrologic system. Only the agricultural diversion from Walker River by the WRIIP to support flood irrigation of fields was simulated. The water in these canals is delivered to a network of lined and unlined canals, lateral canals, and irrigation ditches that bring the water to about 2,100 acres of flood-irrigated fields, mostly of alfalfa. The other diversion is from Cottonwood Creek, Rose Creek, Cat Creek, and other perennial streams in the Wassuk Range by the Army Depot (fig. 3). These diversions are relatively small compared to uncertainties associated with groundwater recharge and, therefore, were not simulated in the model.

Diversions from Walker River were specified in the model on the basis of estimated irrigation demand from the beginning of simulation through 1994 when records of diversions began. Diversions from 1995 through 2007 were specified on the basis of observed streamflow diversions (total WRIIP diversion in table 8). Irrigation demand is the amount of water needed in an irrigation season to fully irrigate crops and was calculated as the product of the area of crops irrigated with Walker River water and the crop consumptive use rate for those crops, divided by irrigation project efficiency. Diversions are made to meet irrigation demand if supply is available; otherwise, diversions are reduced to available supply.

Irrigated acreage in the model was 2,100 acres. The 2,100 acres of Walker River irrigated acreage delineated by Allander and others (2009) was used to determine where the inefficient proportion of irrigation water in the model was recharged to the groundwater system. The model cells where this water was applied are referred to as “field cells” (fig. 16). The locations of field cells are assumed to adequately represent the area where conveyance losses through the irrigation network and infiltration of excess water on fields occur.

Huntington and Allen (2010) estimated the net irrigation water (or crop consumptive use) requirement for the Schurz area to be 3.5 ft/yr. A crop consumptive use rate of 3.5 ft/yr (0.0029 m/d) was used to calculate the irrigation demand.

Irrigation project efficiency is the percentage of diverted water that is transpired through crop consumption and is calculated as the ratio of volume of water consumed by crops to the net diversion. The remaining portion of the diversion not consumed by crops (inefficient portion) infiltrates to the groundwater system. The net diversion of water to the WRIIP was calculated by combining the record of flow from Canal No. 1 and Canal No. 2 and subtracting flow leaving the WRIIP (table 8). Irrigation project efficiency was calculated only for seasons with full irrigation of crops. Full irrigation seasons were determined by using the lake level in Weber Reservoir as an indication of available supply throughout the irrigation season. If lake level in the reservoir remained above the minimum pool level, then the season was considered a full irrigation season, whereas if it was at or below minimum pool level anytime during the season, the season was not considered to be a full irrigation season. Five of the 12 irrigation seasons with diversion data were full irrigation seasons (table 8) and had computed irrigation project efficiencies of 0.39, 0.29, 0.40, 0.39, and 0.40 (unitless). The irrigation project efficiency calculated for 1997 (0.29) is considered an anomaly and was not used in calculation of the mean irrigation project efficiency. In 1997, there was no streamgage to measure flows out of the WRIIP, and it is assumed that some of the total 1997 diversion left the WRIIP as unobserved flow. The computed mean irrigation project efficiency is 0.40.

The model uses an irrigation season of 182.4 days. Available records of diversions indicate actual irrigation on the WRIIP starts near the end of April with a mean start date of April 23 (table 8). Since the model is discretized using approximate monthly time steps (30.4 days), diversions in the model were specified to begin May 1. Diversion records indicate that irrigation is generally discontinued around mid-October with a mean end date of October 21, which is consistent with the decree period of 180 days. The model discontinues diversions on approximately October 30.

Irrigation demand for WRIIP was calculated to be 18,375 acre-ft/yr (62,058 cubic meters per day [m^3/d]) using the annual crop acreage of 2,100 acres (8,498,500 m^2), a crop water use of 3.5 ft/yr (0.0029 m/d), and an irrigation project efficiency of 0.40. Seasonal irrigation demand was 50.4 ft^3/s (123,189 m^3/d) over the 182.4-day irrigation season.

Diversions were incorporated into the model using SFR2. Diversions were taken directly from Walker River at the end of stream segment 3 through diversion segment 30 (not shown) until storage of river water in Weber Reservoir began (end of stress period 2; August 1934), at which time diversions were taken directly from Weber Reservoir through diversion segment 30 or 31 (not shown), depending on minimum pool level for Weber Reservoir. The diversion rate is the irrigation demand if flow in Walker River, or storage in Weber Reservoir, are sufficient to meet the irrigation demand. If the flow in the river or storage in the reservoir is not sufficient to meet the irrigation demand, the diversion rate is reduced to the flow in the river or the available supply from the reservoir. The model used the irrigation project efficiency to remove 40 percent of the diversion from the model (as crop consumptive use), and the remaining 60 percent of the diversion was injected into field cells as recharge to layer 2 using the Unsaturated Zone Flow package in MODFLOW. This is a reasonable approximation of the process as there are no drains or irrigation tail water returns to Walker River from the WRIIP.

Walker Lake and Weber Reservoir

The LWR_MF simulates the fluctuations in lake level, volume, and area in both Walker Lake and Weber Reservoir (fig. 16). The model also accounts for the changing boundary where streams enter the lake and groundwater and lake water are exchanged.

The lakes were simulated in the model using the Lake package in MODFLOW (Meritt and Konikow, 2000). Within the Lake package, lakes are represented as lake cells in model layer 1. Active aquifer cells beneath the lake cells exchange water with the lake cells at a rate determined by the relative water levels and properties of the aquifer model cells, and lake level and lakebed properties of the lake cells. Variations in lake level are determined from a lake water budget computed for each time step and are based on the relation between lake volume and lake level. The lake water budget is iteratively solved by summing all simulated inflows from streams, groundwater, and precipitation on the lake surface and subtracting outflows from groundwater and evaporation from the lake surface. The lake surface area is determined on the basis of the relation between surface area and lake level. Lake cells may become dry or wet as necessary to accommodate changes in lake size. The LWR_MF used relations between lake volume, area, and lake level in look-up tables derived from Lopes and Smith (2007) for Walker Lake and Katzer and Harmsen (1973) for Weber Reservoir.

Although look-up tables are used by the model to compute lake level and lake area, lake bathymetry data are still needed to properly represent the lake and reservoir in the model and to properly simulate lake extent and heads in lake cells needed for computation of lake water exchanges with groundwater. Bathymetric data for Walker Lake and Weber Reservoir were used to assign altitudes of lake-cell bottoms using the composite 40-m DEM, which incorporated Walker Lake bathymetry from Lopes and Smith (2007), and Weber Reservoir bathymetry digitized from Katzer and Harmsen (1973). The Lake package in MODFLOW was used to convert the lake model cell discretization to tables relating lake volume and area to lake level for comparison with the look-up tables used by the model to compute lake level and area. The lake level-volume-area relation simulated for Walker Lake agreed fairly well with Lopes and Smith (2007), but the area is slightly smaller for higher lake levels of the lake (fig. 21*A*). After some minor vertical adjustments of Weber Reservoir lake model cells, the lake level-volume-area relation simulated for Weber Reservoir was also acceptable (fig. 21*B*). The stepwise characteristic of the lake level-volume-area curve for Weber Reservoir model discretization reflects the relatively coarse discretization of Weber Reservoir, but it is an acceptable match.

The lateral extent of the potential active lake cells was determined by using the greatest extents of Walker Lake and Weber Reservoir during the simulation period. For Walker Lake, the largest extent was at the initial lake level of 4,078.0 ft local datum (1244.1 m) on October 1, 1918 (fig. 22*A* and fig. 2). For Weber Reservoir, the greatest extent was based on the total area of the reservoir under maximum operating lake level of 4,208.0 ft local datum (1,283.6 m; fig. 22*B*).

The annual precipitation rates specified for Walker Lake and Weber Reservoir were 0.34 ft/yr (0.000285 m/d) and 0.49 ft/yr (0.000410 m/d), respectively, which were based on the average annual precipitation applied to corresponding HRUs in the LWR_PRMS. An annual evaporation rate

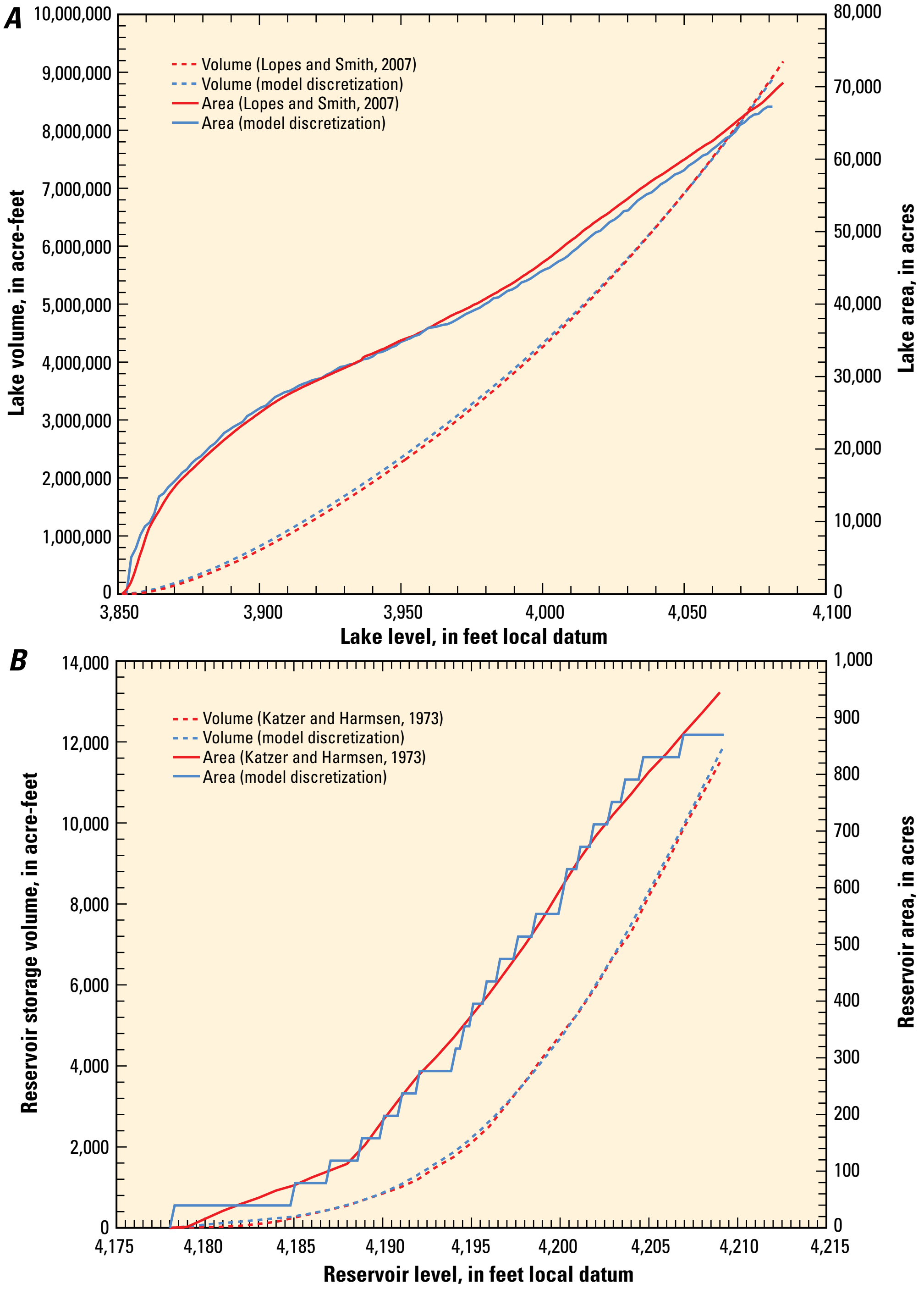
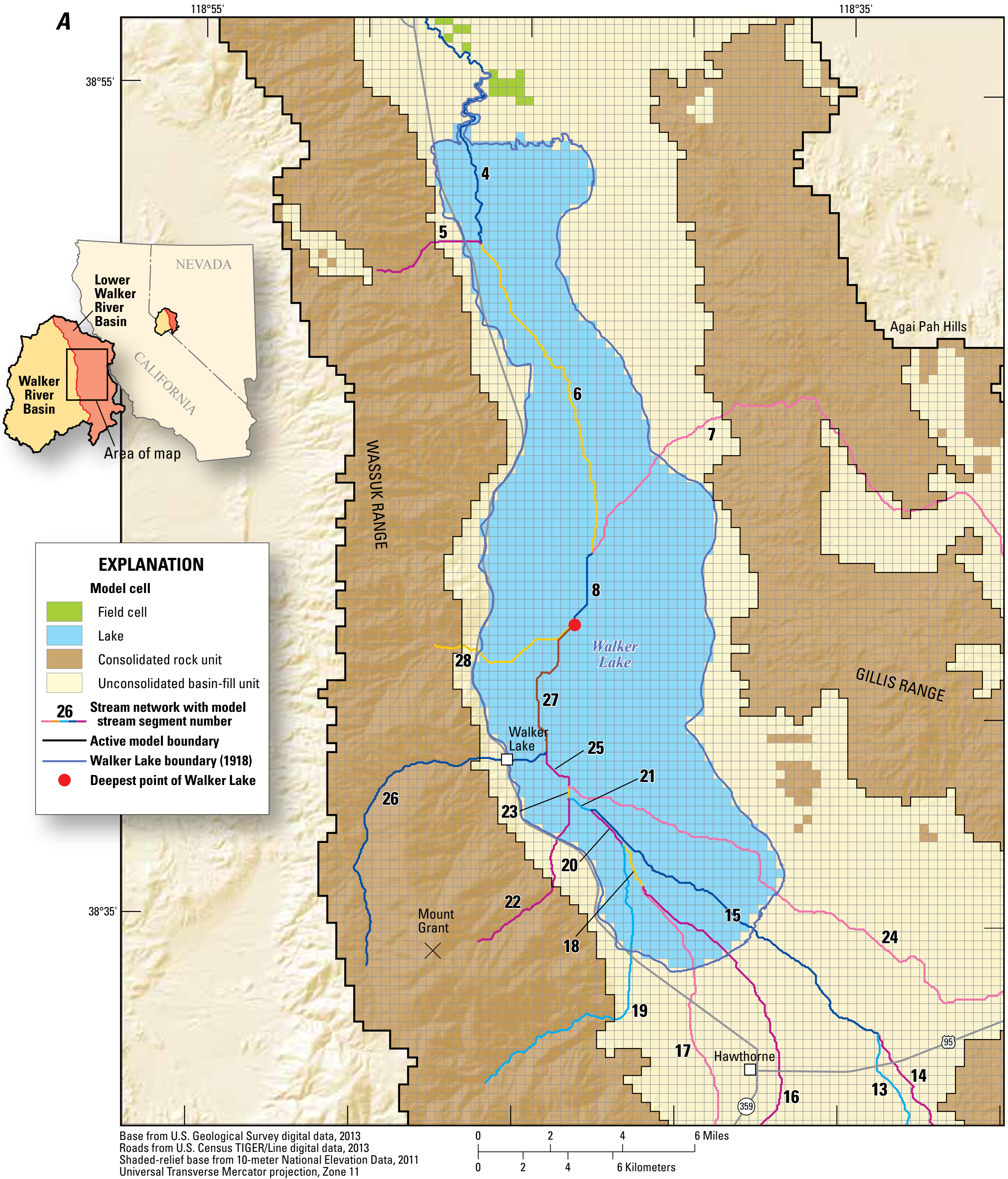


Figure 21. Relations between lake level, storage volume, and surface area, as discretized in the LWR_MF model and bathymetric references for *A*, Walker Lake and *B*, Weber Reservoir, west-central Nevada.

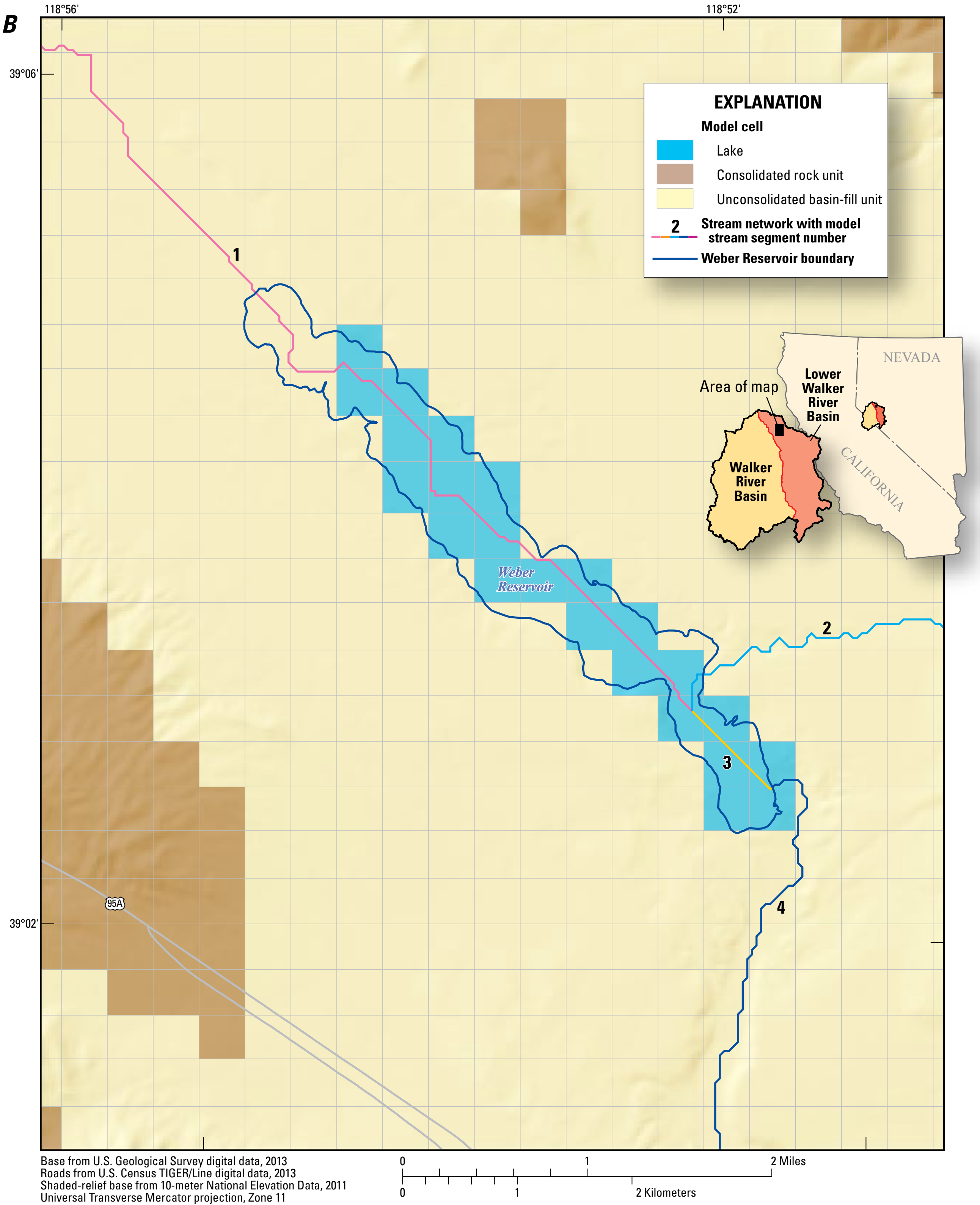
of 4.37 ft/yr (0.00365 m/d) used for the lake and reservoir was determined through model calibration. Surface runoff to Walker Lake was accounted for by the stream network and SFR2 (described previously in section "Streamflow Routing"). Lakebed leakance, the ratio of hydraulic conductivity of the lakebed to the thickness of the lakebed sediments (units of t^{-1}), was assigned a single value for all lake cells and was determined through calibration. A constant lakebed thickness of 3.3 ft (1.0 m) was arbitrarily specified so the lakebed leakance was equivalent to hydraulic conductivity. Lakebed leakance of 0.00111 d^{-1} for Walker Lake and 0.00050 d^{-1} for Weber Reservoir were estimated through calibration.

The maximum operation level of Weber Reservoir is controlled by the altitude of overflow stream segments (spillways). Three different stream segments (4, 32, and 33) were used to control the maximum operation level of Weber



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 22. *A*, model grid representation of Walker Lake and stream segments and *B*, model grid representation of Weber Reservoir and stream segments, west-central Nevada.



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 22. *A*, model grid representation of Walker Lake and stream segments and *B*, model grid representation of Weber Reservoir and stream segments, west-central Nevada.—Continued

Reservoir at the three different operation levels during the model simulation period. Whenever the lake level of Weber Reservoir rises above the spillway, water is released to Walker River; whenever the lake level falls below the spillway, water is no longer released to Walker River. Stream segments 32 and 33 are in the same location and have the same properties as segment 4 but have different streambed altitudes that produce different maximum operating lake levels in Weber Reservoir. Stream segment 4 controls the maximum operating lake level of Weber Reservoir at about 4,208.0 ft local datum (1,283.0 m; 1934–1999), stream segment 32 controls the lake level at about 4,196.5 ft local datum (1,280.1 m; 2000–2003), and segment 33 controls the lake level at about 4,200.0 ft local datum (1,281.2 m; 2004–2007). Because stream segment 4 is the main stream segment downstream from Weber Reservoir that routes flows downstream toward Walker Lake, when stream segments 32 and 33 are being used, their flows are routed back to segment 4 prior to flowing downstream.

The minimum operation level of Weber Reservoir and the minimum pool for the fishery is controlled by both the altitude and flow through diversion segments. Whenever the lake level of Weber Reservoir falls below the altitude of diversion segments, diversions are not allowed. Diversion segment 30 controls the minimum operating lake level at 4,194.0 ft local datum (1,279.4 m; 1919–2000; 2004–2007), and diversion segment 31 controls the lake level at 4,187.0 ft local datum (1,277.3 m; 2000–2003).

Groundwater Inflow and Outflow

Groundwater enters the model boundary through Walker Gap and Parker Gap (fig. 16). Groundwater leaves the model boundary east of the Double Springs area (fig. 3). The groundwater flows through these boundaries were simulated using the General Head Boundary package (GHB) in MODFLOW. GHB simulates flow into or out of a model cell from an external source in proportion to the difference between the simulated water level in the cell and a reference water level assigned to the external source (Harbaugh, 2005). The conductance of the general head boundary controls the rate of flow induced by changes in the simulated water level in the GHB model cell.

The general head boundary for Walker Gap and Parker Gap groundwater inflows is represented by a total of 33 GHB model cells (fig. 16). The Walker gap boundary consists of a total of 16 GHB cells with 4 cells each in model layers 2, 3, 4, and 5. The external source reference water level and boundary conductance of these cells were adjusted so that the flow into the model was approximately 100 acre-ft/yr (340 m^3/d) to be consistent with estimate from Lopes and Allander (2009a). This boundary flux was achieved with an external source reference water level of 4,311.69 ft (1,314.22 m) and a boundary conductance of 24.8 ft^2/d (2.3 m^2/d). The Parker Gap boundary consists of a total of 17 GHB cells with 4 cells each in layers 2, 3, and 4, and 5 GHB cells in layer 5. The external source reference water level and boundary conductance of these cells were adjusted so that the flux into the boundary was approximately 700 acre-ft/yr (2,400 m^3/d) to be consistent with Lopes and Allander (2009a). This was achieved with an external source reference water level of 4,461.46 ft (1,359.87 m) and a boundary conductance of 24.8 ft^2/d (2.3 m^2/d).

The general head boundary for Double Springs groundwater outflow is represented by a total of 14 model cells (fig. 16). All 14 cells are in layer 5. The external source reference water level and boundary conductance of these cells were adjusted so that the flow out of the boundary was approximately 2,700 acre-ft/yr (9,100 m^3/d) to be consistent with Lopes and Allander (2009a). This was achieved with an external source reference water level of 3,660.49 ft (1,115.73 m) and a boundary conductance of 60.3 ft^2/d (5.6 m^2/d).

Groundwater Recharge

Groundwater recharge that ultimately originates from Walker River inflow is referred to as “Walker recharge” and was handled by boundary processes for Walker River and diversions. Groundwater recharge that originates from precipitation falling within the model area (precipitation that reaches the water table either from infiltration through the unsaturated zone, or from seepage losses from tributary streams) is applied in the model using a two-dimensional array in the Unsaturated Zone Flow package (UZF) in MODFLOW-NWT. UZF was already being used to simulate unsaturated zone processes along the lower reach of Walker River, and because it simulates the infiltration of recharge similarly to the recharge package, it was used instead. The groundwater recharge array was obtained from results of the LWR_PRMS (fig. 15) and scaled by a factor of 0.86 during calibration in order to match observed groundwater heads and groundwater discharge to Walker Lake. Because the LWR_PRMS simulated only the period 1978–2007, it was not possible to generate seasonal recharge distributions dating back to the beginning of the LWR_MODFLOW simulation (1919). It is assumed that the average recharge distribution over the 30-year period of the LWR_PRMS is representative of the longer period of recharge needed by the LWR_MF model. Therefore a fixed recharge rate was applied throughout the entire model simulation, which is equivalent to 21,352 acre-ft/yr.

Groundwater Evapotranspiration

Evapotranspiration in the LWR_MF was simulated through three different boundary processes, depending on whether it originates from open water, natural vegetation, and shallow groundwater, or from crop-water use. Evaporation from Walker Lake and Weber Reservoir was simulated using the lake boundary process described earlier in section “Walker Lake and Weber Reservoir.” Crop water use was simulated through diversions from stream segments by the streamflow routing process described earlier in the “Diversions” section.

Evapotranspiration from natural vegetation and shallow groundwater was simulated by UZF which uses a specified Potential Evapotranspiration (PET) rate and a root extinction depth (depth at which evapotranspiration ceases) to simulate evapotranspiration during each stress period (Niswonger and others, 2006; Markstrom and others, 2008). The PET rate diminishes linearly with depth from land surface to the extinction depth where evapotranspiration no longer occurs. If soil moisture is available above the extinction depth, soil water is used to satisfy PET. When soil moisture is absent, water is removed from the water table, if the water table is above the extinction depth. If the water table is below the extinction depth and there is no soil water above the extinction depth, then no evapotranspiration is simulated. Constant values for PET and extinction depth are specified over the seasons and through simulation time. The extinction depth was estimated to be 9.9 ft (3.0 m), and PET was estimated to be 4.0 ft/yr (0.00334 m/d) through calibration of the LWR_MF.

Initial Conditions

The start of simulation of the LWR_MF represents the dynamic equilibrium period 1908 through 1918 (fig. 6). During this period, the range in annual Walker Lake level varied by an estimated 4.0 ft, but the change in lake level from the beginning to end of the period was less than an estimated 1.0 ft. The lack of long-term variability demonstrates that this period was the most appropriate for the steady-state simulation to estimate initial conditions for the lower Walker River Basin transient simulations.

Initial conditions for the LWR_MF were iteratively established for the steady-state period on the basis of the results of coupled steady-state and transient simulations. Lake evaporation rate and average inflow for Wabuska gage had the greatest effect on the Walker Lake level during the steady-state period. Irrigation demand during the steady-state period was held constant at 18,375 acre-ft/yr (62,058 m^3/d).

