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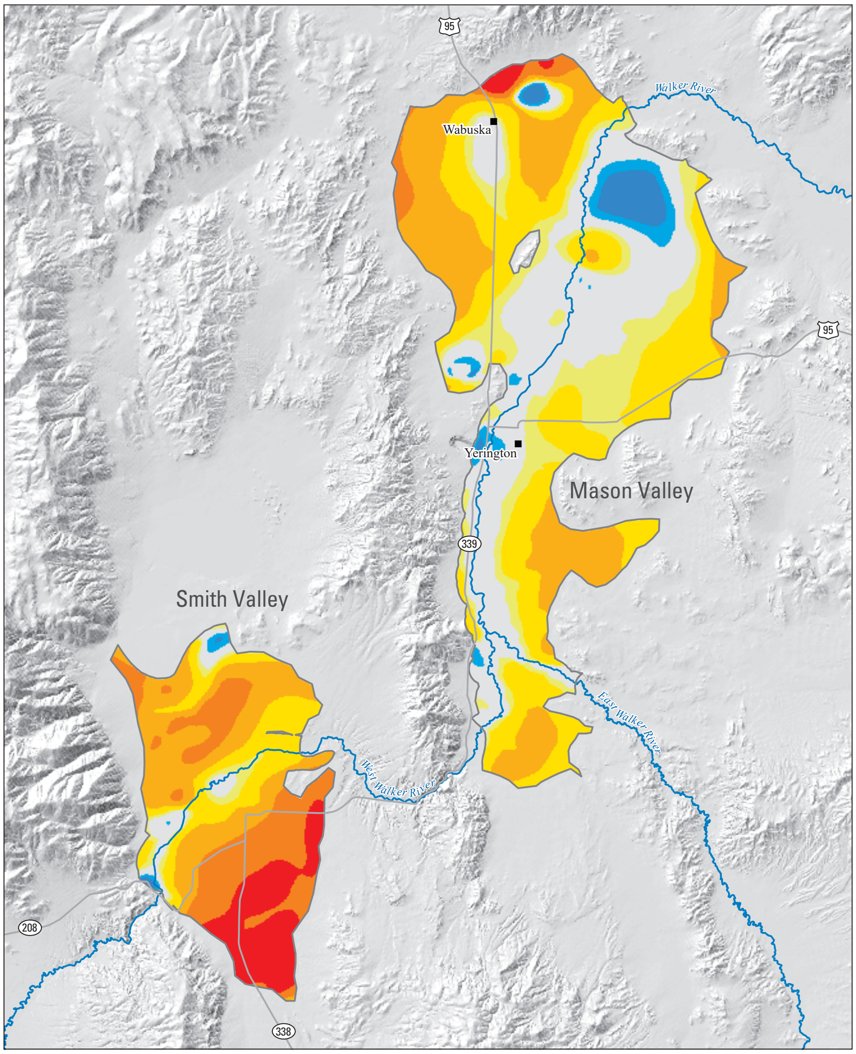
Estimated Effects of Pumping on Groundwater Storage and Walker River Stream Efficiencies in Smith and Mason Valleys, West-Central Nevada



Scientific Investigations Report 2022–5123

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

Cover: Groundwater-level change in Smith and Mason Valleys, Nevada, over period of analysis, 1970–2020.

Estimated Effects of Pumping on Groundwater Storage and Walker River Stream Efficiencies in Smith and Mason Valleys, West-Central Nevada

By Gwendolyn E. Davies and Ramon C. Naranjo

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Buto, S.B, Evetts, D.M., Smith-Sager, S., 2006, Water-table contours of Nevada, U.S. Geological Survey data release, https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2006-5100_wanv_l.xml.

Medina, R. L., Lopes, T.J., and Little, B.D., 2022, Data for the 2009 report Hydrologic Setting and Conceptual Hydrologic Model of the Walker River Basin, West-Central Nevada: U.S. Geological Survey data release, https://doi.org/10.5066/P9US1B3S.

Welborn, T.L., and Medina, R.L., 2022, Data for the 1976 report Geohydrology of Smith Valley, Nevada, with special reference to the water-use period 1953–72: U.S. Geological Survey data release, https://doi.org/10.5066/P9KK0KZW.

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Conversion Factors

U.S. customary units to International System of Units

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	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per 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)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic foot per day (ft^3/d)
cubic feet per second per mile (ft^3/s-mi)	0.017595068	cubic meter per second per kilometer (m^3/s-km)
foot per year (ft/yr)	0.3048	meter per year (m/yr)

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

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.

Supplemental Information

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2015 was from October 1, 2014, to September 30, 2015.

Abbreviations

DEM	digital elevation model
Management Area	Mason Valley Wildlife Management Area
NDWR	Nevada Division of Water Resources
PDSI	Palmer Drought Severity Index
USGS	U.S. Geological Survey
WY	water year

Estimated Effects of Pumping on Groundwater Storage and Walker River Stream Efficiencies in Smith and Mason Valleys, West-Central Nevada

By Gwendolyn E. Davies and Ramon C. Naranjo

Abstract

The Walker River originates in the Sierra Nevada Mountains and flows nearly 160 miles to its terminus at Walker Lake in west-central Nevada. The river provides a source of irrigation water for tens of thousands of acres of agricultural lands in California and Nevada and is the principal source of inflow to Walker Lake. Extraction of groundwater for agricultural use became prevalent in the late 1950s and early 1960s to supplement irrigation demands not met by surface-water diversions during times of drought. There is growing concern that continued groundwater withdrawals within the Walker River Basin are likely contributing to depleted streamflow of the Walker River and the long-term depletion of groundwater storage in the basin. This report documents changes in groundwater storage-volume and trends in Walker River stream efficiency, a measure of change in flow due to gaining or losing conditions, in the two largest agricultural valleys in the Walker River Basin, Smith and Mason Valleys, for a multi-decade period.

Groundwater-level maps from previous studies were used for the beginning (1970) and middle (2006) points of this study. Groundwater levels measured from 1991–95 and 2016–20 were used to construct median groundwater-level maps that represented conditions in 1995 and 2020. Valley wide groundwater-level change was calculated by comparing groundwater-level maps for the periods 1970–95, 1996–2006, and 2007–20 and by observing the overall change from 1970 to 2020. Groundwater storage-volume change was calculated using groundwater-level change and previously defined specific yield values. Between 1970 and 2020, groundwater storage-volume declined 287,600 acre-feet in Smith Valley and 269,000 acre-feet in Mason Valley. Using groundwater storage-volume decline and annual groundwater pumpage rates, a maximum groundwater pumpage rate can be computed to support management of water resources. In Smith Valley, groundwater pumping in excess of 22,300 acre-feet per year would likely result in groundwater storage decline. In Mason Valley, groundwater pumping in excess of 75,200 acre-feet per year would likely result in groundwater storage decline.

Stream efficiency was calculated using continuous streamflow data and monthly diversion volumes on two reaches: (1) the West Walker River in Smith Valley, from 1948 to 2020 and (2) the Walker River in Mason Valley, from 1958 to 2020. Stream efficiency during non-irrigation season in Smith and Mason Valleys declined at a statistically significant rate of 1.1 and 0.6 percent per year, respectively. Trends in stream efficiency corresponded to occurrence of prolonged drought, deviation from average annual streamflows, and total groundwater pumpage.

Long-term declines in groundwater storage-volume and stream efficiency demonstrate that the alluvial aquifer system is becoming increasingly depleted, such that the river can no longer replenish groundwater storage while simultaneously balancing groundwater and surface-water withdrawals. The introduction of supplemental groundwater pumpage was intended to offset surface-water deficits during dry years; however, pumpage occurs even in years when average or above average streamflows meet surface-water demands. Reliance on supplemental groundwater pumpage has resulted in widespread groundwater storage-volume decline and decreased stream efficiency. With each successive drought cycle, the ability of Walker River to sustain streamflows and convey water downstream has diminished. Above average wet periods have a marginal and short-lived effect on rebounding the groundwater levels outside of the river corridor. Moreover, if the trend continues, each future drought cycle may further reduce groundwater supplies and that may further decrease streamflow reliability.

Introduction

Smith and Mason Valleys are the primary agricultural water-using areas within the Walker River Basin (fig. 1). Settlement by white pioneers for agriculture began in 1859 (Horton, 1996). Nathan Mason and members of the Smith family used the vegetated regions bordering the Walker River and West Walker River to support livestock production (Horton, 1996). Extensive ditch construction on the Walker River in Mason Valley occurred between 1861 and 1865 and included the McLeod, Joggles, Spragg-Woodcock, Fox, Greenwood, and Mickey ditches (fig. 2; Horton, 1996). Alfalfa was introduced into the area during this time and, by the mid-1870s, it was the primary irrigated crop along the eastern Sierra Nevada (Horton, 1996). In 1890, the Colony ditch was the first ditch constructed in Smith Valley that diverted water from the West Walker River (fig. 2; Horton, 1996). Surface-water use for agriculture continued to develop rapidly into the turn of the century and by 1919, the U.S. Census of Agriculture estimated approximately 103,000 acres were being irrigated in Smith and Mason Valleys and along the East Walker River (Horton, 1996).

Bridgeport Reservoir on the East Walker River and Topaz Lake on the West Walker River, upstream from Smith and Mason Valleys (fig. 1), were constructed in the early 1920s. Weber Reservoir on the Walker River, downstream from Mason Valley (fig. 1), was constructed in 1935. These reservoirs provide irrigation storage to the basin. In 1939, the Walker River Decree (United States v. Walker River Irrigation District, 1936, Equity No. C-125; California Department of Water Resources, 1992) was finalized and all rights to natural flows on the Walker River were fully allocated with the most senior priority date of 1859 and the most junior priority date of 1921 for decree water rights (Horton, 1996). Storage water rights to Bridgeport and Topaz Reservoirs were awarded to those without adequate decree rights (priority date of 1874 or later; Horton, 1996). Weber Reservoir never received a right to storage and therefore does not have a priority date. Additionally, in 1939, groundwater was first declared subject to appropriation in Nevada (Weldon, 2003). Triggered by severe drought from 1959 to 1962, many irrigation wells were drilled in Smith and Mason Valleys and groundwater became a significant source for agricultural water use (Horton, 1996). Following increased groundwater use, the Nevada Division of Water Resources (NDWR) classified Smith and Mason Valleys as designated groundwater basins in 1960, which authorizes the State Engineer to implement additional administration for groundwater use in basins where permitted groundwater is being depleted (Horton, 1996; Nevada Division of Water Resources, 2019). The filing of applications for supplemental groundwater rights accelerated in the 1960s and 1970s. Supplemental groundwater rights were only to be used to make up the difference when the surface-water decree could not be met during drought years.

Groundwater pumpage volumes were not documented on a consistent annual basis until the 1990s; however, several studies estimated pumpage volumes using electric power consumption records. In Smith Valley, during 1972, an estimated 20,000 acre-feet (acre-ft) of groundwater was extracted for irrigation (acre-feet per year [acre-ft/yr]; Rush and Schroer, 1976, p. 9). In Mason Valley, during the drought of 1959–62, an estimated 10,300 acre-ft/yr of groundwater was extracted for irrigation (Huxel and Harris, 1969, p. 35). In 1994, the NDWR began reporting annual groundwater pumpage volumes by use (fig. 3). From 1994 to 2004, annual total groundwater withdrawal in the Smith and Mason Valleys had grown to 23,100 and 76,800 acre-ft/yr, respectively (Gallagher, 2005). Supplemental groundwater is managed in the Smith and Mason Valleys by the NDWR using the system yield approach. System yield generally is defined as the maximum amount of surface and groundwater that can be removed from the system annually, without depleting the system for an indefinite period of time (Malmberg, 1967, p. 37). Since the late 1970s, the total amount of appropriated groundwater in Smith and Mason Valleys has been generally constant, at approximately 55,000 and 150,000 acre-ft/yr, respectively (Nevada Division of Water Resources, 2021b; W. Fereday, Nevada Division of Water Resources, written commun., 2021).

Basin-wide mapping of irrigated land that was done using satellite imagery acquired in 2000 estimated total irrigated land in Smith Valley at approximately 18,900 acres (Lopes and Allander, 2009a) and 38,900 acres in Mason Valley (Lopes and Allander, 2009a; Carroll and others, 2010; fig. 2), which is nearly 40-percent less irrigated land than in 1919 (Horton, 1996). Alfalfa continues to be the primary crop grown in the Walker River Basin. Other crops grown in the Walker River Basin include pasture grass, onion, garlic, corn, and winter wheat.

In 2015, the U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation, began a project to document the effect of groundwater pumpage on stream efficiency and the aquifer responses to major flow events in Smith and Mason Valleys from the period of first widespread groundwater development (late 1950s) to 2015. In 2020, the USGS, in cooperation with the U.S. Bureau of Indian Affairs, expanded the project to include the most recent drought and wet cycle from 2015 to 2020.

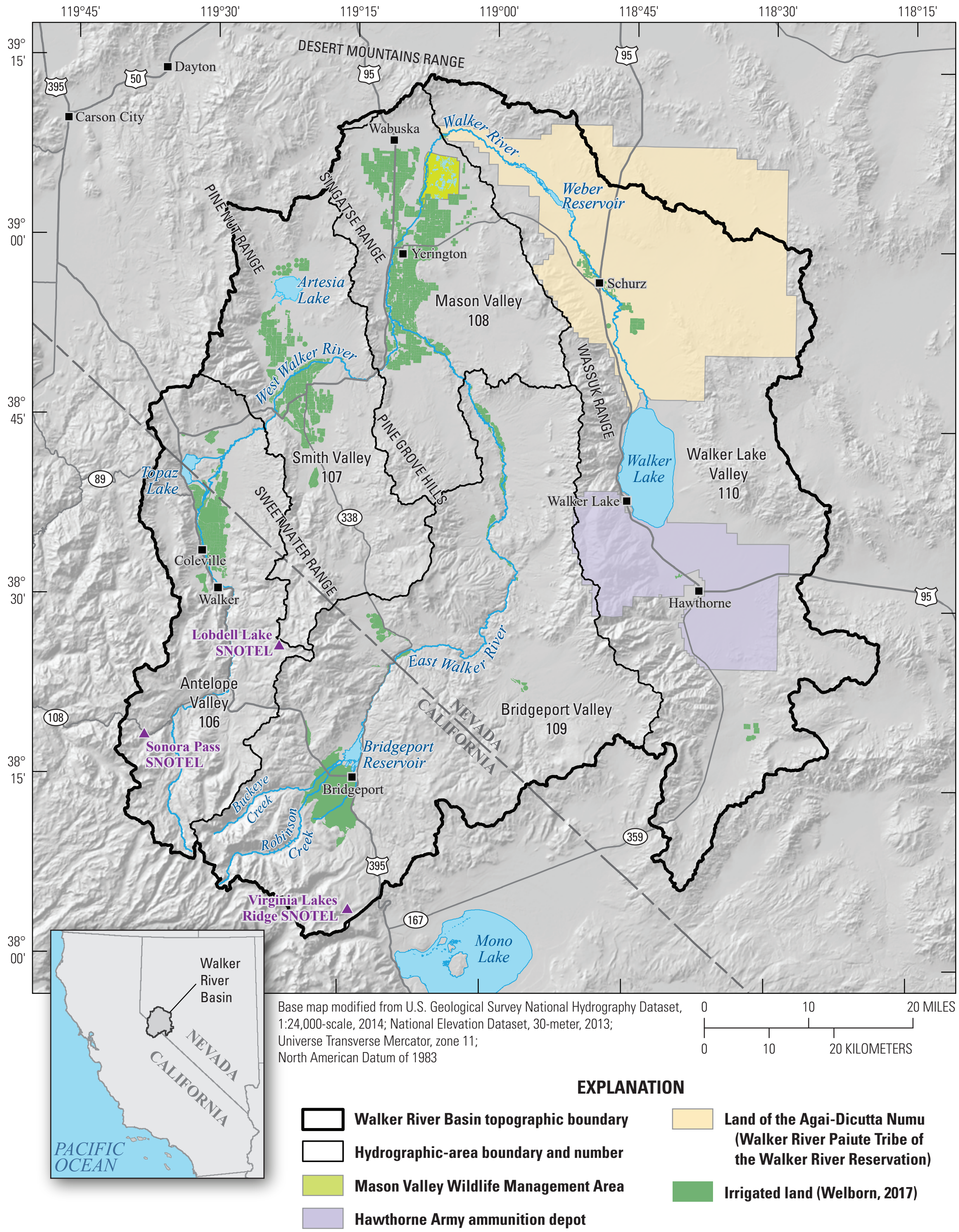
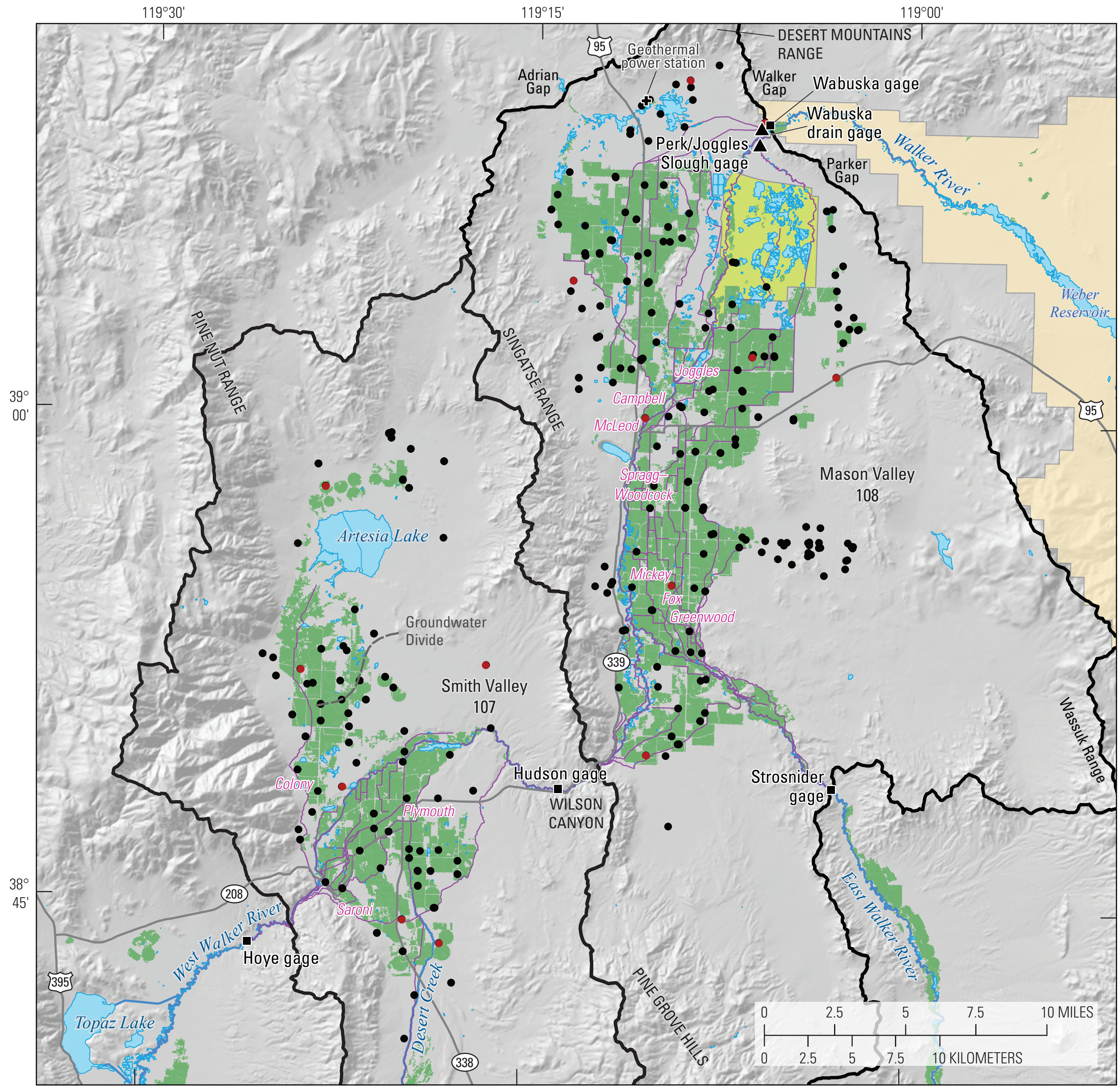


