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Scientific Investigations Report 2016–5045

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

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U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2016

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Suggested citation:
Smith, D.W., Buto, S.G., and Welborn, T.L., 2016, Groundwater-level change and evaluation of simulated water levels for irrigated areas in Lahontan Valley, Churchill County, west-central Nevada, 1992–2012: U.S. Geological Survey Scientific Investigations Report 2016-5045, 23 p., *http://dx.doi.org/10.3133/sir20165045*.

ISSN 2328-0328 (online)

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Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

°C=(°F-32)/1.8

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

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

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations and Acronyms

bls	below land surface
EROS	Earth Resources Observation Systems
GIS	Geographic Information System
DGPS	Differential Global Positioning System
HA	hydrographic area
MODFLOW	modular finite-difference flow model
NAIP	National Agriculture Imagery Program
NAS	Naval Air Station
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NWR	National Wildlife Refuge
PHDI	Palmer Hydrologic Drought Index
TM	Thematic Mapper
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Groundwater-Level Change and Evaluation of Simulated Water Levels for Irrigated Areas in Lahontan Valley, Churchill County, West-Central Nevada, 1992 to 2012

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Abstract

The acquisition and transfer of water rights to wetland areas of Lahontan Valley, Nevada, has caused concern over the potential effects on shallow aquifer water levels. In 1992, water levels in Lahontan Valley were measured to construct a water-table map of the shallow aquifer prior to the effects of water-right transfers mandated by the Fallon Paiute-Shoshone Tribal Settlement Act of 1990 (Public Law 101-618, 104 Stat. 3289). From 1992 to 2012, approximately 11,810 water-righted acres, or 34,356 acre-feet of water, were acquired and transferred to wetland areas of Lahontan Valley. This report documents changes in water levels measured during the period of water-right transfers and presents an evaluation of five groundwater-flow model scenarios that simulated water-level changes in Lahontan Valley in response to water-right transfers and a reduction in irrigation season length by 50 percent.

Water levels measured in 98 wells from 2012 to 2013 were used to construct a water-table map. Water levels in 73 of the 98 wells were compared with water levels measured in 1992 and used to construct a water-level change map. Water-level changes in the 73 wells ranged from -16.2 to 4.1 feet over the 20-year period. Rises in water levels in Lahontan Valley may correspond to annual changes in available irrigation water, increased canal flows after the exceptionally dry and shortened irrigation season of 1992, and the increased conveyance of water rights transferred to Stillwater National Wildlife Refuge. Water-level declines generally occurred near the boundary of irrigated areas and may be associated with groundwater pumping, water-right transfers, and inactive surface-water storage reservoirs. The largest water-level declines were in the area near Carson Lake.

Groundwater-level response to water-right transfers was evaluated by comparing simulated and observed water-level changes for periods representing water-right transfers and a shortened irrigation season in areas near Fallon and Stillwater, Nevada. In the Stillwater modeled area, water rights associated with nearly 50 percent of the irrigated land were transferred from 1992 to 1998, represented by the model scenario reduction in groundwater recharge by 50 percent. The scenario resulted in a simulated average decline of 0.6 foot; average observed water-level change for the modeled area was estimated to be 0.0 foot, or no change. In the Fallon modeled area, transfers of water rights associated with 180 acres of land occurred from 1994 to 2008. The transfer is most similar to the scenario for removal of 320 acres of irrigated land. The model scenario resulted in simulated water-level declines of 0.1; water levels measured from 1994 to 2012 indicate no significant trends in water levels, or approximately zero change in water levels, for the Fallon modeled area.

The model scenarios included the simulation of a irrigation season shortened by 50 percent, which was determined to have occurred in the 1992 irrigation season in both modeled areas. The shortening of the irrigation season in the Fallon modeled area resulted in simulated water-level declines of 1.1 feet; observed declines were estimated to be 1.3 feet. The Stillwater model simulations resulted in a simulated decline of 1.4 feet, and observed water levels declined an estimated 2.3 feet for the area. The estimated difference between simulated and observed water levels are 0.2 and 0.9 foot for the Fallon and Stillwater modeled areas, respectively. Observed water-level changes were generally within one standard deviation of changes from model simulations, based on the selected periods of comparison. Simulated and observed water-level changes agree well, generally within 1 foot; however, the model scenarios were only approximately similar to the observed conditions, and periods of comparison were generally shorter for the observed periods and included additional cumulative effects of water-right transfers. Climate variability was not considered in the model scenarios.

Introduction

From 1992 to 2012, approximately 11,810 water-righted acres, or 34,356 acre-feet (acre-ft) of irrigation water, were transferred from irrigated areas to wetlands in the Lahontan Valley, Nevada, as part of the Fallon Paiute-Shoshone Tribal Settlement Act (Public Law 101–618, 104 Stat. 3289) enacted in 1990. Water-right transfers from agricultural land may have effects on arid desert basin alluvial aquifers. In arid basins, residents often rely on groundwater for domestic supply, which may be affected by declines in groundwater recharge associated with water-right transfers (Herrera and others, 2000). Areas with ongoing water-right transfers are near Fallon and Stillwater, Nevada, in the Carson Desert hydrographic area (HA) about 55 miles east-northeast of Carson City (fig. 1). The Carson Desert HA encompasses approximately 2,000 square miles, most of which is in Churchill County. The south-central area of the HA is known locally as Lahontan Valley (Nevada Division of Water Resources, 2013).

In 1992, water levels in Lahontan Valley were measured to construct a water-table map of the shallow aquifer prior to the effects of water-right transfers from the Fallon Paiute-Shoshone Tribal Settlement Act of 1990 (fig. 2; Seiler and Allander, 1993). Herrera and others (2000) developed two numerical groundwater-flow models to simulate changes in water levels as a response to various land-use changes in the Fallon and Stillwater areas. The models were used to evaluate five land-use scenarios on the basis of water-right transfers.

In 2012, the U.S. Geological Survey (USGS), in cooperation with the U.S. Fish and Wildlife Service (USFWS), began a project to document water-level changes in Lahontan Valley between 1992 and 2012. A second component of the study was to evaluate scenario model results of Herrera and others (2000) by comparing simulated to observed water-level changes. The monitoring of water levels in the modeled areas throughout a 20-year period of water-right transfers presents a unique opportunity to evaulate the model scenario predictions of Herrera and others (2000). The purpose of this study was to (1) examine the change in shallow aquifer water levels associated with changes in irrigation practices in Lahontan Valley between 1992 and 2012 and (2) evaluate previously simulated water- and land-use scenarios for irrigated areas near Fallon and Stillwater, Nevada.

Purpose and Scope

This report documents the water-level changes in Lahontan Valley between 1992 and 2012 with water-table and water-level change maps. The evaluation of model scenarios that simulate water-level response to water-right transfers, a shortened irrigation season, and simulation results, is discussed. Water-level changes evaluated by creating a 2012 water-table map and a water-level change map of Lahontan Valley from 1992 to 2012 are described. When groundwater-level changes were greater than 2 feet (ft), areas near the wells were examined to determine whether water-right transfers and surface-water storage changes had an effect on the water levels. Surface-water-storage changes were evaluated indirectly by using remote sensing methods, given the lack of physical measurements. The model simulations of Herrera and others (2000) were evaluated to determine which of five scenarios occurred in the modeled areas and to compare observed water-level changes to simulated results. The recalibration or new simulations of the groundwater models were not performed in this evaluation. Water-level changes, water-right transfers, and the irrigation season length were determined for 1992–2012 for the modeled areas. Annual irrigated land area within the modeled areas was determined by remote sensing to quantify changes in irrigation. Model scenarios most similar to observed conditions in the modeled areas were used in the post-audit evaluation of observed and simulated water-level change.

Background

Lahontan Valley prior to 1902 was a wetland-dominated environment composed of an estimated 60,000 acres in the Stillwater, Carson Sink, and Carson Lake areas (figs. 1–2); agriculture at the time was limited to small adjoining areas (Hoffman and others, 1990). The Reclamation Act of 1902 provided funding for irrigation projects in the arid southwestern United States, including the Truckee-Carson Project, later renamed the Newlands Project. The Newlands Project was enacted to provide irrigation water to develop agriculture and encourage settlement of Lahontan Valley. In 1916, irrigated agricultural land in Lahontan Valley encompassed an estimated 14,000 acres and, by 2012, approximately 57,000 acres (Lee and Clark, 1916; Bureau of Reclamation, 2013). The Newlands Project formed two areas of irrigated agriculture, known as the Truckee and Carson Divisions. Irrigated lands east of Swingle Bench in Lahontan Valley form the Carson Division of the Newlands Project.

Over-allocation of Carson River water for agricultural use caused loss of wetlands in the Lahontan Valley. For example, Stillwater National Wildlife Refuge (NWR) wetlands declined from an estimated 33,000 acres prior to 1902 to 9,700 acres in 1987 (Hoffman and others, 1990). Further, surface water available to the wetlands consisted of poor quality irrigation return flows and unused Carson River streamflow (Hoffman and others, 1990). The Fallon Paiute-Shoshone Tribal Settlement Act (Public Law 101–618, 104 Stat. 3289) enacted in 1990 required that a long-term average of 25,000 acres of wetlands be sustained in the Stillwater NWR, Carson Lake area, and the Fallon Paiute-Shoshone Tribal Reservation, collectively (fig. 2). The law gave USFWS the authority to purchase water rights in order to achieve those goals.

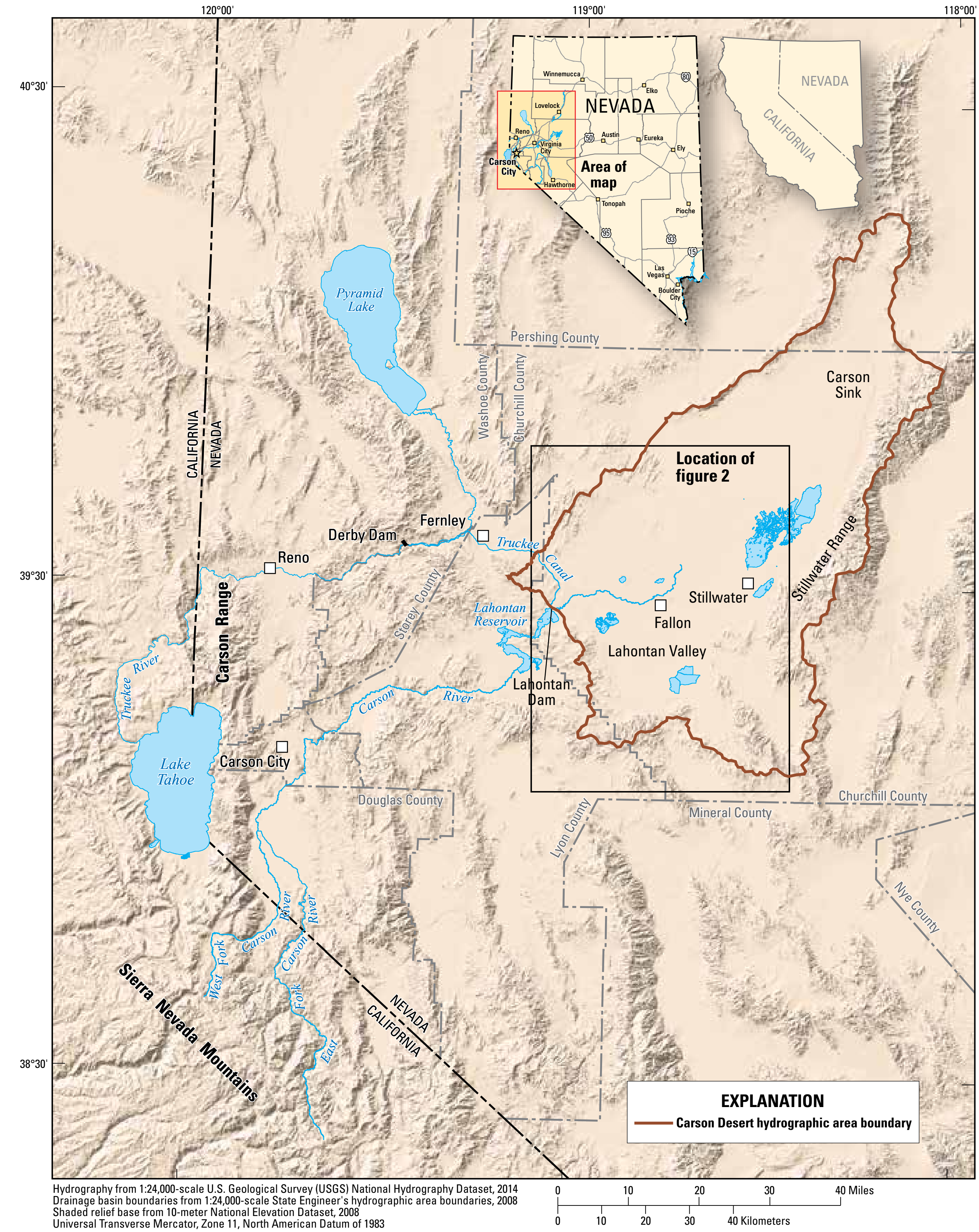

Figure 1. Geographic features of the Lahontan Valley, Nevada.