The evaporation rate that yielded the correct rate of decline for Walker Lake, while providing the correct lake evaporation outflow that balanced with Walker River inflow at the appropriate lake level, 4.37 ft/yr (0.00365 m/d), was determined through calibration. The Walker River inflow into the model at the Wabuska streamgage was 306,500 acre-ft/yr (1.035 million m^3/d). The steady-state streamflow determined for the Wabuska streamgage is greater than the 253,000 acre-ft/yr estimated by this study and the 277,000 acre-ft/yr estimated by Everett and Rush (1967). The difference between these streamflow values is acceptable given that both are estimates and neither is based on actual measurements. The starting groundwater levels for the transient simulation were determined from the steady-state simulation and represent the average groundwater-level distribution for the period 1908–18.

Hydraulic Properties

All hydraulic properties in the LWR_MF were defined using the upstream weighting package (UPW) in MODFLOW-NWT (Niswonger and others, 2011). Hydraulic conductivities were assumed to be laterally isotropic and vertically anisotropic throughout the entire basin-fill aquifer of the model.

Horizontal hydraulic conductivity was distributed throughout the active model cells using pilot points, which are mapped locations where hydraulic conductivities were adjusted through calibration. A total of 194 pilot points were specified at 66 mapped locations projected from model layers 2 through 6 (fig. 23). Layers 2–4 used 26 pilot points each to distribute horizontal hydraulic conductivity, layer 5 used 50 pilot points, and layer 6 used all 66 pilot points. Hydraulic conductivities were interpolated from the pilot points to model cells using two-dimensional kriging (Doherty, 2008b). The same horizontal hydraulic conductivity distribution was computed for layers 3 and 4. Two pilot points were located at or near aquifer-test sites reported in Lopes and Allander (2009a). At these locations, hydraulic conductivities based on the aquifer-test results were specified as prior information for each of the pilot points in layers 2 through 5 but were allowed to vary during calibration.

Ordinary kriging (Isaaks and Srivastava, 1989) was used to interpolate horizontal hydraulic conductivity, and the same variogram was assumed for the basin fill and consolidated rock units. An exponential variogram was assumed for log-transformed values of horizontal hydraulic conductivity with a nugget of zero, a range of 98.4 miles (158,400 m), and a sill of 1.0.

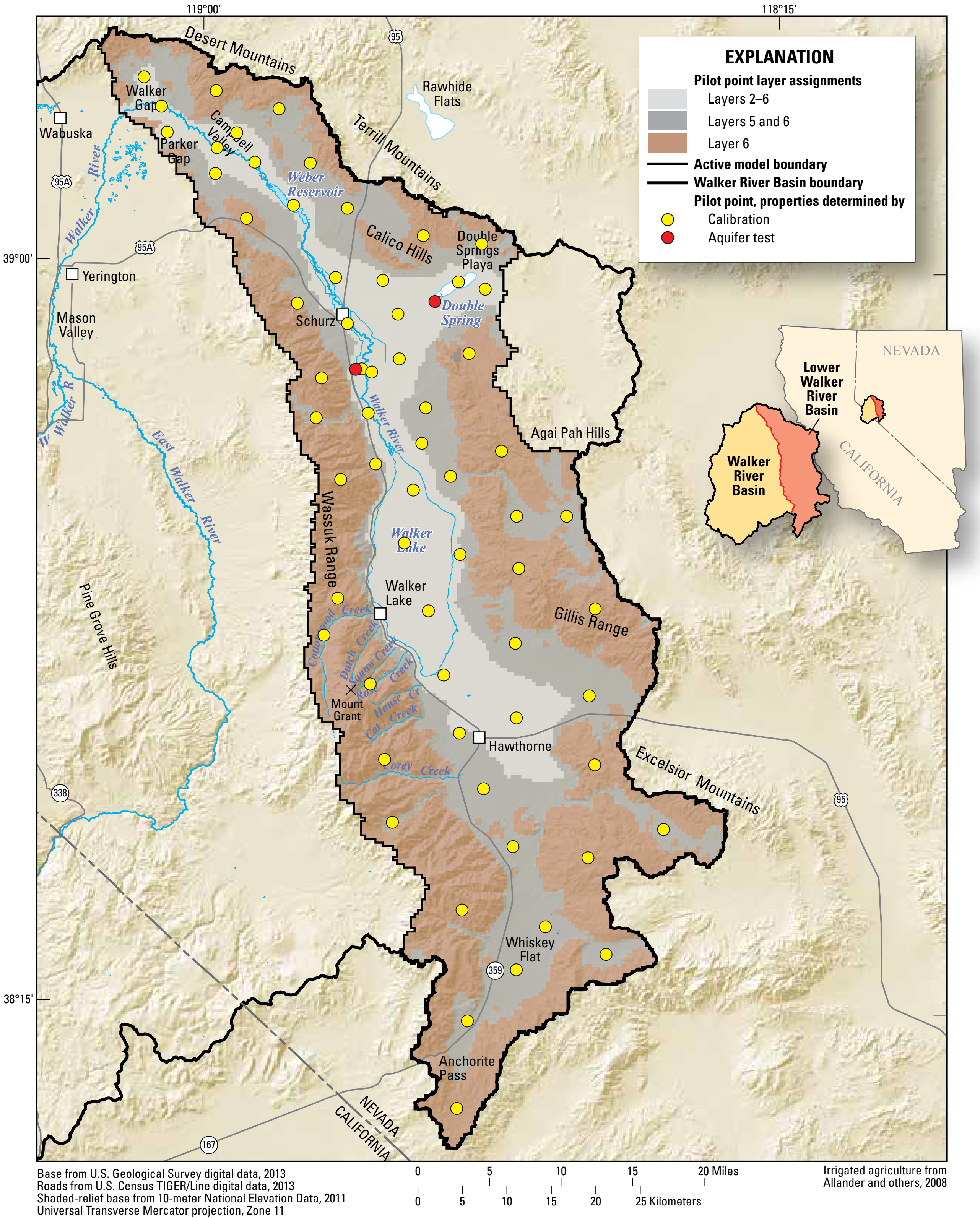
Vertical hydraulic conductivity in the basin fill hydrogeologic units was uniform and specified as 0.30 ft/d (0.092 m/d), as determined through calibration. In the consolidated rock hydrogeologic units, the vertical hydraulic conductivity was assumed to be the same as the horizontal hydraulic conductivity.

Specific yield of the unconfined basin-fill aquifer units was specified as 0.15 on the basis of previously reported estimates (Schaefer, 1980; Everett and Rush, 1967) and results from aquifer tests (Lopes and Allander, 2009a). The consolidated rock units were treated as confined units for numerical stability and were assigned a constant specific storage of $10^{-5.5}$ ft^{-1} (10^{-6} m^{-1}).

Dissolved-Solids Concentrations in Walker Lake

Dissolved-solids concentrations in Walker Lake were calculated using the simulated lake volume from the LWR_MF and the estimated mass of salt in Walker Lake. The salt mass, which is the quantity of salt dissolved in Walker Lake, was computed from observed dissolved-solids concentration and observed lake volume data. Salt mass was computed for each dissolved-solids observation by multiplying dissolved-solids concentration by lake volume on the date of sample collection and the appropriate conversion factor. For this report, salt mass in Walker Lake is reported in tons.

Salt mass in Walker Lake over time is presented in figure 24 only for salt mass computed from measured dissolved-solids concentration data. Contrary to existing estimates of salt loading to Walker Lake (Thomas, 1995; Nevada Department of Environmental Protection, 2005), figure 24 shows an apparent decrease in salt mass over time that is statistically significant (p-value $<<0.001$). However, much of the



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Irrigated agriculture from Allander and others, 2008

Figure 23. Location and layer assignments of pilot points used to distribute horizontal hydraulic conductivity values in LWR_MF.

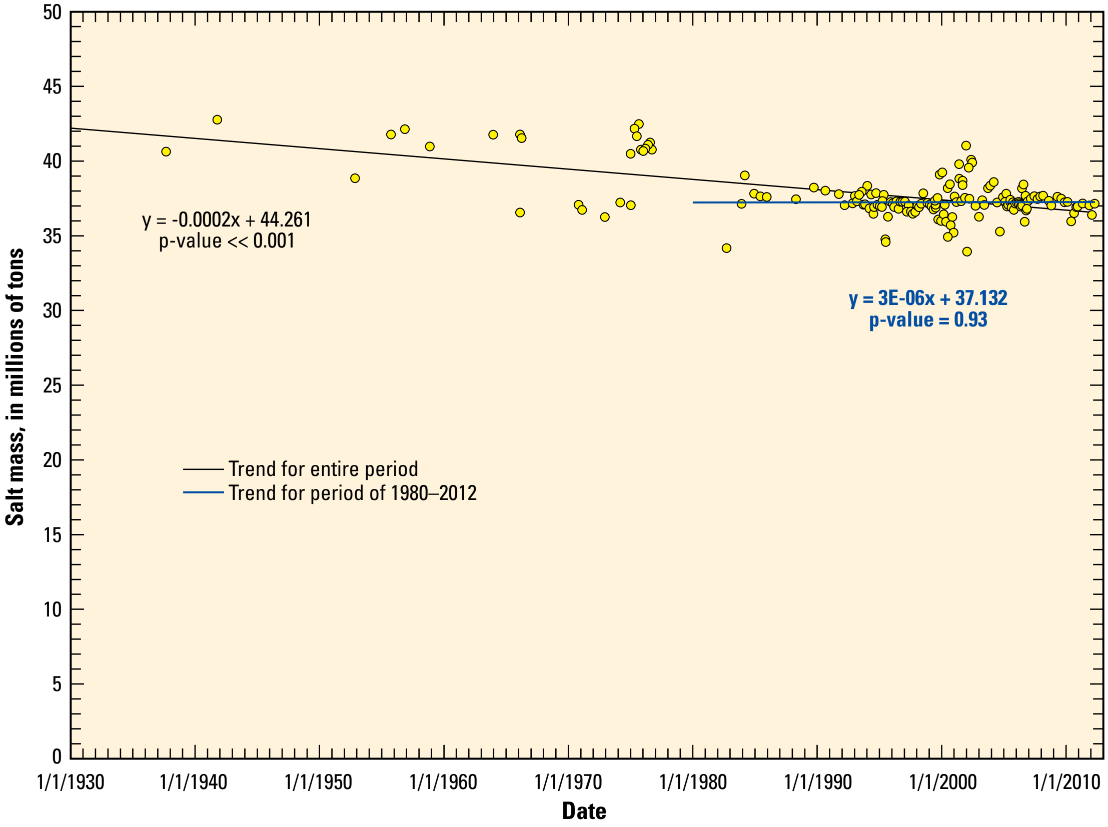


Figure 24. Apparent decreasing trend in measured salt mass in Walker Lake, west-central Nevada, for the period 1937 through 2012 and no apparent trend in measurements of salt mass for the period 1980 through 2012.

dissolved-solids concentration data prior to 1980 are somewhat sporadic, and much of it is calculated as the sum of dissolved constituents rather than measured as the weight of dry residue after evaporation. After 1980, the collection and analysis of Walker Lake dissolved-solids concentrations was more frequent, and the weight of dry residue after evaporation was the predominant method of analysis (fig. 24). Trend tests on the post 1980 salt mass data using both parametric regression (linear regression) and non-parametric (Mann-Kendall) statistical methods (Helsel and Hirsch, 1995) failed to reject the null hypothesis that salt mass in Walker Lake has not been changing since 1980 (p-value >> 0.05 for both tests), indicating no apparent trend. A possible explanation for the apparent neutral salt balance in Walker Lake is that the salt influx is balanced by an equivalent reduction in salt from mineral precipitation or salt deposition along shore zone. Figure 25 shows distribution of the post 1980 salt mass content of Walker Lake and indicates salt mass content is normally distributed with a median salt mass of 37.2 million tons with an interquartile range of 0.72 million tons (1.9 percent of median). The mean salt mass content of Walker Lake is also 37.2 million tons. Dissolved-solids concentrations (in mg/L) were calculated after each model run by dividing the lake salt mass (37.2 million tons) by simulated lake volume (in cubic meters [m^3]) and multiplying by a conversion factor of 0.9070×10^6 m^3/ton*mg/L.

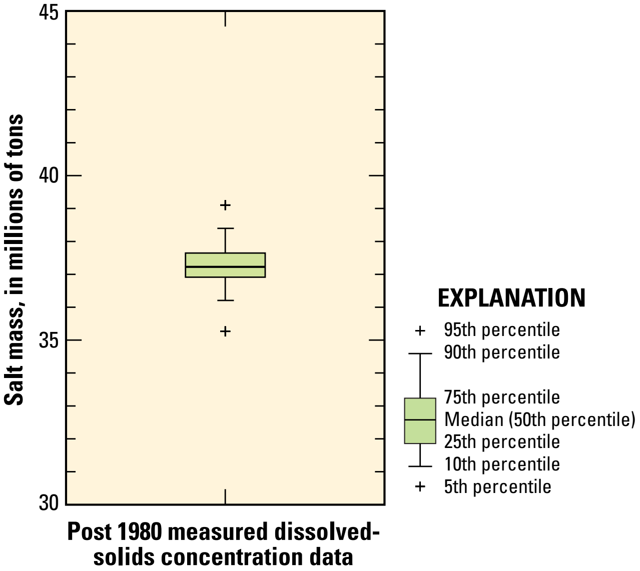


Figure 25. Distribution of measured salt mass in Walker Lake, west-central Nevada, between 1980 and 2012.

Table 9. Parameter values in LWR_MF estimated through model calibration.

[This table excludes parameters associated with distribution of horizontal hydraulic conductivity. Method of determination: Manual Calibration, method involves manually adjusting model parameters to obtain acceptable comparisons of simulated to observed data; Auto Calibration, method involves automatically adjusting model parameters to obtain acceptable comparisons of simulated to observed data; Specified, model parameters specified rather than determined through calibration. m^3/d, cubic meter per day; m/d, meter per day; 1/d, per day; m, meter]

Parameter abbreviation	Parameter description	Parameter value	Units	Method of determination
WabQ1	Steady state inflow of Walker River at Wabuska gage	1.035E+06	m^3/d	Manual Calibration
LakeE	Lake evaporation rate	3.649E-03	m/d	Manual Calibration
StrBedKus	Walker River streambed hydraulic conductivity upstream from Weber Reservoir outlet	7.000E-02	m/d	Manual Calibration
StrBedKds	Walker River streambed hydraulic conductivity downstream from Weber Reservoir outlet	5.000E-03	m/d	Manual Calibration
FINF1	Scaling factor of recharge distribution from LWR_PRMS model	8.559E-01	unitless	Auto Calibration
GWPET1	Maximum potential evapotranspiration of groundwater	3.340E-03	m/d	Auto Calibration
VKAFill	Vertical hydraulic conductivity of alluvial aquifer system	9.161E-02	m/d	Auto Calibration
WLBedK	Walker Lake lakebed leakance	1.106E-03	1/d	Auto Calibration
WeberBedK	Weber Reservoir lakebed leakance	5.000E-04	1/d	Manual Calibration
EXTDP	Extinction depth for groundwater evapotransporation	3.00	m	Manual Calibration
SpYield	Specific yield of basin-fill aquifer	0.15	unitless	Specified

Model Calibration

The LWR_MF was calibrated through coupled steady-state and transient simulations, but almost all water-level and streamflow observations were made during transient conditions when lake level in Walker Lake was declining. The LWR_MF was iteratively calibrated using three steps because of the large number of parameters used in this model, the extreme sensitivity of the model to the evaporation rate from Walker Lake (*LakeE*), and streamflow entering the model at Wabuska streamgage during the steady-state period (*WabQ1*). The first step was manual calibration of the lake long-term evaporation rate and steady-state inflow of Walker River at Wabuska streamgage to match the initial lake level from 1908 through 1918 while simultaneously adequately simulating the long-term lake level decline. The second step was automated calibration of other model parameters using PEST, a parameter estimation routine (Doherty, 2008a; table 9), to match groundwater-levels observed between 1942 and 2007. The third step was manual calibration of streambed hydraulic conductivities (*StrBedKus* and *StrBedKds*), Weber Reservoir lakebed leakance (*WeberBedK*), and extinction depth for groundwater evaporation (*EXTDP*) parameters to match the observed accumulation of streamflow from 1919 through 2007. Streamflow accumulation is the total accumulated volume of flow over periods consistent with streamflow observations. These three calibration steps were repeated until a final acceptable level of calibration was achieved (see “Goodness of Fit” section).

A total of 132 parameters were estimated through calibration. Eleven properties were represented by a single parameter each (table 9). Horizontal hydraulic conductivity (estimated at 194 pilot points in five model layers) was represented by a total of 121 parameters.

Model parameters, including horizontal hydraulic conductivity, vertical hydraulic conductivity of the basin-fill aquifer (*VKAFill*), Walker Lake lakebed leakance (*WLBedK*), scaling factor of recharge distribution from LWR_PRMS (*FINF1*), and potential evapotranspiration from groundwater (*GWPET1*), were calibrated by minimizing a weighted composite, sum-of-squares objective function through nonlinear regression in PEST (Doherty, 2008a). Differences between observed and simulated values of lake level, groundwater level, and streamflow provided goodness of fit. These differences (residuals) were weighted and summed in the objective function

$$\Phi(x) = \sum_{i=1}^{nobs}\left[\left(\hat{o}_i - o_i\right)w_i\right]^2 \quad (1)$$

where

x is the vector of parameters being estimated,

$nobs$ is the number of observations that are compared,

$\hat{o}_i$ is the ith simulated observation,

o_i is the ith measurement or regularization observation, and

w_i is the ith weight.

Water levels simulated by the model were interpolated in space and time to match observation well locations and water-level measurement dates. Tikhonov regularization was used in the automated calibration process to limit horizontal hydraulic conductivity estimates at pilot points to reasonable values in areas where estimates for a pilot point were insensitive to observation data (Doherty, 2008a). As a result, large differences between adjacent values in similar hydrogeologic units were minimized to ensure a relatively continuous and smooth distribution of horizontal hydraulic conductivity.

The third step entailed manually adjusting the Walker River streambed hydraulic conductivities upstream and downstream from the outlet of Weber Reservoir (*StrBedKus* and *StrBedKds*), the lakebed leakance of Weber Reservoir (*WeberBedK*), and the extinction depth for groundwater evaporation (*EXTDP*) to fit streamflow observations for the three streamgages used for calibration: Little Dam gage, Schurz gage, and Lateral 2A gage. In general, streambed hydraulic conductivity was calibrated in a downstream direction. Streambed hydraulic conductivity upstream from Weber Dam and Weber Reservoir lakebed leakance were adjusted first, and then streambed hydraulic conductivity downstream from Weber Reservoir outlet was adjusted. The streambed hydraulic conductivity of the lower reach of Walker River was set equal to the streambed hydraulic conductivity between Walker River at Lateral 2A and Walker River at Little Dam streamgages because insufficient data were available downstream from Walker River at the Lateral 2A streamgage to independently calibrate streambed hydraulic conductivity for this reach.

Observed Lake Level, Groundwater Level, and Streamflow Data

Observed data used to calibrate the model included Walker Lake levels, groundwater levels, and Walker River streamflow (fig. 26). These data were summarized on a monthly basis to coincide with the monthly time step of the model.

Observed and simulated lake level data for Walker Lake were compared over the full simulation period from 1919 through 2007. From 1919 through 1928, only annual lake level data were available with observations made around October 1 each year. Monthly or more frequent lake level data were available from 1928 through the end of simulation period. Lake levels were weighted in the regression such that the composite of observations for each year had a value of 1. For example, a weight of 1 was assigned to lake level for years with only a single observed value, and a weight of 0.083 was assigned to lake levels that were observed monthly. The lake level during the initial steady-state period was assigned a weight of 5 to enable the regression to converge more quickly.

Observed and simulated water levels were compared for 168 wells that had one or more water-level observations (fig. 26). There were 149 wells with multiple water-level observations over time. All of the wells except for one are completed in the basin-fill aquifer. Water levels were assigned to model layers that correspond to depths where the screened intervals were completed. Measured water levels were weighted in the regression such that each observation site had a weight of 1. Sites with multiple water-level observations were weighted so that the composite weight of all observation weights added to 1.

In the Whiskey Flat area, the first observation from each of the eight sites was assigned a weight of 1, and all later observations were not used because pumping in this area was not simulated and observed water levels were declining. The first water-level observation made at each of the sites in the Whiskey Flat area was assumed to be the most representative of conditions prior to the effects of pumping. The first water levels were observed between 1948 and 1963 at 4 sites, in 1983 at 2 sites, and in 2004 at the 2 remaining sites (appendix 1).

Observed and simulated accumulated streamflows for Walker River were compared at three streamgage sites over various time periods of available data (fig. 26). The three streamgage sites used were the Little Dam gage, Schurz gage, and Lateral 2A gage (fig. 3; table 1). The Wabuska gage provided specified inflow to the model and was not used as an observation for calibration. The Cow Camp gage was not used for calibration because streamflow observations do not account for bypass flow that occurs during high flows at this site and are considered unreliable (Lopes and Allander, 2009a, p. 22).

Regularization Observations

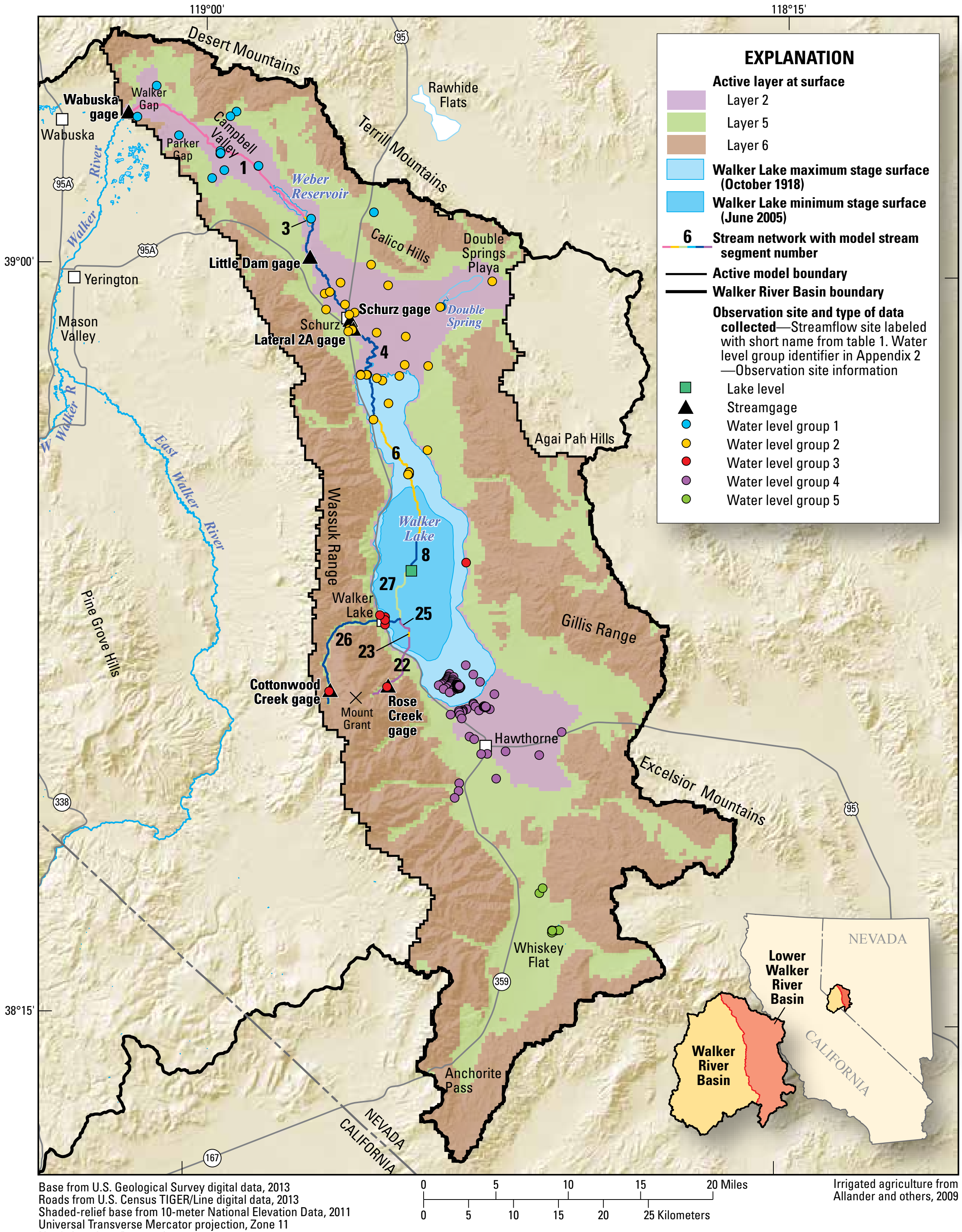
Regularization observations are specified observations or relations used during model calibration when field observation data are lacking or insufficient to adequately guide the calibration process. Regularization observations were specified between pilot points in order to assess a penalty for incorporating too much heterogeneity within the horizontal hydraulic-conductivity distribution. The regularization observations generally affected parameter estimates in regions of the model that were not being affected by variations in parameter values during calibration (low sensitivity). A total of 1,485 regularization observations were used to constrain the distribution of horizontal hydraulic conductivity using the Tikhonov regularization method (Doherty, 2003).

Goodness of Fit

Goodness of fit is demonstrated by statistical and graphical comparisons of simulated and observed data and reflects how well the model performs at simulating the hydrologic system. Three observation data sets were assessed for goodness of fit: lake level, groundwater levels, and streamflow. Basic statistical analyses were used to compare model simulated results with observation data and are discussed independently for each observation dataset.

Walker Lake Level and Dissolved-Solids Concentration

The ability of the model to simulate the Walker Lake level reflects how well the model simulates surface and groundwater inflows to Walker Lake, net evaporation of water from Walker Lake, the accuracy of the lake level-volume-area relations used to characterize the size of Walker Lake, and computation of dissolved-solids concentrations. The ability of the model to collectively simulate these processes is demonstrated through comparisons of simulated lake level with observed lake level presented as (1) time series data, (2) residual plots, and (3)



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Irrigated agriculture from Allander and others, 2009

Figure 26. Locations of Walker Lake level, groundwater levels, and streamflow observations used to calibrate the LWR_MF.

statistics measuring bias and standard error. The ability of the model to simulate dissolved-solids concentrations is demonstrated through comparisons of simulated and observed dissolved-solids concentrations.

Simulated Walker Lake levels and observed lake levels are shown in figure 27*A*. In general, the model did an excellent job at simulating overall lake level decline, the rate of decline, and responses of lake levels to streamflow variability over time. However, there are periods when the model over-estimated (simulated greater than observed) or slightly under-estimated (simulated less than observed) observed lake level.