Figure 1. Geographic features of the Walker River Basin, Nevada, including regional boundaries, major towns, and extend of irrigated lands (Welborn, 2017).



Base map modified from U.S. Geological Survey, National Hydrography Dataset, 1:24,000-scale, 2014;
National Elevation Dataset, 30-meter, 2013; Universe Transverse Mercator, zone 11;
North American Datum of 1983

EXPLANATION

- Hydrographic-area boundary and number
- Mason Valley Wildlife Management Area
- Hawthorne Army ammunition depot
- Land of the Agai-Dicutta Numu (Walker River Paiute Tribe of the Walker River Reservation)
- Irrigated lands from National Land Cover Database (Yang and others, 2018)
- Irrigation canals and ditches
- Long-term USGS streamgages
- Short-term USGS streamgages
- Groundwater monitoring wells (USGS and NDWR)
- Selected long-term monitoring wells

Figure 2. Geographic features of Smith and Mason Valleys, Nevada. State Engineer hydrographic-areas, extent of irrigated lands in the National Land Cover Database (Yang and others, 2018), irrigation canals, and ditches, U.S. Geological Survey (USGS) streamgages (U.S. Geological Survey, 2021), and USGS and Nevada Division of Water Resources (NDWR) groundwater monitoring wells (Nevada Division of Water Resources, 2021a; U.S. Geological Survey, 2021).

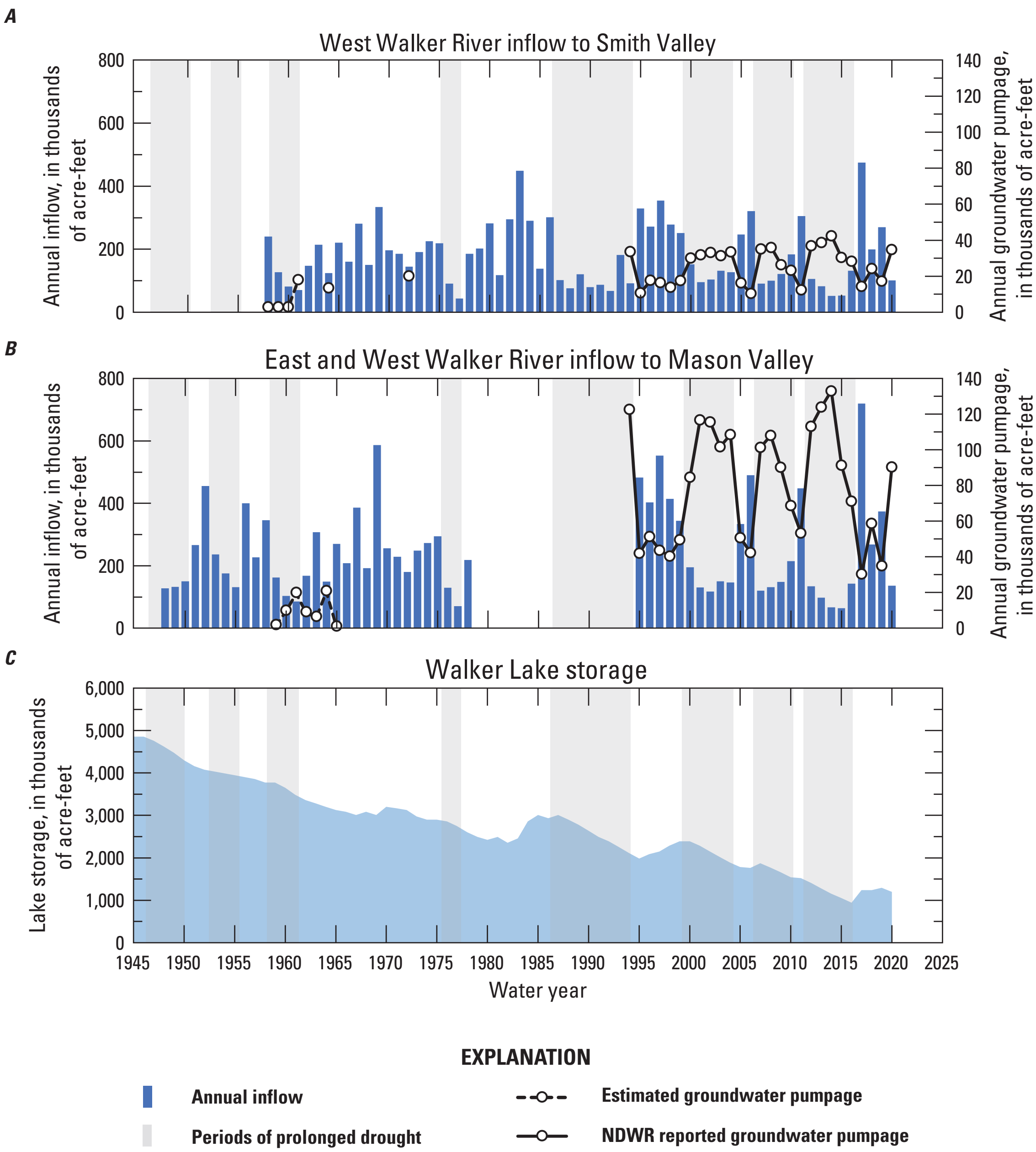


Figure 3. Annual surface-water inflow and groundwater pumpage in the study area and Walker Lake annual storage: *A,* Annual inflow to Smith Valley at the Hoye streamgage, water years 1958–2020 (U.S. Geological Survey, 2021). Smith Valley total groundwater pumpage volumes for calendar years 1994–2020 (Nevada Division of Water Resources, 2021b). Estimated irrigation pumpage volume in 1958–61, 1964, and 1972 (Rush and Schroer, 1976); *B,* Annual inflow to Mason Valley at Hudson and Strosnider streamgages, water years 1948–2020 (U.S. Geological Survey, 2021). Mason Valley total groundwater pumpage volumes for calendar years 1994–2020, (Nevada Division of Water Resources, 2021b). Estimated irrigation pumpage volumes 1959–65 (Huxel and Harris, 1969); and *C,* Walker Lake storage change for water years 1945–2020 (U.S. Geological Survey, 2021). Highlighted drought years include: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16. Abbreviation: NDWR, Nevada Division of Water Resources.

Purpose and Scope

This report documents the groundwater-level changes in Smith and Mason Valleys between water years (WYs) 1965–72 and 2020 with groundwater-level and groundwater-level change maps. Groundwater-level maps developed in Smith Valley in 1972 (Rush and Schroer, 1976) and Mason Valley in 1965–66 (Huxel and Harris, 1969) provide an initial reference point for establishing change in groundwater level. Groundwater-level maps developed by Lopes and Allander (2009a) are used to represent discrete conditions in WY 2006. Two additional groundwater-level maps are created for the multi-year periods of 1991–95 and 2016–20. Groundwater-level changes are evaluated by creating groundwater-level change maps for three longer-term periods: 1970–95, 1995–2006, and 2006–20, as well as total overall change from 1970 to 2020. Total groundwater-storage volume changes are calculated using groundwater-level change maps and previous estimates of specific yield (Huxel and Harris, 1969; Rush and Schroer, 1976). Additionally, groundwater hydrographs are compiled for the few long-term wells in Smith and Mason Valleys that have been measured consistently since the 1960–70s to present. Changes in groundwater-levels are evaluated by considering proximity to the river and deviation from average streamflow. Finally, this report documents the change in stream efficiency of the West Walker River through Smith Valley (from 1948 to 2020) and the Walker River through Mason Valley (from 1958 to 2020). Stream efficiency is calculated using USGS continuous streamflow data and surface-water diversion volumes for the available regulated streamflow record.

Study Area

Smith Valley is a north-south trending valley that is bounded by the Pine Nut Range to the west, the Singatse Range to the east, and the Sweetwater Range and Pine Grove Hills to the south (fig. 1). Land-surface altitudes range from about 11,700 feet (ft) in the Sweetwater Range to about 4,500 ft in Artesia Lake (U.S. Geological Survey, 2020). The West Walker River crosses Smith Valley from west to east, exiting at Wilson Canyon where it flows into Mason Valley (fig. 2). Desert Creek is a minor tributary to the West Walker River at the south end of the valley, with most flow diverted annually before its confluence (Loeltz and Eakin, 1953). A cluster of geothermal springs are located along the toe of the Pine Nut Range (Loeltz and Eakin, 1953). Runoff and hot spring discharge from the mountain ranges at the north end of the valley drains toward Artesia Lake and is considered negligible. Artesia Lake is a playa, consisting of mud and salt flats and intermittently holds surface water.

Mason Valley is a north-south trending valley that is bounded by the Singatse and Pine Grove Hills Ranges to the west, the Wassuk Range to the east, and the Desert Mountains Range to the north (fig. 1). Land-surface altitudes range from about 8,600 ft in the Pine Grove Hills Range to about 4,300 ft in the lowlands at the northern end of the valley (U.S. Geological Survey, 2020). The East and West Walker Rivers flow into the valley from the south and join to form the main stem of the Walker River, which flows northward exiting eastward at Walker Gap (fig. 2). There are no tributaries to Walker River within Mason Valley and runoff from the surrounding ranges is considered negligible.

After exiting Mason Valley, the Walker River flows through lands of the Agai-Dicutta Numu (Walker River Paiute Tribe of the Walker River Reservation, Nevada) and ultimately terminates into Walker Lake (fig. 1). The Walker River is the main source of inflow to Walker Lake. The only outflow from Walker Lake is evaporation from the lake surface. The long-term (1919–2007) combined inflow to Walker Lake is about 118,000 acre-ft/yr, with annual evaporation from Walker Lake of about 195,000 acre-ft/yr (Allander and others, 2014). Thus, the annual difference between inflow and outflow (annual lake storage change) is approximately −76,700 acre-ft/yr. Between 1882 (the year of the earliest USGS lake level measurement) and 2020, Walker Lake water-level has declined 166 ft, which has resulted in a decrease in lake storage of approximately 7,678,000 acre-ft (Lopes and Smith, 2007; U.S. Geological Survey, 2021). This decrease is the result of surface-water withdrawals for irrigation and not from drought conditions (Milne, 1987; Beutel and others, 2001).

For a more thorough description of the Walker River Basin, see Sharpe and others (2008) and Lopes and Allander (2009a).

Hydrogeology

Hydrogeologic units are rocks or sediments that have distinct hydraulic properties with respect to their ability to transmit and store water. Original descriptions of hydrogeologic units were made by Loeltz and Eakin (1953) for Smith Valley and Huxel and Harris (1969) for Mason Valley. State-wide delineations of hydrogeologic units were made by Mauer and others (2004) and were used in this study. There are two main classes of hydrogeologic units: (1) consolidated-rock and (2) unconsolidated-sedimentary deposits. The mountains surrounding Smith and Mason Valleys are comprised of consolidated-rock units with low permeability. The valleys are troughs that have filled in with unconsolidated alluvial deposits derived by erosion from the adjacent uplifted mountains and from materials transported by the Walker River. The valley units include alluvial slopes, fluvial deposits, and valley floor sediments, which generally have much greater permeability than the consolidated rock units. In northern Smith Valley, the Artesia dry lakebed (fig. 2) is characterized by fine-grained playa deposits with lower permeability.

In Smith Valley, a groundwater divide between the West Walker River and Artesia Lake splits the alluvial aquifer system (Loeltz and Eakin, 1953; fig. 2). North of the divide, groundwater flows radially inward toward Artesia Lake and discharges by evapotranspiration from native phreatophytic vegetation, agricultural vegetation irrigated with groundwater, and, to a much lesser extent, the playa surface (Lopes and Allander, 2009a). South of the divide, groundwater flows southward toward the West Walker River and discharges by agricultural or domestic pumping, by evapotranspiration from phreatophyte and riparian vegetation, or discharges southward to the West Walker River (Lopes and Allander, 2009a). Groundwater flow constricts through Wilson Canyon, between the Singatse and Pine Grove Hills Ranges on the east side of Smith Valley, historically forcing groundwater to discharge into the river (Lopes and Allander, 2009a; fig. 2).

In Mason Valley, groundwater generally flows parallel to the direction of surface-water, from the south end of the valley to the north end, and discharges into the river through Walker Gap (Huxel and Harris,1969; Lopes and Allander, 2009a). The Mason Valley Wildlife Management Area (Management Area) is a prominent hydrologic feature in northern Mason Valley that consists of ponds, wetlands, ditches, sloughs, agricultural fields, and a fish hatchery (fig. 2). Before the Management Area's establishment in 1955, ponds and wetlands were created by diverting flows from the Walker River to grow forage for livestock (E. Bull, Nevada Department of Wildlife, written commun., 2008). Several sloughs drain excess surface and groundwater from the Management Area into the Walker River about 1 mile north of the Management Area (Lopes and Allander, 2009a). The geothermal power station in northern Mason Valley began operation in 1984 and pumps from several wells at the base of the Desert Mountains Range (fig. 2; Lopes and Allander, 2009a). In 2000, the geothermal power station pumped 2,360 acre-ft of groundwater (Lopes and Evetts, 2004). Between 2015 and 2019, the geothermal power station pumped an average of 6,700 acre-ft of groundwater annually (W. Fereday, Nevada Division of Water Resources, written commun., 2021). Groundwater extracted by the geothermal power station is discharged to surrounding wetlands or, more recently, to evaporation ponds rather than reinjected into the aquifer.