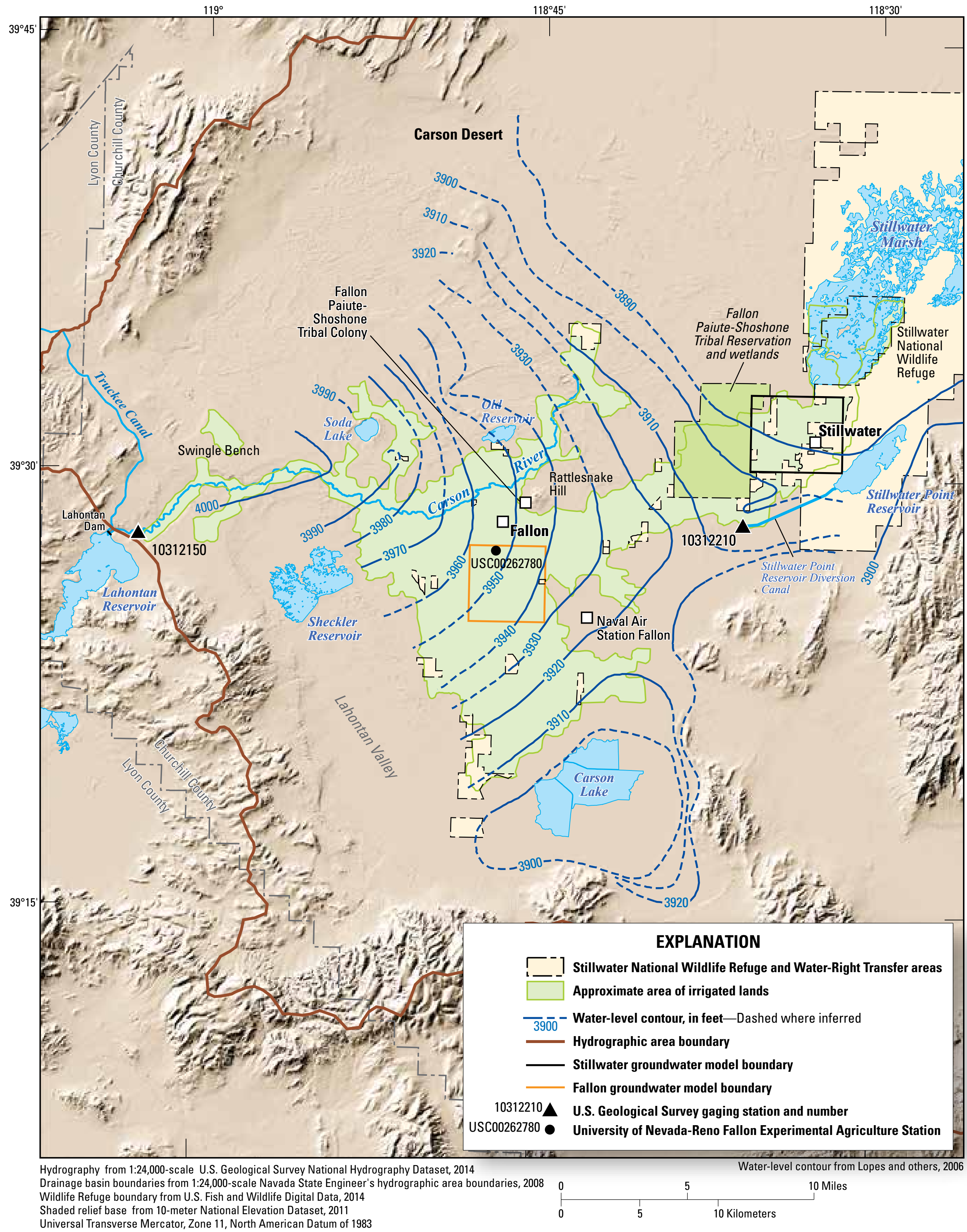

Figure 2. Approximate area of agricultural lands, location of irrigation reservoirs and lakes, and the 1992 water-table contours for Lahontan Valley, Nevada.

Previous Investigations

Seiler and Allander (1993) developed a water-table map and compared it with the 1904 map documented by Stabler (1904) prior to the start of the Newlands Project. The water table represents the groundwater surface of an unconfined aquifer, which is at atmospheric pressure (Lohman, 1972). Seiler and Allander (1993) found general groundwater-level increases of 15 ft in Lahontan Valley by comparing the water-table maps of 1904 and 1992. The effects of land-use and management change in Lahontan Valley were investigated by Maurer and others (1996) with the conclusion that the lining of canals and removal of lands from irrigation could produce water-level declines of 4 to 17 ft and an estimated reduction in recharge of 25,000 to 50,000 acre feet per year (acre-ft/yr). Water-level change in response to five scenarios of land-use change were simulated by Herrera and others (2000) for two areas near Fallon and Stillwater. These models are described in more detail in section “Groundwater-Flow Models.”

In 2004, Maurer and others (1996) evaluated the USGS water-level monitoring network by characterizing the ability of monitoring wells to indicate water-level changes resulting from land-use change. They concluded that wells within 300 ft of active canals were of limited use in detecting changes resulting from reductions in irrigation because seepage from canals maintained relatively stable groundwater levels. Wells within 400 to 1,200 ft of water-right transfers, and more than 300 ft from canals, were determined to be optimal for measuring groundwater-level declines caused by irrigation reductions. Furthermore, groundwater-level declines from water-right transfers may be masked by above and below average irrigation releases from Lahontan Reservoir, affecting the duration and volume of water transported through the irrigation system (Maurer and others, 2004).

Description of Study Area

The study area consists of irrigated and non-irrigated areas of the Newlands Project and wetlands areas in Lahontan Valley (fig. 2). Lahontan Valley includes the Fallon Paiute-Shoshone Tribal Reservation and Colony and the Stillwater NWR. Fallon is the main population center in the valley with a population of 8,453 in 2012 (U.S. Census Bureau, 2014); the town of Stillwater is near the southern edge of the Stillwater NWR (fig. 2).

Lahontan Valley is a northeast trending valley that is bounded by the Stillwater Range to the southeast and by low lying mountains to the north, south, and west (fig. 1). Land-surface altitudes range from 8,727 ft in the Stillwater Range to about 3,884 ft in the Carson Sink. The Lahontan Valley landscape is influenced by the meandering Carson River, which flows northeast from the Carson Range of the Sierra Nevada, west of Lahontan Valley (fig. 1). Non-irrigated areas of the valley are dominated by native xerophytic and phreatophytic vegetation, except for wetlands and marshes where bulrush and marsh grasses are prevalent. Both flood and sprinkler irrigation practices are used to grow hay and forage crops. Irrigation season generally begins in March and ends in November, lasting an average of 214 days, but it may be shorter during drought conditions (Herrera and others, 2000).

Lahontan Valley is a desert environment located in the rain shadow of the Sierra Nevada. For the 30-year period from 1981 to 2010, the average temperature of Fallon, Nevada, was 52.7 degrees Fahrenheit, and the average precipitation was 4.94 inches per year at the University of Nevada-Reno Fallon Experimental Agriculture Station USC00262780 (fig 2; National Oceanic and Atmospheric Administration, 2014a). The area has experienced multiple periods of extreme drought from 1967 to 2012, as indicated by Palmer Hydrologic Drought Index (PHDI) values for the Western Nevada area (fig. 3*A*; U.S. Geological Survey, 2013; National Oceanic and Atmospheric Administration, 2014b). The PHDI is a long-term analysis index for the severity of wet or drought conditions. Periods with PHDI values greater than four or less than negative four are considered to be in the range of extreme wetness or drought, respectively (Karl and others, 1986). There were extreme drought conditions in 10 of 21 years of the study period, 1992 to 2012 (fig. 3*A*); the two periods compared in this study, 1992 and 2012, have average annual PHDI values of -4.6 and -4.3, respectively. Periods of extreme drought and wetness correlate well with periods of below and above average releases from Lahontan Reservoir (fig. 3*B*).

The Newlands Project infrastructure delivers water from the Truckee and Carson Rivers to agricultural fields in Lahontan Valley via an extensive network of irrigation reservoirs, canals, and drains. During irrigation season, discharge in the Carson River below Lahontan Reservoir (USGS gaging station 10312150, fig. 2) averages 670 cubic feet per second (ft^3/s) and is diverted through 370 miles of canals and lateral canals for flood irrigation (Bureau of Reclamation, 2011). Outside irrigation season, Carson River discharge averages less than 10 ft^3/s (U.S. Geological Survey, 2013). From 1967 to 2012, the average annual discharge of the Carson River below Lahontan Reservoir was 342,000 acre-ft (fig. 3*B*; U.S. Geological Survey, 2013). Lahontan Reservoir record peak outflow was 771,900 acre-ft in 1983, and the minimum outflow was 131,500 acre-ft in 1992 (fig. 3*B*). In 2012, approximately 260,800 acre-ft of water was released from Lahontan Reservoir, 202,163 acre-ft of which was allotted for irrigation of an estimated 57,000 acres of agricultural land (Bureau of Reclamation, 2013; U.S. Geological Survey, 2013).

Newlands Project Water-Right Transfers

The transfer of a water right, in the interest of this study, involves moving the point of use from one place to another and results in the removal of irrigation from agricultural fields in Lahontan Valley. Water-right transfers are exchanged through lease and temporary transfers in the Newlands Project, and locations of use may change annually (Bureau of Reclamation, 2013). The quantity of water associated with a water

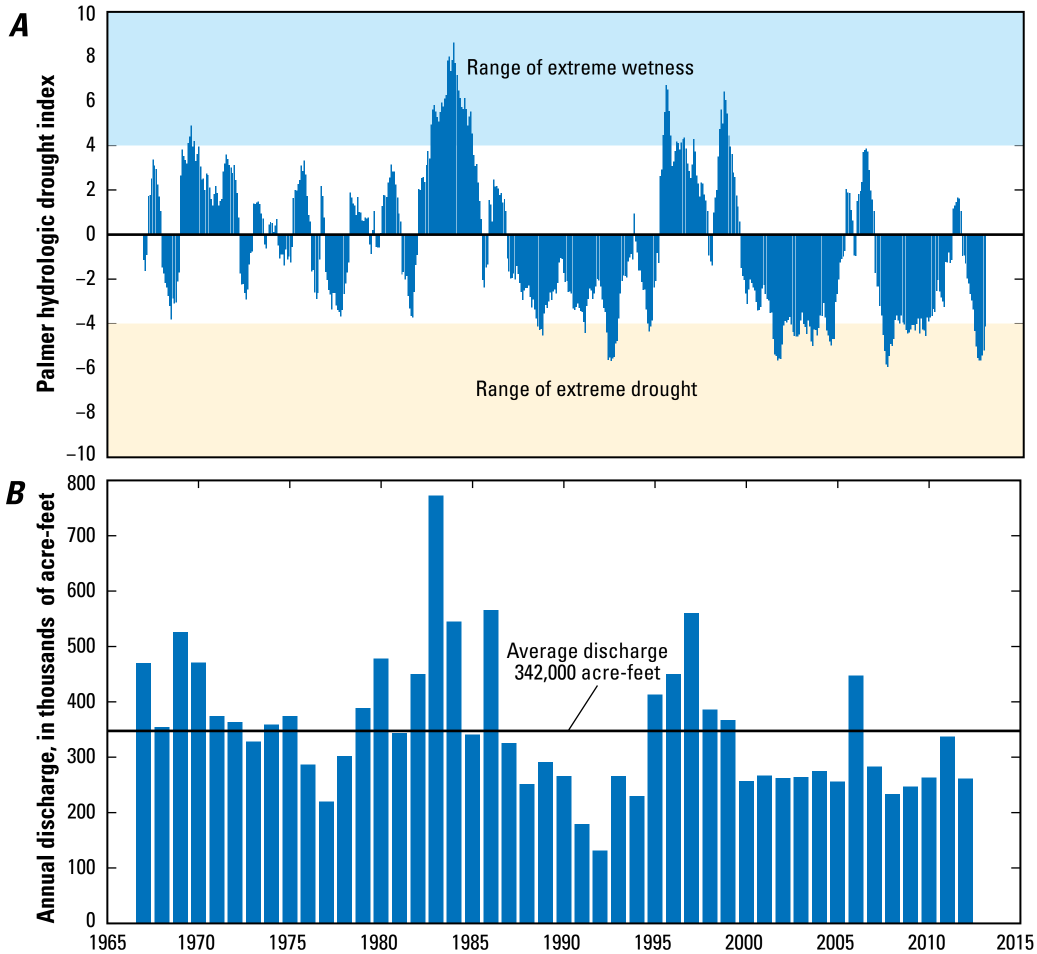

Figure 3. ***A***, Palmer Hydrologic Drought Index for western Nevada, 1967 to 2012 and ***B***, annual discharge at the Carson River below Lahontan Reservoir gaging station 10312150, Lahontan, Nevada,1967 to 2012.

right is based on the characteristics of the land where it is applied and the net consumptive use of the irrigation water required for crops, pasture, or sustaining wetlands (Bureau of Reclamation, 2013). In this report, the quantity of water-right transfers, specified as acres and acre-ft, reflects the amount of water transferred to the wetland areas in Lahontan Valley. Water-right acres and volumes specified in this report have been adjusted to reflect totals that are based on the Bureau of Reclamation (2013) report on the water-right demands of the Newlands Project.

Water-right transfers to wetland areas in Lahontan Valley are managed by USFWS for Stillwater NWR, the Nevada Department of Wildlife for the Carson Lake Area, and the Fallon Paiute-Shoshone Tribe for wetlands in the Tribal Reservation. Total water rights acquired by these agencies are for wetlands of approximately 11,810 water-righted acres for 34,356 acre-ft of water (table 1*A*; Bureau of Reclamation, 2013). Additional water-right transfers for municipal and industrial use and water-right retirement programs from the 1999 Nevada Assembly Bill 380 have occurred in Lahontan Valley (table 1*B*). Water-right transfers for municipal and industrial use and retirement programs total 5,276 water-righted acres for 18,880 acre-ft of water.