Deviations between simulated and observed lake level are apparent in a residual plot (fig. 27*B*). Residuals were computed by subtracting observed lake level values from simulated values. When observed and simulated lake level values did not occur on the same date, simulated lake level values were interpolated to coincide with observation dates. Evaporation from Walker Lake was simulated using an average annual rate, so evaporation during winter months is over-estimated, and evaporation during summer months is under-estimated. As a result, there is an annual variation in the residuals. However, the annual variation is much smaller than the multi-decadal pattern that is apparent. A 12-point moving average is superimposed on the Walker Lake residual curve to provide a smoothed representation of the residuals. Figure 27B demonstrates that the model simulated lake level within 1.6 ft (0.5 m) from 1919 through 1937. From 1938 through 1943, the model under-estimated lake level by just 3.3 ft (1 m) in 1941. From 1943 through 1969, the model over-estimated lake level by about 4.9 ft (1.5 m) in 1961. From 1970 through 2005, the model generally under-estimated lake level by about 3.3 ft (1 m) in 1988 and 2000. By the end of the simulation period (water year 2007), the model was closely simulating lake level and only over-estimated the observed lake level on October 1, 2007, of 3,934.8 ft local datum (1,200.4 m) by 1 ft (0.3 m). The average bias of the lake level simulation from 1919 through 2007 is an under-estimate of 0.26 ft (0.08 m). Approximately 67 percent of all lake levels were simulated within 1.9 ft (0.59 m) of the observed value.

Simulated dissolved-solids concentration of Walker Lake over the full transient simulation is shown in figure 28. In general, figure 28*A* demonstrates that the approach used to compute dissolved-solids concentration did a fair job at representing the dissolved-solids concentrations in Walker Lake. However, figure 28*A* does indicate that the model under-estimated dissolved-solids concentrations prior to 1980. This is due to dissolved-solids concentration data indicating a larger salt mass in Walker Lake prior to 1980 (discussed in “Dissolved-Solids Concentrations in Walker Lake” section). Figure 28*B* shows a scatterplot of simulated dissolved-solids concentrations in relation to observed dissolved-solids concentrations and demonstrates that the assumption of constant salt mass in Walker Lake is reasonable. In order for the model to produce a better fit to the pre-1980 data, the salt mass in Walker Lake would need to be decreasing over time.

Groundwater Levels

Comparisons of simulated and observed groundwater levels reflect how well aquifer properties, hydraulic conductivities, and recharge distribution are represented and how well exchanges of groundwater with Walker Lake and Walker River are represented. Simulated groundwater levels in relation to observed groundwater levels are presented in a scatter plot in figure 29, and selected water-level hydrographs are shown in figure 30. All water-level hydrographs can be viewed from Appendix 1. All water-level observations presented in figure 29 are from wells completed in the basin-fill aquifer and form the basis of calibration of the basin-fill aquifer properties. Water-level observations within the consolidated rock units were not available, so estimated aquifer properties for these units are uncertain, and simulated water levels can be in substantial error.

Simulated and observed water levels are plotted in figure 29 for each observation site (fig. 26, appendix 2) and are grouped by general location within the lower Walker River Basin (fig. 26). Group 1 represents water-level observations along the Walker River corridor between Wabuska gage and Schurz. Group 2 represents water-level observations in the area between Schurz and the northern shoreline of Walker Lake in 2005 and includes water-level observations in the Double Springs area. Group 3 represents water-level observations to the east and west of the 2005 extent of Walker Lake. Group 4 represents water-level observations in the Hawthorne and Army Depot areas. Group 5 represents water-level observations in the Whiskey Flat area. Standard error and bias of residuals are used to demonstrate the goodness of fit. No spatial weighting was used in this basic statistical analysis to compensate for regions of the model with higher densities of observation sites. Therefore, this overall statistical summary and analysis is effectively weighted towards areas with higher densities of sites, such as group 4 (fig. 26). Figure 29 shows that in general, simulated and observed water levels are scattered around a one-to-one line, which visually demonstrates that the model is doing a fair to good job simulating water levels. The standard error was 38.3 ft (11.7 m) with a bias of the model to over-estimate water levels in the basin-fill aquifer by 9.0 ft (2.7 m).

Along the Walker River corridor downstream from Wabuska streamgage within the basin-fill aquifer, the model replicates observed water levels fairly well (well observation sites 127, 136, 148, 164, and 169 in fig. 30). Water levels were generally simulated within 5 ft in wells within the Walker River flood plain (well observation sites 148 and 164) and within 6 to 22 ft for sites located near the river but outside the flood plain (observation sites 127, 136, and 169). Very little water-level data were available to evaluate long-term changes along the Walker River corridor; observation sites 136 and 139 provided the longest records with only three water-level observations prior to 2004.

Within the basin-fill aquifer between Schurz and the northern shoreline of Walker Lake in 2005 (fig. 26), the model estimated water levels well (observation sites 127, 136, and

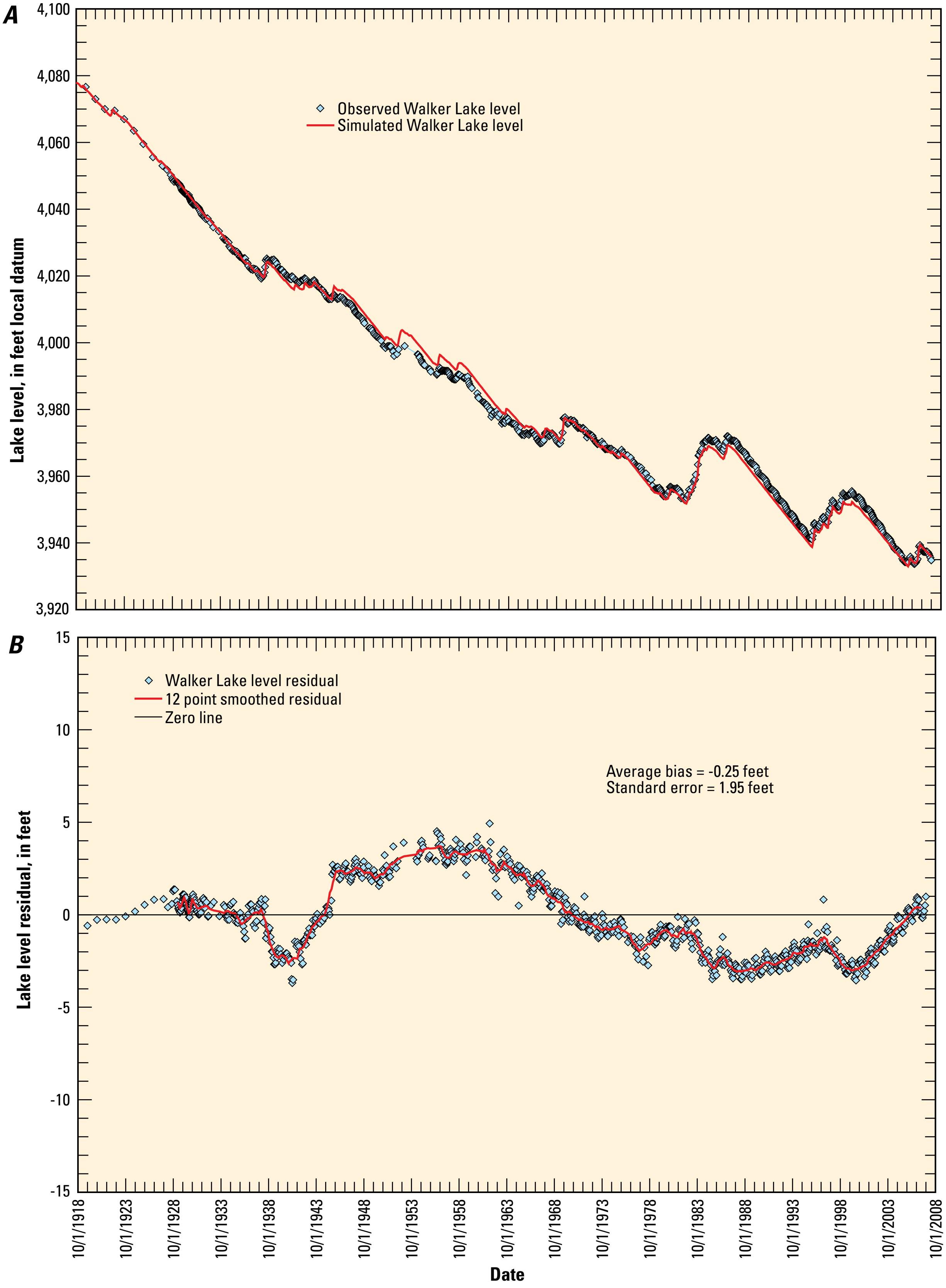


Figure 27. Time series of *A*, model simulated lake level and observed lake level for Walker Lake, west-central Nevada, and *B*, lake level residuals, water years 1918–2007.

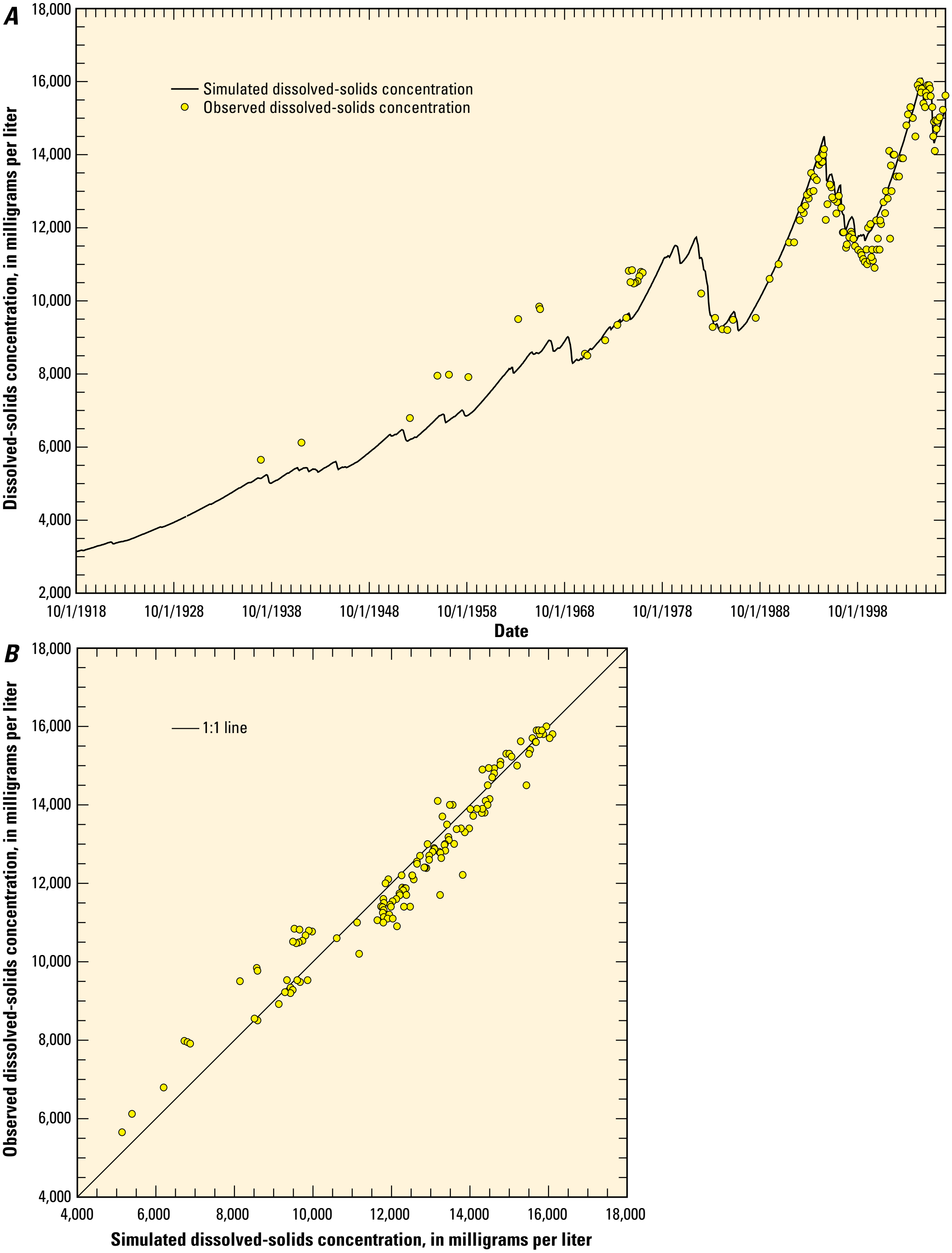


Figure 28. LWR_MF simulated dissolved-solids concentrations in Walker Lake in relation to observed concentrations in *A*, time-series graph; and *B*, scatter plot.

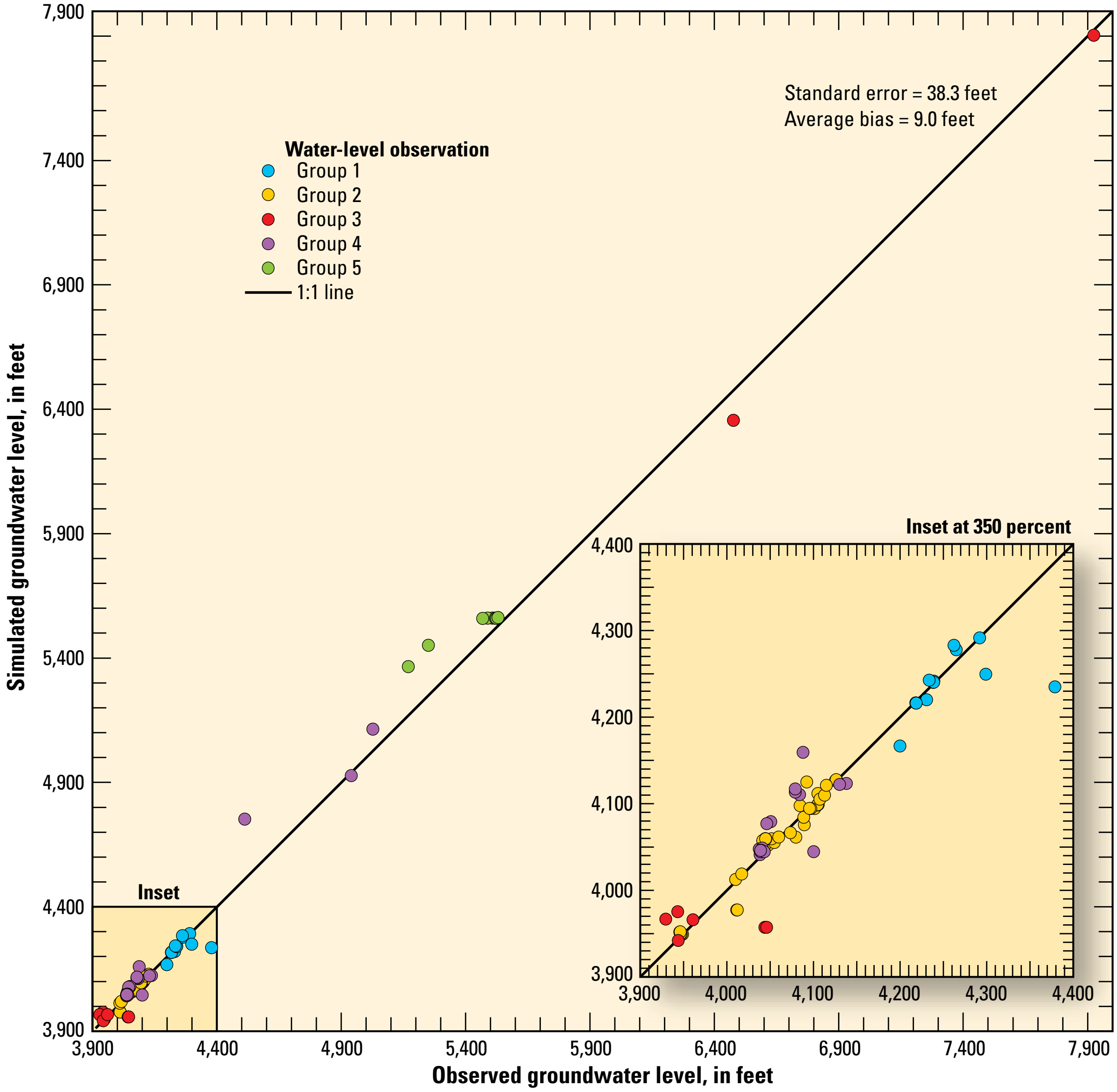


Figure 29. Average water level for each observation site in the lower Walker River Basin, west-central Nevada. All water-level observations were from the basin-fill aquifer.

148; fig. 30). Water levels were generally simulated within 1 to 10 ft of the observed values (observation sites 136 and 148), with the biggest difference being an over-estimate of 18 ft at observation site 127. Very little water-level data were available to evaluate long-term changes in this area.

Within the basin-fill aquifer east of Schurz in the area near Double Springs, the model estimated water levels quite well (observation site 152 in fig. 30), within 8 ft of the observed values. However, data were available only for 2004 to 2007; thus long-term changes in water levels for this area could not be evaluated.

Along the alluvial slope west of Walker Lake in the Town of Walker Lake the model over-estimated water levels and slightly under-estimated the decline (observation site 108 in fig. 30). Observed declines in this area were likely affected by nearby municipal pumping, which was not simulated with the model.

In the basin-fill aquifer south of Walker Lake in the Hawthorne and Army Depot areas, the model estimated water levels fairly well (observation sites 16 and 54 in fig. 30). These observation sites provided longer periods of record for comparison. Site 16 had the first water-level observation in 1942, and site 54 had the first water-level observation in 1978. The hydrographs indicate the model is doing a fair job of simulating declines in this area.

Finally, in the basin-fill aquifer in area of Whiskey Flat, the model simulated the initial observed water level in 1956 within 10 ft of the observed value (observation site 5 in fig. 30). The long-term water levels observed at this site show a substantial decline, which was not simulated by the model. This observed decline is a result of agricultural and municipal pumping in the Whiskey Flat basin-fill aquifer, which was not simulated with the model.

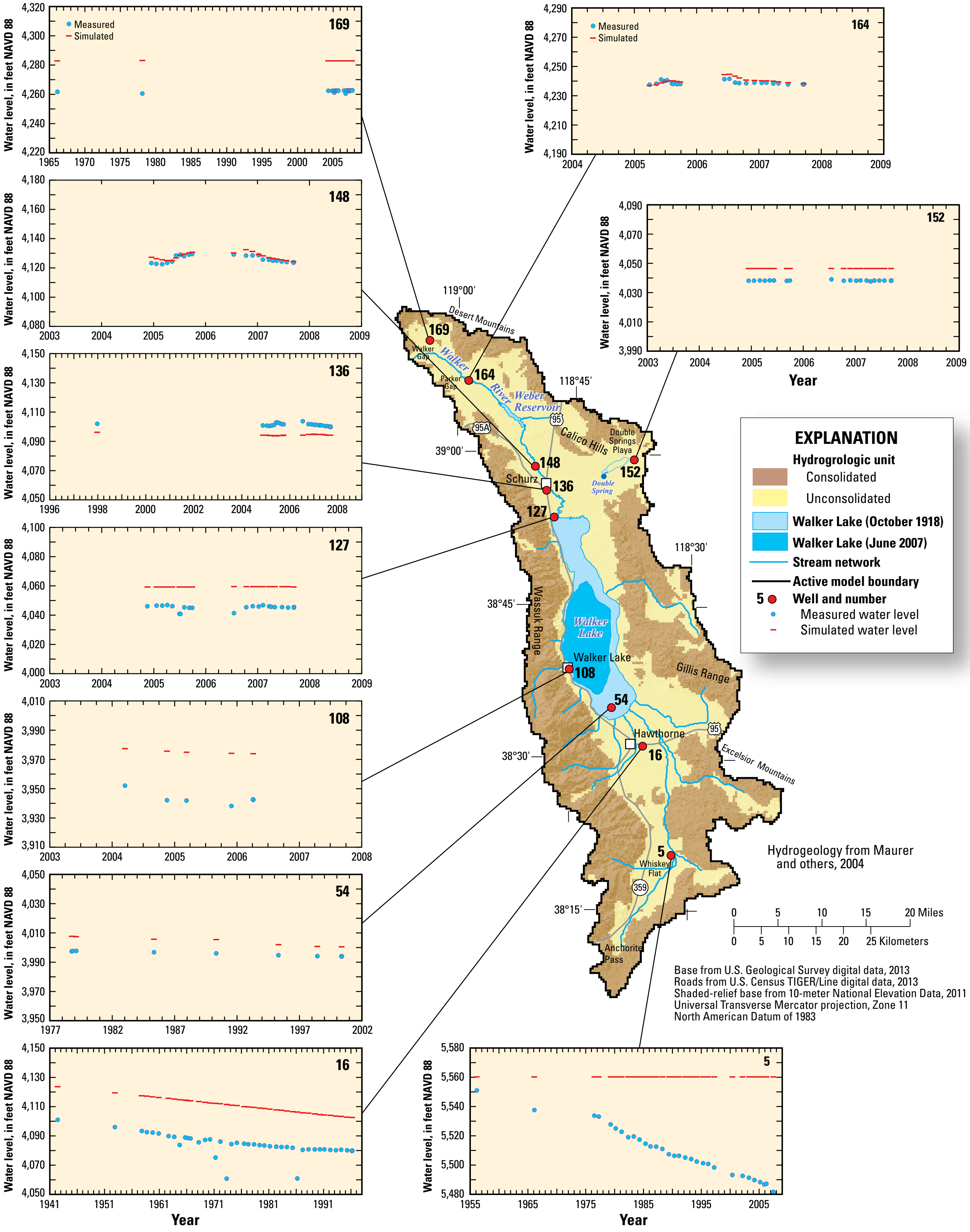


Figure 30. Location of water-level observations and simulated and observed water-level hydrographs for selected wells in the lower Walker River Basin, west-central Nevada.

Streamflow

Comparisons of streamflow hydrographs and streamflow accumulation curves are used to demonstrate the ability of the model to simulate Walker River and small mountain tributary streamflows, how well streambed properties and distributions are represented, how well diversions are represented, and how well the streams interact with the groundwater system. Streamflow hydrographs are used to compare the character and distribution of streamflow over time and demonstrate how the model simulates the timing and magnitude of streamflow events. However, streamflow hydrographs do not provide a good indication of long-term volumetric streamflow bias, if present. Streamflow accumulation curves are a running accumulation of streamflow over time, and if a long-term volumetric bias in simulated streamflow is present, the simulated streamflow accumulation curve departs from the observed streamflow accumulation curve. Streamflow hydrographs and accumulation curves are presented for streamgages along the Walker River and two streamgages in two small perennial streams in the Wassuk Mountains (site locations are shown in figure 26). Streamflow comparisons are presented below in an upstream to downstream order and are followed by streamflow comparisons for Cottonwood and Rose Creeks in the Wassuk Range.

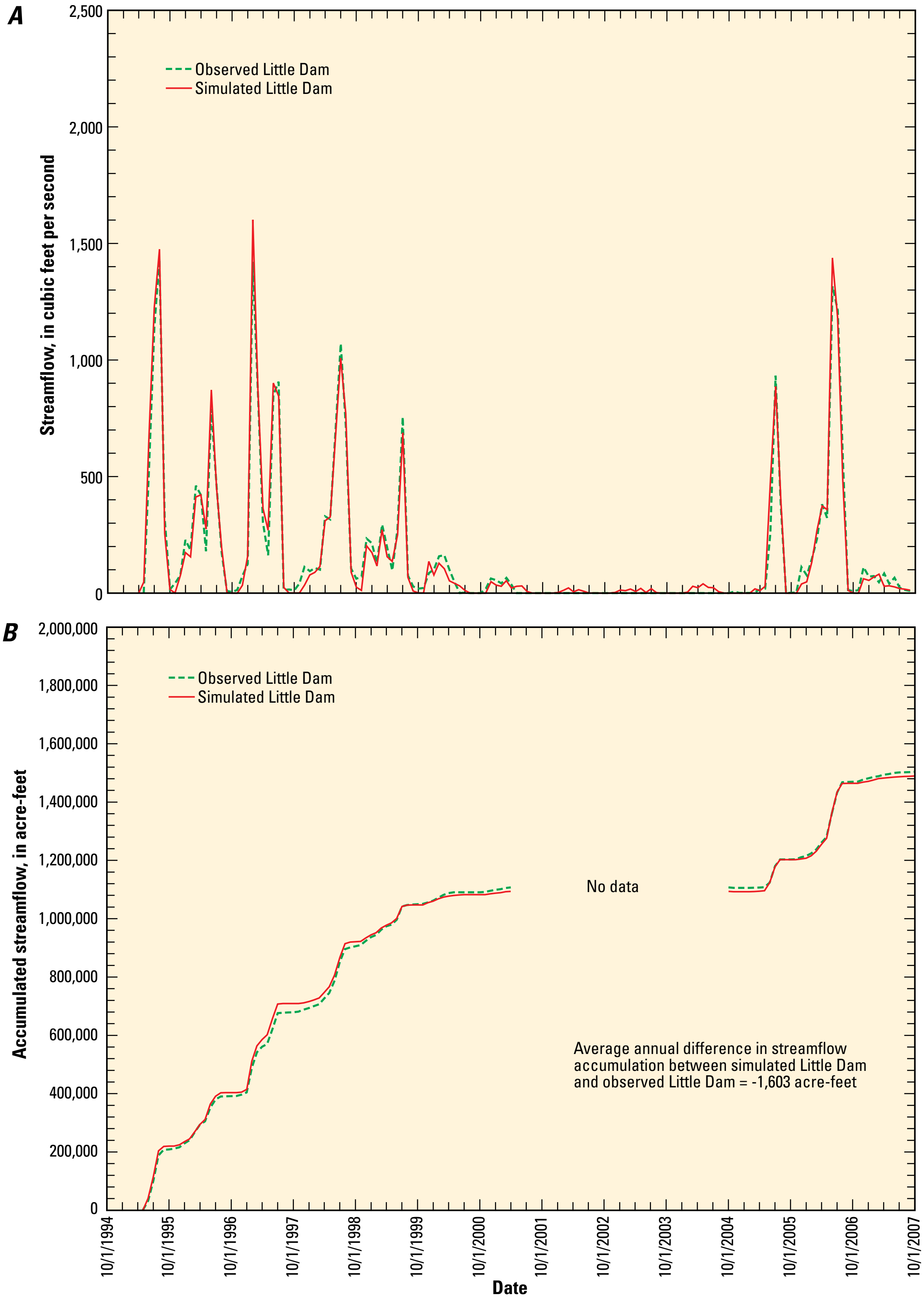
The first streamgage downstream from Wabuska gage with reliable streamflow data is the Little Dam gage (fig. 26). The simulated and observed hydrographs and streamflow accumulation curves for the Little Dam gage are shown in figure 31. Streamflow monitoring at this site did not begin until May 1995 and was discontinued from April 2001 through September 2004, when it was again monitored. This site provides data for only 10 percent of the overall simulation period of the model (8.9 years of record compared with 89 years of simulation). The streamflow hydrograph demonstrates very good agreement between simulated and observed streamflows during high-flow and low-flow conditions (fig. 31*A*). The streamflow accumulation curve demonstrates that the overall long-term simulation is acceptable; departures occur mainly during the wet years of 1997 and 2005 (fig. 31*B*). The simulation bias for this site's period of record was relatively low with an under-estimation of about 1,600 acre-ft/year, which is about 1 percent of the mean annual flow for this site over the same 8.9-year period (178,000 acre-ft/yr).