Previous Studies

The water resources of Smith and Mason Valleys were initially assessed between the 1950s and 1970s (Loeltz and Eakin, 1953; Huxel and Harris, 1969; Rush and Schroer, 1976). A reconnaissance of geology and discussion of groundwater movement in Smith Valley was performed by Loeltz and Eakin (1953). In April 1949, the West Walker River was gaining (about 25 cubic feet per second, ft^3/s) within Smith Valley (Loeltz and Eakin, 1953, p. 44). The principal source of recharge to groundwater was cited as irrigation water in excess of soil moisture requirements (Loeltz and Eakin, 1953, p. 45). Large scale groundwater-level rise was documented before 1950 and attributed to recharge of irrigation water (Loeltz and Eakin, 1953, p. 32; Rush and Schroer, 1976, p. 22). In one well south of the West Walker River, a dramatic rise of nearly 65 feet occurred from 1935 to 1950, followed by a leveling-off after 1950 (Rush and Schroer, 1976, p. 22). Rush and Schroer (1976) provided an expanded discussion of the hydrogeology of Smith Valley by presenting groundwater-level maps during spring 1972, describing the following long-term groundwater-level changes between 1953 and 1972 and detailing short-term groundwater-level changes during the 1972 irrigation season (irrigation season in the Walker River Basin begins March 1st and ends October 31st). During the 1959–62 drought, some localized decline was identified north of the groundwater divide and south of the West Walker River. Groundwater levels in some wells declined 16–20 ft, followed by a slow recovery with the process still incomplete by the end of the study period (1972). Declines were attributed to reduced recharge during a drought period and increased groundwater pumping during the same period. Irrigated areas were considered the principal regions of man-induced groundwater recharge. In 1972, groundwater pumpage was estimated at 20,000 acre-ft, and groundwater storage decline was estimated at 6,000 acre-ft (Rush and Schroer, 1976, p. 67). Groundwater storage decline resulted from a faster rate of groundwater removal than recharge to the system (Rush and Schroer, 1976, p. 65). During the 1972 irrigation season, pumping lowered groundwater levels up to 20 ft in pumping centers. Generally, groundwater levels were lowest in fall 1972 at the close of the irrigation season, and increased during the winter, reaching higher levels in spring 1973 just before the start of irrigation. Groundwater-level comparisons from spring 1972 to spring 1973 showed an average decline of about 2 ft in response to the 1972 irrigation season. The West Walker River was steadily gaining in October 1972 (41 ft^3/s; Rush and Schroer, 1976, p. 60). The average annual recharge to groundwater from precipitation, which is often referred to as perennial yield, was estimated using the Maxey-Eakin method (Eakin and others, 1951) at 17,000 acre-ft/yr (Rush and Schroer, 1976, p. 49). System yield, the amount of water that can be consumed each year without continually removing groundwater from storage or reducing outflow to downstream users, was estimated at 62,000 acre-ft/yr (Rush and Schroer, 1976, p. 73).

Huxel and Harris (1969) provided an initial reconnaissance of the hydrogeology in Mason Valley with groundwater-level maps for 1965–66; an evaluation of the effects of increased supplemental pumping on groundwater and surface water from 1948 to 1965; and a description of groundwater-level changes during the 1965 irrigation season. Huxel and Harris (1969) identified seasonal patterns of streamflow equilibrium from 1948 to 1965 using simple comparison of surface inflow and outflow hydrographs, without accounting for surface-water diversions. Before the initiation of large-scale groundwater pumpage for irrigation in 1959, the Walker River had a near-immediate response to the cessation of irrigation in mid-November, switching from losing flow (due to surface-water diversions) to gaining flow (from groundwater). From 1959 to 1964, the Walker River's response in November was considerably less and was not enough to produce gaining conditions at any point between November and January. During 1948–65, groundwater levels were normally highest in the fall, at the close of the irrigation season, declined during the winter, and reached the lowest levels in the spring before the start of irrigation season. During the 1959–62 drought, groundwater levels in some wells declined an average of 2.7 ft over the 3-year period (Huxel and Harris, 1969, p. 38). The average annual precipitation recharge to the aquifer was estimated at 2,000 acre-ft/yr, using the Maxey Eakin Method (Eakin and others, 1951). Average annual recharge to the aquifer derived by streamflow, ditches, and percolation from flooded fields was estimated at 70,000 acre-ft/year (Huxel and Harris, 1969, p. 27). System yield during an average year was estimated at 100,000 acre-ft/yr; however, it was noted that during periods of drought such as 1959–62, substantial groundwater depletion could result from an average pumpage of 60,000 acre-ft/yr (Huxel and Harris, 1969, p. 58).

In 2004, the U.S. Geological Survey reappraised the water resources of the Walker River Basin to provide federal, state, and local partners updated data and information for the acquisition of water for the Desert Terminal Lakes Program (National Fish and Wildlife Foundation, 2022). Lopes and Allander (2009a) discussed surface-water/groundwater interactions and groundwater-flow directions in Smith and Mason Valleys and presented groundwater-level contours for fall 2006 in Smith, Mason, and Walker Valleys. The direction of flow and magnitude of groundwater gradients mapped in fall 2006 (Lopes and Allander, 2009a) were similar to those mapped in spring 1972 (Rush and Schroer, 1976). Groundwater-level contours indicated that almost the entire reach of the West Walker River was gaining through Smith Valley during spring 1972 and fall 2006. In Mason Valley, the direction of flow and magnitude of groundwater gradients mapped in fall 2006 (Lopes and Allander, 2009a) were quite different to those mapped in 1965–66 (Huxel and Harris, 1969). The West Walker River remained gaining or neutral, whereas the Walker River (below the confluence of the East and West Walker Rivers) changed from gaining to losing. After the 2004 irrigation season, the fall groundwater-levels were an average of 9 ft lower in Smith Valley and 4 ft lower in Mason Valley compared to pre-irrigation season spring levels (Lopes and Allander, 2009a). Groundwater was reported to rebound after the end of irrigation season, being highest in the spring. Since 1960, total groundwater-level declines were reported to be up to 60 ft along the margins of the valleys and 20 ft near Walker River (Lopes and Allander, 2009a).

The influence of groundwater-table declines on irrigation canal seepage was observed at the Saroni and Plymouth Canals in Smith Valley and the Mickey, Fox, and Campbell Ditches in Mason Valley (Naranjo and Smith, 2016). In 2012, the estimated seepage on the Mickey Ditch was 1.6 feet per day (ft/d; 0.44 cubic feet per second per mile [ft^3/s-mi]), during a period when the groundwater-table altitude was at or above the canal altitude. Following extensive declines in the groundwater table, the hydraulic gradient increased between the canal and the shallow aquifer, thereby increasing the seepage rates to 3.2 ft/d (0.87 ft^3/s-mi) in 2013. During the period of hydraulic disconnection, seepage rates increased to 9.5 ft/d (2.58 ft^3/s-mi) over intermittent periods of canal flow (Naranjo and Smith, 2016). Increases in seepage loss in irrigation canals (as a result of seasonal groundwater-table declines) also indicates a loss in efficiency for surface-water deliveries.

Lopes and Allander (2009b) estimated average annual streamflow for a 30-year period (1971–2000) at gaged and ungaged streams in the Walker River Basin. Average annual streamflow into Smith and Mason Valleys was 201,000 and 269,000 acre-ft, respectively. In Smith Valley, this average annual flow was 22,000 acre-ft above the 1958–72 average flow reported by Rush and Schroer (1976). In Mason Valley, this average annual flow was 53,000 acre-ft above the 1948–65 average annual flow reported by Huxel and Harris (1969). These higher average annual flows were largely due to the extreme runoff experienced in 1983, 1995, and 1997 (Lopes and Allander, 2009b).

Streamflow losses resulting from declines in the groundwater-table were recently investigated along the Walker River (Boyle and others, 2010; Carroll and others, 2010; Carroll and others, 2014). Physically based hydrologic models for Smith Valley (Boyle and others, 2010) and Mason Valley (Boyle and others, 2010; Carroll and others, 2010) were developed using the USGS modular hydrologic model: MODFLOW (Harbaugh, 2005) to simulate conditions between 1996 and 2006. In each, a groundwater model was coupled with a surface-water model through the streamflow-routing package to simulate the complex feedback mechanisms between the river/drain network and groundwater system. The Smith Valley model predicted the West Walker River largely gained throughout the year, including in periods of extended drought (Boyle and others, 2010). Annual gains ranged between 5,400 and 14,300 acre-ft/yr. Stream gains were attributed to lower pumping demands (relative to Mason Valley) and mountain-block recharge. The Mason Valley model predicted the Walker River generally gained during the irrigation season and lost during non-irrigation season and during extended periods of drought (Boyle and others, 2010; Carroll and others, 2010). Annual losses ranged between 5,600 acre-ft/yr during a wet year (1999) and 34,300 acre-ft/yr during a drought year (2004). In dry years, extensive groundwater pumping and loss of irrigation recharge were identified as the main contributors to stream losses.

Carroll and others (2014) performed a gain-loss analysis in the Walker River Basin between 1996 and 2011 for five river reaches across Antelope, Bridgeport, Smith, Mason, and Walker Lake Valleys (fig. 1). The water balance of each river reach was calculated using observed streamflow data, surface-water diversions, and estimated surface-water return flows from irrigation. An upper and lower boundary of return flows were estimated considering crop demand and irrigation efficiency. The lower runoff boundary assumed runoff equaled zero, such that all water applied in excess of crop demand returned to the aquifer as groundwater recharge. The upper runoff boundary assumed all water applied in excess of crop demand returned to the river as surface water through the drain system and was estimated by subtracting surface-water diversions by crop demand adjusted for irrigation efficiency. The West Walker River in Smith Valley was reported to gain at a rate of 6,700 acre-ft/yr if runoff equaled zero, or conversely, lose at a rate of 7,900 acre-ft/yr if runoff equaled the upper boundary (Carroll and others, 2014). The Walker River in Mason Valley was reported to lose at a rate of 12,300 acre-ft/yr if runoff equaled zero or 49,400 acre-ft/yr if runoff equaled the upper boundary (Carroll and others, 2014).

Methods

Multiple methods were used to estimate changes in groundwater storage, which included differencing of groundwater-level altitude contours or calculating depth-to-water changes at consistent monitoring points. A single method was used to compute stream efficiency of the Walker River over time. Estimates of change in storage, along with pumping data, were used to provide insight for estimates of the system yield. The following sections explain the data and methods used in these analyses.

Groundwater-Level Data

Groundwater levels in Smith and Mason Valleys have been monitored at varying frequencies by the USGS and NDWR (fig. 2). The earliest groundwater levels date back to the late 1940s, however data from the early period of record is spatially and temporally intermittent. Beginning in the mid-1970s, the USGS and NDWR expanded the monitoring program and collected groundwater levels throughout the valleys on a more frequent basis. Irrigation season generally begins at the beginning of March and concludes at the end of October. Groundwater levels were generally measured in the fall (October–December), after irrigation season had ended, and again in the early spring (February–April) before the start of irrigation season. Currently (2022), approximately 150 wells are monitored at least twice annually in a cooperative effort between USGS and NDWR. Groundwater 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.

Groundwater levels for the entire period of record were retrieved from the USGS National Water Information System (NWIS; U.S. Geological Survey, 2021) and NDWR Water Use and Availability database (Nevada Division of Water Resources, 2021a). Many USGS established wells are also measured and reported by the NDWR. The NDWR uses the site names (Hydrographic Area [HA], Township, Range, Section, Quarter Section) as the identification numbers to report data. Data from both agencies were compiled into a database and organized by site identification number. If a site was established by the USGS and measured by USGS and NDWR, the USGS site identification number was used. If a site was established and measured solely by the NDWR, the NDWR site name was used for identification. Any duplicate measurements reported in both databases were removed.

Groundwater levels are reported as depth to water, in feet below land surface. Groundwater-level altitudes were calculated by subtracting the depth to water from the site's land-surface altitude. For USGS sites, the land-surface altitudes are reported in the site description on NWIS. Most site land-surface altitudes are estimated from topographic maps or digital elevation models with a reported accuracy of 1–25 ft and referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) or 1988 (NAVD88). Overall, reported land-surface altitudes are considered to be generally accurate enough for the purposes of this study. To maintain consistency with previous groundwater-level altitude studies in Smith and Mason Valleys (Huxel and Harris, 1969; Rush and Schroer, 1976; Lopes and Allander, 2009a), all USGS site altitudes in this study were referenced to NGVD29. For NDWR sites, the land-surface altitudes used were the altitudes reported in the NDWR database. For most NDWR sites, land-surface altitudes were estimated from topographic maps, hand held Global Positioning Systems, or well drillers logs. Altitude accuracy and vertical datums are not reported by the NDWR. To confirm the validity of NDWR reported altitudes, site altitudes were extracted from a 10-meter digital elevation model (DEM) and adjusted to NGVD29. The NDWR reported land-surface altitudes were within an acceptable proximity to those extracted from the DEM. Several sites did not have a reported land-surface altitude; for these sites, the extracted DEM altitude was used.

In groundwater-level studies, the positional locations and land-surface altitudes of monitoring wells are important for qualifying groundwater-level measurements and estimating overall uncertainty. Accuracy of groundwater-level measurements in this study is limited by the current accuracy of positional locations and land-surface altitudes of monitoring wells.

Development of Groundwater-Level Maps

The frequency of groundwater-level measurements and the distribution of monitoring wells were examined during the period of record. Groundwater-level measurements were only considered if they were collected between the months of October through April, that is, during static conditions when irrigation wells were not actively being pumped. Singular WYs with data from a sufficient coverage of monitoring wells to map valley-wide groundwater levels were rare, particularly before 2015. An alternative approach was to examine a 5-year window of time to establish representative static groundwater-levels. Two 5-year periods were selected: (1) WYs 1991–95 and (2) 2016–20. These periods provided more groundwater-level measurements with greater spatial coverage to develop valley-wide groundwater-level maps compared to singular WYs. These periods also provided at least a 10-year spacing from the most recent published groundwater-level map (Lopes and Allander, 2009a). During WYs 1991–95 and 2016–20, 96 and 165 wells were measured, respectively. The median groundwater-level altitude was calculated at each well, with at least one groundwater-level measurement during each 5-year period, and used for developing a static groundwater-level contour map. Herein, the 5-year median groundwater levels of WYs 1991–95 will be referred to as the "1995 groundwater-level map" and the 5-year median groundwater-levels of WYs 2016–20 as the "2020 groundwater-level map." Because this study is focused on long-term groundwater-level change, the median value was selected for groundwater-level analysis to provide the most robust representation of change, given variability in measurement frequency or values for any given well throughout the period of analysis could skew the average.

Groundwater-level contour maps were developed in a geographic information system (GIS) database using ArcMap (v. 10.7.1, Environmental Systems Research Institute, 2019). Contours of equal groundwater-level altitude were drawn using the median groundwater-level point data. The Lopes and Allander (2009a) groundwater-level contour map was used as a general guide for interpreting direction of flow and magnitude of groundwater gradients in the 1995 and 2020 groundwater-level contour maps. The intention was to keep the overall interpretation of Lopes and Allander (2009a) comparable to the new groundwater-level contour maps so that change between maps was a result of groundwater-level change and not variation in interpretation. Groundwater-level contours were drafted manually using the "Editor" tool (Environmental Systems Research Institute, 2019). The consolidated-rock units bordering the valleys were treated as no-flow boundaries, at which contours meet at approximately right angles. Contours that cross over the Walker River were drawn to intersect land-surface altitude in 10-ft increments, with the assumption that the groundwater table intersects the river surface and that the river and aquifer are hydraulically connected (consistent with methods of Lopes and Allander, 2009a). The "Smooth Line" tool with a Bezier interpolation algorithm (Environmental Systems Research Institute, 2019), which smooths lines by creating approximate curves to match the input lines, was used to refine contours. The median groundwater-level point data and groundwater-level contours are published in an accompanying data release (Davies and Naranjo, 2022).

Modifications to Early Groundwater-Level Maps

Digitized groundwater-level contours from previous studies (Huxel and Harris, 1969; Rush and Schroer, 1976; Lopes and Allander, 2009a) are published in accompanying USGS data releases (Buto and others, 2006; Davies and Naranjo, 2022; Medina and others, 2022; Welborn and Medina, 2022). The contours from Huxel and Harris (1969) and Rush and Schroer (1976) are herein referred to as the “1970 groundwater-level map.” The contours from Lopes and Allander (2009a) are herein referred to as the “2006 groundwater-level map.” Modifications to the 1970 groundwater-level map were required to maintain consistent methods between the 1995, 2006, and 2020 groundwater-level maps. Authors of the 1970 groundwater-level map neglected the surface altitude of the river where the water-table intercepts the river. The 1970 contours were modified such that contours cross the river perpendicularly along the approximate river surface altitude at 10-ft intervals (consistent with Lopes and Allander, 2009a). In the modified 1970 groundwater-level map, 3 contours in Smith Valley and 21 contours in Mason Valley were adjusted where they approach and cross the river while maintaining their general form and interpretation away from the river.