Water-right transfers and retirements are anticipated to continue in Lahontan Valley, based on 2013 acquisition trends (Bureau of Reclamation, 2013). To meet the 25,000 acres of wetlands required by passage of Public Law 101–618, 104 Stat. 3289, additional water-righted acres required by the USFWS are estimated to be 12,064 for an additional 36,071 acre-ft of water (Bureau of Reclamation, 2013). In the Carson Division of the Newlands Project, water rights acquired for municipal and industrial use, and water-right retirement programs, are estimated to total 250 acres (1,125 acre-ft) and 1,313 acres (5,909 acre-ft), respectively (Bureau of Reclamation, 2013). Future water-right transfers will continue to affect water-use and groundwater recharge in Lahontan Valley.

Table 1. Summary of ***A***, water right use and ***B***, transfer and retirement programs in Lahontan Valley, 2013.

[Data from U.S. Bureau of Reclamation (2013). Water-right retirement is the deactivation of a water right making the right ineligible for transfer or use]

A **Water Rights in Lahontan Valley**	**Acres of land**	**Acre-feet of water**
Irrigated Agriculture	43,403	157,239
Fallon Paiute-Shoshone Reservation Agriculture	3,025	10,588
Total Agriculture	**46,428**	**167,827**
U.S. Fish and Wildlife Service	8,939	25,773
Carson Lake and Carson Lake Pasture, Nevada Division of Wildlife	2,403	7,183
Fallon Paiute-Shoshone Reservation Wetlands	468	1,400
Total Wetlands	**11,810**	**34,356**

B **Lahontan Valley Water-Right Programs**	**Acres of land**	**Acre-feet of water**
Water Right Retired by AB 380[1]	4,166	14,873
City of Fallon and Churchill County[2]	766	2,799
City of Fernley[2]	[3]278	[3]921
Water-Right Compensation Program[4]	66	287
Totals	**5,276**	**18,880**

[1]Water-right retirement program from Nevada State Assembly Bill 380 (AB 380).

[2]Municipal and Industrial use.

[3]Acres in the Swingle Bench area determined from Churchill County Assessors Database.

[4]Compensation program to purchase and retire water rights from Nevada Assembly Bill 380.

Hydrogeology

The groundwater system in Lahontan Valley is characterized by four aquifers, which are defined on the basis of hydrologic characteristics (Glancy, 1986). Three of the aquifers are basin fill, consisting of unconsolidated Quaternary basin-fill deposits from ancient Lake Lahontan (Morrison, 1964) and Carson River deposits. The fourth aquifer is a fractured basalt aquifer beneath Rattlesnake Hill (fig. 2; Glancy, 1986). The basin-fill aquifer system consists of (1) a shallow aquifer (from 0 to 50 ft below land surface (bls), (2) an intermediate aquifer (from 50 to 500 ft bls), and (3) a deep aquifer (greater than 500 ft bls). The shallow and intermediate aquifers serve as the domestic water supply outside municipal areas (Maurer and others, 2004). The basalt aquifer provides the main municipal water supply for the city of Fallon, Naval Air Station (NAS) Fallon, and the Fallon Paiute-Shoshone Tribe.

The shallow aquifer is an unconfined aquifer composed of sand interbedded with clay and stringers of gravel; groundwater flows from west to east in Lahontan Valley (Glancy, 1986; Seiler and Allander, 1993; Maurer and others, 1996). In irrigated areas of Lahontan Valley, the depth to the groundwater surface, or water-table, of the shallow aquifer is generally 5 to 10 ft bls (Seiler and Allander, 1993). However, areas outside irrigated locations may have water-table depths greater than 25 ft bls (Seiler and Allander, 1993). Water levels in the shallow aquifer are affected by canal seepage and recharge from irrigation, and seasonal change can exceed 2 ft (Seiler and Allander, 1993; Maurer and others, 1996). Shallow aquifer water quality and hydraulic properties vary in both the horizontal and vertical directions throughout Lahontan Valley (Lico and Seiler, 1994). The aquifer is characterized by moderately hard water, greater than 70 milligrams per liter (mg/L) of calcium carbonate ($CaCO_3$), and transitions to the hardness of the intermediate aquifer, less than 25 mg/L of $CaCO_3$, at about 50 ft bls (Glancy, 1986).

The intermediate aquifer is confined and extends from 50 to 500 ft bls in Lahontan Valley (Glancy, 1986). The lithology and hydraulic properties are similar to those of the shallow aquifer, but water quality is improved (Glancy, 1986; Lico and Seiler, 1994). In the area between Lahontan Reservoir and Soda Lake, vertical gradients and water-quality characteristics indicate the shallow aquifer recharges the intermediate aquifer (fig. 2; Maurer and others, 1996). Lico and Seiler (1994) estimate that the depth to the intermediate aquifer in west-northwest Soda Lake area may be greater than 100 ft (fig. 2). In the central Fallon area, clay beds separate the shallow and intermediate aquifers (Maurer and others, 1996). East of Fallon, near the Stillwater NWR area, confined pressures of the intermediate aquifer produce vertical gradients of as much as 0.04 foot per foot, indicating groundwater flows upwards from the intermediate aquifer to the shallow aquifer (Maurer and others, 1996). The bottom boundary of the intermediate aquifer is characterized by dissolved solids concentrations of 1,000 mg/L and represents the transition to the deep aquifer (Glancy, 1986). Information on the deep aquifer is limited owing to the few wells that penetrate the aquifer and its non-potable water-quality characteristics (dissolved solids greater than from 1,000 mg/L; Glancy, 1986).

The basalt aquifer crops out at Rattlesnake Hill as a volcanic cone approximately 1 mile in diameter (fig. 2; Maurer and Welch, 2001). The basalt formation beneath Rattlesnake Hill is mushroom shaped, from 4 miles wide at the surface to 10 miles wide at 400–600 ft bls (Glancy, 1986; Maurer and Welch, 2001). The lithology of the basalt aquifer ranges from highly porous to dense and massive basalt (Maurer and Welch, 2001). The basalt aquifer is assumed to intersect and exchange groundwater with all three basin-fill aquifers (Glancy, 1986).

Groundwater-Flow Models

Herrera and others (2000) developed two groundwater-flow models, conceptualized within the irrigated areas of Lahontan Valley to investigate the effects of changing irrigation practices on water levels in the shallow aquifer (fig. 2). The model domains represent a subset of the general groundwater flow in the Fallon and Stillwater areas (fig. 2). The USGS modular three-dimensional finite-difference groundwater-flow model (MODFLOW; Harbaugh and McDonald, 1996a and 1996b) was used to simulate transient water-level conditions for the two modeled areas, each of which are approximately 5,760 acres (Herrera and others, 2000). For additional details about the groundwater-flow model, refer to Herrera and others (2000).

Model grids coincide with Newlands Project irrigation canals and drains and aquifer-flow characteristics; the grid cell discretization is 2.5 acres (Herrera and others, 2000). The Fallon model area represents aquifer characteristics of the shallow aquifer unit, and a no-flow boundary at the base of the shallow aquifer was incorporated because groundwater flow in this area is nearly horizontal (Herrera and others, 2000). The Stillwater modeled area is characterized by upward vertical flow from the intermediate to shallow aquifer to be consistent with conceptualized groundwater flow in the eastern part of the Lahontan Valley (Morgan, 1982; Glancy, 1986). Two model layers were used to simulate vertical flow from the intermediate to shallow aquifer for the Stillwater modeled area. Additional information on applied recharge from canals, laterals, irrigated fields, and precipitation is in Herrera and others (2000).

To investigate the effects of changing irrigation practices, simulated recharge was applied to the model based on irrigation deliveries (canal seepage and applied flood irrigation) and precipitation. Main canals were simulated by a specified head throughout the irrigation season, whereas lateral canals were simulated with specified head for only 50 percent of the season (Herrera and others, 2000). The maximum irrigation delivery for both model areas was 42 inches per year (in/yr), based on Lahontan Valley water rights (Herrera and others, 2000). Discharge from crop evapotranspiration was specified at 28 in/yr, and annual recharge from precipitation was specified as 1.75 in/yr.

The models were calibrated by varying vertical hydraulic conductivity and evapotranspiration extinction depth until physical measurement data were adequately simulated (Herrera and others, 2000). Limited historical water-level data were available for the simulated areas, so the Fallon and Stillwater models were calibrated to water levels in only a few wells. Water-level data from 1992 to 1997 were used to represent average seasonal water-level change of the shallow aquifer (Herrera and others, 2000).

Transient model time, or stress periods, were selected to reflect seasonal changes of applied flood irrigation in the model areas. Irrigation seasons were simulated with a length of 214 days. Seasonal changes of irrigation inflows and outflows were represented by six stress periods per year (Herrera and others, 2000).

The effects of changes in irrigation practices on shallow groundwater levels were tested for five hypothetical changes in irrigation practices: (A) irrigation recharge reduced by 50 percent, (B) irrigation season shortened from 214 to 91 days, (C) removal of 320 acres from irrigation, (D) removal of 320 acres and closure of a lateral irrigation canal, and (E) the removal of irrigation in the modeled areas (table 2). Water-level change was reported after the fifth year of the scenario simulation; therefore, 5 years in the simulation was the time required for the water levels to reach a new state of approximate equilibrium (Herrera and others, 2000).

Table 2. Results of five scenarios simulated using the groundwater-flow models for the Fallon and Stillwater modeled areas, Lahontan Valley, Nevada.

[Scenarios A–E are the results of Herrera and others (2000) simulations; Irrigation and precipation recharge, represents the model scenario change of Herrera and others (2000) in acres of irrigated areas or removal of precipitation in the model areas; Irrigation canal use, represents the management change in the delivery of irrigation through canals, where a closed lateral canal is the discontinued use of a lateral canal used to irrigate the 320 acres removed from irrigation]

Scenario	Model scenario description		Fallon model area			Stillwater model area		
	Irrigation and precipation recharge	Irrigation canal use	Average water-level decline (feet)[1]	Standard deviation	Maximum water-level decline (feet)[1]	Average water-level decline (feet)[1]	Standard deviation	Maximum water-level decline (feet)[1]
A	Irrigation recharge reduced by 50 percent	No change	0.5	0.4	3.2	0.6	0.6	2.6
B	Irrigation season shortened from 214 to 91 days	½ Duration of irrigation season	1.1	1	10.3	1.4	1.4	9.9
C	Irrigation and precipation removed from 320 acres	No change	0.1	0.3	2.9	0.1	0.6	4.2
D	Irrigation and precipation removed from 320 acres	Closure of one lateral canal	0.1	0.4	6.4	0.2	0.7	7.2
E	Removal of all irrigation and precipation from 5,760 acres	No change	1.1	0.9	7.1	1.3	1.1	4.1

[1]Average modeled area water-level decline at the end of the fifth year of model simulation.

Study Methods

Water levels were measured in Lahontan Valley in 2012 and 2013 to assess valley-wide changes in water-levels and to evaluate previous groundwater-flow models for Fallon and Stillwater areas. Water-level declines near reservoirs and lakes were investigated using remote sensing methods to estimate annual changes in surface-water area as a proxy for water-storage changes. To determine how well the modeled scenarios simulated water-level conditions, the water-level change, length of the irrigation seasons, and annual irrigated acres of the modeled areas were obtained from 1992 to 2011.

Water-Table and Water-Level Change Maps

Groundwater-levels were measured by the USGS in 98 wells from 2012 to 2013 to determine static water-table conditions of the shallow aquifer. Water levels were measured using steel and electric measuring tapes according to USGS guidelines (Cunningham and Schalk, 2011) and are accurate to the nearest 0.02 ft. Water-level change from 1992 to 2012 was calculated, although measurements collected in 2013 are included in the dataset and were used to develop the map in cases where the well was being pumped or was inaccessible in 2012. Measurements were attempted at the 110 wells for comparison to the 1992 water-table map (Seiler and Allander, 1993); however, 33 wells either were destroyed or were unavailable during this study. Wells measured in 1992 that were unavailable for this study were replaced by 21 new monitoring wells to improve the spatial distribution of 2012 water-table measurements. Water-level data were reviewed and approved by the USGS and are stored in the National Water Information System (*http://waterdata.usgs.gov/nwis/*).

Wells used for this study were completed in the shallow aquifer. Wells greater than 50 ft in depth were included in areas where the shallow aquifer extends past 50 ft (Seiler and Allander, 1993; Lico and Seiler, 1994). Shallow wells greater than 50 ft are located in the Swingle Bench area west and north of Soda Lake and areas near the Stillwater Range. In many cases, these wells filled gaps in water-level data and were the only monitoring wells available to decrease uncertainty of water-level contours.

Water-level change within the shallow aquifer was determined by differencing water-level measurements made in 1992 by Seiler and Allander (1993) and water-level measurements made in 2012 and 2013. To minimize seasonal bias in water-level differences, current measurements were matched to previous measured water levels within the same month of the year, when possible (appendix 1). Differenced measurements that do not occur within the same month of the year occurred for only a few wells (44, 74, 112, 126, and 148; appendix 1), although the measurements are believed to have occurred during the same time of the irrigation season.

Water-table and water-level change maps were developed in a geographic information system (GIS). Inverse distance weighted interpolation was used to construct water-table contours at 10-ft intervals from 98 water-level measurements in Lahontan Valley. Water levels measured in 73 wells were used to construct contours at 2-ft intervals of water-level change using iterative finite difference interpolation techniques (Hutchinson and others, 2011). Both the water-table map and water-level difference contours were manually adjusted near rivers, reservoirs, and lakes to account for localized effects of surface water on the water table.