The next downstream streamgage is the discontinued Schurz gage (fig. 26). The simulated and observed hydrographs and streamflow accumulation curves for this site are shown in figure 32. Streamflow records for this site are available from the beginning of model simulation period of October 1918 through the end of September 1933 and represent Walker River streamflows prior to the construction of Weber Reservoir. This site has the only streamflow data prior to 1994 downstream from the Wabuska gage and has data for about 17 percent of the overall simulation period of the model (15 years of record compared with 89 years of simulation). The streamflow hydrograph demonstrates very good agreement between simulated and observed streamflows during high-flow and low-flow conditions (fig. 32*A*). The streamflow accumulation curve demonstrates that the model simulated total flow volumes well prior to 1925 but under-estimated flow volumes beginning around 1925 (fig. 32*B*). The overall bias for this site was an under-estimate of about 3,500 acre-ft/yr, which is about 7 percent of the mean annual streamflow at this site during this period (53,300 acre-ft/yr).

The next downstream streamgage is the Lateral 2A gage (fig. 26). The simulated and observed hydrographs and streamflow accumulation curves for this site are shown in figure 33. Streamflow monitoring at this site began in April 1995 and was continuous through the end of the simulation period (October 2007). This site provided data for about 14 percent of the overall simulation period of the model (12.5 years of record compared with 89 years of simulation). The streamflow hydrograph demonstrates very good agreement between simulated and observed streamflows during high-flow and low-flow conditions (fig. 33*A*). The streamflow accumulation curve demonstrates that the overall long-term simulation is good (fig. 33*B*). The simulation bias for this site's period of record was relatively low with an under-estimate of about 1,800 acre-ft/year, which is about 1 percent of the mean annual flow for this site during this period (120,900 acre-ft/year).

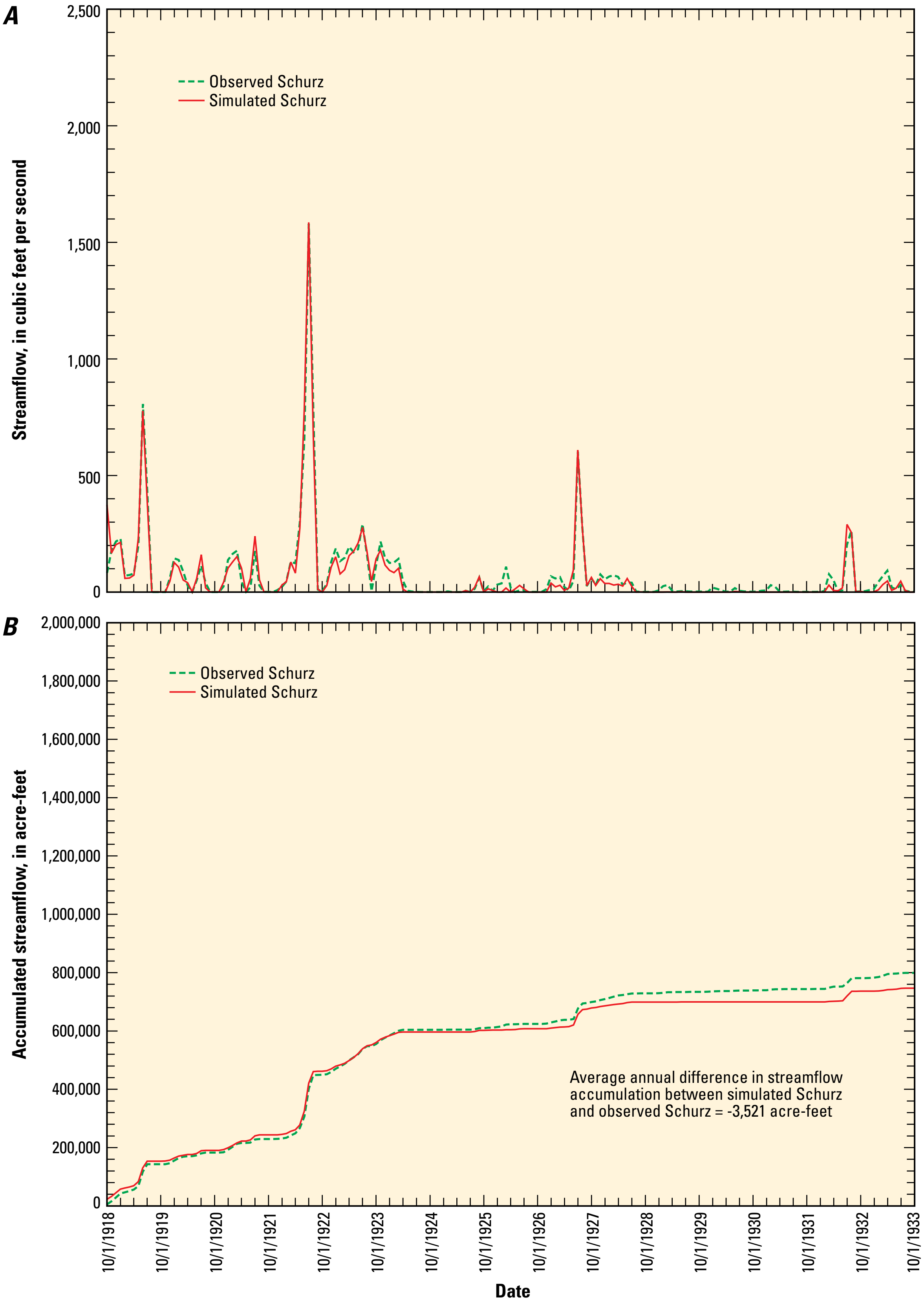
The most downstream streamgage on Walker River is Walker River at Mouth (fig. 3). This site had only a brief period of record (October 2004 through mid-May 2006), and because of the limited number of streamflow measurements, and substantial changes that occurred to the stream channel during this monitoring period, the streamflow record at this site was considered too unreliable to use for calibration or evaluation of the LWR_MF. However, the simulated mean annual streamflow from 1971 to 2000 (105,000 acre-ft/yr) agrees with the mean annual streamflow estimated by Lopes and Allander (2009b) over the same period (105,000 acre-ft/yr).

Two streamgages in the Wassuk Range were used to evaluate how well the LWR_MF simulated mountain streamflow originating from within the model domain. For the LWR_MF, a constant recharge over the simulation period was assumed; the model does not simulate seasonal processes that reflect actual rain and snow events. As a result, simulated streamflow in the mountain tributaries originates only from groundwater discharge to the stream (base flow), which is constant. The LWR_MF does not accurately simulate base flow at the two Wassuk tributary streams with streamgages, but this had little effect on the model results and the quality of the model simulation. Cumulative streamflow at the Cottonwood and Rose Creek streamgages from June 2005 through September 2007 was 885 acre-ft and 1,498 acre-ft, respectively, whereas simulated cumulative streamflow over this period was 19 acre-ft and 0 acre-ft, respectively. These are under-estimates of 384 acre-ft/yr and 619 acre-ft/yr, respectively, which are substantial differences for these two sites, but the error is far less than that associated with the simulation of Walker River inflow to Walker Lake. The differences are small in comparison with the overall water budget components of Walker Lake. This under-estimate of tributary streamflow is mainly the result of under-estimated heads in the drainages.



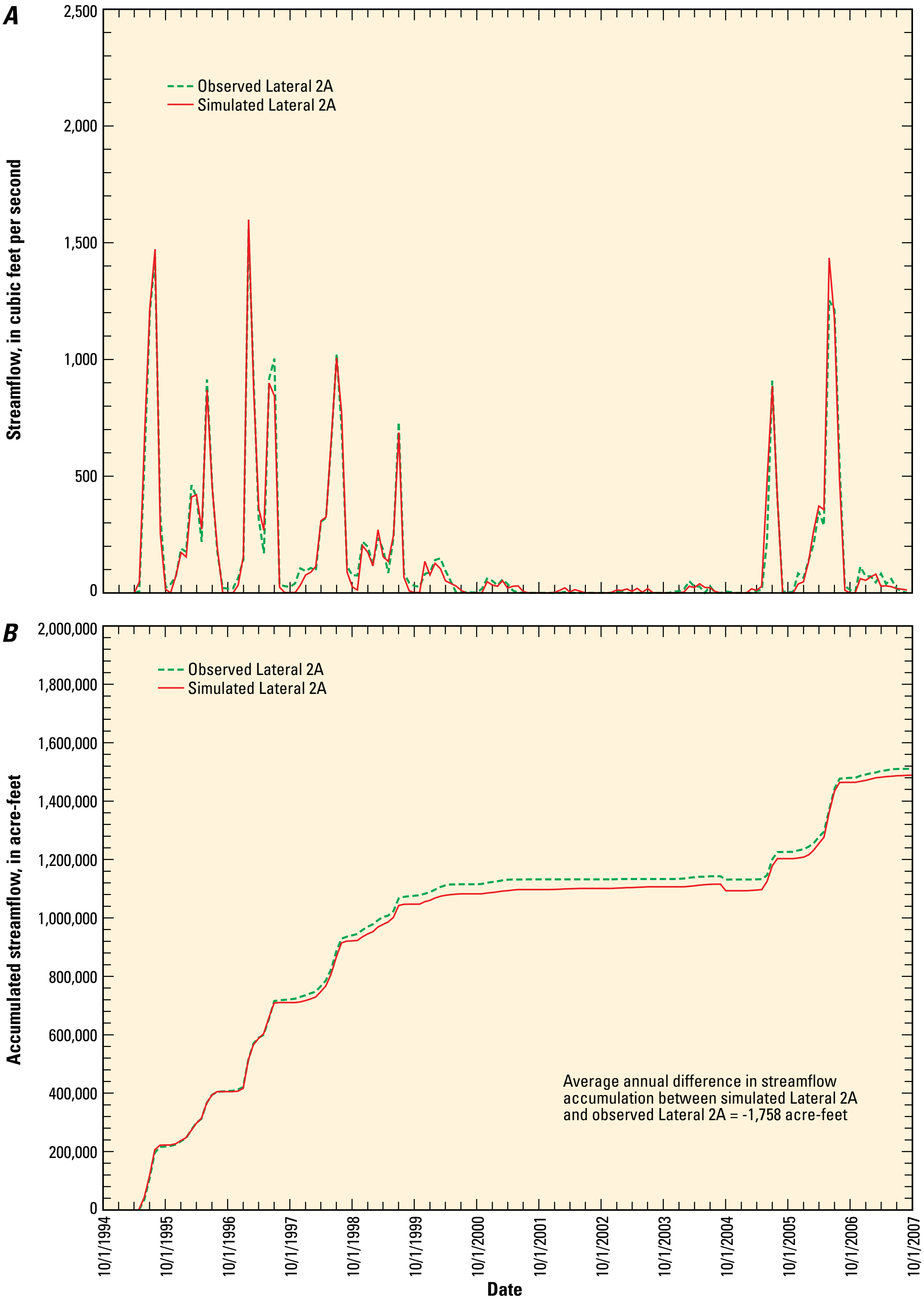
Average annual difference in streamflow accumulation between simulated Little Dam and observed Little Dam = -1,603 acre-feet

Figure 31. Simulated and observed streamflows for Walker River at Little Dam, west-central Nevada, as *A*, streamflow hydrograph and *B*, streamflow accumulation curve.



Average annual difference in streamflow accumulation between simulated Schurz and observed Schurz = -3,521 acre-feet

Figure 32. Simulated and observed streamflows for Walker River at Schurz, west-central Nevada, as *A*, streamflow hydrograph and *B*, streamflow accumulation curve.



Average annual difference in streamflow accumulation between simulated Lateral 2A and observed Lateral 2A = -1,758 acre-feet

Figure 33. Simulated and observed streamflows for Walker River at Lateral 2A, west-central Nevada, as *A*, streamflow hydrograph and *B*, streamflow accumulation curve.

Goodness of Fit Summary

The LWR_MF did a good job simulating lake level, dissolved-solids concentrations, and Walker River streamflow and did a reasonable job simulating water levels and groundwater-level changes. The model under-estimated lake level by an average of 0.25 ft, with a standard error of 1.95 ft. The model did a fair to good job simulating groundwater levels along Walker River, in the Schurz and Double Springs areas, and south of Walker Lake in Hawthorne Army Depot and Hawthorne areas. The model did not do as well simulating water levels away from Walker River, in the alluvial slopes east and northeast of Walker Lake, and in the Whiskey Flat area. The model over-estimated water levels with a bias of 9.0 ft and a standard error of 38.3 ft. The model simulated Walker River streamflow well. Largely because streamflows at Walker River at Wabuska streamgage are specified, the model did an excellent job simulating the overall character of downstream hydrographs. For the mid-1990s through 2007, streamflow accumulations at Walker River at Little Dam and Walker River at Lateral 2A were simulated within 1 percent of the measured annual streamflow. For 1918–33, the model simulated streamflow within 7 percent of annual streamflow. The LWR_MF poorly simulated streamflow in perennial streams in the Wassuk Range. The model simulated minor flow for Cottonwood Creek and no flow for Rosewood Creek. The error in simulated streamflows in the Wassuk Mountain drainages is small in magnitude compared to the error associated with the simulation of Walker River streamflow, and the error is small compared to the total inflow of Walker Lake.

Sensitivity of Lake Level and River Loss Rate to Estimated Parameters

The simulation of Walker Lake level and Walker River loss rates was affected to varying degrees by parameter value estimates. The sensitivity of lake level and river loss rates to estimated parameter values was investigated by individually varying the 11 estimated model parameters in table 9 and evaluating the response of Walker Lake level and Walker River loss. The model parameters were individually varied by factors of 0.8, 0.9, 1.0, 1.1, and 1.2 (factor of 1.0 represents no variation of calibrated LWR_MF parameter values). Walker Lake level was evaluated by computing the mean lake stage residual (in feet) as the average difference between simulated lake level from the adjusted parameter model runs (test models) and the lake level from the calibrated LWR_MF run (base model). The change in Walker River loss rate was evaluated only for the upstream reach of Walker River from Wabuska gage to Weber Reservoir because loss rates are directly affected by natural system hydraulic properties and are negligibly affected by changes in downstream diversions as a result of parameter variations. The change in Walker River loss rate (percent) was evaluated by computing the relative difference in accumulations of streamflow entering Weber Reservoir from August 1, 1934, through September 30, 2007, between the test models and base model.

Simulation of Walker Lake level is most sensitive to lake evaporation rate (parameter *LakeE*) and inflow to Walker River at Wabuska during the steady-state period (*WabQ1*), followed by maximum groundwater evapotranspiration rate (*GWPET1*) and streambed hydraulic conductivity along the lower reach of Walker River below Weber Reservoir (*StrBedKds*, fig. 34*A*). Results for the seven parameters *WabQ1*, *LakeE*, *FINF1*, *SpYield*, *WLBedK*, *StrBedKds*, and *GWPET1* are shown in figure 34*A*. The four remaining parameters listed in table 9 resulted in mean lake level residuals less than that shown for *StrBedKds* (fig. 34*A*). The low sensitivity of lake level to the magnitude of groundwater recharge was not unexpected as most (69 percent) of the local groundwater recharge discharges as groundwater evapotranspiration with only about 17 percent discharging to Walker Lake. Figure 34*A* indicates a disproportionate response of Walker Lake level to a 20-percent reduction in *LakeE* and 20-percent increase in *WabQ1* when compared with other variations of these parameters. This is not an accurate result and reflects the limitation of LWR_MF when simulating lake levels greater than 4,078.0 ft local datum (1,244.1 m), which is the maximum extent of Walker Lake defined in the model. However, the overall conclusion that Walker Lake level is most sensitive to these two parameters was not affected by this limitation.

Simulated loss rates for the upstream reach of Walker River are most sensitive to streambed hydraulic conductivity along the upstream reach (*StrBedKus*), followed by the extinction depth for groundwater evapotranspiration (*EXTDP*), then by the maximum potential groundwater evapotranspiration rate (*GWPET1*, fig. 34*B*). The results for the five parameters that most affected upstream streamflow loss are shown in figure 34*B*. All other parameters listed in table 9 had lesser effects than *FINF1*. Figure 34*B* indicates that loss rates increase along the upper reach of Walker River with increases in streambed hydraulic conductivity (*StrBedKus*), groundwater evapotranspiration extinction depth (*EXTDP*), maximum potential groundwater evapotranspiration rate (*GWPET1*), and vertical hydraulic conductivity of the basin-fill aquifer (*VKAFill*), and decrease with increases in groundwater recharge (*FINF1*).

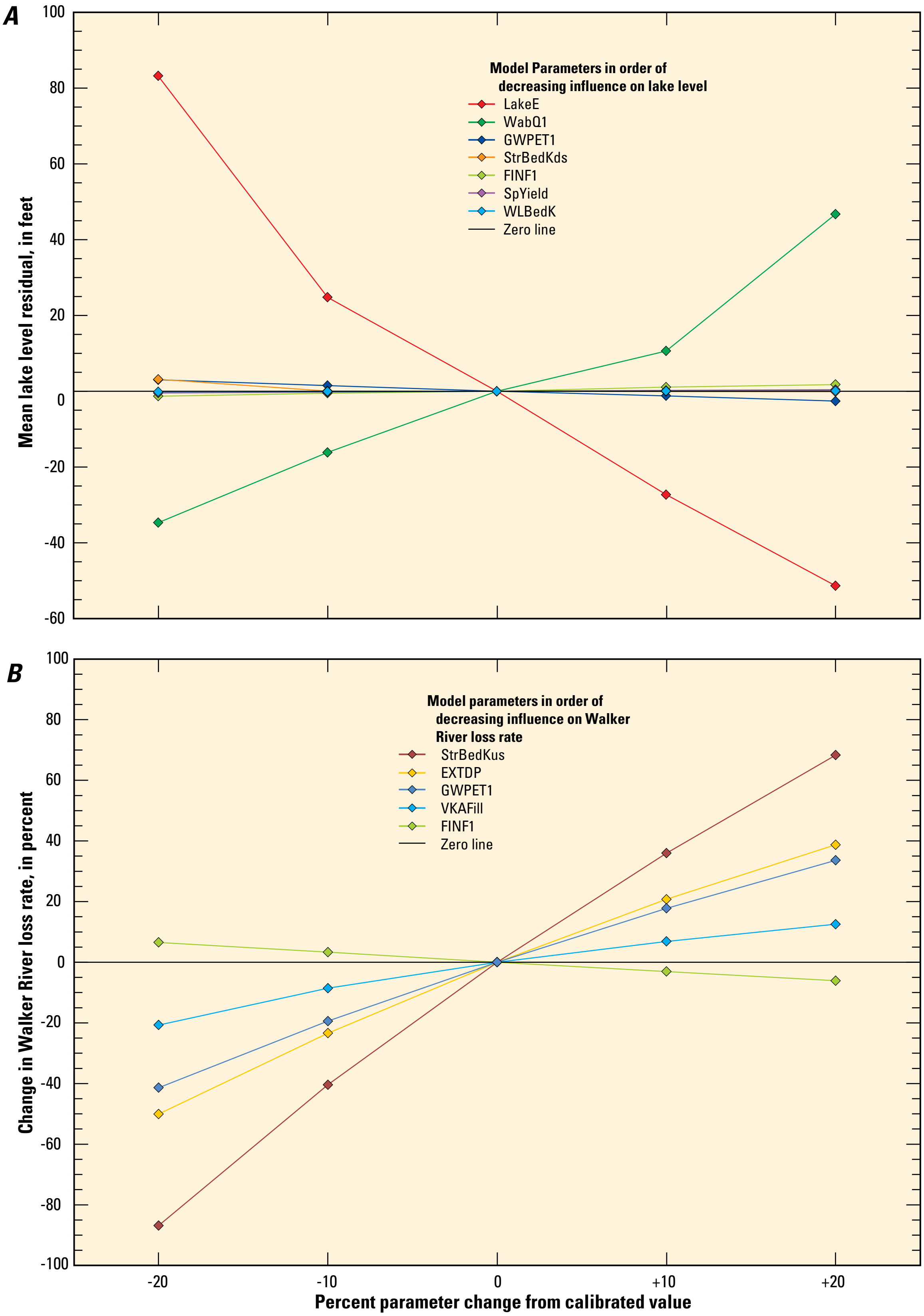


Figure 34. Effects of model parameter variations on *A*, Walker Lake level and *B*, loss rate of the Walker River upstream from Weber Reservoir, west-central Nevada. Parameters are explained in table 9.

Model Results

The calibrated LWR_MF was used to summarize hydrologic conditions in the lower Walker River Basin. The following sections summarize water budgets for Walker River, water budgets and dissolved-solids concentrations for Walker Lake, groundwater budgets, and directions of groundwater flow. The LWR_MF was also used to derive simple relations between streamflow at Wabuska gage and Walker River inflow to Weber Reservoir and Walker Lake.

The simulated water budgets for Walker River, Walker Lake, and the groundwater system are discussed for the steady-state conditions from 1908 to 1918 and transient conditions from 1919 to 2007. The Walker River and Walker Lake water budgets are also discussed for the 30-year period 1971–2000 and compared with results of Lopes and Allander (2009b). Simulated evapotranspiration from groundwater is presented for 2005–07 and compared with results of Allander and others (2009).

Walker River

Summaries of simulated water budgets for the Walker River for steady-state conditions prior to 1919, the transient period 1919–2007, and the transient period of 1971–2000 are presented in table 10. The simulated water budget for Walker River includes inflows at the Wabuska streamgage and groundwater inflow. The outflow components in order of decreasing magnitude are Walker River outflow to Walker Lake, diversions for agriculture use, seepage losses to groundwater, and losses associated with the storage of water in Weber Reservoir (mainly open-water evaporation and some seepage to groundwater).

Walker River inflow at Wabuska streamgage during the steady-state period (306,000 acre-ft/yr) was estimated through calibration (table 10) and accounts for nearly all inflow to the Walker River because inflow from groundwater was only 49 acre-ft/yr. Approximately 88 percent of the Walker River inflow at Wabuska was simulated to discharge to Walker Lake (271,000 acre-ft/yr), 6 percent was diverted for agricultural use (18,400 acre-ft/yr), and 6 percent was lost as seepage to groundwater (18,000 acre-ft/yr). Weber Reservoir did not exist during the steady-state period, and reservoir losses were not simulated for this time frame.

The mean annual streamflow entering the lower Walker River Basin from 1919 through 2007 was specified at about 121,000 acre-ft/yr (table 10), 60 percent less than during the steady-state conditions; a small quantity of water in the river originated from groundwater inflow (32 acre-ft/yr). Approximately 75 percent of the specified inflow at Wabuska was simulated to discharge to Walker Lake (90,600 acre-ft/yr), 13 percent was simulated as diversions for agricultural use (16,300 acre-ft/yr), and 9 percent was simulated as seepage loss to groundwater. Weber Reservoir was constructed and began filling in July 1934, resulting in simulated annual average loss of flow of about 3 percent (4,280 acre-ft/yr) through evaporation and seepage loss (2,930 and 1,350 acre-ft/yr, respectively).

Table 10. Summary of simulated water budgets for Walker River, west-central Nevada, from LWR_MF model for the steady-state period water years 1908–18, transient period water years 1919–2007, and transient period water years 1971–2000.

[Total inflow and outflow components do not exactly agree because these are summations of rounded budget flow components]

Water-budget component	Steady state 1908–1918 flow (acre-feet per year)	Transient 1919–2007 flow (acre-feet per year)	Transient 1971–2000 flow (acre-feet per year)
	Inflow	**Inflow**	**Inflow**
Inflow at Wabuska[1]	306,000	121,000	137,000
Groundwater inflow	49	32	14
Tributary inflow	0	0	0
Total inflow (rounded)	**306,000**	**121,000**	**137,000**
	Outflow	**Outflow**	**Outflow**
Agricultural diversions	18,400	16,300	17,300
Seepage to groundwater	18,000	10,800	11,500
Weber Reservoir losses	[2]0	[3]3,500	4,200
Outflow to Walker Lake	271,000	90,600	105,000
Total outflow (rounded)	**307,000**	**121,000**	**138,000**

[1] Inflow at Wabuska was estimated from calibration for steady-state simulation and specified for transient simulations; all other water budget components are simulated.

[2] Weber Reservoir did not exist during this time period.

[3] Weber Reservoir losses did not begin until August 1934. The number presented in the table includes 0 losses over the period of 1918 through mid-1934 included in computation of mean. Actual simulated losses from Weber Reservoir during it's operational period of mid-1934 through 2007 was 4,276 acre-feet per year.

The mean annual streamflow entering the lower Walker River Basin at the Wabuska gage over the 30-year simulation period from 1971 through 2000 was specified at about 137,000 acre-ft/yr (table 10), about 13 percent more than the entire transient simulation period, but 55 percent less than during steady-state conditions. Only a small amount of water in the river originated from groundwater discharge (14 acre-ft/yr). From 1971 through 2000, approximately 76 percent of the total inflow specified at Wabuska was simulated to discharge to Walker Lake (105,000 acre-ft/yr), 13 percent was diverted for agricultural use (17,300 acre-ft/yr), 8 percent was lost as seepage to groundwater (11,500 acre-ft/yr), and 3 percent was loss associated with evaporation and seepage losses from Weber Reservoir (4,200 acre-ft/yr). Specified Walker River inflow at Wabuska, simulated Walker River outflow to Walker Lake, and agricultural diversions compare well with estimates by Lopes and Allander (2009b) for the same period (138,000 acre-ft/yr, 105,000 acre-ft/yr, and 17,200 acre-ft/yr, respectively). Simulated seepage to groundwater and Weber Reservoir losses (11,500 and 4,200 acre-ft/yr, respectively) do not compare favorably with estimates by Lopes and Allander (2009b) (17,200 acre-ft/yr, 2,200 acre-ft/yr; respectively). These latter estimates by Lopes and Allander (2009b) did not include seepage losses from Weber Reservoir, and the estimated evaporative loss from Weber Reservoir was based on a poorly constrained statistical relation between the storage volume of Weber Reservoir and the storage volume of Bridgeport Reservoir.