The positional coordinates and land-surface altitudes of USGS monitoring wells are periodically updated when new survey data reveal inaccuracies in original well location data. Since the publication of the 2006 groundwater-level contour map, the location and land-surface altitudes at 23 groundwater monitoring wells in Smith Valley have been updated. For consistency in this study, the 2006 groundwater-level contours were adjusted using the updated well locations and land-surface altitudes. A total of 10 contours received minor adjustments while maintaining the original interpretation to the extent possible. Adjustments for updated well locations were not made to the 1970 groundwater-level contours maps because most wells used in the Huxel and Harris (1969) and Rush and Schroer (1976) studies had not been officially established as USGS or NDWR monitoring wells and were not formally digitized.

Common Extent for Evaluating Change in Groundwater Storage-Volume

Each groundwater-level map has slightly different spatial coverage because the distribution of wells used in each map varies. Defining a common bounding extent between all maps was needed to evaluate groundwater-level change and groundwater storage-volume change using consistent approaches. The area of common extent was defined by all valley floor and fluvial deposit units defined by Mauer and others (2004) in the study area. This selection excludes the alluvial slope units, which mainly encompass the outer areas of Smith and Mason Valleys. The margins of the valleys are expected to have the largest groundwater-level change and the most variability between maps due to differences in interpretation and data coverage; therefore, these less-certain valley margin regions were not included in groundwater-level change and groundwater storage-volume change calculations. Additionally, the Artesia Lake region of Smith Valley was not included due to poor well coverage in all maps. The northern extent of Smith Valley was defined by the 4,720-ft groundwater-level contour from the 2006 groundwater-level map (Lopes and Allander, 2009a). The total area of common extent (excluding the margin regions described earlier) used to calculate groundwater-level and groundwater storage-volume change was 58 square miles (mi^2) in Smith Valley and 147 mi^2 in Mason Valley (fig. 4).

Estimation of Groundwater Storage-Volume Change

The accuracy of any groundwater-level map is limited by the horizontal and vertical accuracy of groundwater-level monitoring wells. In this study, groundwater-level monitoring wells varied in horizontal accuracy up to 1 second (101-ft latitude, 80-ft longitude) and vertical accuracy up to 25 ft. Additionally, the number of groundwater-level monitoring wells and the spatial coverage of wells varied between periods, adding to uncertainty when comparing maps from different periods. For these reasons, two methods for estimating groundwater-level change between periods were developed to increase confidence and constrain estimates.

The first approach for estimating groundwater-level change involved interpolating the groundwater-level contours from each map into a 30-meter cell grid using the ArcMap “Topo to Raster” tool (Environmental Systems Research Institute, 2019). Next, groundwater-level grids were clipped by the common extent bounding area (discussed earlier). The final step in this approach differenced the clipped groundwater-level grids using the ArcMap “Raster Calculator” tool (Environmental Systems Research Institute, 2019) between period 1 (1970–95), period 2 (1995–2006), and period 3 (2006–20), as well as for the overall period from 1970 to 2020. Approach 1 was termed the contour method.

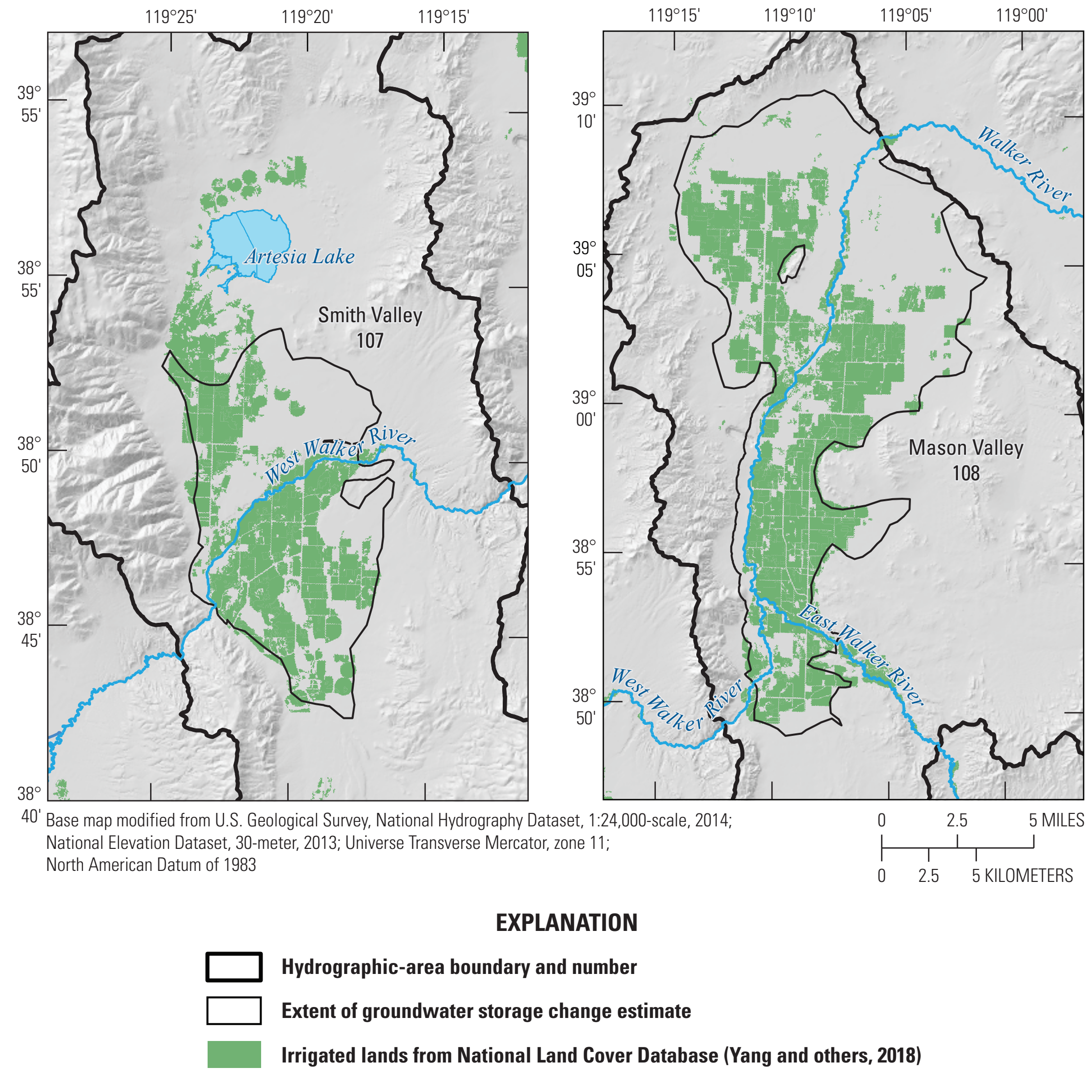


Figure 4. The geographic extent of groundwater-level change and groundwater storage-volume change estimates. The total area assessed in Smith and Mason Valleys was 58 and 147 square miles, respectively (37,120 and 94,080 acres, respectively; Davies and Naranjo, 2022).

The second approach for estimating groundwater-level change used groundwater-level data only from monitoring wells that were consistently measured for all periods. There are a total of 53 common wells in Smith and Mason Valleys that had groundwater-level measurements from 1995, 2006, and 2020. Groundwater-level change in approach 2 was calculated at these 53 wells by differencing the depth-to-water or median depth-to-water measurements between periods. This process removed any uncertainty associated with (1) the spatial distribution of monitoring wells used to generate the 1995, 2006, and 2020 maps and (2) the land-surface altitude accuracy of monitoring wells. To obtain initial depth-to-water values from the 1970 groundwater-level map, groundwater-level altitudes at the 53 well locations were extracted from the 1970 interpolate groundwater-level grid (described earlier in this section). The extracted groundwater-level altitudes at the 53 well locations were then subtracted from each wells' NWIS land-surface altitude to calculate an initial depth to water. Point data from the 53 wells (change in depth to water) and a polyline of the Walker River (change in depth to water equaling zero) were interpolated into a continuous groundwater-level change grid using the ArcMap "Topo to Raster" tool (Environmental Systems Research Institute, 2019) with 30-meter cells. Groundwater-level change grids were clipped by the common extent bounding area. Approach 2 was termed the point method.

Groundwater storage-volume change was calculated by converting each groundwater-level change grid to acre-ft using the ArcMap "Raster Calculator" tool (Environmental Systems Research Institute, 2019), summing all grid cell values using the ArcMap "Zonal Statistics" tool (Environmental Systems Research Institute, 2019), and multiplying the sum by the valley-wide estimate of specific yield. Specific yield is a unitless volume of water per unit bulk aquifer volume that will drain under the force of gravity (Meinzer, 1923). Specific yield in Smith Valley is estimated at 0.15 (Rush and Schroer, 1976, p. 19) and 0.2 in Mason Valley (Huxel and Harris, 1969, p. 12).

Selected Groundwater Hydrographs

Although consistent groundwater-level data in the early period of the record is sparse, several wells have been reliably measured since the early 1970s–80s (table 1; fig. 2). Groundwater-level hydrographs were compiled for long-term sites and evaluated for recovery or declines following very wet WYs. Very wet WYs were identified as water years with the 10 highest annual valley inflows into Smith and Mason Valleys, respectively, during the period of analysis, which includes 1969, 1983–86, 1995–97, 2006, 2011, and 2017 (the period of available streamflow data is not synonymous between valleys, consequently more than 10 years are listed). Additionally, groundwater hydrographs from two regions with recent land-use change or pumping expansion were compiled for evaluation. Those regions include the northern extent of Artesia Lake in Smith Valley, where additional agricultural land irrigated by groundwater was established beginning in the mid-1980s (Welborn, 2017) and the northern extent of Mason Valley at the geothermal power station, which was established in 1984 (fig. 5). In 2014, geothermal discharge was moved from evaporation ponds adjacent to Highway 95 and wetlands area near Adrian Gap to evaporation ponds and irrigation use closer to the Walker River (fig. 5).

Table 1. Groundwater-level monitoring wells with long-term records or with recent land use change in Smith and Mason Valleys, Nevada, used for long-term hydrograph analysis, 1961–2020 (U.S. Geological Survey, 2021).

[Monitoring stations are displayed in figures 13–14 and labeled according to "Label" assignment. Latitude and longitude are in decimal degrees, North American Datum of 1983 (NAD 83). Altitude is reported in feet above the National Geodetic Vertical Datum of 1929 (NGVD 29). Altitude accuracy is 1–25 feet. **Abbreviations**: Oct., October; Apr., April]

Groundwater monitoring well name	Site identification number	Label (figs. 13–14)	Latitude	Longitude	Altitude of datum	Earliest record (Oct.–Apr.)
Smith Valley						
107 N13 E24 30ADDD1	385745119230501	A	38.96222220	−119.3302778	4,614	1976
107 N12 E24 27DACB1 USBLM - HUDSON WELL	385222119154601	B	38.87244444	−119.2769167	4,979	2004
107 N12 E23 34BACB1	385205119225401	C	38.86805556	−119.3983333	4,770	1973
107 N11 E23 23BCBB1	384830119220501	D	38.80824478	−119.3690495	4,760	1972
107 N10 E24 08CBCA1	384426119194601	E	38.74083330	−119.3277778	4,920	1973
107 N10 E24 16ACCC1	384350119172301	F	38.72916667	−119.3030556	4,977	1972
Mason Valley						
108 N15 E25 11DCAC1 USBLM	391004119093201	A	39.17494444	−119.1514444	4,321	2004
108 N15 E26 20BDBB1	390914119060601	B	39.15402778	−119.1017778	4,331	1994
108 N14 E25 18DCBB1	390415119132801	C	39.07075086	−119.2254325	4,344	1965
108 N14 E26 32BCCC1	390201119062001	D	39.03352960	−119.1065416	4,352	1977
108 N13 E25 10CDB 1	390004119103001	E	39.00102868	−119.1759868	4,380	1961
108 N13 E26 02BBCC1	390127119030001	F	39.02408569	−119.0509851	4,406	1965
108 N12 E25 11CACD1	385456119091901	G	38.91547224	−119.1562641	4,439	1961
108 N11 E25 10DBCD1	384942119100801	H	38.82802778	−119.17036100	4,565	1965

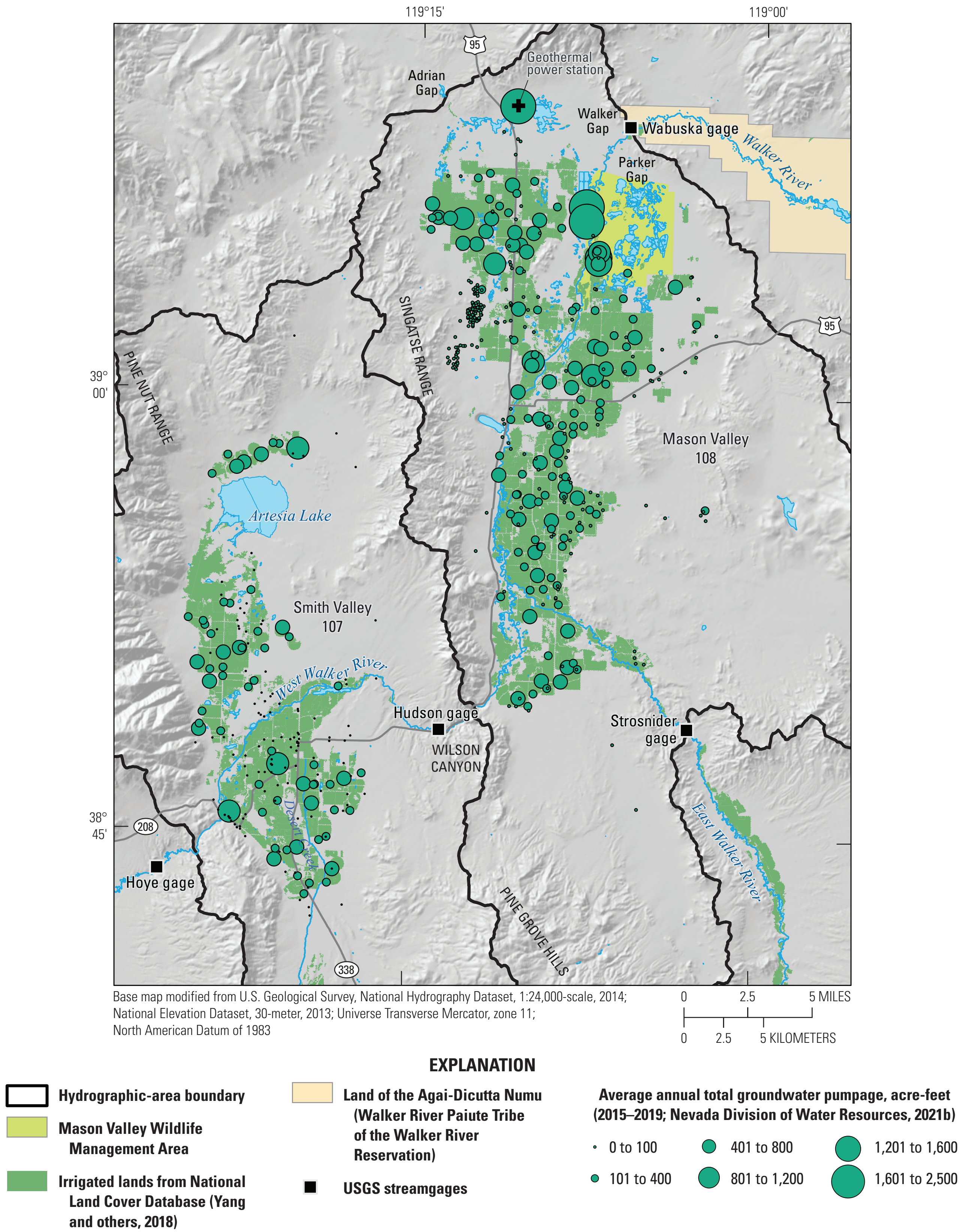


Figure 5. Average annual total groundwater pumpage by well in Smith and Mason Valleys, Nevada, 2015–19 (Nevada Division of Water Resources, 2021b, W. Fereday, written commun., 2021) and locations of U.S. Geological Survey (USGS) streamgages used for stream efficiency analysis (U.S. Geological Survey, 2021).

Stream Efficiency

The net change in discharge over a stream reach, while accounting for all diversions, tributary inflows, and agricultural return flows, is commonly used to estimate the net surface-water groundwater exchange (Winter and others, 1998). For this analysis, each reach is defined as the length of stream between long-term USGS streamgages (table 2). A positive net change between streamgages indicates the reach is gaining flow from groundwater discharge, whereas a negative net change indicates the reach is losing flow to the groundwater system (the stream is recharging the aquifer). The stream efficiency is a ratio of outflow or the change in streamflow to total streamflow or maximum streamflow (Mohammadi and others, 2019; Wilberg and others, 2001). Efficiency is often used to describe seepage losses in irrigation canals (Mohammadi and others, 2019). In this report, stream efficiency is calculated by first summing gaged outflow and all surface-water diversions within the stream reach and then dividing by the gaged inflow (acre-ft):

$$SE = \frac{Q_{out} + Q_{div}}{Q_{in}} \quad (1)$$

where

SE is stream efficiency for a specified reach (unitless fraction),

Q_{out} is the reach outflow as measured at the downstream streamgage (in acre-ft or ft^3/s),

Q_{div} is the sum of all diversions along the reach (in acre-ft or ft^3/s), and

Q_{in} is the reach inflow as measured at the upstream streamgage (in acre-feet or ft^3/s).