Uncertainties in well location and altitude represent limitations in the development of water-level contours or water-table maps. In this study, well location and altitudes were measured to improve the spatial and vertical accuracy of the water-level measurements. The locations of 83 monitoring wells were refined using a differential global positioning system (DGPS) by the USGS and Churchill County in 2013 and 2014. Well locations and altitudes were updated according to USGS guidelines (Rydlund and Densmore, 2012), and vertical and horizontal accuracies generally were improved to less than 0.3 ft. Well locations also were surveyed by digital level to a 0.01-ft accuracy at 10 wells by Fallon NAS, and 5 well altitudes were interpolated from digital elevation models to an accuracy of 5 ft. These refined locations and altitudes were used with water-level measurements to calculate groundwater levels in each well and then to generate groundwater-level contours.

Analysis of Change in Surface-Water Storage

Sheckler and Old Reservoirs, and Carson Lake, are used to intermittently hold water in storage during periods of above average releases from Lahontan Reservoir; however, water-storage records of the reservoirs and lake are unavailable (fig. 2; Maurer and others, 2004). Water held in these reservoirs infiltrates to the groundwater system and affects nearby water levels in the shallow aquifer. Wells near these reservoirs were evaluated for the relation between groundwater-level changes and the surface area of water stored in those reservoirs. The reservoir surface area, indicating the presence of water storage, was evaluated using a time series of summer Landsat images.

Landsat images were used in the evaluation of water present in reservoirs and the irrigation history within the groundwater-flow model boundaries. Cloud-free Landsat 5 Thematic Mapper (TM) images for the 1992–2011 summer growing seasons were evaluated and selected from the image archive at the USGS Earth Resources Observation Systems (EROS) data center (earthexplorer.usgs.gov). Each selected scene was atmospherically corrected by the USGS EROS data center using Landsat Ecosystem Disturbance Adaptive Processing System software (U.S. Geological Survey, 2012a).

Information from multispectral satellite imagery, such as that collected by Landsat 5 TM, can be used to characterize features on Earth's surface on the basis of the light absorption and reflection characteristics of those surfaces. Spectral indexes such as the Normalized Difference Vegetation Index (NDVI; Rouse and others, 1974) and Normalized Difference Water Index (NDWI; Gao, 1996) use the contrast between these distinct absorption and reflectance features to identify and differentiate vegetation communities, urban areas, water, and other natural and anthropogenic features in the image.

Summer Landsat images were evaluated for the presence of water in Sheckler Reservoir, Old Reservoir, Carson Lake, and pastures by modifying the boundaries of those water bodies depicted in the National Hydrography dataset (Simley and Carswell, 2009). An NDWI, based on the ratio of Landsat TM bands 4 and 5, was used to identify open water in the imagery. The NDWI was calculated for each of the 1992–2011 summer images and was then passed through a classification algorithm which clustered the pixels in each NDWI image. The classified data were then used to estimate the total surface area of water within each reservoir boundary for each image for a time series of the reservoir boundary area.

Scenario Conditions Observed in the Groundwater Model Areas

Herrera and others (2000) simulated water-level change in the shallow aquifer for five scenarios that decreased the length of an irrigation season or removed varying amounts of land from irrigation for modeled areas near Fallon and Stillwater (fig. 2; table 2). To determine the degree to which model scenario(s) occurred in the modeled areas, (1) the length of the annual irrigation season was determined using Carson River flows, and (2) annual changes in irrigated acres of the modeled areas from 1992 to 2011 were estimated using remote sensing methods (imagery from 2012 was not available as a result of the failure of Landsat 7).

The start and end of the irrigation seasons were determined from flow releases from Lahontan Reservoir, as observed at Carson River below Lahontan Reservoir (USGS gaging station 10312150). Flows greater than or equal to 10 ft^3/s were used to signify the start of irrigation season, and flows less than 10 ft^3/s signified the end of irrigation season. The lengths of irrigation seasons from 1992 to 2012 are presented in appendix 2. The irrigation season lengths were compared to the scenario B (table 2) irrigation season length of 214 days (Herrera and others, 2000).

Annual Irrigated Acreage

The Fallon and Stillwater modeled areas have complex irrigation histories, including water-right transfers and land-use changes from 1992 to 2012. Irrigation status of the modeled areas is further complicated by the water-rights leases and temporary transfers of water rights that may occur annually (Bureau of Reclamation, 2013). Annual irrigated acres from 1992 to 2011 in the Fallon and Stillwater modeled areas were estimated using remote sensing analysis to evaluate changes in irrigation status (irrigated vs non-irrigated) of agricultural fields in the modeled areas.

Agricultural field boundaries were delineated for the modeled areas (fig. 2) by reviewing black and white Digital Orthophoto Quadrange images collected in 1994 and color-infrared National Agricultural Imagery Program (NAIP) imagery collected in 2010 (U.S. Geological Survey, 2012b; U.S. Department of Agriculture, 2009). Agricultural fields were identified in the 1994 imagery and digitized as field boundaries in a GIS. The boundaries were verified using the 2010 NAIP imagery. Irrigation status was estimated for the delineated fields using summer Landsat satellite images from 1992 to 2011.

Capturing cycles of plant growth and harvest in irrigated agricultural lands requires evaluation of multiple Landsat images that span the growing season. Crops are planted and germinate under different conditions, producing peak vigor at different times throughout a growing season, although most generally reach peak vigor during mid-summer (Ozdogan and Gutman, 2008). Some crops, like alfalfa, may be harvested multiple times throughout the season. Using multiple images for each summer growing season to differentiate irrigated agricultural lands from non-irrigated agricultural lands increases the chance that a field will be correctly classified as irrigated or non-irrigated. A minimum of 3 and maximum of 7 images per year were used for this analysis.

The NDVI was calculated for all the selected Landsat images, and a growing season maximum NDVI image was created by merging all NDVI images for a single growing season so that each pixel in the resultant image was the highest NDVI value from all the images in that year. Irrigated lands were identified by selecting a threshold value for the maximum NDVI image so that pixels above that value were assumed to correspond to areas with healthy, well irrigated vegetation, and pixels below that value were assumed to correspond to agricultural lands not being irrigated during that season. A threshold value of 0.3 was determined by evaluating NDVI values within several center pivot irrigated fields near the study area. Center pivot fields were evaluated to determine the irrigated lands NDVI threshold because they are clearly identifiable, human-constructed agricultural lands that would not contain healthy, green vegetation without the presence of irrigation. Fields delineated within the modeled areas were classified as “irrigated” for a growing season if more than 45 percent of the field area had a maximum NDVI value greater than or equal to 0.3. Otherwise, the field was classified as “not irrigated.” The process was repeated using NDVI thresholds of 0.25 and 0.35 to evaluate the uncertainty of delineated irrigated areas at a selected NDVI threshold value.

Water-level Changes from 1992 to 2012

In 1992, water levels in Lahontan Valley were measured to construct a water-table map of the shallow aquifer prior to the transfer of water rights as a result of the Fallon Paiute-Shoshone Tribal Settlement Act of 1990 (fig. 2; Seiler and Allander, 1993). From 1992 to 2012, approximately 11,810 water-righted acres for 34,356 acre-ft of irrigation water were transferred to wetland areas in the Lahontan Valley. The following sections describe changes in water levels associated with these water transfers.

Water-Table and Water-Level Change Maps

A 2012 water-table map, representing contoured altitudes of depth to water measurements made at 98 wells, is shown on plate 1. Additional information about well identification, depth, altitude, and water-level differences is given in appendix 1. Water-table altitudes reach a maximum of 4,065 ft at well 135 near Lahontan Reservoir; water-table altitudes decrease through the central area of Lahontan Valley to a minimum of 3,869 ft at well 118 in Stillwater NWR (plate 1). The direction of horizontal groundwater flow in the shallow aquifer can be inferred from contour gradients depicted on plate 1. Groundwater flows from the high to the low water-table altitude in a direction perpendicular to the water-table altitude contours. Water-table altitude contours indicate shallow aquifer groundwater flow is generally from west to east, parallel to the Carson River, to Fallon. Groundwater flow diverges east of Fallon toward the southeast near Carson Lake and Pasture at 3,880 ft and to the northeast towards the Stillwater NWR at 3,869 ft (plate 1). Interpreted flow directions are consistent with those reported in 1993 by Seiler and Allander (1993).

Water-level changes between 1992 and 2012 were computed by differencing the 1992 measurements from the 2012 measurements in 73 wells available for comparison to water levels collected by Seiler and Allander (1993; fig. 4; appendix 1). From 1992 to 2012, the average water-level difference, or change, in these 73 wells was a decline 0.5 ft, which is considered insignificant in comparison to the typical seasonal water-level change of about 2 ft (Seiler and Allander, 1993). However, at individual wells, water-level changes ranged from a maximum decline of 16.2 ft in well 3 to a 4.1 ft increase in well 72 (fig. 4; appendix 1).

Water-level change contours depicting shallow aquifer water-level change from 1992 to 2012 were developed using iterative finite difference interpolation techniques (Hutchinson and others, 2011; fig. 4). In the central irrigated areas of the Lahontan Valley, water levels were estimated to have remained at the same level measured during the irrigation season of 1992 (fig. 4). Water-level increases were observed in irrigated areas east and northeast of Fallon, in areas near Stillwater, and near lakes in the Stillwater NWR. Contours of water-level decline generally followed the irrigated area boundary of Lahontan Valley north of the Carson River, near the Swingle Bench area and northeast of Soda Lake. The largest declines were observed south and southeast of Carson Lake. In the Fallon and Stillwater modeled areas, water-level changes ranged from 0 to 2 ft (fig. 4).

Water-level Change Associated with Changes in Land Use

Water-level changes greater than 2 ft were examined for relation to land-use and management change in nearby agricultural fields and to patterns of surface-water use from 1992 to 2012. Water-level increases of 2.0 to 4.1 ft were observed in 9 wells (sites 21, 59, 66, 69, 72, 76, 77, 96, and 112) in the central and eastern Newlands Project (fig. 4). Seepage from nearby irrigation canals may have contributed to the rise in water levels observed in these wells (plate 1). From 1992 to 1993, water levels declined as much as 4 ft in areas near Stillwater NWR during a period of extreme drought (fig. 3*A*; Seiler and Allander, 1993). In 1992, annual discharge of 131,400 acre-ft from Lahontan Reservoir (fig. 3*B*) resulted in shorter duration canal flows, reduced canal seepage, and reduced application of irrigation water. Increases in Lahontan Reservoir releases after 1992 have likely contributed to water-level increases in wells 21, 59, 66, 69, 72, 76 and 77 (fig. 4; plate 1), which are within 300 ft of a primary or lateral canal, as indicated in Maurer and others (2004).

Drought conditions in 1992 also affected the volume of water available for wetlands within Stillwater NWR when compared to 2012. For example, surface-water flow into Stillwater Point Reservoir, monitored at USGS gaging station 10312210 (Stillwater Point Reservoir Diversion Canal near Fallon, NV; fig. 2), averaged 4,680 acre-ft/yr from 1991 to 1992. From 2011 to 2012, the annual average flow was 21,970 acre-ft/yr, representing a 469 percent increase in flow since 1991 and 1992 (U.S. Geological Survey, 2014). The increase in flow and seepage from canals and lakes likely contributed to the water-level rises observed in 2012 for wells within 300 ft of canals or laterals (wells 21, 59, 66, 69, 72, 76, and 77) and wells near lakes or reservoirs (wells 96 and 112) in Stillwater NWR (fig. 4).

Water-level declines generally were observed near the boundary of irrigated areas in the Lahontan Valley and were more widespread in the southeastern area near Carson Lake and northwestern areas near Soda Lake (fig. 4). Declines from 2 to 16.2 ft were observed in wells 1, 3, 4, 34, 46, 54, 58, 104, 105, 106, and 110 in the study area. When groundwater-level declines were greater than 2.0 ft, areas near the wells were examined for the effects of water-right transfers, groundwater pumping, or reservoir and lake surface-water changes to determine whether they may be contributing to water level declines.