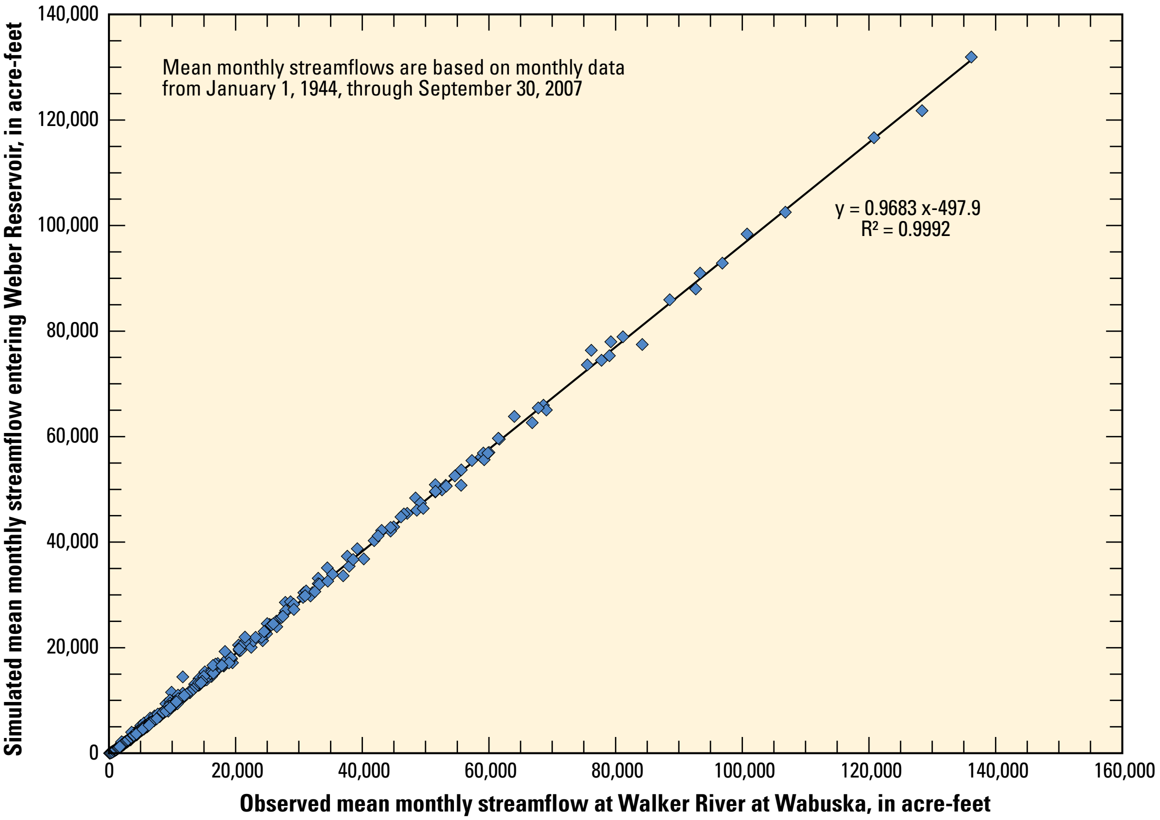


Figure 35. Relation of simulated mean monthly Walker River streamflow entering Weber Reservoir to observed mean monthly streamflow at Walker River at Wabuska gage, west-central Nevada.

The relation of simulated mean monthly Walker River streamflow entering Weber Reservoir and observed mean monthly streamflow at Wabuska gage was estimated for the period 1944–2007 (the period of complete streamflow record for Wabuska gage) and is shown in figure 35. On average, Walker River inflow to Weber Reservoir can be estimated as 96.8 percent of the mean monthly streamflow at Wabuska (in units of acre-ft) minus 498 acre-ft.

The relation of simulated mean annual Walker River streamflow entering Walker Lake to observed mean annual streamflow at Wabuska gage was estimated for the period 1944–2007 (fig. 36). On average, Walker River streamflow to Walker Lake is 95.0 percent of the mean annual streamflow at Wabuska gage (in units of acre-ft) minus 25,800 acre-ft. The relation also indicates streamflows generally reach Walker Lake when annual Wabuska gage streamflow is greater than 27,200 acre-ft.

Walker Lake

The simulated water budget for Walker Lake consists of the following inflow components in order of decreasing magnitude: Walker River, direct precipitation, groundwater, and tributary streams other than Walker River. There are two simulated components of outflow for Walker Lake: evaporation and seepage losses to groundwater. Decreases in the lake storage result when outflow rates are greater than inflow rates. The simulated water budgets for Walker Lake for steady-state conditions prior to 1919, the transient decline period of 1919–2007, and the transient period 1971–2000 are summarized in table 11.

The average simulated stream, groundwater, and precipitation inflow to Walker Lake during the steady-state period was balanced by evaporation losses and resulted in an initial lake level of 4078.0 ft local datum, which is consistent with estimated lake level in October 1918 (fig. 27*A*). The steady-state streamflow entering Walker Lake from Walker River was about 271,000 acre-ft/yr; precipitation, 23,200 acre-ft/yr; groundwater inflow, about 2,500 acre-ft/yr; and other tributary inflow, about 1,800 acre-ft/yr (table 11). The average surface area of Walker Lake was about 68,000 acres. The average evaporation was about 297,000 acre-ft/yr, and groundwater outflow was about 1,500 acre-ft/yr. Simulated dissolved-solids concentration was around 3,100 mg/L (fig. 28*B*).

The average simulated streamflow entering Walker Lake from the Walker River over the transient simulation period 1919–2007 was about 91,000 acre-ft/yr; precipitation, 15,300 acre-ft/yr; groundwater inflow, 10,400 acre-ft/yr; and tributary inflow, about 1,500 acre-ft/yr (table 11). Simulated lake level decreased from 4,078.0 ft to 3,935.8 ft local datum (fig. 27A). Although the model simulated tributary inflow as base flow rather than as stormflow or snowmelt

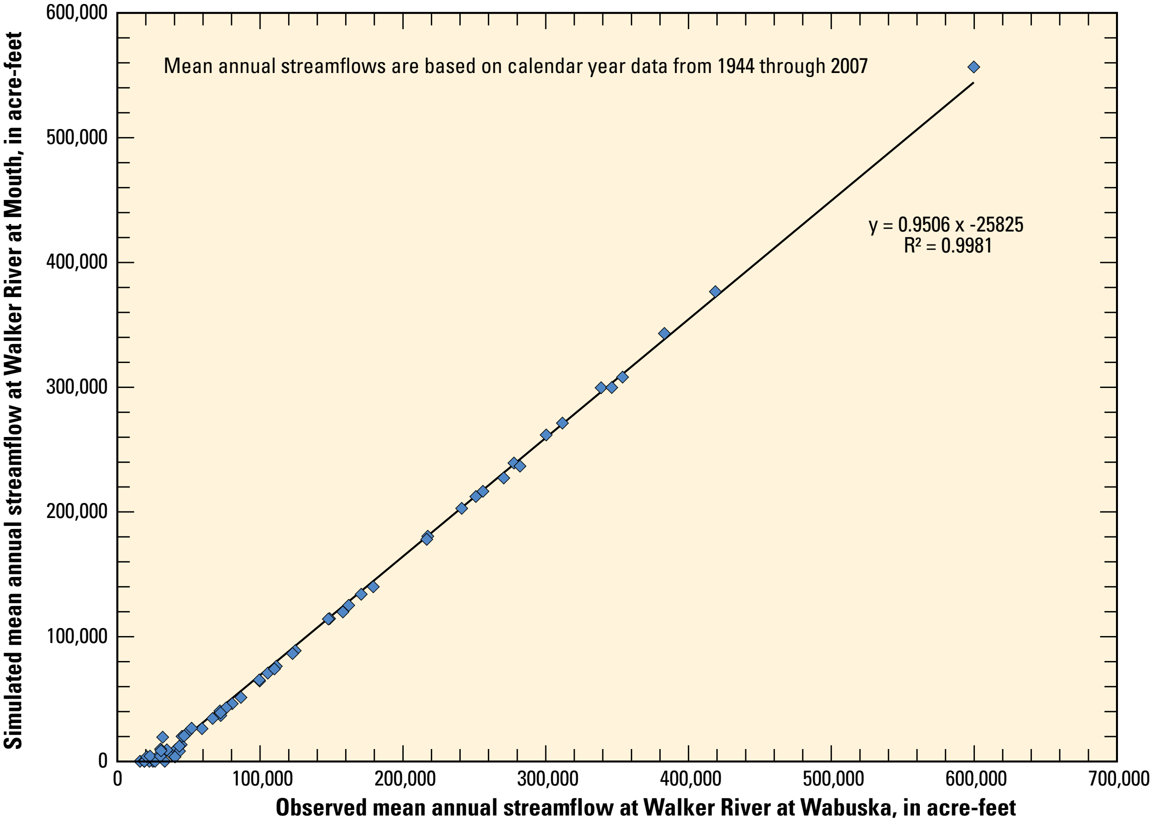


Figure 36. Relation of simulated mean annual Walker River streamflow entering Walker Lake at Mouth to observed mean annual Walker River streamflow at Wabuska streamgage, west-central Nevada.

runoff, the simulated tributary inflow was similar to the estimated annual inflow of 3,000 acre-ft/yr by Everett and Rush (1967). The average surface area of Walker Lake was about 44,600 acres. Evaporation from Walker Lake averaged about 195,000 acre-ft/yr, groundwater outflow was less than 1,000 acre-ft/yr, and storage decreased by about 76,700 acre-ft/yr. Simulated dissolved-solids concentrations increased from 3,100 mg/L to 15,300 mg/L (fig. 28*B*).

The average simulated streamflow entering Walker Lake from Walker River over the 30-year transient simulation period 1971–2000 was about 105,000 acre-ft/yr; precipitation, 12,500 acre-ft/yr; groundwater inflow, about 7,600 acre-ft/yr; and tributary inflow, 1,930 acre-ft/yr (table 11). These values compare well with Walker Lake water budget inflow components estimated by Lopes and Allander (2009b) for the same period, which were 105,000; 14,600; 7,800; and 3,000 acre-ft/yr, respectively. The average simulated surface area of Walker Lake was about 36,500 acres, which compares well with the 36,620 acres reported by Lopes and Allander (2009b). Simulated outflows for this period were 159,000 acre-ft/yr of evaporation, 1,320 acre-ft/yr of groundwater outflow, and a 33,500-acre-ft/yr decrease in storage. The outflow components also compare well with those estimated by Lopes and Allander (2009b), which were 157,400 acre-ft/yr of evaporation, 2,200 acre-ft/yr of groundwater outflow, and 29,000 acre-ft/yr decrease in storage. Simulated lake level for this period declined from 3,975.6 to 3,948.6 ft, local datum (fig. 27*A*), and simulated dissolved-solids concentrations increased from 8,500 mg/L to 12,300 mg/L (fig. 28*B*).

Groundwater

The groundwater budget for the lower Walker River Basin consists of the following components of inflow, in order of decreasing magnitude: recharge (associated with precipitation), releases from groundwater storage (associated with a decrease in storage), infiltration from stream leakage, infiltration from irrigation, seepage from lakes, and inflow from Mason Valley. The outflow components in order of decreasing magnitude are groundwater evapotranspiration, discharge to lakes, uptake to groundwater storage (associated with increases in groundwater storage), outflow through Double Springs area, spring discharge, and discharge to streams. Groundwater pumping is a relatively small component of the overall water budget and was not simulated. The simulated groundwater budgets for steady-state conditions prior to 1919 and the transient simulation period 1919–2007 are presented in table 12. Allander and others (2009) estimated net evapotranspiration from a 193-mi^2 area (123,290 acres) surrounding Walker Lake (fig. 37) from 2005 to 2007, providing a comparison with simulated evapotranspiration for this period.

Table 11. Summary of simulated water budgets for Walker Lake, west-central Nevada, from LWR_MF model for the steady-state period water years 1908–18, transient period water years 1919–2007, and transient period water years 1971–2000.

[Total inflow and outflow components do not exactly agree because these are summations of rounded budget flow components; na, not applicable]

Water-budget component	Steady state 1908–1918		Transient 1919–2007		Transient 1971–2000	
	Flow (acre-feet per year)	Rate per unit area[1] (feet per year)	Flow (acre-feet per year)	Rate per unit area[2] (feet per year)	Flow (acre-feet per year)	Rate per unit area[3] (feet per year)
	Inflow		**Inflow**		**Inflow**	
Walker River	271,000	3.99	91,000	2.04	105,000	2.88
Precipitation	23,200	0.34	15,300	0.34	12,500	0.34
Groundwater inflow	2,470	0.04	10,400	0.23	7,590	0.21
Tributary inflow	1,810	0.03	1,510	0.03	1,930	0.05
Total inflow (rounded)	**298,000**	**4.38**	**118,000**	**2.64**	**127,000**	**3.48**
	Outflow		**Outflow**		**Outflow**	
Lake evaporation	297,000	4.37	195,000	4.37	159,000	4.36
Lake storage decrease	na	na	-76,700	-1.72	-33,500	-0.92
Groundwater outflow	1,540	0.02	720	0.02	1,320	0.04
Total outflow (rounded)	**299,000**	**4.40**	**119,000**	**2.67**	**127,000**	**3.48**

[1] Area of Walker Lake during steady-state period water years 1908–1918 was 68,000 acres.

[2] Average area of Walker Lake during transient period water years 1919–2007 was 44,600 acres.

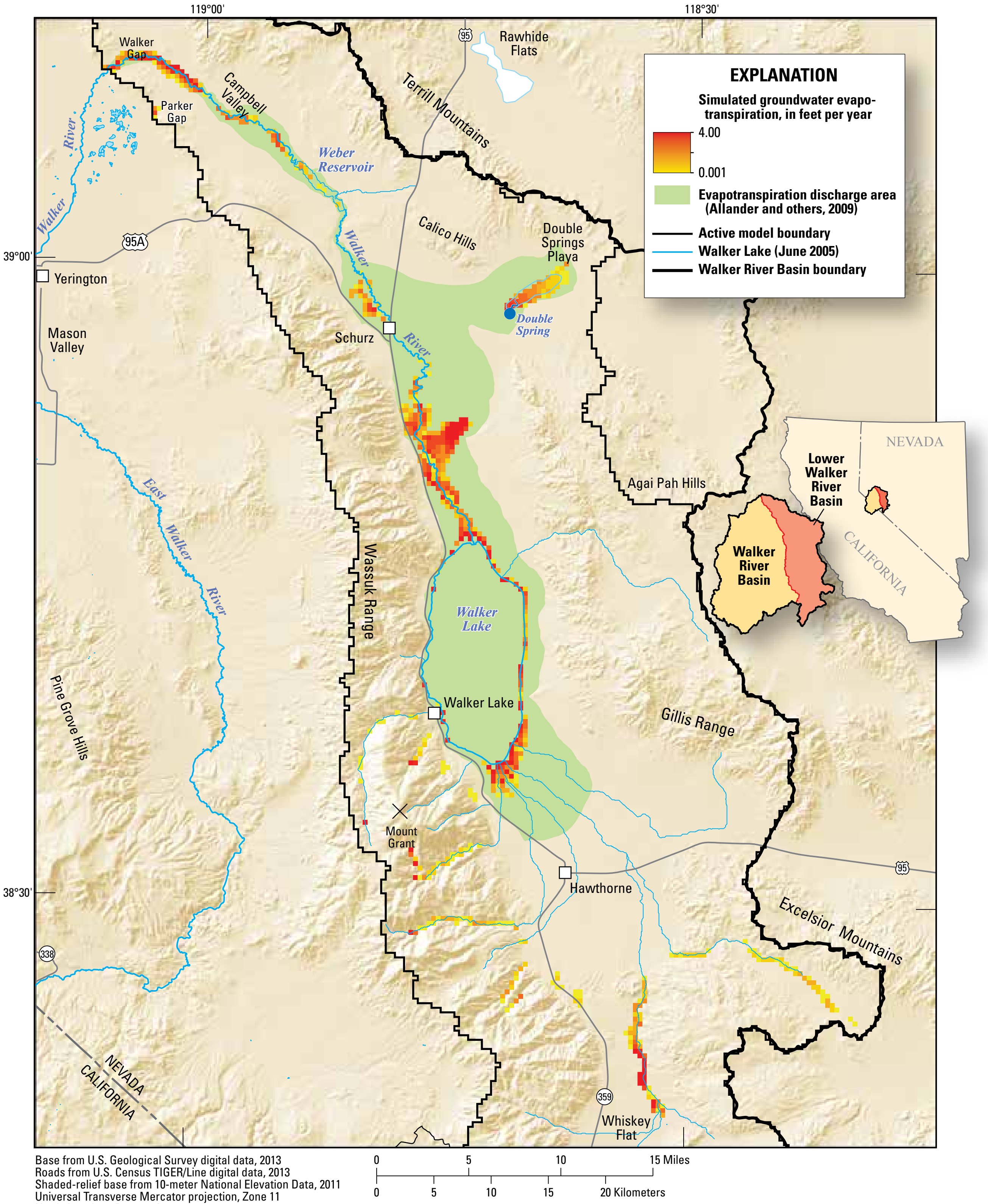
[3] Average area of Walker Lake during transient period water years 1971–2000 was 36,500 acres.

Table 12. Summary of simulated groundwater budgets for the lower Walker River Basin, west-central Nevada, from the LWR_MF model for steady-state period water years 1908–18 and transient period water years 1919–2007.

[Total inflow and outflow components do not exactly agree because these are summations of rounded budget flow components; na, not applicable]

Water-budget component	Steady state 1908–1918		Transient 1919–2007	
	Flow (acre-feet per year)	Percentage of total	Flow (acre-feet per year)	Percentage of total
	Inflow		**Inflow**	
Local recharge	20,700	40	20,900	34
Decrease in storage	na	na	18,200	29
Stream leakage	18,000	35	10,800	17
Infiltration from irrigation	11,000	21	9,800	16
Seepage from lakes	1,500	3	1,800	3
Inflow from Mason Valley	580	1	590	1
Total inflow (rounded)	**51,800**	**100**	**62,100**	**100**
	Outflow		**Outflow**	
Groundwater evapotranspiration	44,000	85	42,600	69
Outflow through Double Springs area	2,300	4	2,200	4
Discharge to streams	49	0	32	0
Discharge to lakes	2,500	5	10,400	17
Spring discharge	2,900	6	1,600	3
Increase in storage	na	na	5,300	9
Total outflow (rounded)	**51,700**	**100**	**62,100**	**100**

Total simulated groundwater inflow to the lower Walker River Basin during the steady-state period prior to 1919 was about 52,000 acre-ft/yr (table 12). Of this inflow, 40 percent was from local recharge (20,700 acre-ft/yr), 35 percent from stream leakage (18,000 acre-ft/yr), 21 percent from infiltration of irrigation water beneath canals and fields (11,000 acre-ft/yr), 3 percent from seepage from Walker Lake (1,500 acre-ft/yr), and 1 percent groundwater inflow from Mason Valley (580 acre-ft/yr). Total groundwater outflow in the lower Walker River Basin during the steady-state simulation was about the same as inflow (about 52,000 acre-ft/yr). Of this outflow, 85 percent of groundwater was removed from the system by evapotranspiration (44,000 acre-ft/yr), 6 percent by spring discharge (2,900 acre-ft/yr), 5 percent by groundwater discharge to Walker Lake (2,500 acre-ft/yr), and 4 percent by groundwater outflow near Double Springs (2,300 acre-ft/yr). Only a negligible amount of groundwater discharge to streams (49 acre-ft/yr) was simulated.



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 37. Simulated distribution of groundwater evapotranspiration in July 2005 for entire model area, west-central Nevada, and the evapotranspiration discharge area defined by Allander and others (2009).

Table 13. Summary of simulated groundwater evapotranspiration discharge for lower Walker River Basin, west-central Nevada, from the LWR_MF model for water years 2005–2007.

[ET, evapotranspiration]

Year	Simulated groundwater evapotranspiration discharge		Observed groundwater discharge from evapotranspiration (Allander and others, 2009)
	Entire model area (acre-feet per year)	ET discharge area[1] (acre-feet per year)	ET discharge area[1] (acre-feet per year)
2005	40,800	32,300	25,100
2006	42,000	34,800	22,100
2007	39,300	33,000	32,100
Average	**40,700**	**33,400**	**26,400**

[1] This is the evapotranspiration discharge quantification area as defined by Allander and others (2009) and is shown in figure 37.

Total simulated groundwater inflow to the lower Walker River Basin during the transient simulation period 1919–2007 was about 62,000 acre-ft/yr (table 12). Of this inflow, 34 percent was from local recharge (20,900 acre-ft/yr), 29 percent from decreases in groundwater storage during years with declining Walker Lake level (18,200 acre-ft/yr), 17 percent from leakage of Walker River (10,800 acre-ft/yr), 16 percent from infiltration of irrigation water beneath canals and fields (9,800 acre-ft/yr), 3 percent from seepage from Walker Lake (1,800 acre-ft/yr), and 1 percent groundwater inflow from Mason Valley (590 acre-ft/yr). Total groundwater outflow in the lower Walker River Basin during the transient simulation period 1919–2007 was the same as inflow (about 62,000 acre ft/yr). Of this outflow, 69 percent was due to groundwater evapotranspiration (42,600 acre-ft/yr); 17 percent, groundwater discharge to Walker Lake (10,400 acre-ft/yr); 9 percent, increases in groundwater storage associated with occasional increases in Walker Lake level (5,300 acre-ft/yr); 4 percent, groundwater outflow near Double Springs (2,200 acre-ft/yr); and 3 percent, spring discharge (1,600 acre-ft/yr). Only a negligible amount of the groundwater discharge was to Walker River and tributary streams (32 acre-ft/yr).

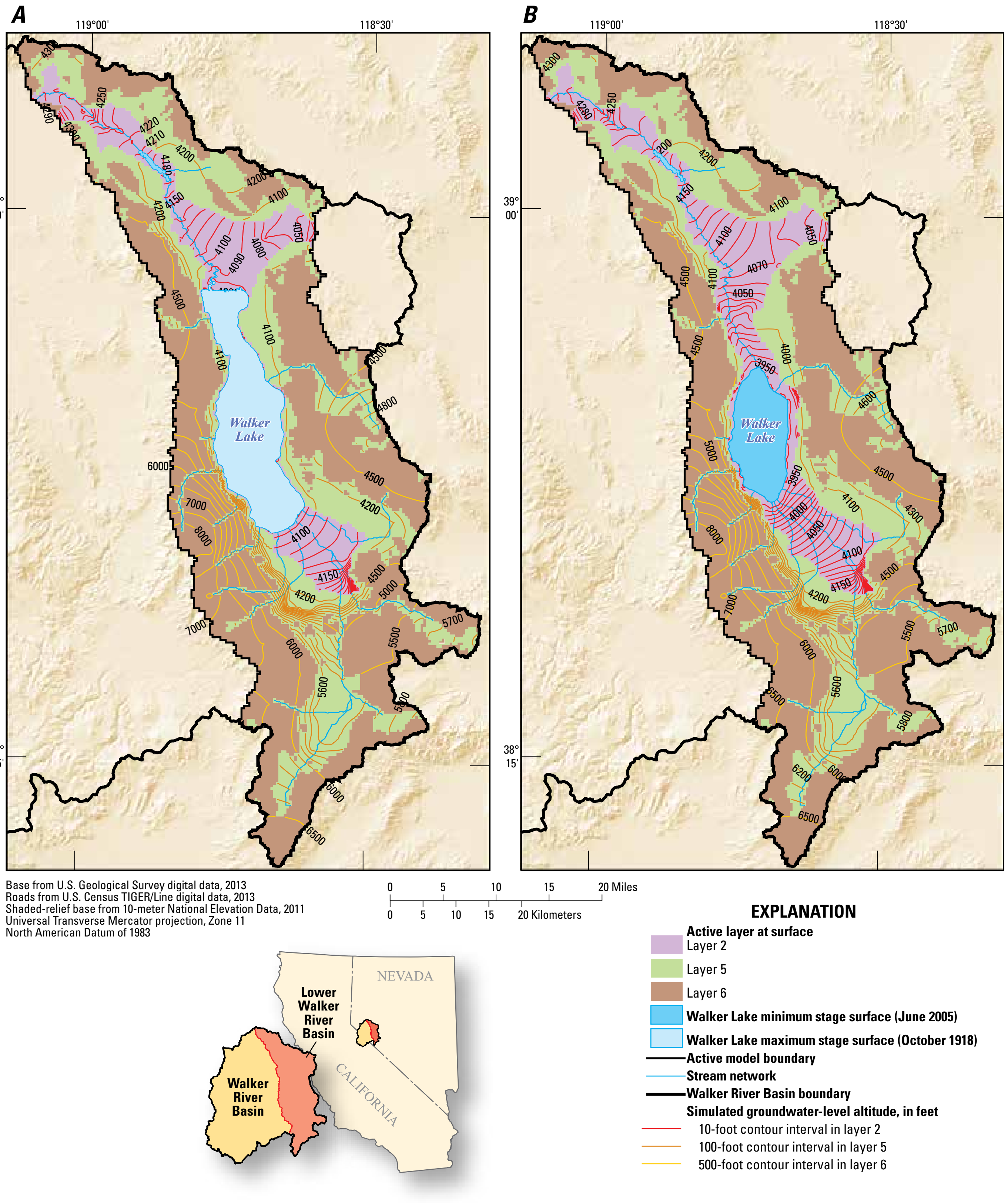
Simulated groundwater evapotranspiration is summarized in table 13 for water years 2005–07 for the entire model area, as well as for the evapotranspiration discharge area defined in Allander and others (2009; fig. 37). Simulated groundwater discharge within the evapotranspiration discharge area was 33,400 acre-ft/yr and accounted for 82 percent of the total simulated groundwater evapotranspiration from the lower Walker River Basin (40,700 acre-ft/yr). Simulated evapotranspiration from the evapotranspiration discharge area was 25 percent greater than that observed by Allander and others (2009) (26,400 acre-ft/yr).

A comparison of simulated hydrologic conditions during the steady-state period (1908–18; highest simulated lake level) and at the maximum decline of Walker Lake in December 2005 indicates that groundwater conditions are similar throughout the study area except in the vicinity of Walker Lake (fig. 38). In the northern half of the study area, groundwater flows downgradient parallel to Walker River until just upstream from the boundary of the 1918 Walker Lake surface where the flow diverges eastward to Double Springs and southward to Walker Lake. In 1918 (fig. 38*A*), groundwater discharged to Walker Lake just 2 miles south of this point. In December 2005, when the lake was at its lowest level, groundwater flowed southward more than 10 miles before discharging to Walker Lake (fig. 38*B*).

In the southern half of the study area, groundwater flows parallel to topography in a northward direction toward Walker Lake (fig. 38). In 1918 (fig. 38*A*), groundwater discharged to Walker Lake nearly 4 miles farther south at a much higher altitude (4,081 ft) than during the lowest lake level in December 2005 (3,936 ft; fig. 38*B*).

Maximum declines in simulated groundwater level in the vicinity of Walker Lake were calculated by subtracting water levels simulated for 1918 from the water levels simulated for December 2005 (fig. 39). Simulated groundwater declines in the mountains west of the lake (model layer 6) are highly uncertain (due to lack of hydrologic data) but have only a slight effect on the simulated hydrologic budget.

Changes in groundwater storage in the lower Walker River Basin are correlated with the declining Walker Lake level (fig. 40). As Walker Lake recedes, groundwater storage adjacent to Walker Lake declines, and during periods when the lake expands, there is a slight increase in groundwater storage. The total decrease in simulated groundwater storage from October 1918 to September 2007 is 1.14 million acre-ft (13,000 acre-ft/yr) which is equivalent to about 16 percent of the overall loss in volume in Walker Lake (6.92 million acre-ft).



Base from U.S. Geological Survey digital data, 2013
Roads from U.S. Census TIGER/Line digital data, 2013
Shaded-relief base from 10-meter National Elevation Data, 2011
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983

Figure 38. Simulated groundwater-level contours in active layers at model surface, lower Walker River Basin, west-central Nevada, for *A*, LWR_MF steady-state conditions prior to 1919 when Walker Lake was at the highest lake level of the simulation period and *B*, LWR_MF transient conditions in December 2005 when Walker Lake was at the lowest lake level of the simulation period. Contour intervals are variable.