Stream efficiency is conceptually analogous to percentage gain or percentage loss calculations. Stream efficiencies calculated over time represent a normalized metric of streamflow gains or losses because it is scaled to inflow and thus removes variability that is primarily related to climatic streamflow variability. A stream efficiency greater than one indicates the reach is gaining and is more efficient at conveying water downstream than a reach with a stream efficiency less than one, which indicates the reach is losing and is therefore inefficient at conveying water downstream. A reach that is several miles in length most likely contains a mixture of gaining and losing conditions on a localized scale and may fluctuate throughout the year. In this study, stream efficiency is calculated on two reaches that extend across entire valleys in order to assess the overall behavior of the East Walker, West Walker, and Walker Rivers.

Table 2. Information for streamgages used in steam efficiency analysis in Smith and Mason Valleys, Nevada, 1902–2020 (U.S. Geological Survey, 2021).

[Latitude and longitude are in decimal degrees, North American Datum of 1983 (NAD 83). Altitude is reported in feet above National Geodetic Vertical Datum of 1929 (NGVD 29). Altitude accuracy is 0.01 to 25 feet. **Abbreviation**: mm/dd/yyyy, month/day/year]

Streamgage name	Streamgage identification number	Short name	Latitude	Longitude	Altitude of streamgage datum	Period of record (mm/dd/yyyy)
W WALKER RV AT HOYE BRG NR WELLINGTON, NV	10297500	Hoye streamgage	38.72806389	−119.42786100	4,980	05/01/1910–08/31/1910; 07/01/1920–09/30/1923, 03/01/1924–09/30/1932; 10/01/1957–present
W WALKER RV NR HUDSON, NV	10300000	Hudson streamgage	38.80963660	−119.22737700	4,650	10/01/1914–09/30/1924; 10/01/1947–09/30/1978; April–September 1979–94; 10/01/1994–present
E WALKER RV ABV STROSNIDER DITCH NR MASON, NV	10293500	Strosnider streamgage	38.81371389	−119.04799170	4,574	10/01/1947–09/31/1978; April–September 1979–94; 10/01/1994–present
WALKER RV NR WABUSKA, NV	10301500	Wabuska streamgage	39.15246110	−119.09888890	4,300	07/22/1902–12/31/1904; 01/16/1920–09/30/1924; 03/01/1925–09/30/1935; 01/01/1939–11/30/1941; 02/01/1942–present

The rate at which a stream gains or loses flow from an adjoining aquifer depends on the hydraulic gradient between the two water bodies and the hydraulic conductivity of geologic material at the groundwater/surface-water interface (Barlow and Leake, 2012). The state of hydraulic connection also has an important influence on the rate of infiltration between the stream and aquifer. A stream is considered hydraulically connected if the groundwater/surface-water interface is fully saturated and is hydraulically disconnected if an unsaturated zone between the streambed and groundwater-table exists. Infiltration rates in a connected stream will be largely influenced by the hydraulic gradient. If the groundwater table is lowered (by groundwater pumping or by natural causes), the stream will lose flow proportionally to the hydraulic gradient. If the groundwater table is further lowered, the stream will change to a transitional state and eventually a disconnected state, where loss rates will approach a constant value. Loss rates in a disconnected stream will not be substantially affected by further changes in the groundwater-table (Winter and others, 1998; Brunner and others, 2009). Examining long-term trends in stream efficiency over time could provide insight on the state of hydraulic connection and future impacts of groundwater-table lowering on stream loss rates.

Stream efficiency was calculated using streamflow data from USGS streamgages (U.S. Geological Survey, 2021; table 2; fig. 2) on a monthly basis for all years with continuous data: WYs 1948–2020 in Smith Valley and WYs 1958–2020 in Mason Valley. Sparce streamflow data are available in the early 1920s, however, these data are not included in the analysis period because regulation of the Walker River commenced in the 1920–30s with the completion of upstream water-storage reservoirs (this study only examines the post-regulation period). The Smith Valley reach contains approximately 21 river miles of the West Walker River and is defined as the reach between the upstream streamgage, West Walker River at Hoye Bridge near Wellington (Hoye streamgage, 10297500) and the downstream streamgage, West Walker River near Hudson (Hudson streamgage, 10300000). The Mason Valley reach contains approximately 9 river miles of the West Walker River, 13 river miles of the East Walker River, and 24 miles of the mainstem Walker River (collectively 46 river miles). The Mason Valley reach is comprised of the river reaches among (1) the upstream Hudson streamgage and the confluence with the East Walker River; (2) the upstream East Walker River above Strosnider Ditch near Mason (Strosnider streamgage, 10293500) and the confluence with the West Walker River; and (3) from the confluence to the downstream streamgage Walker River near Wabuska (Wabuska streamgage, 10301500). The Hudson and Strosnider streamgages were only operated during irrigation season from 1979 to 1994, so stream efficiency was not calculated during the non-irrigation season for those years.

Surface-water diversions have been recorded since 1934 by the Walker River Irrigation District (Pahl, 2000). Total monthly diversions (decree, storage, and flood) were compiled for both reaches from 1931 to 1995 (Pahl, 2000), 1996 to 2011 (C. Garner, Desert Research Institute, written commun., 2020), and 2012 to 2020 (B. Bryan, Walker River Irrigation District, written commun., 2021) using similar compilation methods described in Pahl (2000). The compiled monthly diversions are published in an accompanying USGS data release (Davies and Naranjo, 2022). Additional sources of surface-water inflow may include tributary streams or return flow drains that discharge to the river between the upstream and downstream streamgages. Return drains transport irrigation flows in excess of crop demands back to the river. Return flow in drains typically results from inefficient irrigation practices like flood irrigation, or during very high WYs when flood water rights are served. Return drains also may transport groundwater discharge if the canal is gaining. Groundwater-derived return flow is implicitly included in the stream-efficiency calculation in this study through the flow of the downstream streamgage. In Smith Valley, minor streams and springs make up less than 5 percent of the total annual inflow to the valley and generally do not contribute any surface flow to West Walker River (Rush and Schroer, 1976). Additionally, in Smith Valley, there is little return flow to West Walker River through drains (Rush and Schroer, 1976, p. 51). In Mason Valley, there are no other sources of surface inflow to the river except some return drain flows. The two main points of return flow to the Walker River in Mason Valley were gaged continuously by the USGS for a limited period between 2013 and 2017. These streamgages included Perk/Joggles Slough, above confluence with Walker River (Perk/Joggles streamgage, 10301290) and Wabuska Drain, above Walker River confluence near Parker Butte (Wabuska drain streamgage, 10301495), approximately 0.75 and 0.25 miles upstream from the Wabuska streamgage, respectively (fig. 2; table 3). Complete WYs of streamflow data are available at the Perk Joggles streamgage in 2016–17 and at the Wabuska drain streamgage in 2015–17. The combined annual return flow into the Walker River in 2016 and 2017 was 200 and 11,000 acre-ft, respectively. These two WYs provide a relative constraint for expected surface-water drain-return flows because 2016 was the final year of a 5-year drought period and 2017 was an exceptionally wet year. The magnitude of these return flows (200 to 11,000 acre-ft/yr) are negligible in the calculation of stream efficiency or total gains/losses across a valley-wide reach and are therefore excluded in this report. This approach to gain-loss analysis is similar to gain-loss analysis performed by Carroll and others (2014) where the runoff variable equaled zero.

Table 3. Streamgaging information for additional surface-water sites of interest in Mason Valley, Nevada, 2013–2017 (U.S. Geological Survey, 2021).

[Latitude and longitude are in decimal degrees, North American Datum of 1983 (NAD 83). Altitude is reported as feet above National Geodetic Vertical Datum of 1929 (NGVD 29). Altitude accuracy is 5 feet. **Abbreviation**: mm/dd/yyyy, month/day/year]

Streamgage name	Streamgage identification number	Short name	Latitude	Longitude	Altitude of streamgage datum	Period of record (mm/dd/yyyy)
WABUSKA DRAIN ABV WALKER RV CNFL NR PARKER BUTTE	10301495	Wabuska drain streamgage	39.15090830	−119.10378600	4,297	10/01/2013–10/03/2017
PERK/JOGGLES SLOUGH ABV CONFL WITH WALKER RV, NV	10301290	Perk/Joggles streamgage	39.14250000	−119.10481940	4,300	09/30/2013–10/02/2017

Statistical methods were used to evaluate trends in monthly stream efficiencies during the period of analysis (1948–2020 and 1958–2020 for Smith and Mason Valleys, respectively). The Mann-Kendall trend test with the Theil-Sen estimator was used because this method is applicable to non-normally distributed datasets (Helsel and others, 2020). The Mann-Kendall trend test is a non-parametric hypothesis test used to determine whether the central tendency changes over time using the tau coefficient (Helsel and others, 2020). The null hypothesis was no correlation exists between stream efficiency and time, whereas the alternate hypothesis was a monotonic relationship exists between stream efficiency and time (for example, stream efficiency is trending upward or downward). The p-value, a quantitative measure of the strength of the evidence, was used to determine if the null hypothesis could be rejected. If a p-value less than 0.05 ($p<0.05$) resulted from the test, the null hypothesis was rejected and a trend was considered statistically significant (Helsel and others, 2020). The Theil-Sen estimator was used to quantify the change in stream efficiency in percent per year (Helsel and others, 2020). Trend tests were completed using the R software package (R Core Team, 2022) following methods described in Helsel and others (2020).

Stream efficiency can change between different periods of the year due to seasonal variation in the hydrologic cycle and groundwater pumping (in this case, irrigation season versus non-irrigation season). Thus, the statistical methods for trend analysis were computed for irrigation season and non-irrigation season separately. The irrigation season generally begins March 1st and ends October 31st; however, exact dates could vary depending on seasonal temperature and moisture conditions. For this reason, seasonal stream efficiencies for the irrigation and non-irrigation season included the following months: April through September and November through February, respectively, and excluded the months of March and October, which more often express a combination of irrigation and non-irrigation conditions (Pahl, 2000). Additionally, for the period of analysis, the monthly maximum, minimum, and average stream efficiency were reported for each season to demonstrate the overall range in monthly stream efficiencies.

Annual stream efficiency was computed by averaging all monthly stream efficiencies in each WY (October–September). Trends in annual stream efficiency were compared to exogenous factors including climate and groundwater pumping. Monthly Palmer Drought Severity Index (PDSI) values for the Western Nevada area were used to classify periods of climate variability between 1948 and 2020 (National Oceanic and Atmospheric Administration, 2021). The PDSI is a long-term analysis index for the severity of wet or dry climate conditions. The PDSI values less than –3 indicate severe drought conditions, whereas values greater than +3 indicate severe wetness. Severe drought conditions occurred in 36 of the 72 years of the study period (fig. 6*A*). A period was considered a prolonged drought when at least two consecutive WYs with negative average PDSI values occurred. Eight periods of prolonged drought occurred during the study period: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, and 2012–16. Trends in annual stream efficiency were evaluated by considering periods of prolonged drought, deviation from average annual streamflows, and annual groundwater pumpage volumes. Total groundwater pumpage volumes were compiled from 1994 to 2020 (Nevada Division of Water Resources, 2021b; W. Fereday, Nevada Division of Water Resources, written commun., 2021). Trends in annual stream efficiency and groundwater pumpage were examined using linear regression (Helsel and others, 2020). The coefficient of determination, or the fraction of the variance explained by regression (R^2), was used to evaluate the relation between total groundwater pumpage and annual stream efficiency.

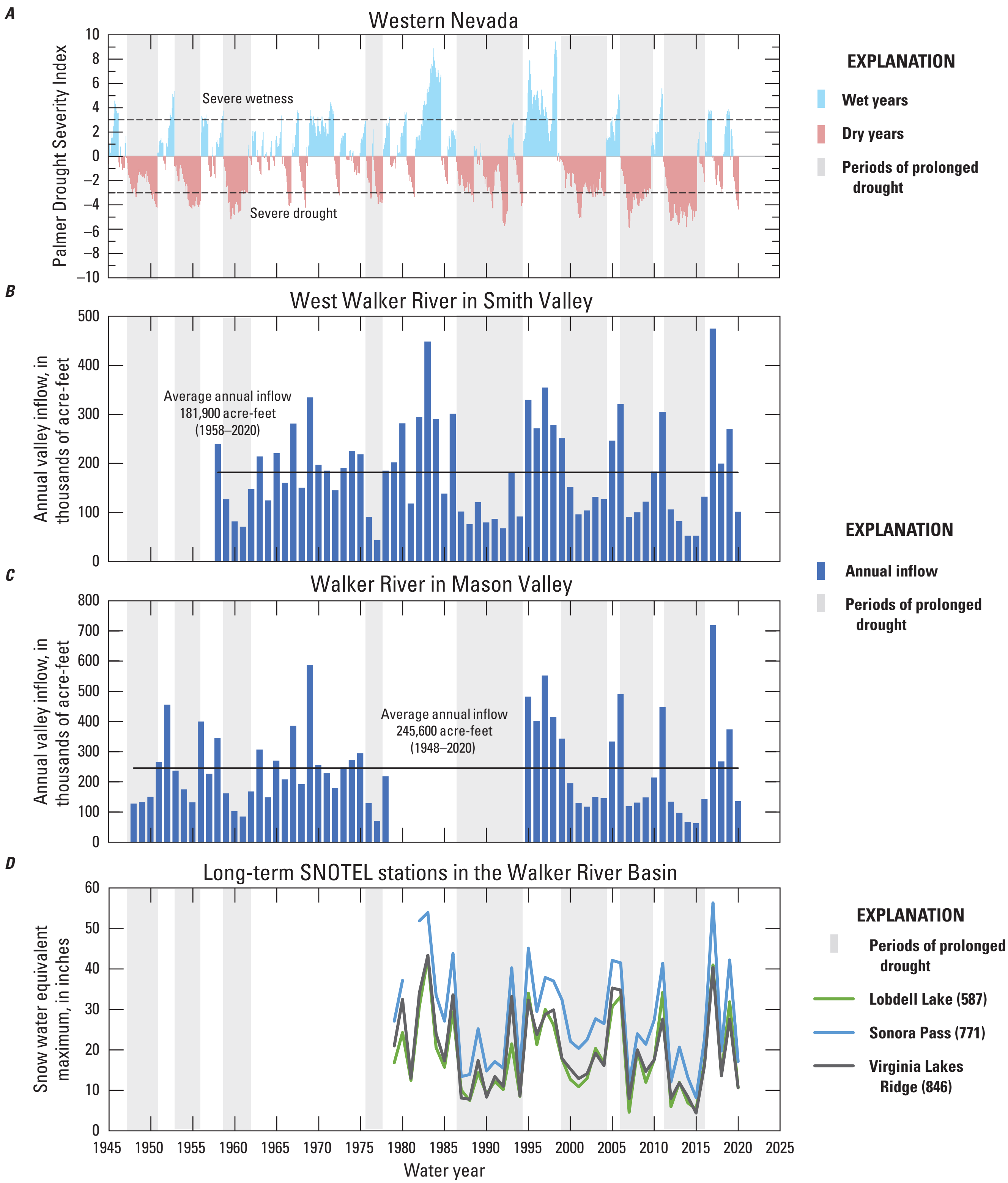


Figure 6. General climate variability during the period of analysis. *A,* Palmer Drought Severity Index for Western Nevada for water years 1945–2020 (National Oceanic and Atmospheric Administration, 2021). Highlighted drought years include: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16; *B,* annual valley inflow to Smith Valley (as measured at Hoye streamgage), water years 1958–2020 (U.S. Geological Survey, 2021); *C,* annual valley inflow to Mason Valley (as measured at Strosnider and Hudson streamgages), water years 1948–2020 (U.S. Geological Survey, 2021; missing values from 1979 to 1994 are due to seasonal operation of U.S. Geological Survey streamgages); and *D,* snow water equivalent, maximum, in inches for selected SNOTEL stations in the Walker River Basin, water years 1979–2020 (Natural Resources Conservation Service, 2021).

In addition to stream efficiency, the magnitude of the streamflow gains and losses were calculated on an annual basis using the following equation (modified from Simonds and Sinclair, 2002):

$$GL = (Q_{out} + Q_{div}) - Q_{in} \quad (2)$$

where

GL is streamflow gain or loss (in acre-ft or ft^3/s),

Q_{out} is the reach outflow as measured at the downstream streamgage (in acre-ft or ft^3/s),

Q_{div} is the sum of all diversions along the reach (in acre-ft or ft^3/s), and

Q_{in} is the reach inflow as measured at the upstream streamgage (in acre-ft or ft^3/s).

A positive GL indicates the volume of streamflow that has been gained from groundwater discharge into the reach. A negative GL indicates the volume of streamflow lost to the aquifer.