The NDWI was calculated annually for years 1992–2011 for Old Reservoir, Sheckler Reservoir, and Carson Lake to relate groundwater levels in wells 3, 4, 55, and 58 to reservoir surface area (fig. 5). Analysis of satellite imagery indicates that surface water was impounded periodically in these

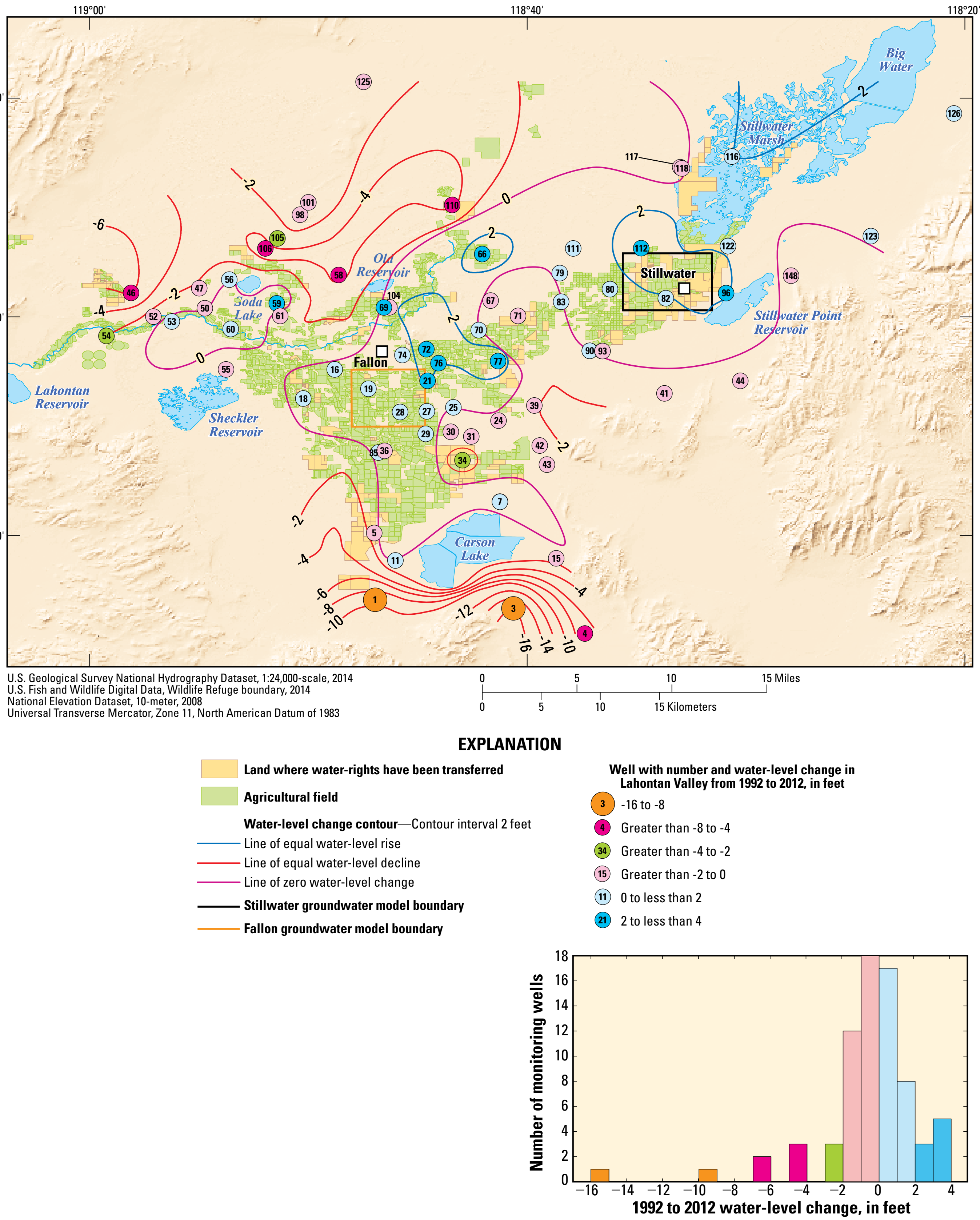

Figure 4. Water-level change contours and locations of monitoring wells with water-level changes, Lahontan Valley, Nevada, 1992–2012.

reservoirs between 1995 and 2011. Groundwater levels near Old and Sheckler Reservoirs (wells 58 and 55; fig. 5) peaked in 1997 and subsequently declined 1.2 and 4.3 ft, respectively, by 2012. The largest measured declines (16.2 ft) between 1992 and 2012 occurred southeast of Carson Lake in well 3. Well 4, also southeast of Carson Lake, declined 6.7 ft between 1992 and 2012. Vegetation southeast of the Carson Lake and pastures (near wells 3 and 4) partly consists of phreatophytic vegetation, the natural source of groundwater discharge by evapotranspiration in the area. Evapotranspiration losses of groundwater from phreatophytic vegetation combined with the lack of groundwater seepage from reservoirs, or operational and management changes of Carson Lake, is likely influencing water-level declines in this area.

Near areas of water-right transfers, water-level declines greater than 2 ft were observed for wells 1, 34, 46, 104, 105, 106, and 110 (fig. 5). The largest water-level change near a water-right transfer was observed at well 1, located 1.25 miles southeast of a 285-acre (998 acre-ft) water-right transfer to USFWS that occurred in 1998 (fig. 5). This transfer was followed by the discontinued operation of a lateral canal 1,500 ft west of well 1 (Maurer and others, 2004). Between 1992 and 2007, water levels declined at least 9.5 ft until the well became dry (fig. 5). The total decline in well 1 is unknown but is reported as greater than 9.5 ft and may be affected by the nearby storage and operation of Carson Lake.

Water-level declines were observed following the discontinued use of a flood irrigation ditch north of wells 104, 105, and 106 (fig. 5). The wells are about 480 ft from the irrigation ditch that supplies irrigation water to fields 1.4 miles west of the wells. Water rights for approximately 76 acres (226 acre-ft) of agricultural fields that utilized the irrigation ditch west of wells 104, 105, and 106 were transferred to USFWS in 1991. In 2003 water rights for an additional 66 acres (231 acre-ft) were transferred to the USFWS. Water levels declined 2.7 ft at wells 104 and 105 between 1992 and 2012 (fig. 5). Water levels in well 106, which is in closer proximity to the area from which water rights were transferred, declined 4.7 ft between 1992 and 2012.

Additional water-level declines following water-right transfers were observed in wells 34, 46, and 110 (fig. 5; Maurer, and others, 2004) following groundwater pumping near well 54 (fig. 4). Well 34 is within the boundary of a cattle feed lot and adjacent to the transfer of 1,336 acres (Maurer, 2004); the water level has declined 2.8 ft between 1992 and 2012. Well 46 is located in Swingle Bench area, within the Truckee Division of the Newlands Project (fig. 2), where water-right retirements and municipal water-right transfers totaling approximately 785 acres (3,270 acre-ft) occurred between 1998 and 2012. Well 46 is downgradient from these transfers, and the water level has declined 6.0 ft since 1992 (fig. 5; Maurer and others, 2004). Well 110 is within 215 acres of fields removed from irrigation in 1997, and the water level has declined 2.8 ft (fig. 5). Well 54 is near center pivot irrigated fields located northwest of Sheckler Reservoir, and the water level has declined 2.0 ft between 1992 and 2012 (fig. 4).

Limitations of Water-Level Change Analysis

Differences in water-level contour locations between the 1992 and 2012 water-table maps may correspond, in part, to improvements in geospatial locations of wells used to develop water-table altitudes. Additionally, well locations not used in the 1992 water-table map may affect changes in water-table contour locations. Limitations of water-table change contours may include temporal differences in water-level measurements. In general, water levels were measured in 2012, but water levels in 12 wells were measured in 2013. Eight of the 12 wells measured in 2013 are in non-irrigated areas near the Stillwater Range and within NAS Fallon (wells 24, 25, 30, 31, 111, 123, 126, 148; figs. 4, 5). Wells 35, 76, 112, and 116 are in irrigation areas but have internannual water-level fluctuations within 2 ft of change (Seiler and Allander, 1993).

The water-level change contours (fig. 4) are intended to represent an approximation of water-level change in the shallow aquifer at the valley scale. The contours are intended to describe general areas of water-level change between 1992 and 2012 and are not accurate at a scale for engineering use or design applications. Field-scale variability in the application of flood irrigation, pumping, or the use of irrigation structures may affect water-level change, thus potentially changing contour locations. Contours are considered approximate, and accuracy is limited by the number and spatial distribution of wells in the study area.

Evaluation of Groundwater Model Scenarios

Lahontan Valley water-right transfers were simulated by Herrera and others (2000) for two areas—south of Fallon and Stillwater, Nevada—using five irrigation scenarios (table 2). The evaluation of the model scenarios was completed by (1) determining water-level change in the modeled areas, (2) comparing the simulated water-level change to observed water-level change in the modeled areas, and (3) evaluating the degree to which model scenario conditions actually occurred in the modeled areas from 1992 to 2012.

Water-Level Change Observed in Modeled Areas

Water levels within and near the Fallon and Stillwater modeled areas were monitored at various frequencies between 1992 and 2012 (appendix 3A and B). Historical water-level data were limited in the modeled areas; therefore, wells near the model boundaries were included to increase spatial water-level observations for model evaluation. The Fallon modeled area has 3 wells within the model boundary (wells 19, 28, and 134) and 3 wells within 0.4 miles of the model boundary (wells 21, 27, and 29; plate 1). Herrera and others

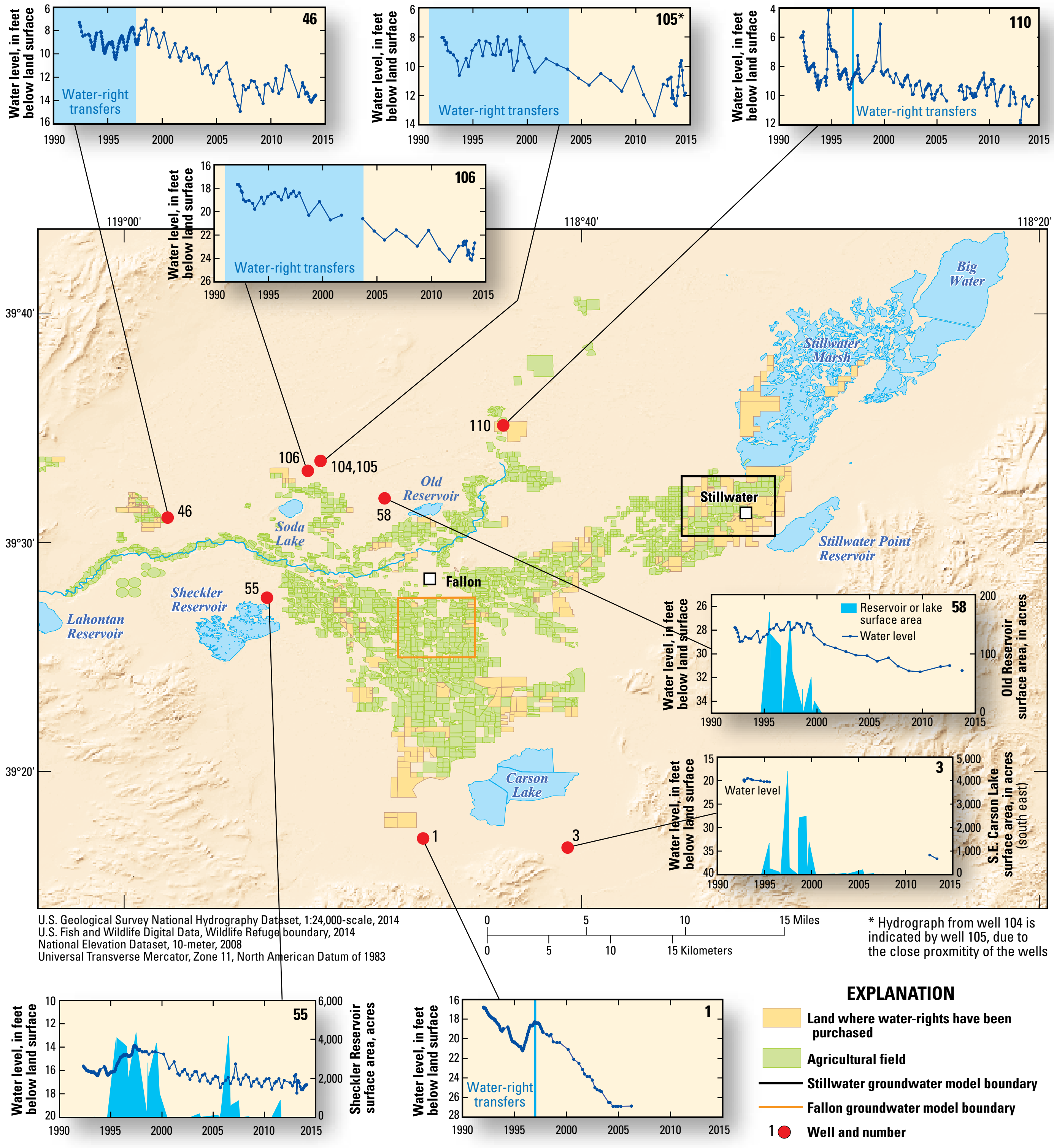

Figure 5. Locations of monitoring wells with hydrographs for 1992–2012, areas of water-right transfers, and agricultural fields, Lahontan Valley, Nevada.

(2000) selected wells 19 and 28 for model calibration. The lowest water levels in the Fallon modeled area occurred in the spring of 1993, prior to the start of irrigation, during a period of extended drought that began in 1988 (appendix 3A; Seiler and Allander, 1993). Water levels after the 1993 water year rebounded to stable conditions and do not exhibit a significant (greater than or less than 2 ft) positive or negative trend from 1994 to 2012 (appendix 3A).

The Stillwater modeled area contains well 82, which was used for model calibration (Herrera and others, 2000); four additional wells, 80, 96, 97, and 112 are within 0.75 miles of the modeled area (plate 1; appendix 3B). Well 149 is near the Stillwater modeled area (plate 1); however, the well has a period of record beginning in 2012. Well 97 was destroyed in 2011 and is not displayed on plate 1; however, the well was approximately 1,000 ft south of well 96 (plate 1).The lowest water levels for the five wells were observed prior to the start of irrigation in 1993. However, the water levels in 1992 and 1994 experienced drawdown from pumping near the wells (appendix 3B). Water levels measured in well 82 exhibited no long-term trends after the 1992 shortened irrigation season.

Scenario Conditions Observed in the Modeled Areas from 1992 to 2012

Water-right transfers in the Fallon modeled area totaled 180 acres (538 acre-ft) between 1994 and 2009 (fig. 6*A*). In the Stillwater modeled area approximately 2,740 acres (8,190 acre-ft) or nearly 50 percent of the modeled area was transferred between 1990 and 2008 (fig. 6*A*). The greatest number of water-right transfers occurred in 1997 with 1,344 acres (4,018 acre-ft) transferred from the Stillwater modeled area. Water-right records indicate the amount of water-right transfers to the USFWS; however, the records do not identify changes in annual irrigation practices in fields outside the water-right transfer areas.

The annual irrigated acres estimated in the Fallon and Stillwater modeled areas determined by remote sensing analysis are shown in figures 6*B* and *C*. Estimated agricultural acreage was 4,420 and 5,738 acres in the Fallon and Stillwater modeled areas, respectively. Estimated irrigated area, as determined by the NDVI threshold of 0.3, ranged between 3,620 and 4,410 acres for the Fallon modeled area and 2,610 and 4,960 acres for the Stillwater modeled area (figs. 6*B*, *C*).