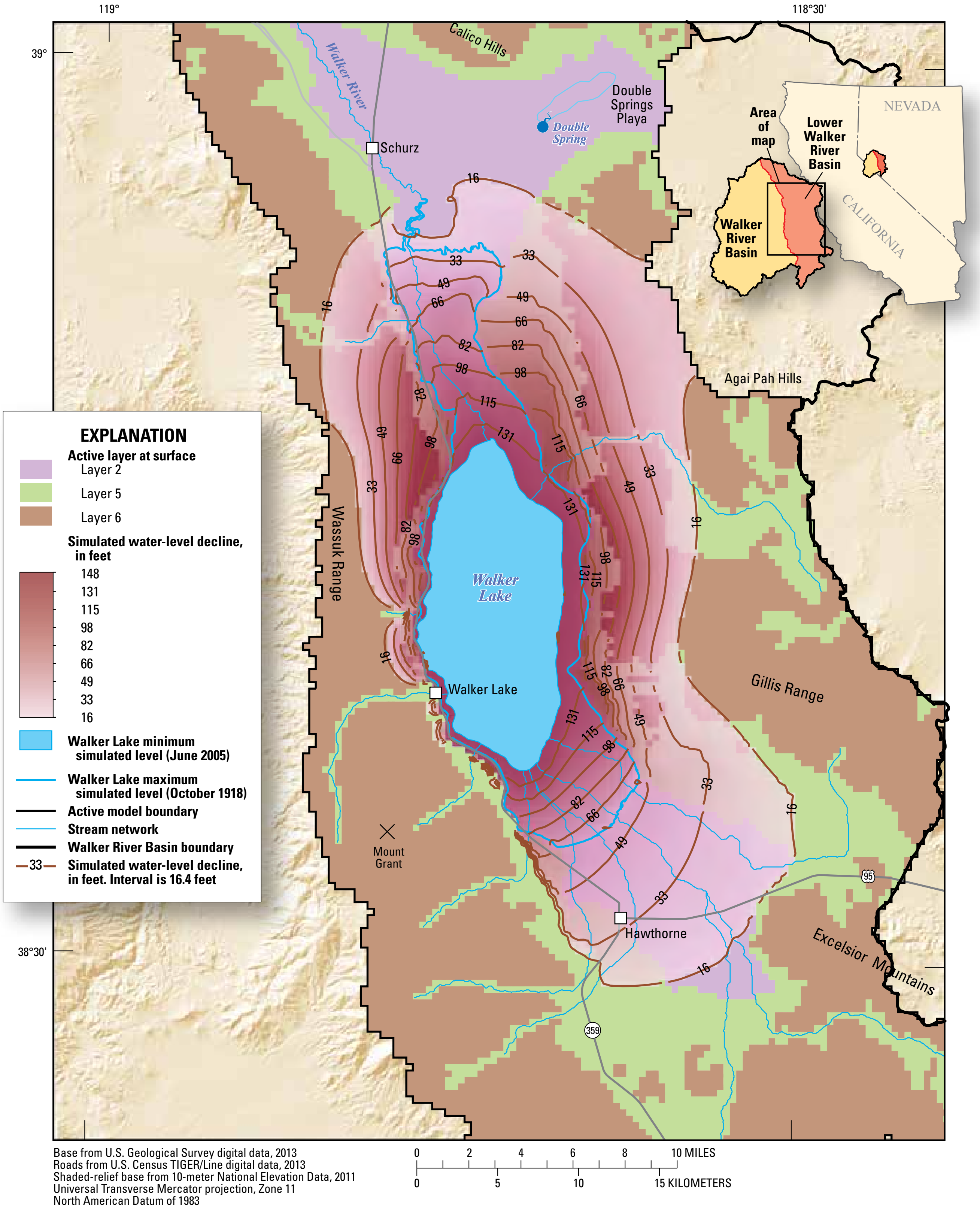


Figure 39. Simulated groundwater-level decline in the vicinity of Walker Lake, west-central Nevada, as a result of the long-term decline of Walker Lake from October 1918 when lake was at the highest simulated lake level to December 2005 when lake was at the lowest simulated lake level.

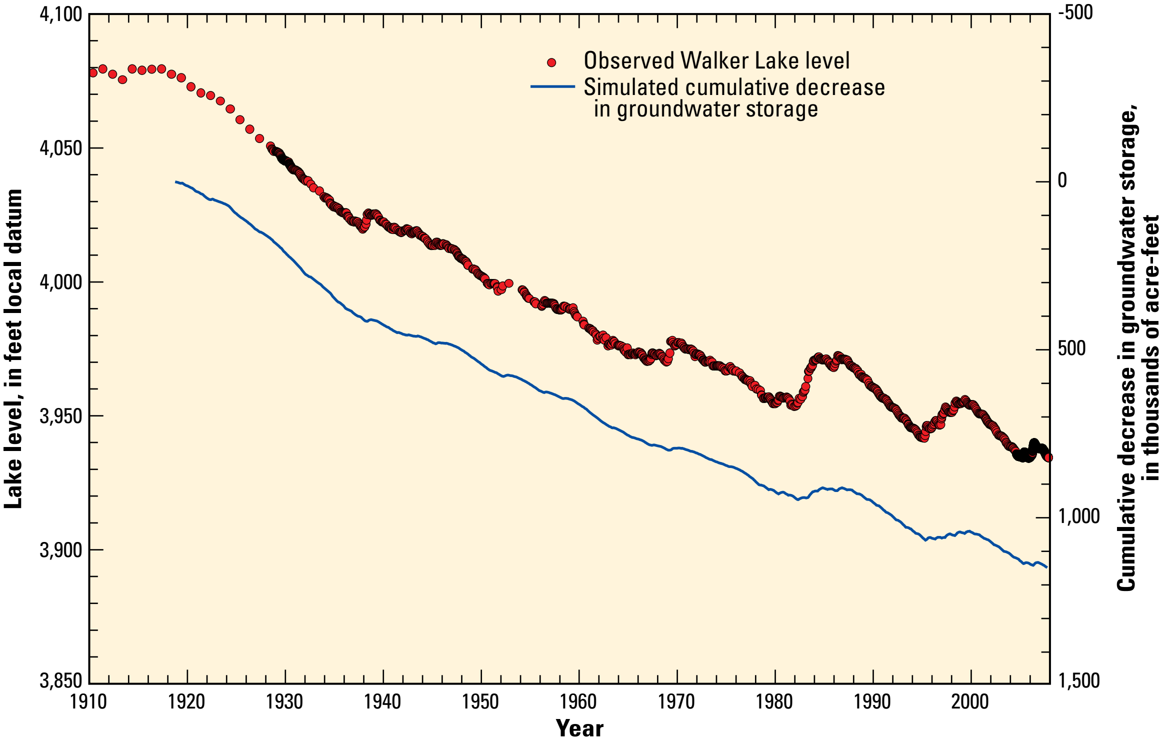


Figure 40. Lake level and cumulative decrease in groundwater storage in lower Walker River Basin, west-central Nevada, during the simulation period water years 1919–2007.

Model Limitations

As with all models, the LWR_MF is a mathematical simplification and representation of the hydrology of the lower Walker River Basin. As such, there are limitations to the usefulness and application of the model in representing actual hydrologic conditions. In order to represent the groundwater, river, and lake systems in the lower Walker River Basin, many simplifying assumptions about the hydrologic system were necessary, such as coarseness of model discretization, homogeneous hydraulic properties within model cells, constant streambed hydraulic conductivity over long reaches of river, and a single evapotranspiration rate. Additionally, hydraulic properties of basin-fill deposits and distribution of water levels are seldom known, and the calibration process is constrained by the availability of data.

There are three types of model error: model design, parameter, and observation measurement. Model design error results from discretizing a complex hydrologic system into a gridded framework used to formulate a system of equations to numerically solve the continuity equation derived from the three-dimensional groundwater flow equation. Parameter error is the uncertainty in specified and calibrated parameter values. Observation measurement error is the error associated with the observed data used to guide model calibration; typically measurement error contributes the least to overall model error.

The LWR_MF is designed for evaluating large-scale hydrologic processes in the lower Walker River Basin. The LWR_MF model is useful for evaluating long-term trends in Walker Lake, Walker River, irrigation use, and overall groundwater conditions as a result of changes in stresses or changes in water management within the lower Walker River Basin. However, there are some specific limitations to this model's ability to simulate certain features of the hydrologic system, as well as scale of its use.

Simulation of groundwater levels and fluxes within the consolidated rock units may have substantial errors. This is mainly due to the lack of observation data to guide determination of hydraulic properties specific to the rock units. The hydraulic properties of the consolidated rock units were determined by fitting water levels at a point along the perennial reach of Cottonwood Creek and a point along the perennial reach of Rose Creek. The goal of this calibration was to have the water table be at or just below the level of the creeks so that base flow can occur when the GSFLOW model is used. However, this involves the assumption that these perennial reaches are the result of groundwater discharge (base flow) from the consolidated rocks rather than as the result of a perched water table supported by seasonal surface runoff. Although it is likely that the consolidated rock units beneath the perennial streams are saturated, it is unknown whether the groundwater in the consolidated rock unit is discharging to the stream or whether the consolidated rock unit is saturated as a result of long-term focused recharge along the perennial stream reaches.

Related to the limitation of groundwater levels and hydraulic properties within the consolidated rock units is the limitation of the LWR_MF to adequately simulate tributary streamflows. The main purpose of having the streamflow network and tributaries included in the LWR_MF was to provide the framework for the GSFLOW model, which should simulate tributary flows more characteristically. The LWR_MF does not incorporate temporal variation of hydrologic stresses in the mountains (precipitation, evapotranspiration, and so on); rather, a constant magnitude and distribution of recharge is applied over the simulation period. As such, there is no mechanism to drive variability in mountain tributary streamflows. This results in constant base flows in some of the mountain tributaries but likely does not simulate actual streamflow variability. However, the long-term constant base-flow contribution to Walker Lake from the mountain tributaries is nearly equivalent to the estimated contribution from the tributaries from infrequent large flow events.

Another limitation of the LWR_MF is that it does not simulate groundwater pumping, which has an effect on groundwater levels and fluxes in areas where pumping occurs. Essentially, the LWR_MF simulates the system as if it were pre-development, with the major exception of Walker Lake declines and long-term diversions from Walker River. For the most part, excluding the effects of groundwater pumping has a negligible effect on the overall simulation of storage change in Walker Lake or Walker River streamflows as those components of flow are much greater than the pumping from the lower Walker River Basin. The long-term simulated discharge to Walker Lake from Walker River is 91,000 acre-ft/yr, whereas the estimated pumping along the Walker River corridor (mainly from the Schurz area) is 200 acre-ft/yr (Everett and Rush, 1967). Stated otherwise, pumping along Walker River is equivalent to about 0.2 percent of the flow in Walker River that discharges to Walker Lake. Similarly, the overall groundwater pumpage in the lower Walker River Basin is estimated to be about 2,900 acre-ft/yr (Boyle Engineering Corp, 1976), which is about 4 percent of the annual loss of storage in Walker Lake (77,000 acre-ft/yr) and 22 percent of the annual net reduction in groundwater storage as a result of the decline of Walker Lake (12,900 acre-ft/yr). However, in the Whiskey Flat region of the model, the amount of pumpage compared to the recharge contributing to that area is substantial, resulting in drawdown of groundwater levels over time that is not simulated by the model. Because of this, the model simulates only natural groundwater discharge in the form of a spring and groundwater evapotranspiration from the northern end of Whiskey Flat (fig. 37). In all likelihood, the groundwater that historically supplied the spring and groundwater evapotranspiration may have been partially captured by the pumping in Whiskey Flats, and these simulated hydrologic features may no longer exist.

Another substantial limitation of the model is that simulation of seasonal processes is simplified, and as a result, model results may not be accurate at seasonal time scales. This is due in large part to the approach used to specify or simulate stresses in the model. Large scale stresses, such as evapotranspiration and groundwater recharge, are treated as constant over time. From year to year, the use of constant stresses over time balance out, and overall model results are likely to be representative of the system. However, more seasonally or temporally detailed evaluations reveal that the model does not handle seasonal characteristics or variability very well. Major stresses, such as streamflow entering at the Wabuska streamgage and diversions from Walker River, are specified on a temporal scale that allows the model to be useful for evaluation of long-term trends with specific focus on water supply issues related to Walker River, Weber Reservoir, diversions, and Walker Lake.

The LWR_MF begins to improperly compute Walker Lake water-budget components above a lake level of 4,097.5 ft local datum (1,250.0 m). This is because the lake level capacity table in the LWR_MF is defined to a maximum lake level of 4,097.5 ft (1250 m). Above this lake level, the model misrepresents lake area and all water-budget components relying on lake area for computation (evaporation and precipitation). The LWR_MF simulates groundwater interactions with Walker Lake up to a maximum lake extent associated lake level of 4,078.0 ft (local datum). However, the model will continue to adequately simulate lake level, volume, and area above this lake level if increased (or decreased) lake interactions with groundwater are assumed to be negligible in comparison to the stream inflows required to support a lake level above 4,078 ft.

Possible limitations to the simulation of dissolved-solids concentration in Walker Lake are related to the assumption of constant salt mass over time, interpolation of lake level to dates of measured dissolved-solids concentrations, and potential errors or uncertainties associated with the lake level capacity relations for Walker Lake from Lopes and Smith (2007). An additional limitation is that with simulated increases in lake level and volume, there is a potential for increases in salt content associated with re-dissolution of salts stored in the unsaturated part of the shore zone. In contrast, another limitation is that with simulated decreases in lake level and volume, decreases in salt content associated with increasing mineral precipitation may occur.

Response of Lower Walker River Hydrologic System to Changes in Water Management

The LWR_MF calibrated groundwater flow model was modified and used in a series of predictive simulations to evaluate hydrologic system response to changes in the management of Walker River resources. Four hypothetical management scenarios, including a baseline scenario representing no change in management scenario, were developed in consultation with stakeholders. Three water-management scenarios were evaluated with respect to the baseline scenario. The first management scenario evaluated the effects of improvements in project irrigation efficiencies of the WRIIP (efficiency scenarios) on irrigation, groundwater, Walker River, and Walker Lake. The second scenario evaluated the response of Walker River and Walker Lake to additional streamflow at Wabuska for two management strategies of Weber Reservoir (streamflow scenarios). The third scenario evaluated the effect fallowing of WRIIP fields from 2007 to 2010 had on Walker Lake. The first two management scenarios represent the period 2011–70, using 120 6-month stress periods (fig. 41); the third management scenario simulated a 4-year period, 2007–10, using 8 6-month stress periods. Initial conditions were derived from LWR_MF with transient simulation extended by 3 years to simulate through 2010.

No Changes in Water Management (Baseline Scenario)

The LWR_MF was modified to predict baseline conditions 60 years from 2011 on the basis of specified flows at Wabuska for use in evaluating the effects of management scenarios (baseline scenario). The baseline scenario model (LWR_MF-B) is the calibrated LWR_MF extended 3 years (2008–10), using observed streamflows at Wabuska gage to simulate initial conditions plus 60 years of projected streamflows at Wabuska gage to simulate the prediction period (2011–70). Streamflow at Wabuska gage is observed streamflow through September 2010. Then beginning in October 2010, the simulation twice repeats the 30-year streamflow record observed at Wabuska from1981 through 2010 (fig. 41). The 1981–2010 30-year period was used because it contains a representative mix of drought and wet cycles that could occur in the future. However, this 30-year period was modified to normalize the bias of the period with respect to the long-term mean annual flow by replacing the extreme runoff year of 1983, which is unlikely to recur in any given 30-year period, with the large but more realistic streamflow observed in 1995. For the 60-year prediction period, Weber Reservoir is operated at maximum operating lake level of 4,208 ft (local datum), and all agricultural diversions are based on irrigation demand of 18,375 acre-ft/yr.

Results of the baseline scenario indicate that if Walker River streamflow conditions remain similar to those for the period 1981–2010, Walker Lake level and volume continue to decline and dissolved-solids concentrations continue to increase (fig. 42). Most notable is the general behavior of the simulated dissolved-solids concentrations in Walker Lake as changes in dissolved solids become more exaggerated over

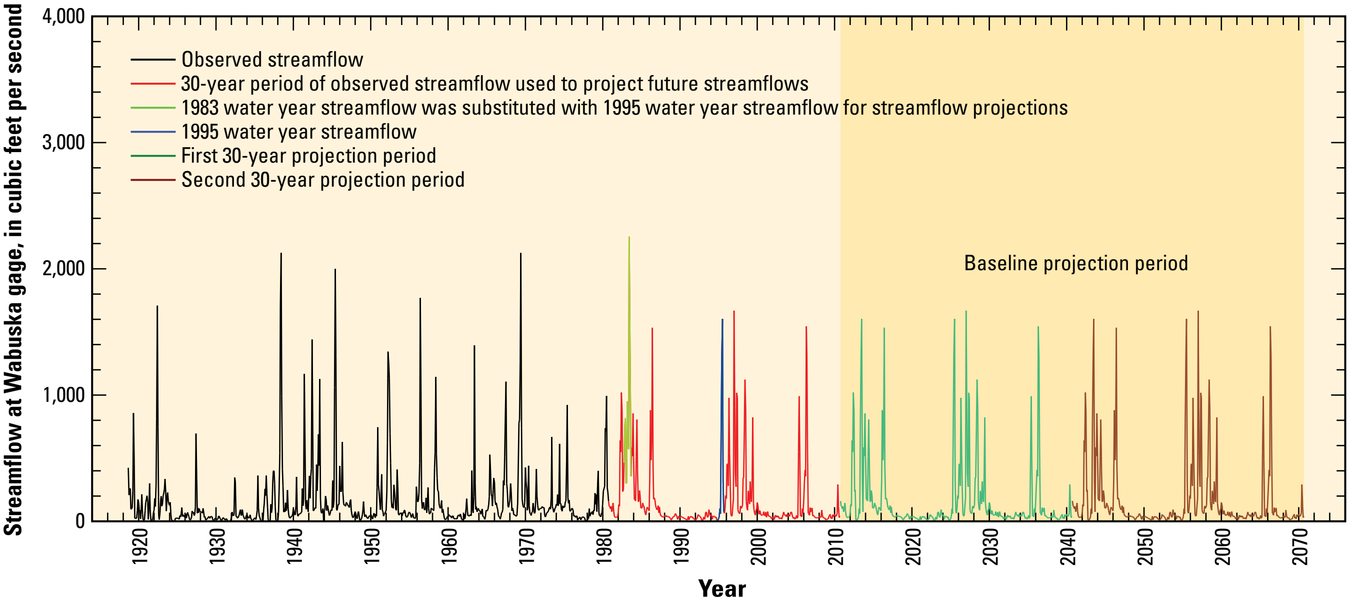


Figure 41. Observed and projected streamflow at Walker River at Wabuska streamgage, west-central Nevada, used in LWR_MF-B scenario for entire simulation period water years 1919–2070.

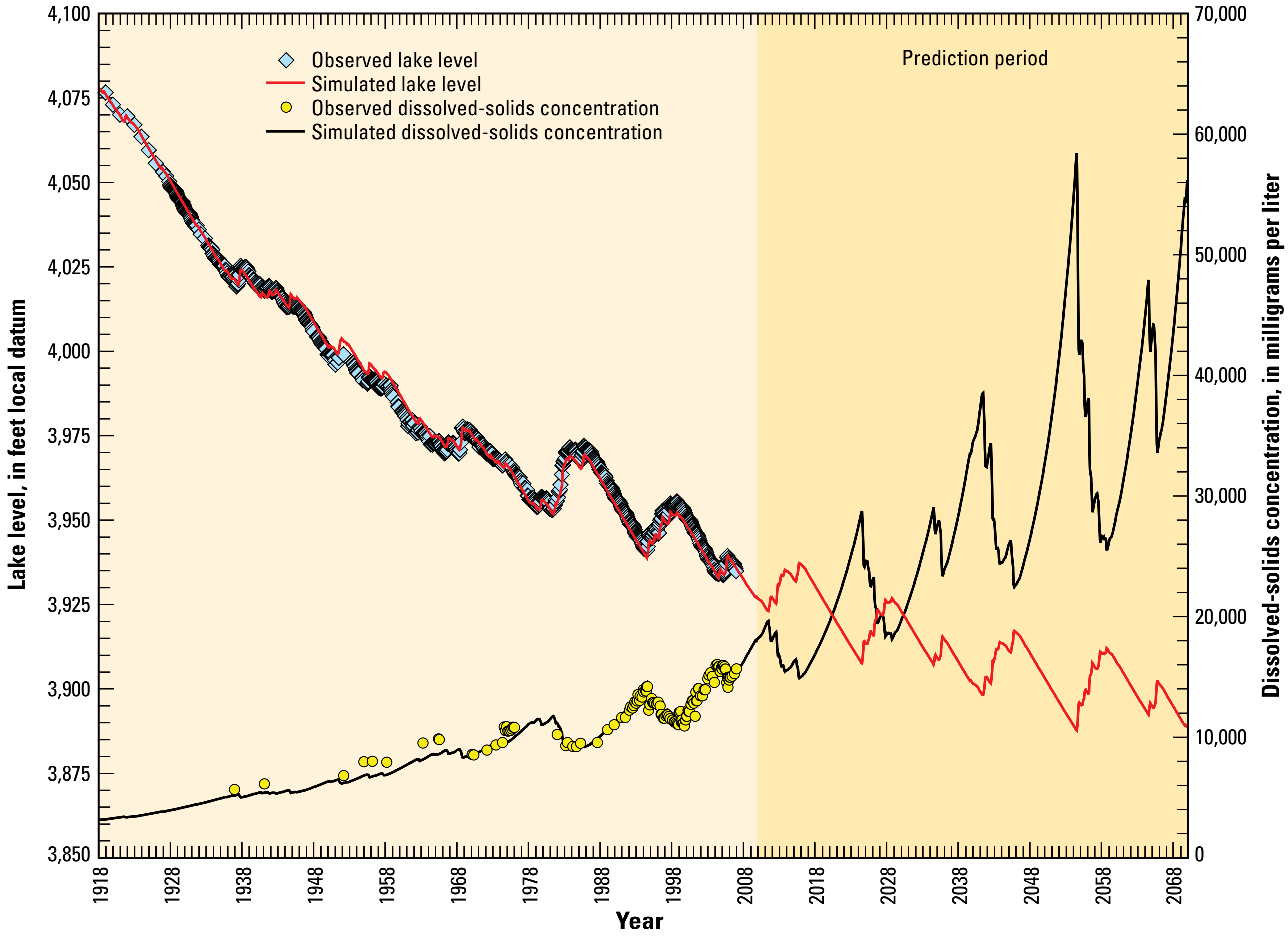


Figure 42. LWR_MF-B model simulated lake level and dissolved-solids concentrations in Walker Lake, west-central Nevada, for the transient period water years 1919–2010 and the prediction period water years 2011–70.

time. Although the rate of decline of Walker Lake level is becoming less, the relative change in volume per unit change in lake level becomes much greater, resulting in greater increases and variability of dissolved-solids concentrations in the future as compared with the past. For instance, a 1-ft decline in lake level at 3,890 ft (predicted lake level in 2054) is equivalent to a 4.2 percent reduction in volume, whereas a 1-ft decline in lake level at 3,950 ft (simulated lake level in 2000) is equivalent to a 1.5 percent reduction in volume. Of particular interest is the sharp increase in dissolved-solids concentrations simulated between 2047 and 2055, which is a hypothesized drought (synonymous with the drought of April 1, 1987–April 1, 1995) when there is no inflow to Walker Lake from Walker River. Simulated dissolved-solids concentrations during this 8-year period more than doubled from about 23,000 mg/L to 58,000 mg/L with an associated lake level decline of 28 ft. This demonstrates that for a potentially smaller future Walker Lake, under conditions of no stream inflow from the Walker River, the rate of increase of dissolved-solids concentrations will be much greater than that observed in the past.

The baseline scenario LWR_MF-B model simulated a water budget for the prediction period 2011–70 for Walker Lake that has lower total inflow and outflow than for the 1981–2010 period (table 14). The lower inflows are mainly affected by three factors. First, specified inflow at Wabuska gage for the anomalously high runoff year of 1983 was replaced with lower streamflow from the wet year of 1995, which resulted in a little less streamflow reaching Walker Lake than in the 1981–2010 period. Second, the smaller predicted lake surface results in less inflow from direct precipitation. Third, there is decreased groundwater inflow, resulting from a smaller perimeter of Walker Lake to interact with groundwater. The reduction in outflow is mainly attributed to a smaller lake surface area and the associated decrease in evaporation.

The baseline scenario LWR_MF-B model simulated a water budget for Walker River for the prediction period 2011–70 that has less total inflow and outflow than the 1981–2010 period (table 15). The lower inflows principally are a result of replacement of the anomalously high inflow of 1983 with lower inflow from the wet year of 1995. Agricultural diversions are greater during the prediction period because Weber Reservoir operates at full lake level for the entire period and is not restricted by earthquake operation criteria. Additionally, diversions were not restricted because of the fallowing of fields, as they were from 2007 to 2010.

Table 14. Summary of simulated water budgets for Walker Lake, west-central Nevada, from the LWR_MF model for transient period water years 1981–2010 and prediction period water years 2011–2070.

[Total inflow and outflow components may not exactly agree because these are summations of rounded budget flow components. Computation of change from 1981–2010 period is based on unrounded numbers]

Water-budget component	Transient 1981–2010 flow[1] (acre-feet per year)	Prediction 2011–2070 flow[2] (acre-feet per year)	Change from 1981–2010 period (acre-feet per year)
	Inflow	**Inflow**	**Inflow**
Walker River	99,300	85,900	-13,393
Precipitation	11,900	9,400	-2,502
Groundwater inflow	7,600	6,900	-720
Tributary inflow	2,100	2,000	-82
Total inflow (rounded)	**120,900**	**104,200**	**-16,697**
	Outflow	**Outflow**	**Outflow**
Lake evaporation	152,000	120,000	-31,993
Lake storage decrease	-32,200	-16,900	15,295
Groundwater outflow	1,400	1,200	-180
Total outflow (rounded)	**121,100**	**104,200**	**-16,878**

[1] Average area of Walker Lake during transient period of 1981–2010 was 34,700 acres, and average stage was 3,948.7 feet local datum.

[2] Average area of Walker Lake during transient period of 2011–2070 was 27,400 acres, and average stage was 3,911.2 feet local datum.

Table 15. Summary of simulated water budgets for lower Walker River, west-central Nevada, from the LWR_MF-B model for transient period water years 1981–2010 and prediction period water years 2011–2070.

[Total inflow and outflow components may not exactly agree because these are summations of rounded budget flow components; difference is calculated from unrounded numbers]

Water-budget component	Transient 1981–2010 flow (acre-feet per year)	Prediction 2011–2070 flow (acre-feet per year)	Difference (acre-feet per year)
	Inflow	**Inflow**	**Inflow**
Inflow at Wabuska	127,400	116,600	-10,767
Groundwater inflow	10	6	-4
Tributary inflow	0	0	0
Total inflow (rounded)	**127,400**	**116,600**	**-10,771**
	Outflow	**Outflow**	**Outflow**
Outflow to Walker Lake	99,300	85,900	-13,393
Agricultural diversions	[1]13,900	16,100	2,213
Seepage to groundwater	10,800	10,500	-294
Weber Reservoir losses	[1]3,800	4,000	273
Total outflow (rounded)	**127,800**	**116,600**	**-11,201**

[1] Weber Reservoir simulated with smaller storage during earthquake operational criteria period 2000–2010, and no diversions were simulated between 2007 and 2010 due to fallowing of fields. This is the reason for smaller diversion for the 1981–2000 period.