Results and Discussion

Groundwater-level change, groundwater storage-volume change, and stream-efficiency results are discussed by period and valley. Results are presented in figures 7–22 and tables 4–8. Groundwater-level contours, groundwater-level change grids, streamflow data, and calculated stream efficiencies are published in the accompanying USGS data release (Davies and Naranjo, 2022). Streamflow data is also available in NWIS (U.S. Geological Survey, 2021).

Groundwater-Level and Groundwater Storage-Volume Change

General climatic conditions during each period of groundwater-level and groundwater storage-volume change analyses are summarized in table 4. In Smith Valley, average annual stream inflow for the study period of analysis (1958–2020) was 181,900 acre-ft. In Mason Valley, average annual stream inflow for the study period of analysis (1948–2020) was 245,600 acre-ft.

Table 4. Average annual surface-water inflow (U.S. Geological Survey, 2021) and groundwater pumpage (Nevada Division of Water Resources, 2021b) in Smith and Mason Valleys, Nevada, for 1970–95, 1996–2006, 2007–20, and overall 1970–2020 in acre-feet per year.

[Smith Valley average annual stream inflow for study period of analysis (1958–2020) was 181,900 acre-feet per year (acre-ft/yr). Mason Valley average annual stream inflow for study period of record (1948–2020) was 245,600 acre-ft/yr. Smith and Mason Valley groundwater pumpage period of record 1994–2020. Smith Valley average annual pumpage for period of record was 25,800 acre-ft/yr. Mason Valley average annual pumpage for period of record was 79,200 acre-ft/yr. Total appropriated groundwater rights in Smith and Mason Valleys during the groundwater storage-volume change period of analysis (1970–2020) were approximately 55,000 and 150,000 acre-ft/yr, respectively (Nevada Division of Water Resources, 2021b). For deviation columns, positive value indicates above period average, negative indicates below period average. **Abbreviations**: acre-ft/yr, acre-feet per year; —, no data; %, percent]

Period	Smith Valley				Mason Valley			
	Surface water		Groundwater		Surface water		Groundwater	
	Average annual inflow Hoye streamgage (acre-ft/yr)	Deviation from study period average annual inflow [acre-ft/yr (percent)]	Average annual pumpage (acre-ft/yr)	Deviation from study period average annual pumpage [acre-ft/yr (percent)]	Average annual inflow Hudson and Strosnider streamgages (acre-ft/yr)	Deviation from study period average annual inflow [acre-ft/yr (percent)]	Average annual pumpage (acre-ft/yr)	Deviation from study period average annual pumpage [acre-ft/yr (percent)]
Period 1: 1970–95	180,600	−1,300 (−1%)	—[1]	—[1]	[2]238,300	[2]−7,300 (−3%)	—[1]	—[1]
Period 2: 1996–2006	212,300	+30,400 (+17%)	22,900	−2,900 (−11%)	298,100	+52,500 (+21%)	73,200	−6,000 (−8%)
Period 3: 2007–20	162,400	−19,500 (−11%)	28,600	+2,800 (+11%)	219,100	−26,500 (−11%)	83,400	+4,200 (+5%)

[1]Pumpage data not available during this period.

[2]Average of years 1970–78 and 1995 because Hudson and Strosnider streamgages operated seasonally from 1979 to 1994.

As shown in table 4, during period 1 (1970–95), average annual inflow to Smith Valley at the Hoye streamgage was 180,600 acre-ft/yr (deviation from study-period average was −1,300 acre-ft/yr, or –1 percent of average). Average annual inflow to Mason Valley could not be computed for this complete period due to seasonal operation of the Strosnider and Hudson streamgages, however, the average of available data for this period was 238,300 acre-ft/yr (deviation from study-period average −7,300 acre-ft/yr, or –3 percent of average). Prolonged periods of drought occurred during period 1 from 1976 to 1977 and 1987 to 1994, totaling 10 years. Notably wetter conditions occurred over a 5-year period from 1982 to 1986. During period 2 (1996–2006), average annual inflow to Smith Valley at the Hoye streamgage was 212,300 acre-ft/yr and average annual inflow to Mason Valley at the Strosnider and Hudson streamgages was 298,100 acre-ft/yr (deviation from study-period average was +30,400 [+17 percent] and +52,500 [+21 percent] acre-ft/yr, respectively; table 4). Wetter conditions occurred from 1995 to 1999 and 2005 to 2006, whereas prolonged drought occurred from 2000 to 2004. During period 3 (2007–20), average annual inflow to Smith Valley at the Hoye streamgage was 162,400 acre-ft/yr and average annual inflow to Mason Valley at the Strosnider and Hudson streamgages was 219,100 (deviation from study-period average −19,500 [−11 percent] and −26,500 (−11 percent) acre-ft/yr, respectively). Prolonged drought occurred from 2007 to 2010 and 2012 to 2016, totaling 9 years. Notably wetter conditions occurred in 2011 and 2017. The scale and spatial extent of groundwater-level change and groundwater storage-volume change between each period are discussed by valley.

Groundwater-level contour maps from 1970, 1995, 2006, and 2020 are shown in figures 7–8. Groundwater-level change maps from the four periods, calculated using the groundwater-level contour differencing approach and the depth-to-water differencing point approach, are shown in figures 9–12. Estimated groundwater storage-volume change, calculated using approach 1 (contour method; figs. 9, 10) and approach 2 (point method; figs. 11, 12) is summarized in table 5. Estimated average groundwater-level change (in ft and feet per year [ft/yr]) and groundwater storage-volume change (in acre-feet and acre-ft/yr) are summarized in table 6.

Groundwater-level contours are considered approximate and accuracy is limited by the spatial distribution of wells in the study area, the positional accuracy of wells, and assumptions about the heterogeneity of the aquifer material. The contour method incorporated all available groundwater-level data but was limited by differing spatial distribution of wells between the study periods and the positional accuracy of wells. The point method, which only incorporated data from the 53 consistent wells measured during all study periods and used change in depth to water in lieu of groundwater-level altitude, removed uncertainty related to differing spatial distributions and positional accuracy of wells. However, the point method also introduced uncertainty by lacking the hydrologic nuances of interpretation of groundwater-level contours, particularly in complex regions with low spatial distribution of wells. The two methods provided estimates of groundwater-level change that can be used to address measurement uncertainty. The contour method provided an assessment of change across local and broad spatial scales, whereas the point method describes the average change.

Estimates from the two methods were of the same order of magnitude, with the exception of the change value for Smith Valley during period 2 (1996–2006; table 5). During this period, groundwater storage-volume change was generally much lower in magnitude compared to the other periods. The average difference between the two methods for each period was +14,800 and +13,000 acre-feet for Smith and Mason Valleys, respectively (table 5). The point approach tended to result in lower groundwater storage-volume change estimates. In Smith Valley, the point approach had poor well resolution in the eastern valley near Wilson Canyon and likely underestimated change in that region. In Mason valley, the point approach had poor well resolution in the northern region of the valley near Walker Gap and likely underestimated change in that region. Considering both methods generally produced comparable and reasonable estimates of groundwater storage-volume change, only the values calculated using the contour method are used to support the discussion that follows because this method incorporated all available data.

Without high accuracy positional locations and land surface altitudes of wells, as well as more spatially precise specific yield estimates, undesirable uncertainty in groundwater-level measurements and groundwater storage-volume estimates can occur. Refinement of well positional locations and land-surface altitudes with a high precision differential global positioning system or light detection and ranging (lidar) imagery and more precise lithologic descriptions for specific yield, could improve future groundwater-level and storage-volume estimates in the study area (Skinner and others, 2007).

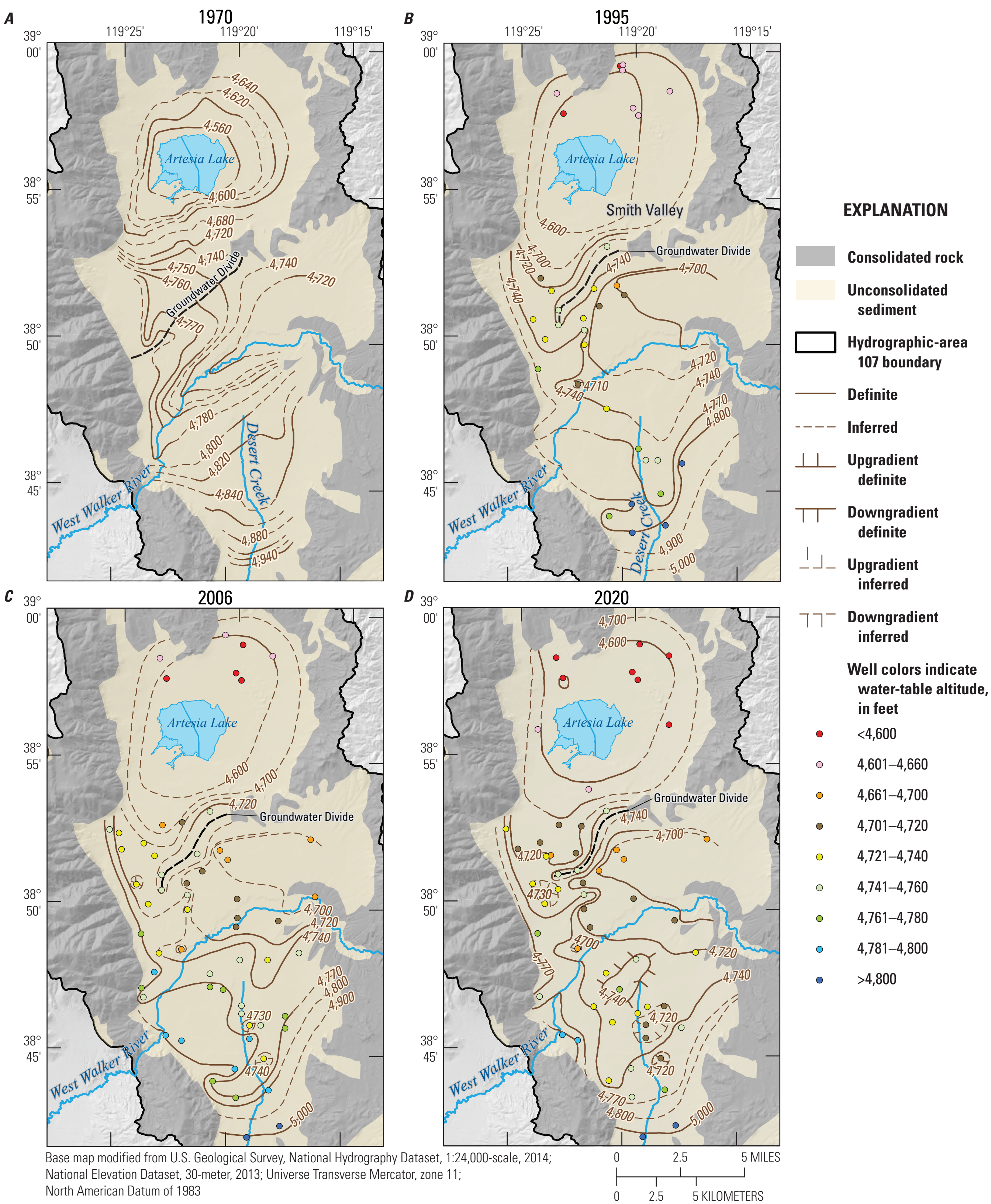


Figure 7. Groundwater-level maps representing contoured water-table altitudes in Smith Valley, Nevada, in *A*, 1970 (*Rush and Schroer, 1976); *B*, 1995, calculated from median groundwater levels in water years 1991–95 (Davies and Naranjo, 2022); *C*, 2006 (*Lopes and Allander, 2009a); and *D*, 2020, calculated from median groundwater levels in water years 2016–20 (Davies and Naranjo, 2022). *Indicates contours were updated from their original publication. Abbreviations: <, less than; >, greater than.

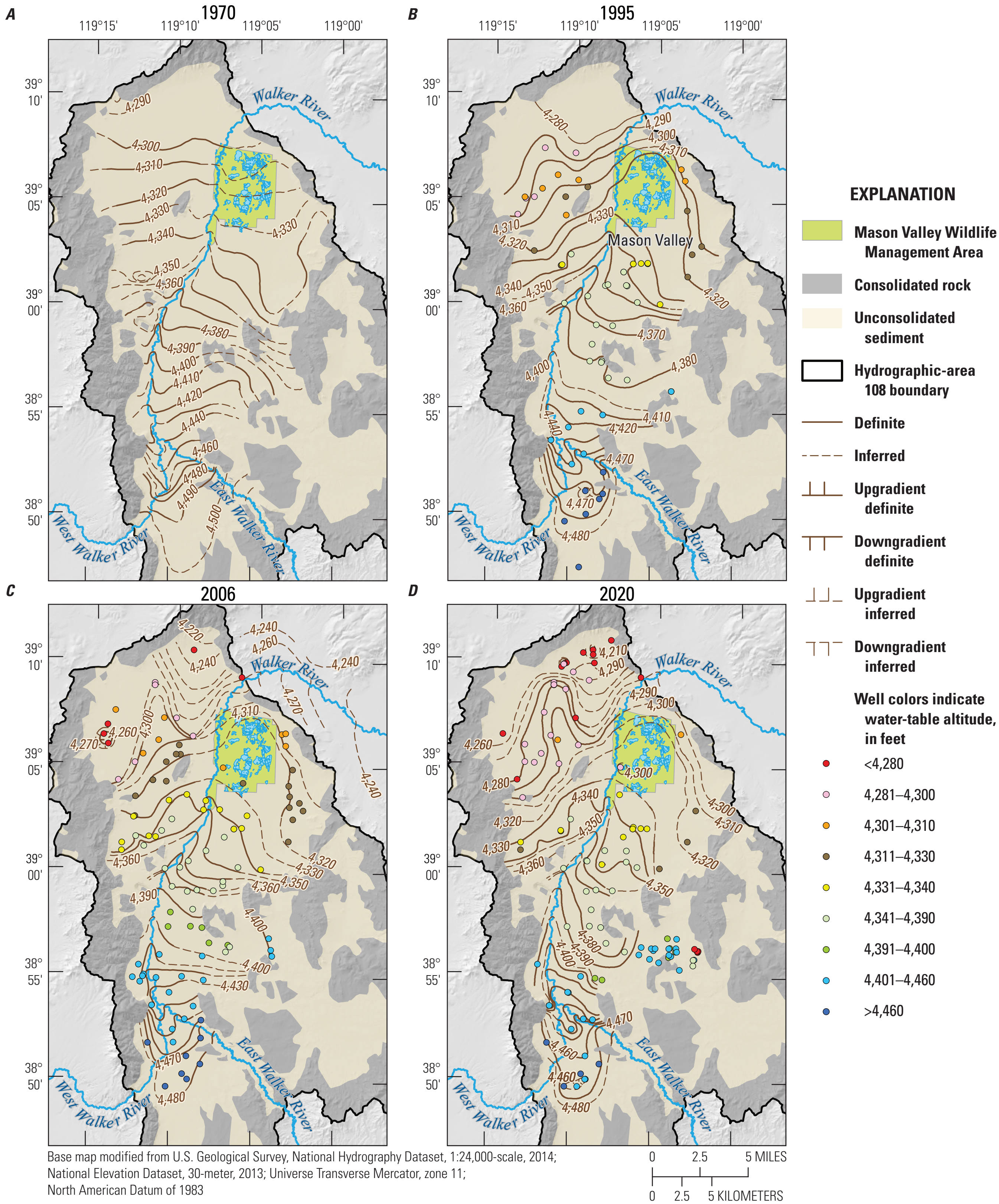


Figure 8. Groundwater-level maps representing contoured water-table altitudes in Mason Valley, Nevada, in *A*, 1970 (*Huxel and Harris, 1969); *B*, 1995, calculated from median groundwater levels in water years 1991–95 (Davies and Naranjo, 2022); *C*, 2006 (*Lopes and Allander, 2009a); and *D*, 2020, calculated from median groundwater levels in water years 2016–20 (Davies and Naranjo, 2022). *Indicates contours were updated from their original publication. Abbreviations: <, less than; >, greater than.