In the Fallon modeled area, irrigated acres remained mostly stable from 1992 to 2011 (fig. 6*B*). Minimum estimated irrigated acreage was observed in 1992, with 82 percent of area or 3,621 acres likely irrigated in the modeled area. Subsequently, the maximum estimated irrigated acres occurred in 1993 and 2005, with an estimated 100 percent or 4,417 acres irrigated in the modeled area. Estimated irrigation was greater than or equal to 98 percent of agriculture field area during the irrigation seasons of 1993, 1995, 1996, 1998, 2005, and 2006 (fig. 6*B*).

In the Stillwater modeled area, there were much greater fluctuations in estimated irrigated acres between 1992 and 2011 (fig. 6*C*). The minimum estimated irrigated acres occurred in 2004, with 46 percent or 2,610 acres classified as irrigated. The Stillwater modeled area maximum estimated irrigated acres occurred in 1993 with 86 percent or 4,964 acres of fields irrigated. Water-right transfers in the Stillwater modeled area represent a decrease of irrigated acres by about 50 percent or 2,740 acres by 2008 (fig. 6*C*). Analysis indicates that changes in irrigated acres are delayed following water-right transfers in the Stillwater modeled area (figs. 6*A*, *C*). For example, changes in irrigated acres from water-right transfers in 1997 were not observed to affect irrigated acres until 1999 (figs. 6*A*, *C*).

Evaluation of Fallon and Stillwater Models

Water-right transfer records, annual changes in irrigated acres, and the length of irrigation seasons evaluated for the modeled areas were used to determine periods from 1992 to 2012 that best approximate the five model scenarios listed in table 2. The simulated water-level declines, based on the five scenarios, were compared to periods of observed water-level change that best represented the scenario conditions (table 3).

Scenario A simulated the removal of 50 percent of groundwater recharge from applied irrigation in the Stillwater modeled area (table 2). Water-right transfers in the Fallon modeled area totaled 180 acres between 1992 and 2012 (fig. 6*A*); therefore, the equivalent of scenario A did not occur in the Fallon modeled area during the study period. In the Stillwater modeled area, water-right records indicate that nearly 50 percent of the irrigated land was transferred by 1998; however, changes in irrigated acres lagged behind the date of water-right transfers in the area (figs. 6*A*, *C*). To relate observed land-use change to model scenario A, average observed water levels from 1994 to 1998 were subtracted from average observed water levels from 1999 to 2012 in the Stillwater modeled area (table 3A). The period 1994–98 was used to avoid the effects of drought conditions that occurred from 1992 to 1993 and ended prior to the decrease in irrigated acres observed in 1999 (figs. 6*A*, *C*). The period 1999–2012 was used to represent water-level conditions after the removal of nearly 50 percent of the irrigated areas (fig. 6*A*).

Scenario A resulted in average simulated water-level declines of 0.6 ft in the Stillwater modeled area (table 3*A*; Herrera and others, 2000). The observed average water-level change for the modeled area is 0.0 ft, and the difference between observed and model simulation results is 0.6 ft. Water-level changes observed in Stillwater modeled area ranged from -0.2 to 0.3 ft (table 3*A*) and are within one standard deviation of the model results for 3 of 5 wells (fig. 7). Observed water-level change in well 82, which was used for model calibration, is a 0.1-ft increase. The maximum difference between scenario A simulated average water-level change

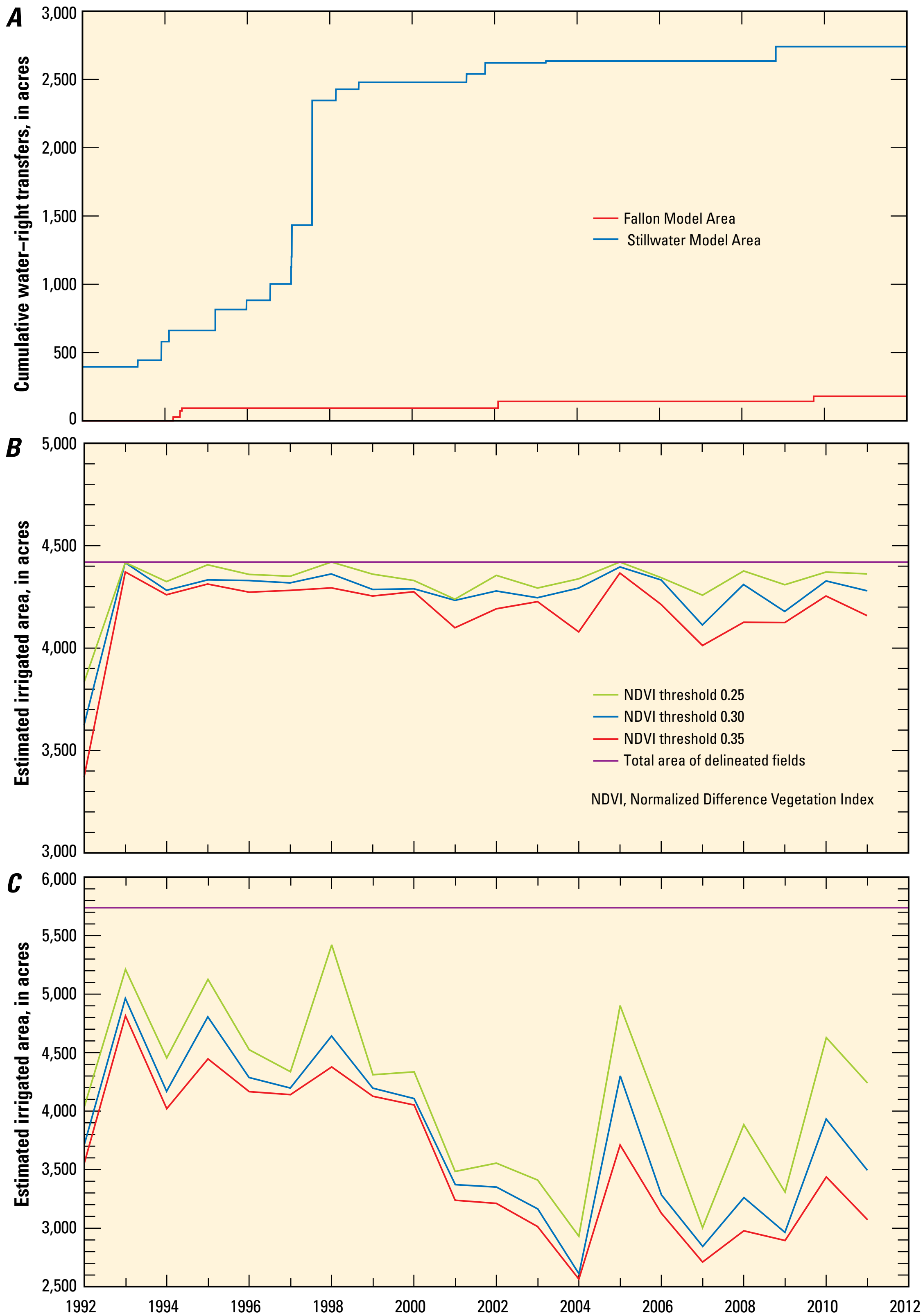

Figure 6. ***A***, Cumulative water-right transfers from 1992 to 2012, and estimated area of fields classified as irrigated using varying Normalized Difference Vegetation Index thresholds within the ***B***, Fallon, and ***C***, Stillwater groundwater model areas, 1992–2012, Lahontan Valley, Nevada.

Table 3. Observed water-level changes in selected monitoring wells in Lahonton Valley, Nevada, and simulated water-level changes from groundwater model scenarios *A*, *B*, and *C*.

[The average observed water-level change is presented with model area declines reported by Herrera and others, 2000; n/a, indicates water-level data are not available for the comparison]

Scenario A—Reduction in irrigation recharge by 50 percent

Model area	Well number	U.S. Geological Survey site identification	Number of measurements	Observed water Level 1994 to 1998 (feet)	Observed water-Level 1999–2012 (feet)	Water-level change (feet)
Stillwater	[1]82	393052118333501	157	4.1	4.0	0.1
	97	393056118304901	57	8.1	7.8	0.3
	96	393106118305301	68	5.5	5.8	-0.3
	80	393114118361001	63	5.2	5.4	-0.2
	112	393309118344701	20	8.1	8.1	0.0
					Observed average water-level change	**0.0**
					Scenario *A* simulated water-level change	**-0.6**

***Scenario B*—Shortened irrigation season by 50 percent**

Model area	Well number	U.S. Geological Survey site identification	Number of measurements	Observed water level for 50 percent irrigation season (1992–1993) (feet)	Observed water level for 100 percent irrigation season 1994–1998 (feet)	Water-level change (feet)
Fallon	[1]19	392642118470901	124	9.1	8.0	-1.1
	21	392705118443001	22	6.2	4.8	-1.4
	27	392540118443301	18	5.7	4.6	-1.1
	[1]28	392540118454501	26	9.6	7.8	-1.9
	29	392439118443401	86	8.6	7.7	-0.8
					Observed average water-level change	**-1.3**
					Scenario *B* simulated water-level change	**-1.1**
Stillwater	[1]82	393052118333501	119	6.5	4.1	-2.4
	97	393056118304901	15	11.0	8.1	-2.8
	96	393106118305301	17	8.7	5.5	-2.7
	80	393114118361001	19	6.7	5.2	-1.4
	112	393309118344701	17	9.6	8.1	-1.3
					Observed average water-level change	**-2.3**
					Scenario *B* simulated water-level change	**-1.4**

***Scenario C*—Water-right transfer of 320 acres**

Model area	Well number	U.S. Geological Survey site identification	Number of measurements	Average water level 1994 to 2012 (feet)	Water-level standard deviation 1994 to 2012 (feet)	Water-level trend from 1994 to 2012 (feet/year)[2, 3]
Fallon	[1]19	392642118470901	225	8.3	0.6	[3]0.00
	21	392705118443001	n/a	n/a	n/a	n/a
	27	392540118443301	n/a	n/a	n/a	n/a
	[1]28	392540118454501	63	5.8	0.8	[3]0.02
	29	392439118443401	119	8.7	0.9	[3]0.03
					Observed average water-level change	**Non-Detect**
					Scenario *C* simulated water-level change	**-0.1**

[1]Indicates wells used for model calibration by Herrera and others (2000).

[2]Trend from linear regression of water-level data from 1994 to 2012.

[3]Regression p-values are greater than 0.05, ranging from 0.09 to 0.33, and no trend is present.

and average observed water-level change in any of the wells is 0.9 ft in well 97.

The groundwater model scenario A included the removal of 50 percent of irrigation; however, the scenario did account for the potential increase in canal conveyance caused by water-right transfers. Herrera and others (2000) did not include the scenario of increasing flow in canals as a result of water-right transfers heading through (or near to) the modeled area on conveyance to Stillwater NWR. The increase in canal seepage potentially made up for decreases in water levels as a result of moving water rights away from the fields included within the Stillwater modeled area. Therefore, the conceptual model of scenario A did not include an accurate prediction of future irrigation canal use, potentially causing an over-estimation of simulated water-level declines by 0.6 ft in the Stillwater modeled area.

Scenario B simulated the water-level change caused by a reduction in the irrigation season length by 50 percent (table 2). Analysis of the irrigation season length in Lahontan Valley indicates that scenario B occurred in 1992 (appendix 2). The irrigation season length for the Fallon and Stillwater modeled areas in 1992 was assumed to be similar to the overall Lahontan Valley irrigation season length. Observed water-level declines in 1992 were extended into the 1993 irrigation season, and declines were averaged over the 2-year period for comparison (table 3*B*). Water levels representing average irrigation season length and limited water-right transfers were observed in the Fallon and Stillwater modeled areas from 1994 to 1998 and were used for comparison to the short duration irrigation seasons of 1992 and 1993 (fig. 6*A*; table 3). In the Fallon modeled area, scenario B simulations resulted in an average water-level decline of 1.1 ft (table 2), and the average observed decline was 1.3 ft (table 3*B*). In the Stillwater modeled area, scenario B simulations resulted in an average decline of 1.4 ft (table 2), and average observed water-level decline was 2.3 ft (table 3*B*). The estimated difference between scenario B and observed water levels are 0.2 and 0.9 ft for the Fallon and Stillwater modeled areas, respectively. Water-level change in all wells used for comparison were within one standard deviation of stimulated model results (figs. 8*A*, *B*).

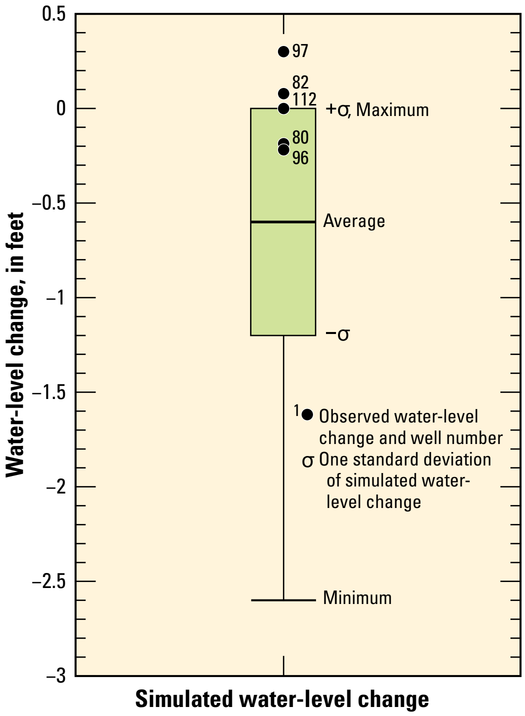

Figure 7. Distribution of scenario A simulated and observed water-level changes for the Stillwater modeled area, Lahontan Valley, Nevada.