Table 16. Summary of simulated groundwater budgets for the lower Walker River Basin, west-central Nevada, from the LWR_MF-B model for transient period water years 1981–2010 and prediction period water years 2011–2070.

[Total inflow and outflow components may not exactly agree because these are summations of rounded budget flow components;
difference is calculated from unrounded numbers]

Water-budget component	Transient 1981–2010 flow (acre-feet per year)	Prediction 2011–2070 flow (acre-feet per year)	Difference (acre-feet per year)
	Inflow	**Inflow**	**Inflow**
Local recharge	20,900	20,900	-17
Inflow from Mason Valley	590	590	-1
Stream leakage	10,800	10,500	-294
Seepage from lakes	2,500	2,400	-66
Infiltration from irrigation	8,400	9,700	1,323
Decrease in storage	18,500	17,000	-1,498
Total inflow (rounded)	**61,600**	**61,100**	**-553**
	Outflow	**Outflow**	**Outflow**
Groundwater evapotranspiration	41,300	39,700	-1,586
Outflow through Double Springs area	2,200	2,200	-7
Discharge to streams	10	6	-4
Discharge to lakes	7,700	6,900	-753
Spring discharge	1,600	1,500	-98
Increase in storage	8,800	10,700	1,887
Total outflow (rounded)	**61,600**	**61,100**	**-561**

Results of the baseline scenario indicate that the simulated groundwater budget is similar to the 1981–2010 period but with greater fluctuations in groundwater storage (table 16). Seepage from streams and lakes and releases from groundwater storage are decreased slightly in the 2011–70 budget. The decreasing inflow components are mostly offset by an increase in induced infiltration from irrigation. Infiltration from irrigation is increased for the 2011–70 prediction period compared with the 1981–2010 period because irrigation of fields from 2007 through the end of 2010 was not simulated because of fallowing, but irrigation of fields over the equivalent projected periods (2037–40 and 2067–70) was simulated. Some groundwater outflow components that have decreased slightly are evapotranspiration from groundwater and outflow to lakes. The decreased outflow components are mostly offset by an increase in the uptake of groundwater to groundwater storage. Future fluctuations of groundwater storage are indicated by modest increases to groundwater moving in and out of groundwater storage in the 60-year prediction period (2011–70), compared with the 1981–2010 period. How much of this response was due to the difference in lake level or the difference in how irrigation was simulated between the two periods was not determined.

Improvements in Walker River Indian Irrigation Project Irrigation Efficiencies (Efficiency Scenario)

Effects of potential improvements to the irrigation project efficiencies of WRIIP on Walker Lake inflow, lake level, and dissolved-solids concentrations, and on WRIIP crop consumptive use were evaluated using five predictive simulations (efficiency scenario). The LWR_MF-B model was modified into a series of efficiency scenario models (LWR_MF-E%) for comparison with the baseline scenario results. The efficiency models implemented changes to irrigation project efficiencies and predicted corresponding hydrologic conditions from 2011 through end of 2070. All boundary conditions, including streamflow at Walker River at Wabuska, are the same as with the baseline scenario, except for irrigation diversions from Walker River. For the baseline scenario (LWR_MF-B), an irrigation project efficiency of 40 percent with irrigation demand of 18,375 acre-ft/yr was assumed and represented no improvement in irrigation efficiency (0 percent improvement). The scenarios tested are for efficiency improvements of 5, 10, 15, 20, and 25 percent, which correspond to project irrigation efficiencies of 45, 50, 55, 60, and 65 percent, respectively. These irrigation efficiency improvements have annual irrigation demands of 16,330; 14,700; 13,360; 12,250; and 11,310 acre-ft/yr, respectively, but maintain a crop water use of 7,350 acre-ft/yr (3.5 ft/yr of water applied to 2,100 irrigated acres). The inefficient portion of annual diversions, which is the portion of irrigation demand delivered that does not go to crop consumptive use, enters the groundwater as recharge beneath the agricultural fields. The irrigation demand is diverted throughout the irrigation season if storage in Weber Reservoir is adequate for supplying the demand; otherwise, the irrigation demand is only partially supplied, and water lost by crop consumption and recharge is reduced accordingly.

Improvements in irrigation project efficiencies increase the recurrence frequency of full irrigation seasons on the WRIIP (table 17). For this analysis, a full irrigation season is defined as an irrigation season with 90 percent or more of seasonal irrigation demand delivered. The baseline scenario has recurrence rate of 57 percent, 34 out of 60 years with full irrigation seasons. Improvements in irrigation project efficiencies of 5 to 25 percent increased the recurrence rates from 68 to 95 percent, indicating potential increases in agricultural production.

The improvements in irrigation project efficiencies result in increases in Walker River flow to Walker Lake, crop consumptive use, and Weber Reservoir losses, as compared with the baseline scenario (table 17; table 18; fig. 43). The increase in Walker River flow to Walker Lake ranged from about 1,000 to 4,300 acre-ft/yr, whereas the increase in crop consumptive use ranged from about 260 to 760 acre-ft/yr. The increase in Weber Reservoir losses ranged from around 100 to 530 acre-ft/yr.

The efficiency scenario indicates water conservation is achieved as less water is lost through groundwater discharge by evapotranspiration (table 19). Because of this conservation, more water reaches Walker Lake, is consumed by crops, and evaporates from Weber Reservoir even though river inflow at Wabuska gage is unchanged (table 18; fig. 43). Of the conserved water, most is going to Walker Lake by increased flows in Walker River, followed by increased crop consumptive use, and then increased evaporation from Weber Reservoir (table 17; table 18; and fig. 43).

The efficiency scenario indicates the level of Walker Lake increased as a result of project irrigation efficiency improvements (fig. 44), and dissolved-solids concentrations are reduced. Improvements in WRIIP irrigation efficiency contribute to improvements in Walker Lake level and salinity, but improvements are modest.

Table 17. Summary of irrigation water use for efficiency scenarios for the Walker River Indian Irrigation Project, west-central Nevada, for the prediction period water years 2011–2070.

[%, percent; acre-ft/yr, acre-feet per year]

Model and period	LWR_MF-B 2011–2070 (baseline)	LWR_MF_E% 2011–2070 (efficiency)				
Improvement in irrigation project efficiency:	**0% improvement**	**5% improvement**	**10% improvement**	**15% improvement**	**20% improvement**	**25% improvement**
Irrigation demand for scenario (acre-ft/yr)	18,375	16,333	14,700	13,364	12,250	11,308
Average diversion (acre-ft/yr)	16,094	14,876	13,793	12,807	11,897	11,077
Average crop consumptive use (acre-ft/yr)[1]	6,438	6,694	6,897	7,044	7,138	7,200
Recurrence rate of full irrigation seasons[2]	57%	68%	82%	85%	90%	95%

[1] Full crop consumptive use is 7,350 acre-ft/yr for all scenarios.

[2] Full irrigation season is defined as 90% of irrigation demand delivered.

Table 18. Summary of water budgets for lower Walker River Basin, west-central Nevada, for efficiency and baseline scenarios for the prediction period water years 2011–2070.

[Total inflow and outflow components may not exactly agree because these are summations of rounded budget flow components; computation of change from baseline scenario is based on unrounded numbers. %, percent; acre-ft/yr, acre-feet per year]

Model and period	LWR_MF-B 2011–2070 (baseline)	LWR_MF_E% 2011–2070 (efficiency)				
Improvement in irrigation project efficiency: **Water-budget component**	**0% improvement Flow (acre-ft/yr)**	**5% improvement Change from baseline scenario (acre-ft/yr)**	**10% improvement Change from baseline scenario (acre-ft/yr)**	**15% improvement Change from baseline scenario (acre-ft/yr)**	**20% improvement Change from baseline scenario (acre-ft/yr)**	**25% improvement Change from baseline scenario (acre-ft/yr)**
	Inflow	**Inflow**	**Inflow**	**Inflow**	**Inflow**	**Inflow**
Inflow at Wabuska	116,600	0	0	0	0	0
Groundwater inflow	6	0	0	0	0	1
Tributary inflow	0	0	0	0	0	0
Total inflow (rounded)	**116,600**	**0**	**0**	**0**	**0**	**1**
	Outflow	**Outflow**	**Outflow**	**Outflow**	**Outflow**	**Outflow**
Outflow to Walker Lake	85,900	1,037	1,979	2,822	3,595	4,288
Agricultural diversions	16,100	-1,221	-2,307	-3,296	-4,208	-5,031
Seepage to groundwater	10,500	20	41	66	99	143
Weber Reservoir losses	4,030	107	222	340	444	529
Total outflow (rounded)	**116,600**	**-57**	**-65**	**-68**	**-70**	**-71**

Table 19. Summary of groundwater budgets for the efficiency and baseline scenarios for the lower Walker River Basin, west-central Nevada, for the prediction period water years 2011–2070.

[Total inflow and outflow components may not exactly agree because these are summations of rounded budget flow components. %, percent; acre-ft/yr, acre-feet per year; <, less than]

Model and period	LWR_MF-B 2011–2070 (baseline)	LWR_MF_E% 2011–2070 (efficiency)				
Improvement in irrigation project efficiency: **Water-budget component**	**0% improvement Flow (acre-ft/yr)**	**5% improvement Change from baseline scenario (acre-ft/yr)**	**10% improvement Change from baseline scenario (acre-ft/yr)**	**15% improvement Change from baseline scenario (acre-ft/yr)**	**20% improvement Change from baseline scenario (acre-ft/yr)**	**25% improvement Change from baseline scenario (acre-ft/yr)**
	Inflow	**Inflow**	**Inflow**	**Inflow**	**Inflow**	**Inflow**
Local recharge[1]	20,900	<1	<1	<1	<1	<1
Inflow from Mason Valley[1]	590	<1	<1	<1	<1	<1
Stream leakage	10,500	20	40	66	99	142
Seepage from lakes	2,400	54	108	165	213	253
Infiltration from irrigation	9,700	-1,484	-2,778	-3,919	-4,930	-5,818
Decrease in storage	17,000	-664	-1,233	-1,703	-2,077	-2,372
Total inflow (rounded)	**61,100**	**-2,075**	**-3,863**	**-5,392**	**-6,695**	**-7,796**
	Outflow	**Outflow**	**Outflow**	**Outflow**	**Outflow**	**Outflow**
Groundwater evapotranspiration[2]	39,700	-1,225	-2,282	-3,144	-3,814	-4,353
Outflow through Double Springs area[2]	2,200	-1	-3	-5	-6	-8
Discharge to streams	6	<1	<1	<1	<1	<1
Discharge to lakes	6,900	9	24	36	37	46
Spring discharge[2]	1,500	-59	-65	-65	-65	-65
Increase in storage	10,700	-799	-1,536	-2,212	-2,846	-3,413
Total outflow (rounded)	**61,000**	**-2,076**	**-3,863**	**-5,390**	**-6,693**	**-7,793**
Conserved water that would have been lost from lower Walker River Basin through groundwater system.		1,285	2,350	3,214	3,885	4,426
Percentage of reduced irrigation infiltration that is conserved.		83%	82%	80%	77%	75%

[1] Groundwater inflow components that contribute water to lower Walker River Basin.

[2] Groundwater outflow components that remove water from the lower Walker River Basin.

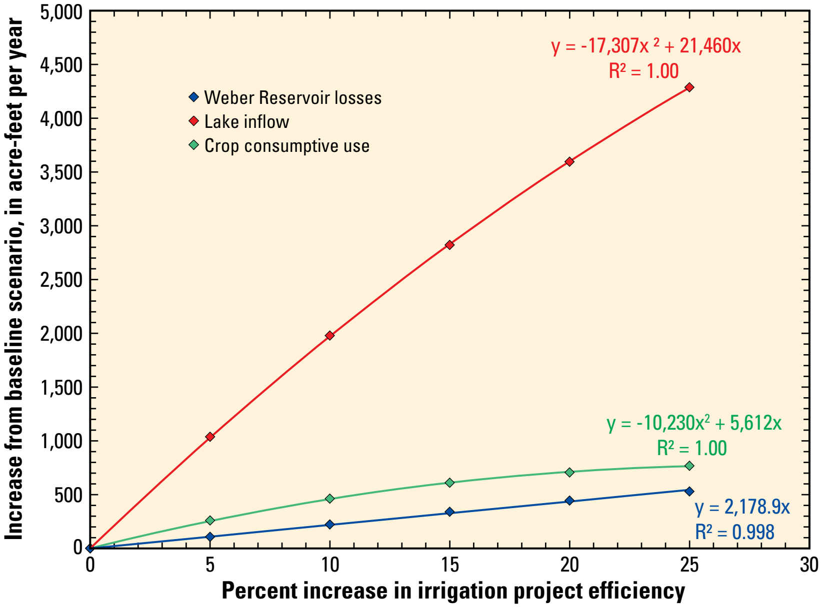


Figure 43. Simulated increases in Walker Lake inflow, crop consumptive use, and Weber Reservoir losses associated with improvements in the west-central Nevada Walker River Indian Irrigation Project efficiencies over the 60-year prediction period, water years 2011–70, compared with the baseline scenario.

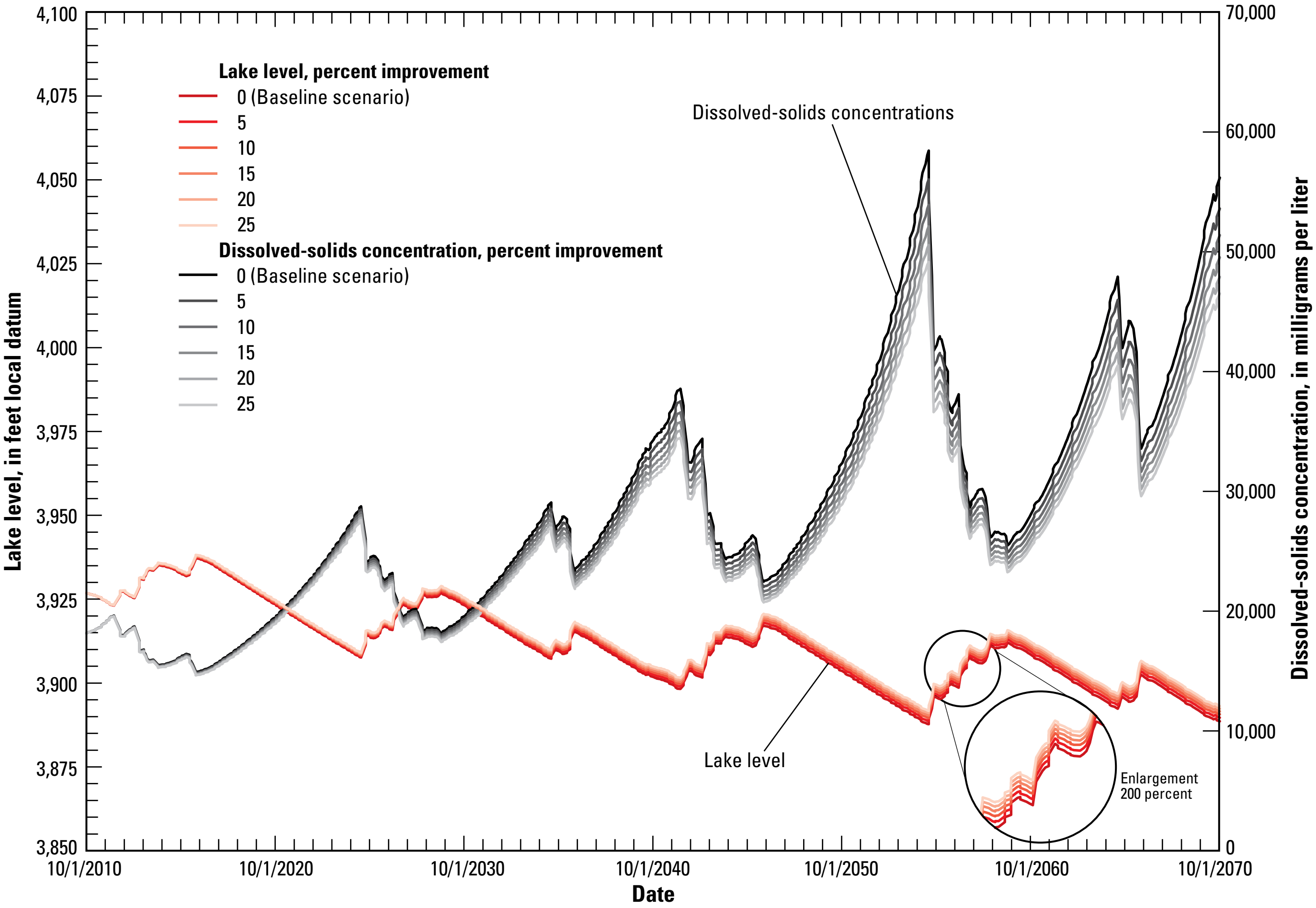


Figure 44. Effects of improvements in Walker River Indian Irrigation Project, west-central Nevada, efficiencies on Walker Lake level and dissolved-solids concentrations, compared with baseline reference scenario over the 60-year prediction period, water years 2011–70.

Increased Streamflow at Wabuska Gage (Streamflow Scenario)

Effects of potential increases in streamflow entering the lower Walker River Basin at the Wabuska streamgage on Walker Lake inflow, level, dissolved solids, and on WRIIP crop consumptive use were evaluated with 7 predictive simulations (streamflow scenario) for 2 different approaches to management of Weber Reservoir for a total of 14 simulations. The two reservoir management options are the no-pass-through approach (LWR_MF-Qnopass models) and the pass-through approach (LWR_MF-Qpassthru models).

Increases in streamflow at the Wabuska streamgage are implemented in the streamflow scenarios from 2011 through 2070. All boundary conditions are the same as for the baseline scenario, except for the increased irrigation-season streamflows at the Wabuska streamgage. The streamflow scenarios are hypothetical and were designed to reflect the seasonal variability of irrigation flows associated with seasonal priorities established by the U.S. Board of Water Commissioners for the Walker River. Dates in priority were obtained from the U.S. Board of Water Commissioners for the Walker River for each day of the period 1981 through 2010 (Camp, 2013) and were used to estimate the relative seasonal irrigation deliveries as a percentage of full irrigation (Erik Borgen, Ecosystem Economics, LLC, written commun., November 14, 2013). The increased streamflows used in this scenario are simplified to constant increased flow over each irrigation season (fig. 45), whereas actual irrigation-season streamflows vary day to day on the basis of date in priority and operational variability. Increased streamflow at Wabuska gage through the first half of the prediction time period for each of the streamflow scenarios (2011–40) is shown in figure 45. This additional streamflow is repeated for the second half of the prediction period (2041–70). The increased streamflow scenarios are equivalent to increased mean annual streamflows of 2,500; 7,500; 15,000; 25,000; 40,000; 50,000; and 75,000 acre-ft/yr at the Wabuska gage.

With the no-pass-through simulations, Weber Reservoir is managed as it has been in the past; all available flow is stored in the reservoir for irrigation use, and flow only passes downstream to Walker Lake when reservoir inflow and storage exceed irrigation demand. In the no-pass-through simulations, the increased streamflow is available for irrigation use if Weber Reservoir is below capacity. Although it is likely that this style of reservoir management will not be used to convey additional water through the reservation, it is included as a scenario for reference if a different conveyance approach is contemplated in the future.

With the pass-through simulations the increased streamflow is passed downstream to Walker Lake without being stored in the reservoir or diverted for agricultural use. The increased streamflow is not available for irrigation use and diversions.

The effect of increased streamflow at Wabuska on inflow to Walker Lake under the two reservoir management options is shown in (fig. 46). More streamflow reaches Walker Lake under the pass-through option than under the no-pass-through option. For streamflow increases of 15,000 acre-ft/yr or less, the pass-through option results in 14 percent greater streamflow reaching Walker Lake than with no-pass-through option. For streamflow increases greater than 15,000 acre-ft/yr, the pass-through option results in a nearly constant 2,500 to 3,000 acre-ft/yr of additional flow reaching Walker Lake than with no-pass-through option.

Irrigation for the WRIIP is not affected by increased streamflow under the pass-through management of Weber Reservoir. However, under no-pass-through management of Weber Reservoir, increased streamflow at Wabuska increases the water supply available for irrigation. The frequency of recurrence of full irrigation seasons with increased streamflow of 2,500; 7,500; and 15,000 acre-ft/yr improves to 65, 75, and 85 percent, respectively, compared with 57 percent under the baseline scenario. Corresponding crop consumptive use increases by 3, 7, and 11 percent, respectively (table 20). For streamflow increases of 25,000 acre-ft/yr or more, full irrigation seasons recur 98 percent of the time, and crop consumptive use increases by 13 percent. This indicates that with no-pass-through management of Weber Reservoir, streamflow increases of 25,000 acre-ft/yr result in nearly full irrigation on the WRIIP each season. Pass-through management of Weber Reservoir results in no changes in storage in Weber Reservoir; therefore, irrigation on the WRIIP is not affected by increases in streamflow.

Increased streamflows at Wabuska result in increases in Walker Lake level and decreases in dissolved-solids concentrations compared with the baseline scenario. Figure 47*A* shows Walker Lake level and figure 47*B* shows Walker Lake dissolved-solids concentrations for each streamflow scenario under pass-through management of Weber Reservoir. The predictive scenarios indicate that streamflow increases of 25,000 acre-ft/yr and less result in a continued decline in lake levels and increasing dissolved-solids concentrations. Streamflow increases of 40,000 acre-ft/yr result in stabilized lake levels and dissolved-solids concentrations, and streamflow increases of 50,000 acre-ft/yr or more result in rising lake levels and decreasing dissolved-solids concentrations. Assuming that future streamflows in the Walker River Basin are similar to those in the 1981–2010 period and the starting Walker Lake level and dissolved-solids concentration are similar to those in 2011, the increased irrigation-season streamflow of 50,000 acre-ft/yr observed at the Wabuska gage could result in a lake-level increase of 48 ft and a dissolved-solids concentration of 15,200 mg/L after 60 years, and increased streamflow of 75,000 acre-ft/yr could result in a lake-level increase of 70 ft and a dissolved-solids concentration of 10,600 mg/L.

A simplified relation to estimate dissolved-solids concentrations at the end of 60 years, based on mean annual flow increases at Wabuska gage under pass-through management of Weber Reservoir, is shown in figure 48. The relation in figure 48 was developed by correlating the simulated dissolved-solids concentrations at the end of 60 years (*DS* in mg/L) shown in figure 47*B* with the mean annual flow increases at

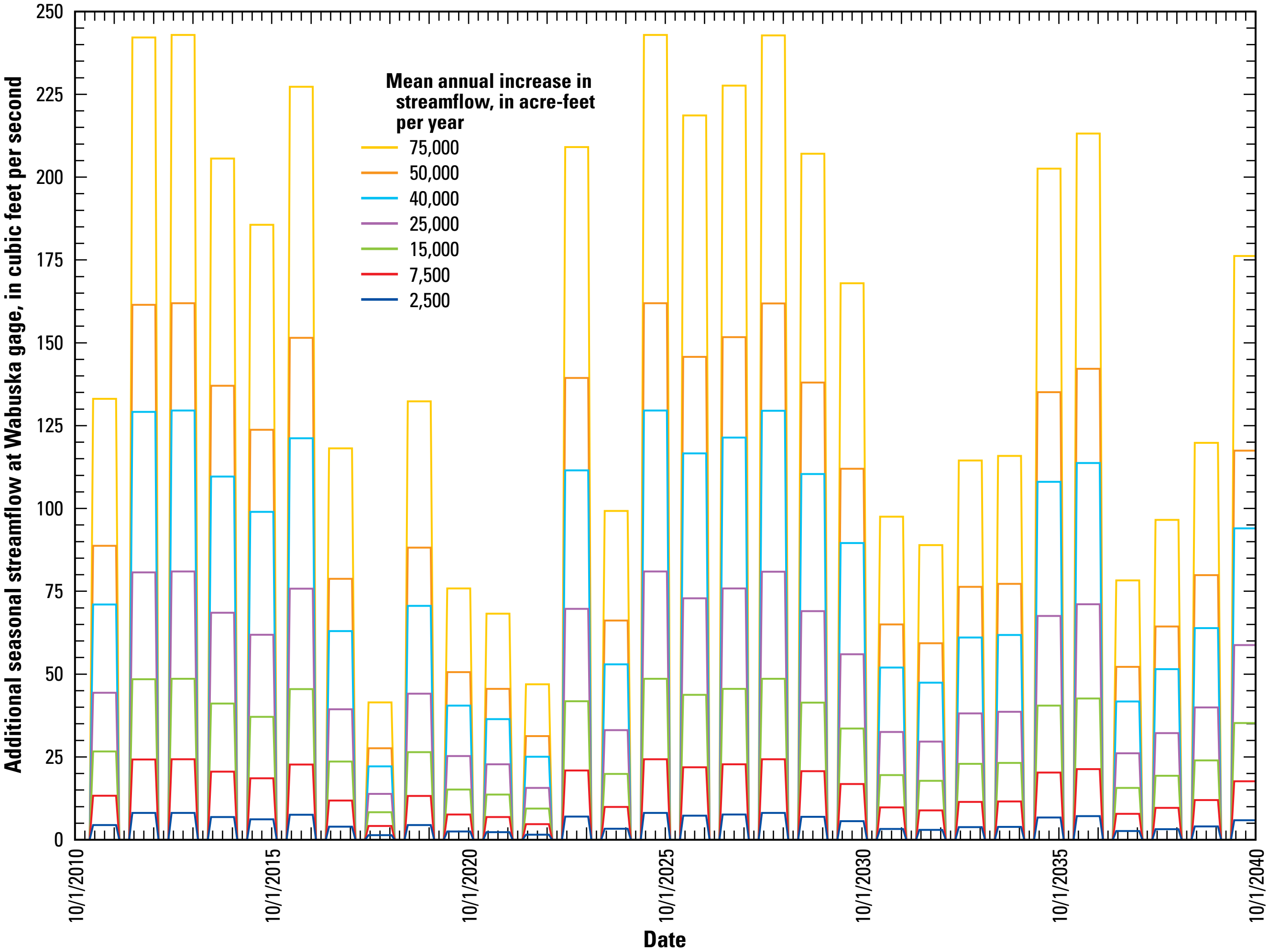


Figure 45. Distribution of increase in streamflows to Walker River at Wabuska streamgage, west-central Nevada, for increased flow scenarios of 2,500; 7,500; 15,000; 25,000; 40,000; 50,000; and 75,000 acre-feet per year for the first half of prediction period water years 2011 through 2040. This distribution is repeated for the second half of the prediction period water years 2041–70.