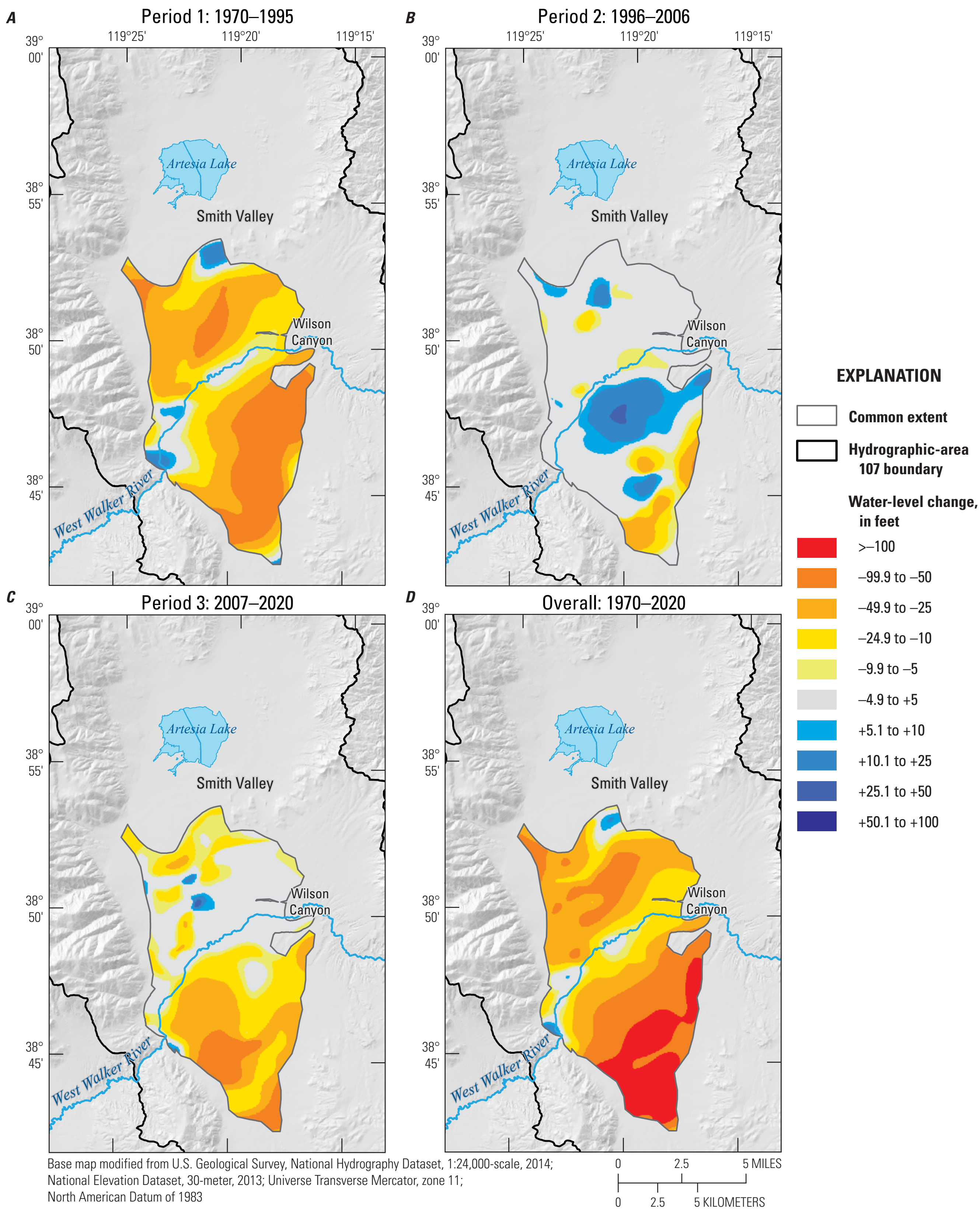


Figure 9. Groundwater-level change in Smith Valley, Nevada (Davies and Naranjo, 2022), for *A*, period 1: 1970–95; *B*, period 2: 1996–2006; *C*, period 3: 2007–20; and *D*, overall 1970–2020. Calculated using interpolated groundwater-level contours presented in figure 7 (Contour method/Approach 1). Abbreviation: >, greater than.

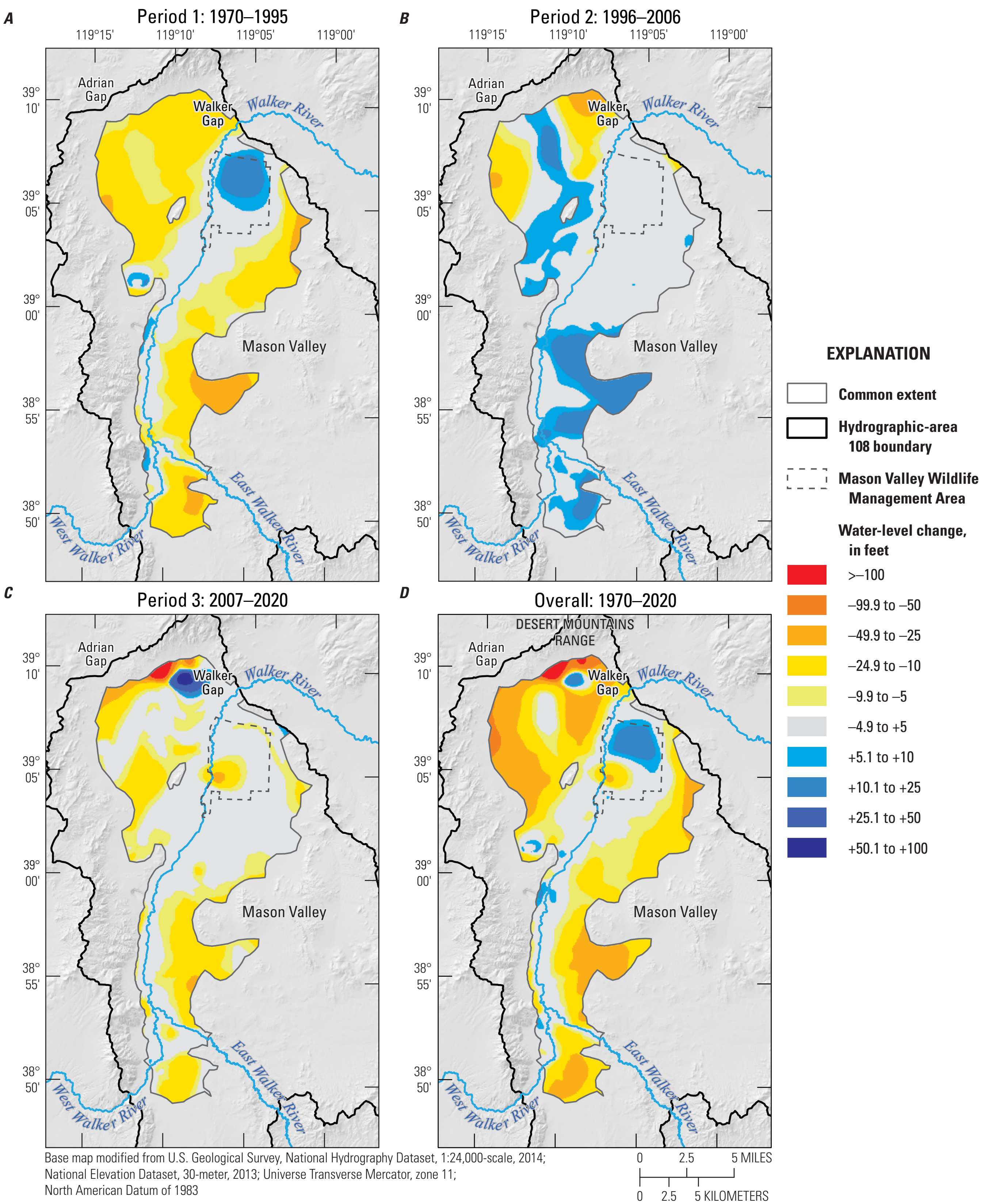


Figure 10. Groundwater-level change in Mason Valley, Nevada (Davies and Naranjo, 2022), for *A*, period 1: 1970–95; *B*, period 2: 1996–2006; *C*, period 3: 2007–20; and *D*, overall 1970–2020. Calculation used interpolated groundwater-level contours presented in figure 8 (Contour method/Approach 1). Abbreviation: >, greater than.

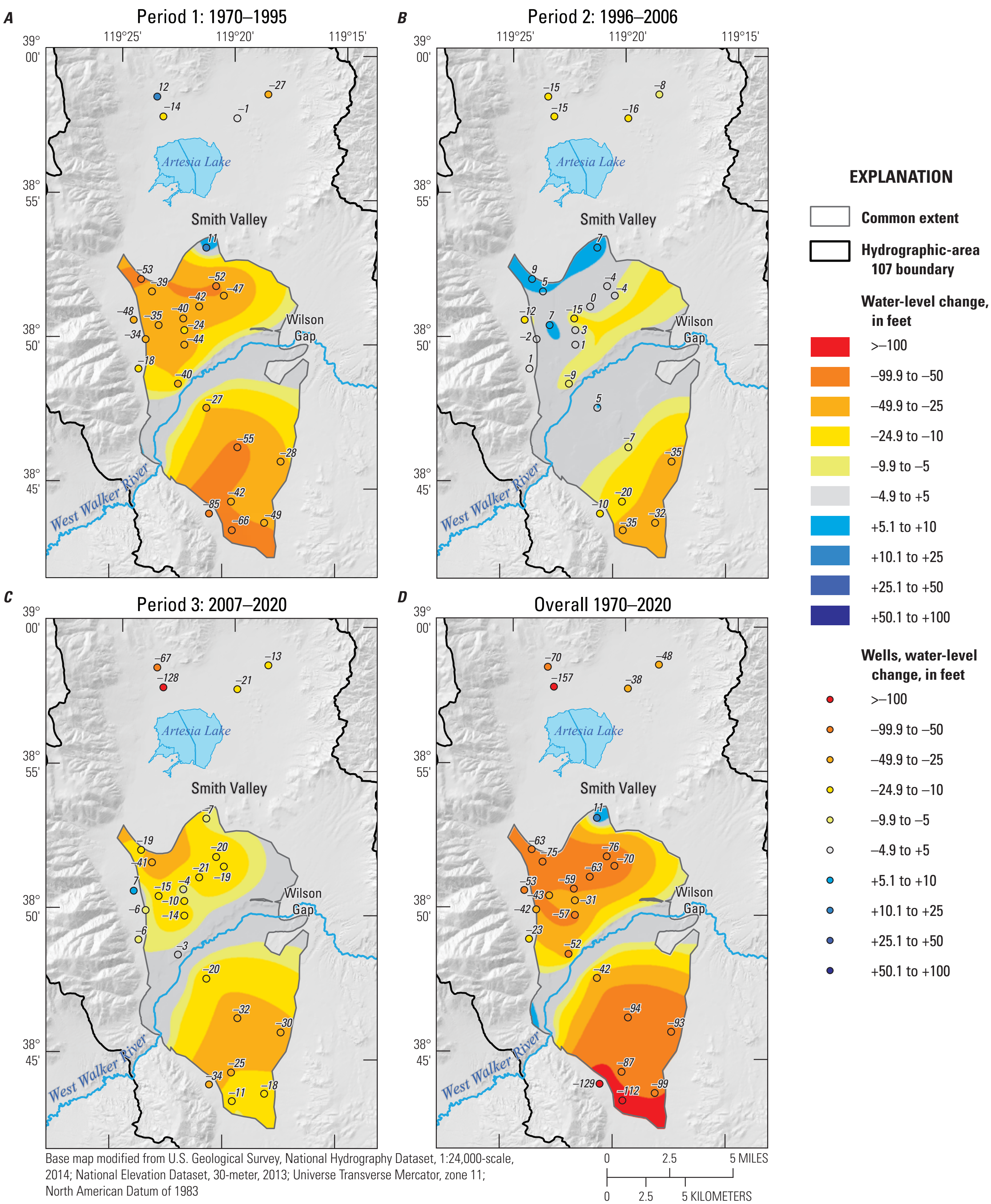


Figure 11. Groundwater-level change in Smith Valley, Nevada (Davies and Naranjo, 2022), for *A*, period 1: 1970–95; *B*, period 2: 1996–2006; *C*, period 3: 2007–20; and *D*, overall 1970–2020. Calculated using depth-to-water change at 25 consistent wells (53 total wells in Smith and Mason Valleys; point method/approach 2). Abbreviation: >, greater than.

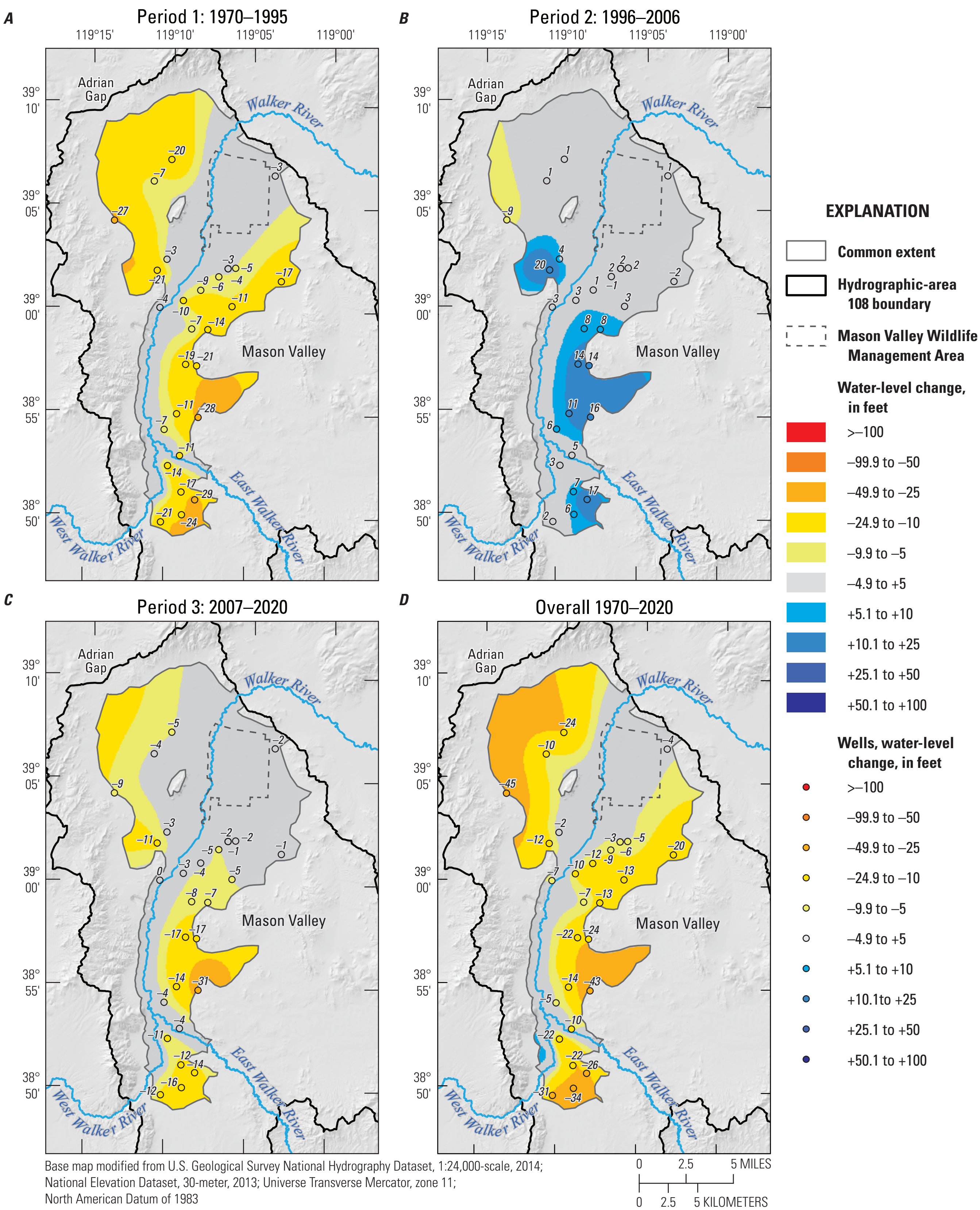


Figure 12. Groundwater-level change in Mason Valley, Nevada (Davies and Naranjo, 2022), for *A*, period 1: 1970–95; *B*, period 2: 1996–2006; *C*, period 3: 2007–20; and *D*, overall 1970–2020. Calculated using depth-to-water change at 28 consistent wells (53 total wells in Smith and Mason Valleys; Point method/Approach 2). Abbreviation: >, greater than.

Table 5. Groundwater storage-volume change (acre-feet) for 1970–95, 1996–2006, 2007–20, and overall 1970–2020, using two different approaches (Davies and Naranjo, 2022).

[The average difference between the two methods was plus (+) 14,800 and +13,000 acre-feet, for Smith and Mason Valleys, respectively. The total area assessed in Smith and Mason Valleys was 58 and 147 square miles, respectively (37,120 and 94,080 acres, respectively). For approach columns, positive value indicates storage increase; negative value indicates storage decline. **Abbreviations**: acre-ft, acre-feet; —, not applicable]

Period	Smith Valley			Mason Valley		
	Contour approach (acre-ft)	Point approach (acre-ft)	Difference (acre-ft)	Contour approach (acre-ft)	Point approach (acre-ft)	Difference (acre-ft)
Period 1: 1970–95	−191,700	−148,400	+43,300	−176,100	−179,300	−3,200
Period 2: 1996–2006	−3,700	−36,300	−32,600	+19,100	+38,000	+18,900
Period 3: 2007–20	−92,200	−78,800	+13,400	−112,000	−103,700	+8,300
Overall: 1970–2020	−287,600	−252,500	+35,100	−269,000	−241,100	+27,900
Average	—	—	+14,800	—	—	+13,000

Table 6. Average groundwater-level change (feet and feet per year) and groundwater storage-volume change (acre-feet and acre-feet per year) for 1970–95, 1996–2006, 2007–20, and overall 1970–2020 (Davies and Naranjo, 2022).