The maximum difference between the scenario B simulated and observed well water-level change is 0.8 ft and 1.4 ft in the Fallon and Stillwater modeled areas, respectively.

Observed water-level changes resulting from a shortened irrigation season are reasonably similar (within 1 ft of difference) to simulated results from Herrera and others (2000). This indicates the models are adequately capturing the effect of flow duration in canals and recharge from application of irrigation water to fields and that, overall, water levels may be more sensitive to the duration of the irrigation season than to existing transfers of water rights in the modeled areas. Further, the agreement of simulated and observed results of the shortened irrigation season supports model conclusions from Herrera and others (2000) that a shortened irrigation season caused by drought conditions may result in larger groundwater declines than water-right transfer scenarios in the modeled areas.

Scenario C simulated the removal of 320 irrigated acres in the modeled areas, and scenario D included the additional removal of a lateral canal servicing the water-right transfer areas of scenario C. Water-right transfers in the Stillwater modeled area totaled 2,740 acres during the study period, exceeding conditions simulated in model scenarios C and D by 8 times. In the Fallon modeled area water-right transfers totaled 180 acres, 140 acres less than the scenario C simulation. Transfers occurred over an extended period from 1994 to 2009 (fig. 6*B*), and observed water levels indicate no significant change in water level from 1994 to 2012 (table 3*C* and appendix 3). Lateral canals servicing water-right transfer areas

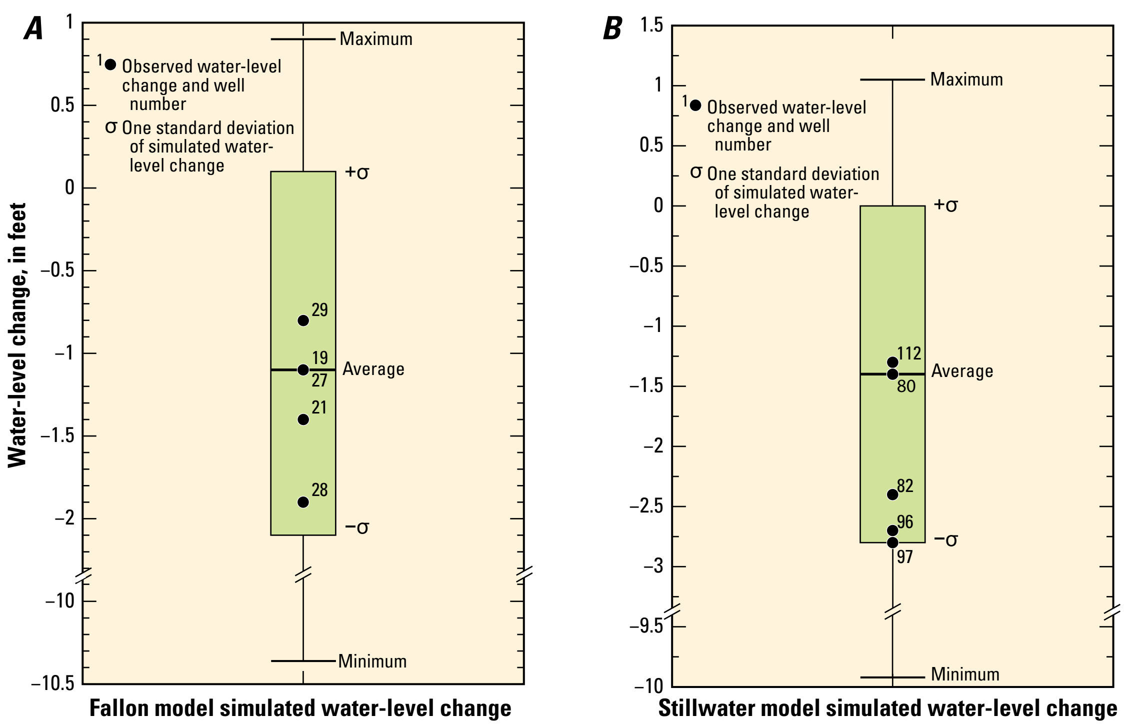

Figure 8. Distribution of scenario B simulated and observed water-level changes for the ***A***, Fallon and ***B***, Stillwater modeled areas, Lahontan Valley, Nevada.

were not removed from use, thus excluding scenario D from comparison. The transfer of water-rights over the extended period 1994–2009 and the transfer of nearly one-half of scenario C water rights precludes a direct comparison of simulated to observed water-level change for scenario C. However, scenario C simulated only modest declines in Fallon modeled area of about 0.1 ft (table 2). Scenario E represented the removal of 100 percent of irrigation from the modeled areas (5,760 irrigated acres) while maintaining recharge from irrigation canals and laterals in the simulation (table 2). Water-right transfers in the Fallon and Stillwater modeled areas totaled 180 acres (538 acre-ft) and 2,740 acres (8,190 acre-ft) from 1992 to 2012 (fig. 6*A*). Owing to the high percentage of irrigated acres in the modeled areas, scenario E is not comparable to observed land-use changes in Fallon and Stillwater modeled areas between 1992 and 2012.

Limitations of the Evaluation of Groundwater Model Scenarios

The model scenarios of Herrera and others, (2000) represent conceptual simplifications of complex physical systems in the modeled areas. The evaluation of model simulations of Herrera and others (2000) to observed conditions in the modeled areas has limitations that include the effects of annual and long-term climate variability on water levels, period of observed water levels used to compare with simulated results, and the spatial distribution and limited number of monitoring wells in the modeled areas.

The cumulative effects of the annual variability of changing climatic conditions and water-right transfers were not simulated by Herrera and others (2000). Annual climate variability affects the amount of water available for irrigation and, therefore, groundwater recharge and water-level change in Lahontan Valley. However, water-level changes caused by the cumulative effect of annual climate variability and water-rights transfers were not evaluated in this study.

For the evaluation of model scenarios, observed periods in the modeled areas were selected to represent approximations of model scenarios developed by Herrera and others, (2000). Recalibration of the models to observed conditions was outside of the scope of this study; therefore, the best available periods for comparison were selected. Owing to this limitation, the periods of observed water-level change selected for comparison to the results of model simulations do not necessarily represent the exact conditions specified by the model scenarios. For example, in the evaluation of Scenario B, the period 1994–98 represents only an approximation of normal conditions for the comparison to the shortened irrigation season of 1992. Water-right transfers occurred throughout the Stillwater modeled area prior to and during the study period, and additional water-level data potentially unaffected by land-use change were not available.

Annual irrigated acres in the modeled areas, estimated using the NDVI threshold of 0.3, may have included relatively healthy vegetation that extends outward from adjacent canals or laterals. The health of this vegetation may be the result of seepage from canals traversing the fields rather than regular application of irrigation water to those fields. Misclassification of irrigation status can also result from wet conditions in early June that caused an elevated maximum NDVI value in years where precipitation in the spring season is above normal. Fields classified as irrigated are assumed to receive regular water throughout the growing season; however, a single application of water may be sufficient to raise the NDVI in a single image. The time required for a field to revert to native vegetation is unknown; consequently, a field may exhibit slightly elevated NDVI values for several years after being permanently removed from irrigation (fallowed).

Scenario results from Herrera and others (2000) represent average water-level change after the 5th year of scenario simulation. In a comparison of observed land-use or irrigation duration change to model scenarios, the duration or transfer period may represent more or less time than is represented in the scenario simulation. Observed land-use or irrigation length changes in the modeled areas represent the general conditions of the model scenarios. Field-scale data on the timing and application of irrigation water were not available; therefore, time periods selected to compare to model scenarios represent only the approximate conditions of the model scenarios and are a limitation of the model evaluation.

Historical water-level records for the modeled areas were not examined for the purpose of model evaluation, and wells near the modeled areas were included to improve the spatial distribution of water levels. Well location and the frequency and timing of water-level measurements may affect the comparison of the observed water-level changes to the results of model scenario simulations. Baseline water levels prior to the effects of water-right transfers and drought conditions were not available for evaluation. Water-level records for wells in the modeled areas begin in 1992, and water levels may have been affected by water-right transfers prior to the start of data collection.

Summary and Conclusions

The acquisition and transfer of water rights to wetland areas of Lahontan Valley, Nevada, has caused concern over the potential effects on shallow aquifer water levels. In 1992, water-levels in Lahontan Valley were measured to construct a water-table map of the shallow aquifer prior to the effects of water-right transfers mandated by the Fallon Paiute-Shoshone Tribal Settlement Act of 1990 (Public Law 101-618, 104 Stat. 3289). From 1992 to 2012, approximately 11,810 water-righted acres, or 34,356 acre-feet of water, were acquired and transferred to wetland areas of Carson Lake and Pasture, Fallon Paiute-Shoshone Tribal Wetlands, and Stillwater National Wildlife Refuge (NWR). A study of the change in water levels in a shallow aquifer and a comparison of simulated and observed water-level changes was conducted by the U.S. Geological Survey in cooperation with the U.S. Fish and Wildlife Service. This report presents water-level changes observed over the period of water-right transfers during 1992–2012 and an evaluation of groundwater-flow model scenarios simulating water-level changes in Lahontan Valley in response to water-right transfers and the reduction in irrigation season length by 50 percent.

Shallow aquifer water-level change was investigated by measuring water levels in 98 wells, 73 of which had water-level change data available from 1992 to 2012. Increases of 2.0 to 4.1 feet were observed in 9 of 73 wells in the central irrigated area of the Newlands Project and near Stillwater NWR. Increases in water levels may correspond to the rebound of groundwater levels and canal discharge from the exceptionally dry and shortened irrigation season of 1992 and the increased conveyance of water owing to water-right transfers to Stillwater NWR.

Water-level declines of 2.0 to 16.2 ft were observed in 11 of 73 wells from 1992 to 2012. Water-level declines were generally observed near the boundary of irrigated and non-irrigated areas of Lahontan Valley. The largest water-level declines were observed near and south of the Carson Lake area. Lahontan Valley water-level declines were observed for 1 well near groundwater pumping (decline of 2.0 ft), 7 wells near the transfer of water rights, of which 3 wells reflect the discontinued use of canals or drains (average decline of 4.7 ft), and 3 wells near inactive surface-water storage reservoirs and lakes (average decline 9.1 ft).

The five goundwater scenarios used to simulate water-right transfers and a reduction in irrigation season length were determined to generally represent observed conditions in the modeled areas from 1992 to 2012. Model scenario results were evaluated by comparing simulated to observed water-level changes for periods representing water-right transfers in areas south of Fallon and near Stillwater. In the Stillwater modeled area, water-right records indicate water rights for nearly 50 percent of the irrigated land were transferred from 1992 to 1998, which is represented by the model scenario reduction in groundwater recharge from irrigation by 50 percent. The model scenario simulated an average decline of 0.6 ft, and average observed water-level change for the modeled area was estimated to be 0.0 ft, or no change. In the Fallon modeled area, water-right transfers of 180 acres occurred from 1994 to 2008. Water-right transfers in the Fallon modeled area were most similar to the scenario with removal of 320 acres from the modeled area. However, the transfer of only one-half of the water rights in the scenario, and the transfer of the water rights over the extended period 1994–2009, precludes a direct comparison of simulated to observed water-level changes. The model scenario resulted in simulated water-level declines of 0.1 ft. Observed water levels available from 1994 to 2012 indicate no significant trends in water levels during the period of water-right transfers and stable water-level conditions or no change in the Fallon modeled area.

The model scenarios included the simulation of a irrigation season shortened by 50 percent, which approximately occurred in 1992 irrigation season. The shortening of the irrigation season in the Fallon modeled area resulted in simulated water-level declines of 1.1 ft; observed declines were estimated to be 1.3 ft. The Stillwater model simulations resulted in a simulated water-level decline of 1.4 ft; observed water levels declined an estimated 2.3 ft for the area. The estimated differences between simulated and observed water levels are 0.2 and 0.9 ft for the Fallon and Stillwater modeled areas, respectively.

Observed water-level change was generally within one standard deviation of model scenario simulations, based on the selected periods of comparison. Simulated and observed water-level changes reasonably agree with each other; however, the model scenarios were based on conditions approximated by the model scenarios, and periods of comparison were generally shorter in duration than those specified by the model scenarios. The potential effect of climate on water-level change was not addressed by the original models and, therefore, was not represented in this evaluation. Model scenarios did not account for the potential increased conveyance and seepage from irrigation canals owing to water-right transfers. Additionally, the limited number of wells in the modeled areas and the proximity of wells to irrigation structures represent a major constraint in evaluating water-level predictions from the model scenarios.

References Cited

Bureau of Reclamation, 2011, Project details: Newlands Project, accessed August 17, 2015, at *http://www.usbr.gov/projects/Project.jsp?proj_Name=Newlands+Project*.

Bureau of Reclamation, 2000, Environmental assessment: Assembly Bill 380 Water Rights Acquisition Program Lahontan Basin Office, 142 p., accessed April 16, 2014, at *http://www.usbr.gov/mp/nepa/documentShow.cfm?Doc_ID=5828*.

Bureau of Reclamation, 2013, Newlands Project Planning Study: Special Report – Appendix C: Projected Future Water Rights and Demands for the Newlands Project.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1, 151 p., *http://pubs.usgs.gov/tm/1a1/.*

Gao, Bo-cai, 1996, NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space: Remote Sensing of Environment, v. 58, no. 3, p. 257–266.