Wabuska gage (*Flow* in acre-ft/yr). The relation was developed for the simulated range of flows (0 to 75,000 acre-ft/yr) and is not intended to be used with flow increases greater than 75,000 acre-ft/yr. For a mean annual flow increase at Wabuska gage of 65,000 acre-ft/yr, the relation indicates that the resulting dissolved solid concentration at the end of the 60-year period is about 12,000 mg/L, which is the TMDL for Walker Lake established by the State of Nevada (Nevada Division of Environmental Protection, 2005). However, when interpreting the results shown in figure 48, the variability of simulated dissolved-solids concentrations needs to be considered. Figure 48 also shows the variability of dissolved-solids concentrations simulated for each of the scenarios over the full 60-year prediction period. Figure 48 indicates that for mean annual flow increases at Wabuska gage of less than 25,000 acre-ft/yr, there is high variability of dissolved-solids concentrations, and because the indicated concentrations are at or above the upper 5th percentile, concentrations continue to increase following the end of the 60-year simulation. With flow increases greater than or equal to 40,000 acre-ft/yr, dissolved-solids concentrations generally vary below the starting concentration in 2011. For flow increases of 75,000 acre-ft/yr, dissolved-solids concentrations are mostly less than 12,000 mg/L; because the predicted concentration at the end of 60 years is less than the 50th percentile even though the last 4 years was a simulated drought period, this indicates lake dissolved-solids concentrations are not yet stabilized and likely will continue to decrease.

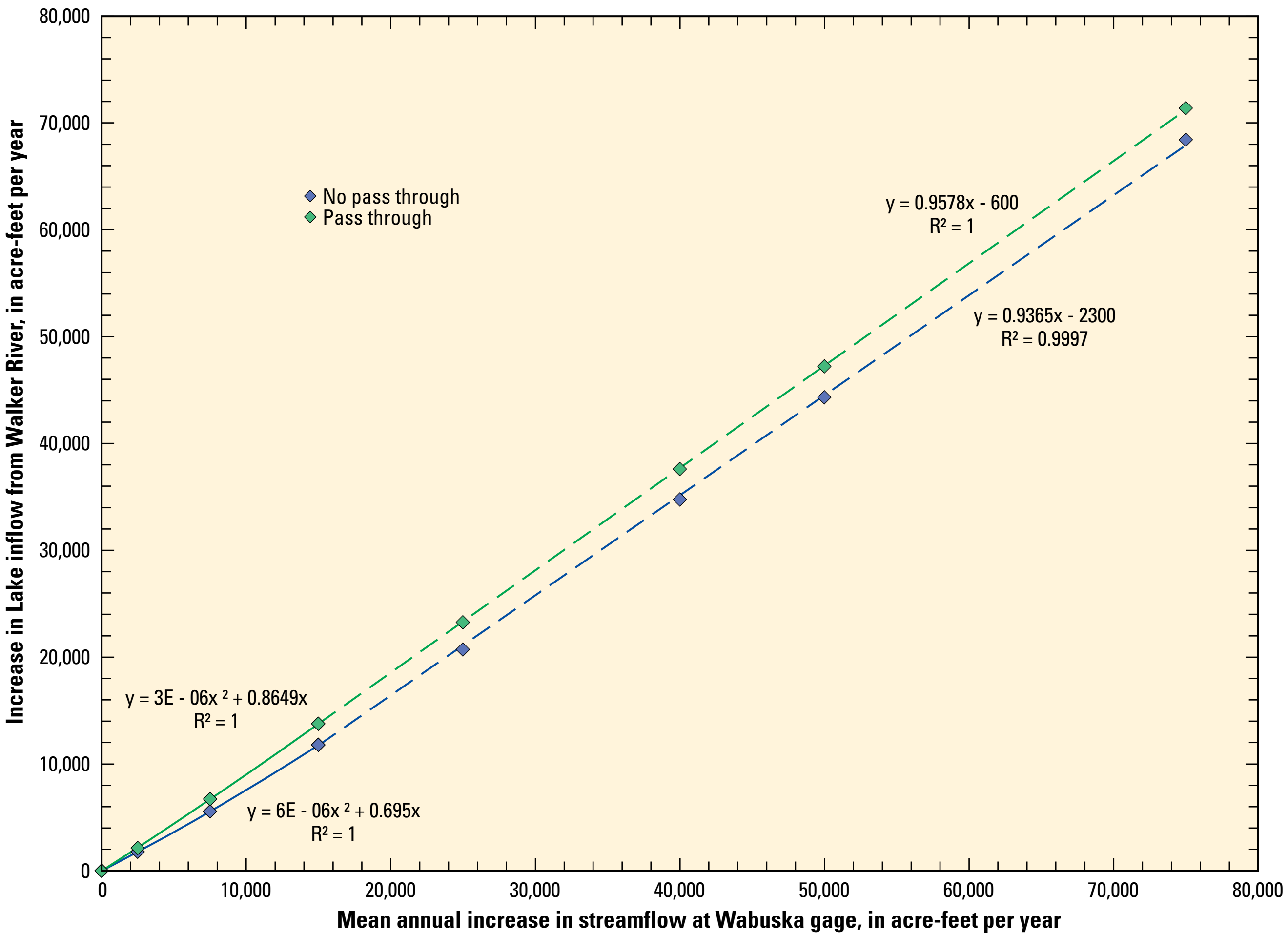


Figure 46. Relative increases in Walker Lake inflow from Walker River associated with increases in seasonal streamflows at Walker River at Wabuska, west-central Nevada.

Table 20. Summary of irrigation water use for streamflow and baseline scenarios for lower Walker River Basin, west-central Nevada, for the prediction period water years 2011–2070.

[%, percent; acre-ft/yr, acre-feet per year; acre-ft, acre-feet]

Model and period	LWR_MF-B 2011–2070 (baseline)	MF_Qpassthru 2011–2070 (streamflow with pass-through)	MF_Qnopass 2011–2070 (streamflow with no-pass-through)						
Average increase in streamflow at Wabuska gage (acre-ft/yr)	**0**	**All increased flows**	**2,500**	**7,500**	**15,000**	**25,000**	**40,000**	**50,000**	**75,000**
Irrigation demand for scenario (acre-ft/yr)	18,375	18,375	18,375	18,375	18,375	18,375	18,375	18,375	18,375
Average diversion (acre-ft/yr)	16,094	16,094	16,556	17,252	17,800	18,126	18,188	18,188	18,188
Average crop consumptive use (acre-ft/yr)[1]	6,438	6,438	6,622	6,901	7,120	7,250	7,275	7,275	7,275
Recurrence rate of full irrigation seasons[2]	57%	57%	65%	75%	85%	98%	98%	98%	98%

[1] Full crop consumptive use is 7,350 acre-ft/yr.

[2] Full irrigation season is defined as 90% of irrigation demand delivered (16,538 acre-ft).

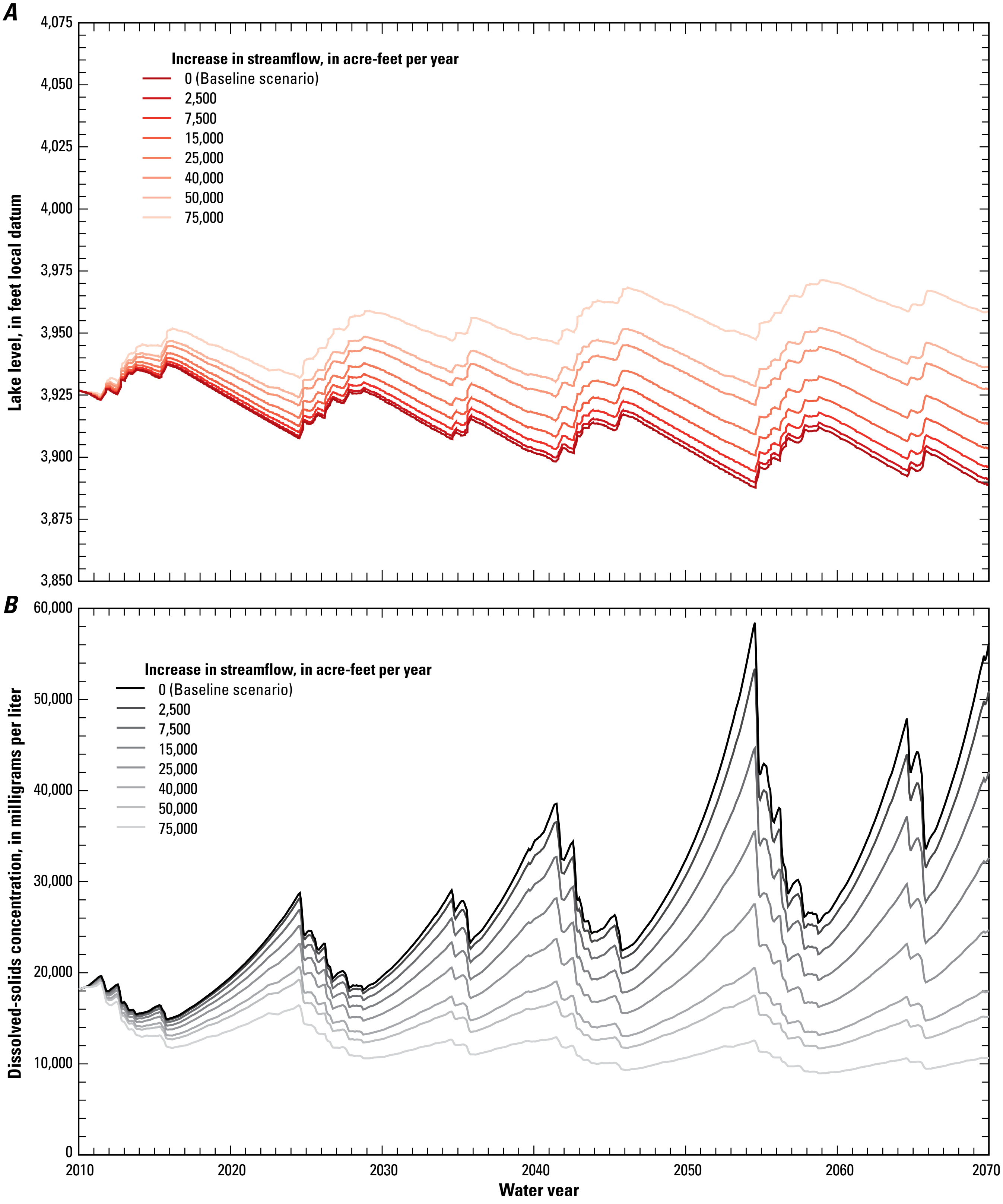


Figure 47. Effects of increased streamflows at Wabuska gage, west-central Nevada, under pass-through management of Weber Reservoir on *A*, Walker Lake level and *B*, Walker Lake dissolved-solids concentrations for the period water years 2011–70 as compared with baseline reference scenario.

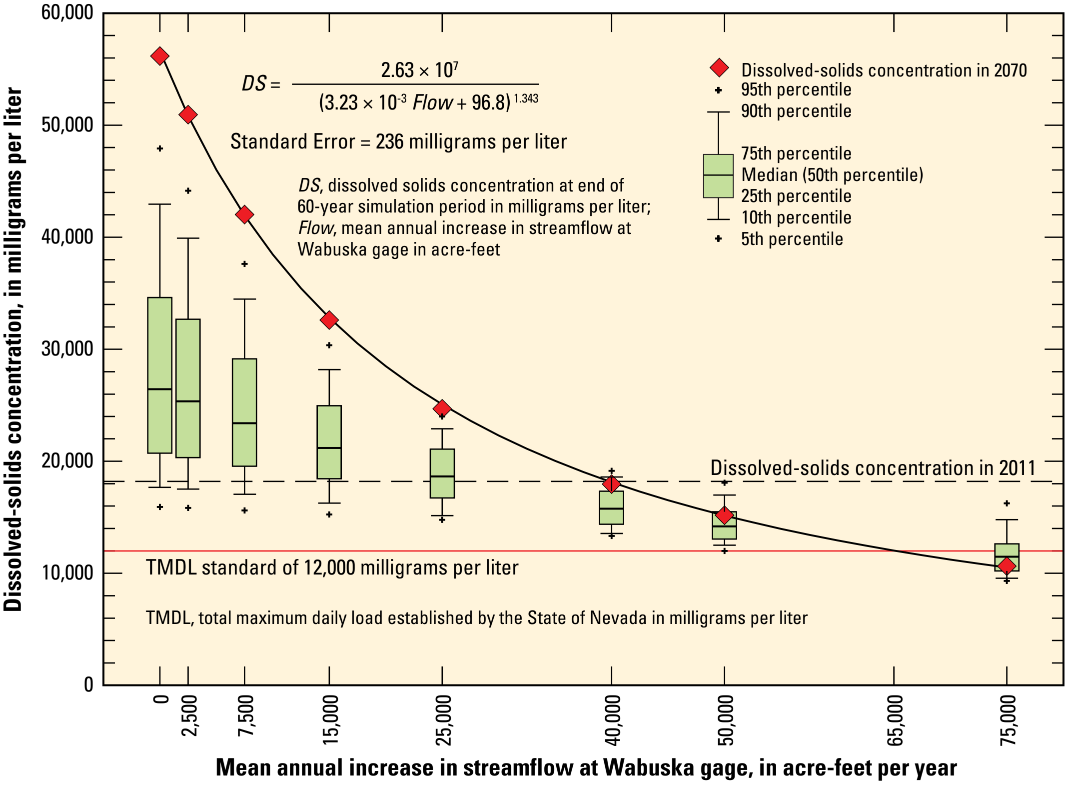


Figure 48. Relation and variability of dissolved-solids concentrations in Walker Lake as a result of flow increases at the Wabuska gage, west central Nevada.

Fallowing of Walker River Indian Irrigation Project from 2007 to 2010 (Fallowing Scenario)

The effects of fallowing of WRIIP fields from 2007 to 2010 on Walker Lake inflow, level, and dissolved solids were evaluated with this scenario (fallowing scenario). The LWR_MF-B model was modified into a no-fallowing scenario model (LWR_MF-NoFallow) for comparison with the results of the baseline scenario model, which simulates fallowing of fields from 2007 to 2010. The LWR_MF-NoFallow model simulates irrigation diversions from 2007 through the end of the 2010 irrigation season under the earthquake operating criteria of Weber Reservoir discussed earlier in section “Walker River, Weber Reservoir, and Walker River Indian Irrigation Project.” Diversions from 2007 through 2010 are based on seasonal irrigation demand of 18,375 acre-ft/yr. Only the period 2007 through end of 2010 was evaluated in this analysis.

Results of the fallowing scenario indicate inflow to Walker Lake, and Walker Lake level increased, and dissolved-solids concentration decreased, as a result of fallowing of fields from 2007 to 2010 (fig. 49). Walker River inflow to Walker Lake nearly doubled under fallowing and was simulated at about 95,400 acre-ft from 2007 to 2010; without fallowing (with irrigation), the inflow was simulated to be about 48,700 acre-ft. Fallowing resulted in a Walker Lake level increase of about 1.4 ft and dissolved-solids concentration decrease of about 540 mg/L (fig. 49), compared with lake conditions if irrigation had occurred during this period.

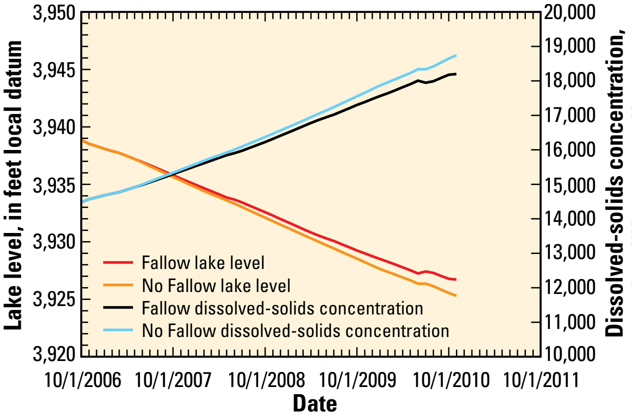


Figure 49. Effects of fallowing of Walker River Indian Irrigation Project, west-central Nevada, from water years 2007 to 2010 on Walker Lake level and dissolved-solids concentration.

Limitations of Water-Management Evaluations

The evaluation of the response of lower Walker River hydrology to the prescribed management scenarios relies on assumptions and limitations that need to be considered within the context of the results presented. Since the LWR_MF was used to develop the scenario models, the limitations of the LWR_MF discussed previously also apply to these evaluations. These limitations include the ability of the models to simulate certain features of the hydrologic system, the resolution of space and time discretization used in the model, inherent model error, and simplification of seasonal processes. The calculation of dissolved solids in Walker Lake assumed that the total salt mass in the lake was constant during the simulation periods.

For the scenario models, future baseline conditions, a simplified representation of future flow increases, and a starting lake condition equivalent to that observed in 2011 were assumed; other management changes were not implemented. For the future baseline conditions, it was assumed that streamflows at Wabuska gage are nearly the same as in the 1981–2010 period, which is conjecture, but does provide a plausible realization of possible future flows. Future flow increase simulations were seasonally scaled on the basis of average yearly priorities and a constant increase in streamflow each irrigation season was assumed. However, this is not consistent with the way in which the real system operates. In practice, priorities generally decline through a season with up and down fluctuations and, when combined with operational variability, generate a more complex seasonal flow distribution. However, it is reasonable to assume that when constant seasonal flow increases are combined with the baseline flow, which incorporates real monthly variability, a reasonable representation of possible future flow increases is produced. Except for the fallowing scenario, each of the scenarios includes initial conditions for Walker Lake in 2011, and management changes are implemented instantaneously at that time. Additionally, the baseline streamflow conditions used with these scenarios represent wetter than normal conditions which, with the exception of 2011, has not been realized for other intervening years at the time of this publication. For each of the scenarios, no other management changes were implemented over the 60-year prediction period, which is not likely. A number of management actions likely will be implemented in the future that will have a compounding effect on the hydrologic system. However, the evaluation of individual management scenarios presented is informative for understanding the magnitude of their effects and for a general understanding of the response of the hydrologic system.

The baseline condition used for the scenarios ignores the likely effects of climate change on future water supplies and deliveries. It is generally recognized among the scientific community that climate change will likely result in warmer temperatures and earlier timing of spring snowmelt runoff in the eastern Sierra headwaters (Dettinger and others, 2004). How climate change ultimately translates through the system to streamflows at the Wabuska gage is a significant challenge to understand due to the complexities of the upstream water system and its management and operations, and was beyond the scope of this project. As the majority of the water supply to the lower Walker River basin originates outside of the model domain, it was not possible to incorporate climate-change effects on the amount of streamflow at the Wabuska gage within the present scope of the analysis. However, the upstream DST models being developed by the Desert Research Institute and the University of Nevada Reno are intended to incorporate this capability, and when coupled with the lower Walker River basin model, the effects of climate change on lower Walker River basin hydrology could be simulated. The development of a future climate-change scenario using the upstream DST model coupled with the lower Walker River basin model is needed in order for water managers to have a better understanding of how the hydrology of the system and water management actions will be affected by climate change.

Summary

Walker Lake is a terminal lake in west-central Nevada with nearly all outflow occurring through evaporation. Diversions from Walker River since the early 1900s have contributed to a substantial reduction in flow entering Walker Lake, and as a result, the lake is receding. Salt concentrations have increased to the point that *Oncorhynchus clarkii hensawi* (Lahontan Cutthroat trout) are no longer present, and the lake ecosystem is threatened. Currently (2014), there is a concerted effort to restore the Walker Lake ecosystem and fishery to a sustainable level. However, Walker Lake is complexly interlinked with the lower Walker River and adjacent groundwater system, which makes it difficult to fully understand how upstream water-management actions ultimately affect the overall hydrologic system in addition to the conditions of Walker Lake. To better understand the effects of water-management actions on the lower Walker River Basin hydrologic system, a watershed model and groundwater flow model have been developed.

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation and National Fish and Wildlife Foundation, conducted a study to construct and calibrate a precipitation runoff (watershed) modeling system (PRMS) model and MODular groundwater FLOW model (MODFLOW). The MODFLOW model, is useful for efficiently simulating the long-term and large-scale effects of water-management actions on groundwater hydrology, streamflow, and Walker Lake level, volume, and dissolved-solids concentrations.

The lower Walker River Basin PRMS model (LWR_PRMS) was constructed using a subbasin approach to aid in development and calibration, and to simulate a 30-year period from 1978 to 2007 using daily time steps. Streamflow data for areas near the downstream ends of basins are limited, and most drainages are ephemeral, resulting in use of a water budget and idealized hydrograph approach for calibrating the model. The PRMS model was also used to derive an estimated groundwater recharge distribution for use with the MODFLOW model. The resulting distribution has the highest groundwater recharge rates in the mountains beneath perennial and ephemeral stream channels; the next highest recharge rates occur along mountain fronts where intersected by alluvial fans. The total groundwater recharge estimated using PRMS was about 25,000 acre-feet per year (acre-ft/yr).

The lower Walker River Basin MODFLOW model (LWR_MF) is discretized with 1,312-feet (400-meter) square cells and six layers of varying thickness, and simulates conditions using a monthly time step. The initial LWR_MF stress period is steady state and represents dynamic equilibrium conditions of the basin from 1908 to 1918. Subsequent transient stress periods simulated transient conditions for an 89-year period, 1919–2007. The model was calibrated using a combination of manual and automated methods of adjusting model parameters to minimize errors between model simulated results and weighted groundwater level, streamflow, and lake level observations. The automated calibration method used weighted observation data with highly parameterized inversion methods to minimize an objective function while using regularization to penalize solutions that differed from a preferred homogeneous state where parameter solutions were insensitive to observation data.

Dissolved-solids concentrations of Walker Lake were simulated using lake volume and a constant lake salt mass of 37.2 million tons. Analysis of lake salt mass over time indicated that the salt balance in the lake is neutral or decreasing rather than increasing, as has been indicated by previous studies.

Results from the calibrated lower Walker River MODFLOW model (LWR_MF) indicate that for the period 1908–18, the mean annual streamflow for Walker River at Wabuska was about 306,000 acre-ft/yr of which about 271,000 acre-ft/yr reached Walker Lake as surface inflow. During this period Walker Lake maintained a steady lake level of about 4,078.0 ft (local datum), a dissolved-solids concentration of 3,100 milligrams per liter (mg/L), and a mean annual groundwater inflow of about 2,500 acre-ft/yr.

For the period 1919 through 2007, the mean annual streamflow observed at the Wabuska gage was about 121,000 acre-ft/yr of which about 90,600 acre-ft/yr was simulated to reach Walker Lake as surface inflow. The simulated rate of decline for Walker Lake was 1.6 feet per year (ft/yr) with an evaporation rate of 4.37 ft/yr. The simulated mean annual groundwater inflow to Walker Lake was 10,400 acre-ft/yr, about four times greater than simulated groundwater inflow prior to the steady decline of Walker Lake. During this period, simulated dissolved-solids concentrations increased from 3,100 mg/L to 15,300 mg/L.

The LWR_MF was modified to project future baseline conditions of the hydrologic system and Walker Lake from 2011 to 2070 by twice repeating the streamflow conditions entering the lower Walker River Basin from 1981 to 2010. The LWR_MF-B baseline model was used to evaluate a set of potential and hypothetical water-management scenarios. These scenarios include improved irrigation efficiencies for the Walker River Indian Irrigation Project and a range of increased streamflows entering the lower Walker River Basin, associated with upstream water right transfers for two different management approaches for Weber Reservoir.

Results of the baseline reference scenario indicate that if streamflow conditions from 1981 to 2010 were repeated twice from 2011 to 2070, Walker Lake level and volume would continue to decline but at a slower rate than observed during the 1981 to 2010 period as a result of smaller lake surface area, thereby reducing lake evaporation and bringing the lake water budget closer to balance. Dissolved-solids concentrations in Walker Lake continue to increase and, because of the smaller lake size, increase much more rapidly during periods when minimal flows reach the lake. However, as the lake gets smaller, years with large runoff will contribute to larger increases in lake level and larger decreases in dissolved solids, compared to equivalent runoffs experienced during 1981–2010.

The effects of improving Walker River Indian Irrigation Project (WRIIP) efficiencies on Walker River streamflows, Walker Lake level and dissolved-solids concentrations, and crop consumptive use, were evaluated with an irrigation project efficiency scenario. Improvements in WRIIP efficiencies resulted in water conservation through a reduction in irrigation induced groundwater recharge, which leads to a reduction in groundwater discharge through evapotranspiration. The conserved water mostly went to increased streamflow to Walker Lake, followed by increased crop consumptive use, then increased evaporation from Weber Reservoir.

The effects of increased streamflows at Wabuska gage on Walker Lake inflow, level, and dissolved-solids concentrations, and crop consumptive use, were evaluated with the streamflow scenario. Hydrologic conditions and crop consumptive use were evaluated for pass-through and no-pass-through management of Weber Reservoir. Walker Lake level and dissolved-solids concentrations were evaluated for pass-through management of Weber Reservoir. Walker Lake levels and dissolved-solids concentrations began to stabilize with increased mean irrigation-season streamflows of about 40,000 acre-ft/yr. Walker Lake level increased and dissolved-solids concentration decreased with increased flows of 50,000 acre-ft/yr or more. Under the projected streamflows and lake conditions of the baseline reference model and pass-through management of Weber Reservoir, after 60 years with additional irrigation-season streamflows of 50,000 acre-ft/yr, Walker Lake level increased by 48 ft, and lake dissolved-solids concentration decreased by 3,000 mg/L. With 75,000 acre-ft/yr of additional streamflow, Walker Lake level increased by 70 ft, and dissolved-solids concentration decreased by about 7,600 mg/L.

The effects of fallowing of WRIIP fields from 2007 to 2010 on Walker Lake inflow, level, and dissolved solids were evaluated. Simulations indicate that fallowing resulted in a near doubling of Walker River inflow to Walker Lake during this period, an increase in Walker Lake level of about 1.4 ft, and a decrease in dissolved-solids concentration of about 540 mg/L.

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Appendix 1. Water-Level Hydrographs

Hydrographs for all water-level observation sites can be viewed in a Microsoft Excel workbook which can be accessed and downloaded at *http://pubs.usgs.gov/sir/2014/5190*. Individual hydrographs are viewed in this workbook by selecting a well site from a drop down menu. If hydrograph doesn't appear in plot, then use Update Axis button to the right of site selection box to adjust plotting scale. The Update Axis button re-centers the hydrograph scale so that data are viewable. The Water Level Range scale is held constant so Hydrographs are visually comparable.

Appendix 2. Observation-Site Information

Observation sites, easting, northing, altitude, site identifier, local names, group number, and Parameter ESTimation (PEST) identifier are tabulated in a Microsoft Excel workbook, which can be accessed and downloaded at *http://pubs.usgs.gov/sir/2014/5190*.

Appendix 3. PRMS and MODFLOW Files and Supporting Utilities

All PRMS and MODFLOW files with supporting utilities are in the zipped file sir2014-5190_appendix3.zip and can be accessed and downloaded at *http://pubs.usgs.gov/sir/2014/5190*. Supporting utilities are batch files, FORTRAN and PYTHON programs, and Excel workbooks. The calibrated PRMS model (LWR_PRMS), calibrated MODFLOW model (LWR_MF), and predictive models (LWR_MF-B; LWR_MF-E%; LWR_MF-Qnopass; LWR_MF-Qpassthru; and LWR_MF-NoFallow) are all included with this zip file. Contents of all directories are summarized in a README.txt file in the CONTENTS directory of the unzipped file.

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