Glancy, P.A., 1986, Geohydrology of the basalt and unconsolidated sedimentary aquifers in the Fallon Area, Churchill County, Nevada: U.S. Geological Survey Water-Supply Paper 2263, 62 p., *http://pubs.usgs.gov/wsp/2263/report.pdf.*

Hallock, R.J., and Hallock, L.L., eds., 1993, Detailed study of irrigation drainage in and near wildlife management areas west-central Nevada, 1987–90, Part B. Effect on biota in Stillwater and Fernley Wildlife Management areas and other nearby wetlands: U.S. Geological Survey Water-Resources Investigations Report 92–4024B, 84 p.

Harbaugh, A.W., and McDonald, M.G., 1996a, Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-file Report 96–486, 56 p.

Harbaugh, A.W., and McDonald, M.G., 1996b, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-file Report 96–485, 150 p.

Herrera, N.B., Seiler, R.S., and Prudic, D.E., 2000, Conceptual evaluation of ground-water flow and simulated effects of changing irrigation practices on the shallow aquifer in the Fallon and Stillwater areas, Churchill County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 99–4191, 70 p., *http://pubs.er.usgs.gov/publication/wri994191*.

Hoffman, R.J., Hallock, R.J., Rowe, T.G., Lico, M.S., Burge, H.L., and Thompson, S.P., 1990, Reconnaissance investigation of water quality, bottom sediments, and biota associated with irrigation drainage in and near Stillwater Wildlife Management Area, Churchill County, Nevada, 1986–87: U.S. Geological Survey Water-Resources Investigations Report 89–4105, 150 p., *http://pubs.er.usgs.gov/publication/wri894105.*

Hutchinson, M.F., Xu, T., and Stein, J.A., 2011, Recent Progress in the ANUDEM Elevation Gridding Procedure: Redlands, California, Geomorphometry 2011 Conference, T. Hengel, I.S. Evans, J.P. Wilson, and M. Gould, eds., p. 19–22, accessed July, 2013 *http://geomorphometry.org/HutchinsonXu2011*.

Karl, T.R., Knight, R.W., Ezell, D.S., and Quinlan, F.T., 1986, Probabilities and precipitation required to end/ameliorate droughts, Historical Climatology Series 3–16, Asheville: National Oceanic and Atmospheric Administration, National Climatic Data Center, 315 p.

Lee, C.H., and Clark, W.O., 1916, Report of Soda Lakes investigation, Truckee-Carson Project, near Fallon, Nevada: U.S. Geological Survey Report, p. 657–706.

Lico, M.S., 1992, Detailed study of irrigation drainage in and near wildlife management areas, west-central Nevada, 1987–90, Part A. water quality, sediment composition, and hydrogeochemical processes in Stillwater and Fernley Wildlife Management Areas: U.S. Geological Survey Water-Resources Investigations Report 92–4024A, 65 p.

Lico, M.S., and Seiler, R.L, 1994, Ground-water quality and geochemistry, Carson Desert, Western Nevada: U.S. Geological Survey Open-File Report 94–31, 91 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p., accessed May 17, 2008, at *http://pubs.er.usgs.gov/publication/pp708.*

Lopes, Thomas J., Buto, Susan G., Smith, J. LaRue, Welborn, Toby L., 2006, Water-table levels and gradients, Nevada, 1947–2004: U.S. Geological Survey Scientific Investigations Report 2006–5100, 35 p., 3 pls, at *http://pubs.usgs.gov/sir/2006/5100/*.

Maurer, D.K., Johnson, A.K., and Welch, A.H., 1996, Hydrogeology and potential effects of changes in water use, Carson Desert Agricultural Area, Churchill County, Nevada: U.S. Geological Survey Water-Supply Paper 2436, 106 p., *http://pubs.usgs.gov/wsp/2436/report.pdf.*

Maurer, D.K., Seiler, R.L., and Watkins, S.A., 2004, Evaluation of U.S. Geological Survey monitoring-well network and potential effects of changes in water use, Newlands Project, Churchill County, Nevada: U.S. Geological Survey Scientific Investigations Report 2004–5246, 46 p., *http://pubs.usgs.gov/sir/2004/5246/.*

Maurer, D.K., and Welch, A.H, 2001, Hydrogeology and geochemistry of the Fallon Basalt and adjacent aquifers, and potential sources of Basalt recharge, in Churchill County, Nevada. U.S. Geological Survey Water-Resources Investigations Report 01–4130, 73 p.

Morgan, D.S., 1982, Hydrogeology of the Stillwater geothermal area, Churchill County, Nevada: U.S. Geological Survey Open-File Report 82–345, 95 p.

Morrison, R.B., 1964, Lake Lahontan—Geology of southern Carson Desert, Nevada: U.S. Geological Survey Professional Paper 401, 156 p., *http://pubs.er.usgs.gov/publication/pp401*.

National Oceanic and Atmospheric Administration, 2014a, 1981–2010 Climate normals: Climatology of the United States No. 81, 26 Nevada: Asheville, North Carolina, National Climatic Data Center, 26 p., *http://www.ncdc.noaa.gov/oa/climate/normals/usnormals.html*.

National Oceanic and Atmospheric Administration, 2014b, The National Climatic Data Center: North American drought monitor indices, accessed April 20, 2014, at *http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/indices.php*.

Nevada Division of Water Resources, 2013, Nevada's hydrographic regions, accessed July 2013, at *http://water.nv.gov/mapping/hydrographic.cfm*.

Olmsted, F.H., 1985, Ground-water discharge and recharge in the Soda Lakes and Upsal Hogback geothermal areas, Churchill County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 85–4033, 27 p., *http://pubs.usgs.gov/wri/1985/4033/report.pdf*.

Ozdogan, M., and Gutman, G., 2008, A new methodology to map irrigated areas using multi-temporal MODIS and ancillary data: An application example in the continental U.S.: Remote Sensing of Environment, v. 112, no. 9, p. 3520–3537.

Rouse, J.W., Haas, R.H., Schell, J.A., and Deering, D.W., 1974, Monitoring vegetation systems in the Great Plains with ERTS: Proceedings of the third Earth Resources Technology Satellite-1 Symposium, NASA, Scientific and Technical Information Office, Washington (1974), p. 309–317.

Rush, F.E., 1972, Hydrologic reconnaissance of Big and Little Soda Lakes, Churchill County, Nevada: Nevada Department of Conservation and Natural Resources, Water-Resources-Information Report 11, 1 sheet, accessed July 2013 at *http://images.water.nv.gov/images/publications/Information%20series/11.pdf*.

Rydlund, P.H., Jr., and Densmore, B.K., 2012, Methods of practice and guidelines for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, book 11, chap. D1, 102 p. with appendixes.

Seiler, R.L., and Allander, K.K., 1993, Water-level changes and directions of ground-water flow in the Shallow Aquifer, Fallon Area, Churchill County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 93–4118, 74 p., *http://pubs.er.usgs.gov/publication/wri934118*.

Simley, J.D., and Carswell, W.J., Jr., 2009, The National Map—Hydrography: U.S. Geological Survey Fact Sheet 2009–3054, 4 p., *http://pubs.usgs.gov/fs/2009/3054/*.

Simonds, J., 1996, The Newlands Project: Bureau of Reclamation Report, 39 p., *http://www.usbr.gov/projects//ImageServer?imgName=Doc_1305124117489.pdf*.

Stabler, Herman, 1904, Report on ground waters of Carson Sink: U.S. Geological Survey Reclamation Service, 49 p.

U.S. Census Bureau, 2014, State & county quickfacts, accessed April 11, 2014, at *http://quickfacts.census.gov/qfd/states/32/3224100.html*.

U.S. Department of Agriculture, 2009, National Agricultural Imagery Program (NAIP) Information Sheet: 2 p., accessed July, 2013, at http:// *www.fsa.usda.gov/Internet/FSA_File/naip_2012_final.pdf*.

U.S. Geological Survey, 2012a, Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) Algorithm Description Document, December 2012, 20 p., *http://landsat.usgs.gov/documents/ledaps_add.pdf*.

U.S. Geological Survey, 2012b, Digital Orthophoto Quadrangle (DOQs), accessed September 9, 2014, at *https://lta.cr.usgs.gov/DOQs*.

U.S. Geological Survey, 2013, Water-resources data for the United States, water year 2012: U.S. Geological Survey Water-Data Report WDR-US-2012, site 10312150, at *http://wdr.water.usgs.gov/wy2012/pdfs/10312150.2012.pdf*.

U.S. Geological Survey, 2014, Water-resources data for the United States, Water Year 2013: U.S. Geological Survey Water-Data Report WDR-US-2013, site 10312150, *http://wdr.water.usgs.gov/wy2013/pdfs/10312150.2013.pdf*.

Appendix 1: Site identification, construction data, and water-level measurements for selected monitoring wells, in Lahontan Valley, Nevada, 1992 and 2013.

The following tables are distributed as part of this report in Microsoft® Excel 2010 format and is available for download at *http://dx.doi.org/10.3133/sir20165045*

Appendix 2: Estimated durations of Newlands Project Irrigation Seasons, 1992–2012, Lahontan Valley, Nevada.

The following tables are distributed as part of this report in Microsoft® Excel 2010 format and is available for download at *http://dx.doi.org/10.3133/sir20165045*.

Appendix 3: Hydrographs for selected monitoring wells in and near the A, Fallon and B, Stillwater modeled areas, Lahontan Valley, Nevada.

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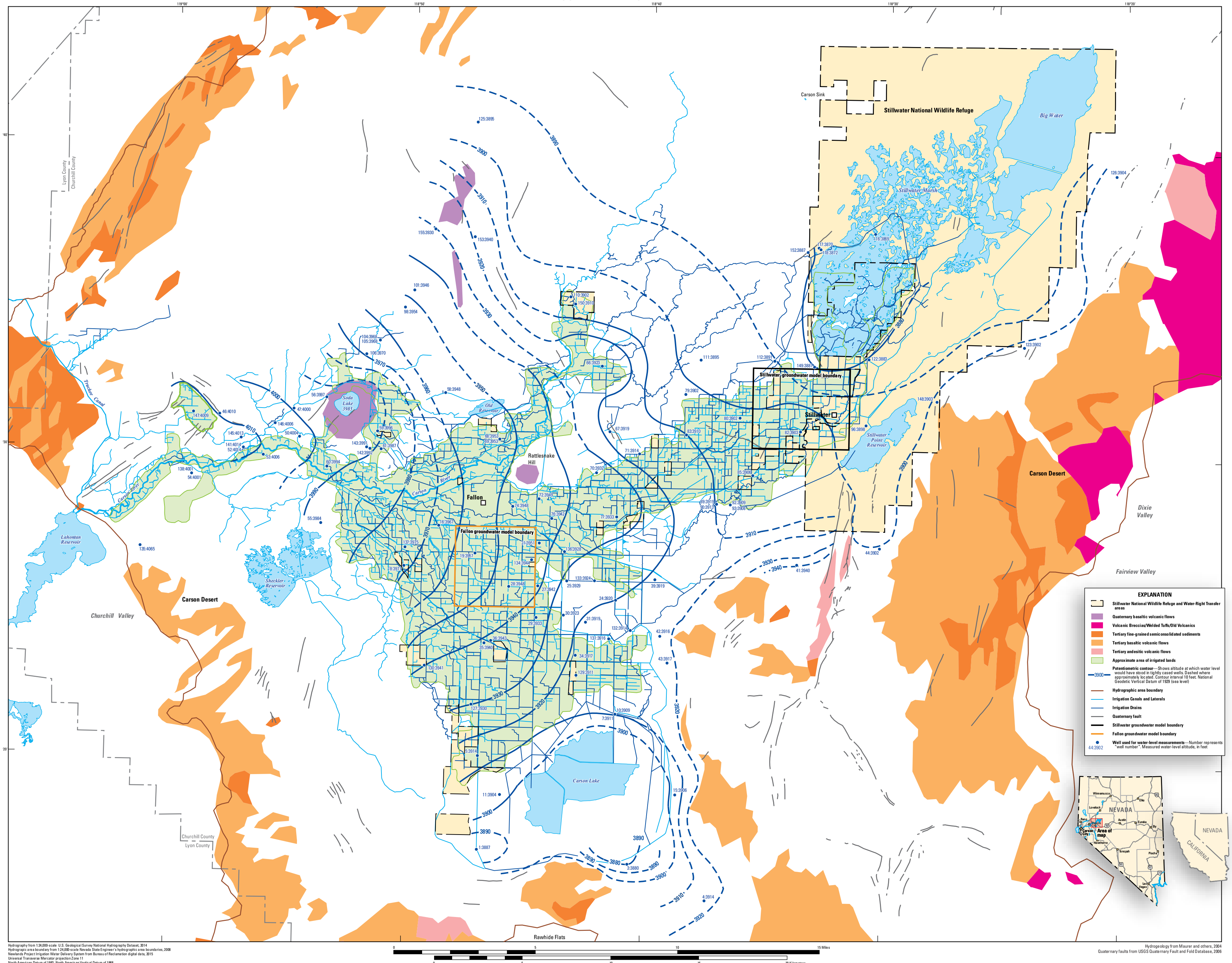

Hydrography from 1:24,000-scale U.S. Geological Survey National Hydrography Dataset, 2014
Hydrograpic area boundary from 1:24,000-scale Nevada State Engineer's hydrographic area boundaries, 2008
Newlands Project Irrigation Water Delivery System from Bureau of Reclamation digital data, 2015
Universal Transverse Mercator projection Zone 11
North American Datum of 1983. North American Vertical Datum of 1988

Hydrogeology from Maurer and others, 2004
Quaternary faults from USGS Quaternary Fault and Fold Database, 2006

Water-table contours of Lahontan Valley

By

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2015

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Smith and others—**Groundwater-Level Change and Evaluation of Simulated Water Levels for Irrigated Areas in Lahontan Valley, Churchill County, West-Central Nevada, 1992–2012**—SIR 2016–5045

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20165045