[Positive value indicates increase; negative value indicates decline. **Abbreviations**: GW, groundwater; acre-ft, acre-feet; acre-ft/year, acre-feet per year; ft/yr, feet per year]

Period	Smith Valley				Mason Valley			
	Average water-level change		GW storage-volume change		Average water-level change		GW storage-volume change	
	(feet)	(ft/yr)	(acre-ft)	(acre-ft/ yr)	(feet)	(ft/yr)	(acre-ft)	(acre-ft/ yr)
Period 1: 1970–95	–35	–1.3	–191,700	–7,400	–9	–0.3	–176,100	–6,800
Period 2: 1996–06	–1	–0.1	–3,700	–300	+1	+0.1	+19,100	+1,700
Period 3: 2007–20	–17	–1.2	–92,200	–6,600	–6	–0.4	–112,000	–8,000
Overall: 1970–2020	–52	–1.0	–287,600	–5,600	–14	–0.3	–269,000	–5,300

Period 1: 1970–1995 Change

In Smith Valley, although groundwater levels declined dramatically between 1970 and 1995, groundwater-flow directions remained similar to those originally identified by Rush and Schroer (1976). The West Walker River changed from strongly gaining to moderately gaining or near neutral conditions (figs. 7*A*–7*B*). The groundwater divide between Artesia Lake and the West Walker River, identified in 1970, was still evident in 1995 and positioned near the same location but more challenging to define across the valley. The location and extent of this groundwater divide is expected to change as recharge and discharge patterns change. The divide was located near the Colony Ditch system and could be the result of recharge from irrigating and leakage from the Colony Ditch (fig. 2).

The most dramatic and widespread groundwater-level decline in Smith Valley occurred south of the West Walker River (fig. 9*A*). In particular, the region south of Wilson Canyon experienced declines up to approximately 80 ft. From 1970 to 1995, the average water-level change across Smith Valley was −35 ft and groundwater storage-volume change was −191,700 acre-ft (−1.3 ft/yr and −7,400 acre-ft/yr; table 6). During period 1, streamflow into Smith Valley at the Hoye streamgage was 1,300 acre-ft/yr below the study-period average (−1 percent; table 4). In other words, period 1 streamflow was representative of the study period of analysis average. Sustained groundwater declines during a period of average surface-water availability would indicate there was an overreliance on supplemental groundwater in Smith Valley. Groundwater pumpage data were not available for this period.

In Mason Valley, groundwater levels declined throughout the valley and groundwater-flow directions were varied from those identified by Huxel and Harris (1969). The West Walker River reach changed from gaining to near neutral conditions (figs. 8*A*–8*B*). The East Walker River reach changed from gaining to losing conditions (figs. 8*A*–8*B*). The Walker River downstream from the confluence of the East and West Walker Rivers progressed to more losing conditions (figs. 8*A*–8*B*). Groundwater levels increased at the Management Area and created an apparent recharge mound, steepening the groundwater gradient at the north end of Mason Valley, east of the Walker River (figs. 8*A*–8*B*). Moderate groundwater-level decline was seen throughout Mason Valley, with the exception of the Management Area (fig. 10*A*). From 1970 to 1995, the average groundwater-level change across Mason Valley was −9 ft and groundwater storage-volume change was −176,100 acre-ft (−0.3 ft/year and −6,800 acre-ft/yr; table 6). During this period, streamflow into Mason Valley from the Strosnider and Hudson streamgages was 7,300 acre-ft/yr below (−3 percent) the study-period average (table 4). Similar to Smith Valley, sustained groundwater declines during a period of near average surface-water availability would indicate there was an overreliance on supplemental groundwater in Mason Valley (groundwater pumpage data were not available for this period).

Period 2: 1996–2006 Change

In Smith Valley, groundwater levels and groundwater-flow directions generally were unchanged between 1996 and 2006 (figs. 7*B*–7*C*). The southern edge of Smith Valley continued to experience moderate groundwater-level decline, whereas the center of the valley, adjacent to the West Walker River, experienced notable groundwater-level rise (fig. 9*B*). The location of the groundwater divide in Smith Valley was relatively unchanged. From 1996 to 2006, the average groundwater-level change across Smith Valley was −1 ft and groundwater storage-volume change was −3,700 acre-ft (−0.1 ft/yr and −300 acre-ft/yr; table 6). During this period, streamflow into Smith Valley at the Hoye streamgage was 30,400 acre-ft/yr above the study-period average (+17 percent) and groundwater pumpage was 2,900 acre-ft/yr below the study-period average (–11 percent; table 4). The reliance on groundwater pumping was less during this period given the greater supply of surface water to meet irrigation demands (fig. 3*A*); however, there were still regions of moderate groundwater-level decline in southern Smith Valley (fig. 9*B*). The first 4 years of period 2 (1996–2000) were very wet, with streamflows at the Hoye streamgage 79,900 acre-ft/yr above the study-period average (+43 percent), whereas the following 4 years of this period (2001–04) experienced prolonged drought, with streamflows at the Hoye streamgage 67,100 acre-ft/yr below the study-period average (–37 percent). Above-average streamflows for the final 2 years of this period (2005–06) provided some rebound but not enough to completely offset the period of prolonged drought.

In Mason Valley, there were no prominent shifts in the river gaining or losing condition (figs. 8*B*–8*C*). The West Walker River reach maintained neutral conditions, the East Walker River reach maintained losing conditions, and the Walker River below the confluence maintained losing conditions. Mason Valley experienced some notable groundwater-level rise in the northern and southern parts of the valley (fig. 10*B*). The only region of groundwater-level decline occurred at the northwest and north edge of the valley, near Adrian Gap and the geothermal power station, respectively. From 1996 to 2006, the average groundwater-level change across Mason Valley was +1 ft and groundwater storage-volume change was +19,100 acre-ft (+0.1 ft/yr and +1,700 acre-ft/yr; table 6). During this period, streamflow into Mason Valley from the Strosnider and Hudson streamgages was 52,500 acre-ft/yr above the study-period average (+21 percent) and groundwater pumpage was 6,000 acre-ft/yr below the study-period average (–8 percent; table 4). Similar to Smith Valley, reliance on groundwater pumpage was reduced between 1995 and 2000 and increased between 2001 and 2005 (fig. 3*B*).

Period 3: 2007–2020 Change

In Smith Valley, groundwater levels declined between 2007 and 2020 and groundwater-flow directions deviated from those identified by Lopes and Allander (2009a). The West Walker River changed from gaining conditions throughout the valley in 2006 to losing conditions on the west side of the valley to progressively neutral conditions on the east side of the valley in 2020 (figs. 7*C*–7*D*). The spatial extent of the groundwater divide constricted with the gradient steepened, likely due to continued application of irrigation water along the divide and increase pumping to either side of it. Considerable groundwater-level decline occurred throughout Smith Valley, particularly in the region south of the West Walker River, but not to the same amount of decline seen during period 1 (1970–95; fig. 9*C*). From 2007 to 2020, the average groundwater-level change across Smith Valley was −17 ft and groundwater storage-volume change was −92,200 acre-ft (−1.2 ft/yr and −6,600 acre-ft/yr; table 6). During this period, streamflow into Smith Valley at the Hoye streamgage was 19,500 acre-ft/yr below the study-period average (–11 percent) and groundwater pumpage was 2,800 acre-ft/yr above the study-period average (+11 percent; table 4). Less streamflow available for diversions resulted in greater demands on supplemental groundwater to meet irrigation needs during this period, which further intensified the imbalance of surface-water and groundwater withdrawals.

In Mason Valley, groundwater levels declined throughout the valley, whereas groundwater-flow directions remained relatively unchanged since 2006. The West Walker River reach maintained neutral conditions, whereas the East Walker River reach and the Walker River below the confluence changed to stronger losing conditions (figs. 8*C*–8*D*). Moderate groundwater-level decline (10–25 ft) occurred along the valley peripheries but not to the same magnitude seen during period 1 (1970–95; figs. 10*A*, 10*C*). One notable area of groundwater-level rise occurred adjacent to the geothermal power station and could be associated with a change in water disposal locations by the geothermal power station. From 2007 to 2020, the average groundwater-level change across Mason Valley was −6 ft and groundwater storage-volume change was at −112,000 acre-ft (−0.4 ft/yr and −8,000 acre-ft/yr; table 6). During this period, streamflow into Mason Valley from the Strosnider and Hudson streamgages was 26,500 acre-ft/yr below the study-period average (–11 percent) and groundwater pumpage was 4,200 acre-ft/yr above the study-period average (+5 percent; table 4). Similar to Smith Valley, less streamflow available for diversions in Mason Valley resulted in greater demands on groundwater during this period.

Overall Change: 1970–2020

In Smith Valley, from 1970 to 2020, the average groundwater level across the valley declined 52 ft and groundwater storage-volume declined 287,600 acre-ft (table 6). The most dramatic groundwater-level decline occurred south of the West Walker River, where a region covering 10 mi^2 experienced declines greater than 100 ft (fig. 9*D*). The fluvial deposit units of the West Walker River, which comprise a 0.5 mile wide buffer on either side of the river, experienced a much smaller average groundwater-level decline of 12 ft, which was far less than the remaining area of Smith Valley. This less severe groundwater-level decline was due to the West Walker River remaining in connection with the aquifer and supporting the groundwater levels along the river corridor. Groundwater pumping in fluvial deposit units in close proximity to the river will capture a larger fraction of streamflow and offset lowering of the groundwater table, whereas pumping farther away from the river will deplete groundwater storage and capture a much smaller fraction of streamflow, resulting in a larger decline of the groundwater table (Barlow and Leake, 2012).

In Mason Valley, from 1970 to 2020, the average groundwater-level across the valley declined 14 ft and groundwater storage-volume declined 269,000 acre-ft (table 6). Groundwater-level decline in Mason Valley was more gradual and evenly distributed than in Smith Valley. The most dramatic groundwater-level decline in Mason Valley occurred at the north-northwest periphery of the valley, near Adrian Gap and at the foot of the Desert Mountains (fig. 10*D*). Groundwater-level rise occurred at the Management Area and the various discharge regions associated with the geothermal power station. Similar to Smith Valley, the fluvial deposit units of the West Walker, East Walker, and Walker Rivers in Mason Valley experienced far less groundwater-level decline than any other region in the valley due to streamflow capture. In Mason Valley, the average groundwater-level decline in fluvial deposit units was 2 ft.

Total groundwater storage-volume decline by volume in Smith and Mason Valleys was of similar magnitude (287,600 and 269,000 acre-ft, respectively) despite Mason Valley containing more irrigated land (approximately 19,000 and 37,000 acres, for Smith and Mason Valleys, respectively) and diverting a larger part of its streamflow (approximately 35 and 55 percent of valley inflow is diverted annually for irrigation in Smith and Mason Valleys, respectively; Davies and Naranjo, 2022). Similar groundwater storage-volume declines in both valleys despite differing irrigated acreage and proportional river diversions is likely, in part, due to different dynamics between the river and aquifer (the implications of this are further discussed later in this report).

Overall, the groundwater-level change maps in both valleys indicate substantial groundwater-level decline over recent decades since implementation of supplemental groundwater use. Decline was most prominent along the valley peripheries and less pronounced along the river corridor. The West Walker River in Smith Valley, historically a gaining reach, changed to a losing and more neutral reach between 2006 and 2020. The West Walker River in Mason Valley changed from a gaining reach to a neutral reach between 1970 and 1995 and maintained neutral conditions through 2020. The East Walker River in Mason Valley changed from a neutral reach to a losing reach between 1970 and 1995 and maintained losing conditions through 2020. The Walker River below the confluence in Mason Valley has mainly been losing throughout the period 1970–2020.

Groundwater Storage-Volume Change and Groundwater Pumpage

A summary of the annual rates of groundwater storage decline and groundwater pumpage by period are presented in table 7. For a given period, the difference between the annual rate of groundwater pumpage and the annual rate of groundwater storage-volume decline may provide insight on the magnitude to which the aquifer can be pumped without incurring storage decline. In Smith Valley, for periods 2 and 3, the difference between the groundwater pumpage rate and the groundwater storage-volume decline rate was 22,600 and 22,000 acre-ft/yr, respectively. In Mason Valley, for periods 2 and 3 the difference between the groundwater pumpage rate and the groundwater storage-volume decline rate was 74,900 and 75,400 acre-ft/yr, respectively. For both valleys, the differences were nearly equal for periods 2 and 3, whereas climatic conditions were notably different during the two periods. Period 2 was characterized by generally wetter conditions than period 3. The groundwater storage-volume decline rate represents the imbalance of aquifer recharge and groundwater withdrawal. In Smith Valley, groundwater pumping in excess of 22,300 acre-ft/yr will likely result in groundwater storage-volume decline. In Mason Valley, groundwater pumping in excess of 75,200 acre-ft/yr will likely result in groundwater storage-volume decline.

Groundwater Hydrograph Analysis

Groundwater-level decline was prevalent throughout Smith Valley (fig. 13**)**. The greatest declines during the period of analysis occurred in northern Smith Valley adjacent to Artesia Lake. At one well (fig. 13*A*), groundwater level declined 158 ft from 1976 to 2020, with most of the decline occurring over a 4-year period between 2007 and 2011. South of the groundwater divide, which separates the Lake Artesia area from the part of Smith Valley where groundwater moves toward the West Walker River, groundwater-level declines were steady regardless of proximity to the river (figs. 13*B*–13*F*). Groundwater levels in wells north of the West Walker River (figs. 13*C*–13*D*) declined 24–30 ft since the 1970s, whereas groundwater levels south of the West Walker (figs. 13*E*–13*F*) declined 65–103 ft since the 1970s. The locations of these four wells range from 0.4 to 4.75 miles from the river however, groundwater-levels at all four wells followed the pattern of annual valley inflow (as measured at the Hoye streamgage), declining during periods with below average streamflow and recovering to varying intensity during periods of above average streamflow (fig. 13*G*). Groundwater levels closer to the river increased promptly in response to above average streamflow in WYs 1983, 1995–97, 2006, 2011, and 2017. Groundwater levels typically remained elevated for 1–5 years following WYs with above average streamflow. In particular, the series of consecutive wet years between 1995 and 1999 provided groundwater-level recovery into 2000. On the eastern edge of Smith Valley, north of Wilson Canyon (fig. 13*B*), in a well that is outside of irrigated areas and away from the river, groundwater levels steadily declined a total of 3 ft since the early 2000s and showed little response to changes in streamflow. More than 50 percent of the aquifer south of the groundwater divide has declined more than 50 feet since 1970.

In Mason Valley, groundwater-level decline was prevalent throughout the valley but greatest along the valley margins (fig. 14). Groundwater levels in wells along the fringe (figs. 14*C*, 14*E*, 14*H*) declined 22–32 feet from the 1960s to 2020. Groundwater levels in wells closer to the center of Mason Valley that are in proximity with Walker River (figs. 14*D*, 14*F*, 14*G*) declined less than 10 feet since the 1960s. However, these same sites experienced more notable short-term declines and increases related to annual valley inflow (as measured at the Strosnider and Hudson streamgage; fig. 14*I*), and groundwater pumping because of their proximity to the river. Considerable groundwater-level decline occurred more recently at the northern end of Mason Valley, near the geothermal power station. In one nearby well (fig. 14*A*), groundwater levels declined 100 feet since the early 2010s. Southeast of the geothermal power station at Walker Gap and 0.2 miles from the Walker River, the groundwater level rose 4 feet since 2004 (fig. 14*B*). Similar to Smith Valley, groundwater levels throughout Mason Valley rebounded promptly and typically remained elevated for several years following WYs with above average streamflow (fig. 14*I*).

Table 7. Groundwater storage-volume decline and groundwater pumpage (acre-feet per year) for 1970–95, 1996–2006, and 2007–20 (Nevada Division of Water Resources, 2021b; Davies and Naranjo, 2022).

[Groundwater storage decline (acre-feet per year; positive value indicates decline and negative value indicates increase; Davies and Naranjo, 2022); average total groundwater pumpage for the available period of record (acre-feet per year; Nevada Division of Water Resources, 2021b); difference between groundwater storage decline and average total groundwater pumpage (acre-feet per year). **Abbreviations**: GW, groundwater; acre-ft/yr, acre-feet per year; —, no data; =, equals]

Period	Smith Valley			Mason Valley		
	GW storage decline (acre-ft/yr) (1)	Average annual GW pumpage (acre-ft/yr) (2)	Difference (acre-ft/yr) (3) = (2) – (1)	GW storage decline (acre-ft/yr) (1)	Average annual GW pumpage (acre-ft/yr) (2)	Difference (acre-ft/yr) (3) = (2) – (1)
Period 1: 1970–95	7,400	—[1]	—	6,800	—[1]	—
Period 2:1996–2006	300	22,900	22,600	–1,700	73,200	74,900
Period 3: 2007–20	6,600	28,600	22,000	8,000	83,400	75,400
Average	—	—	22,300	—	—	75,200

[1]Groundwater pumpage data were not available for this period.

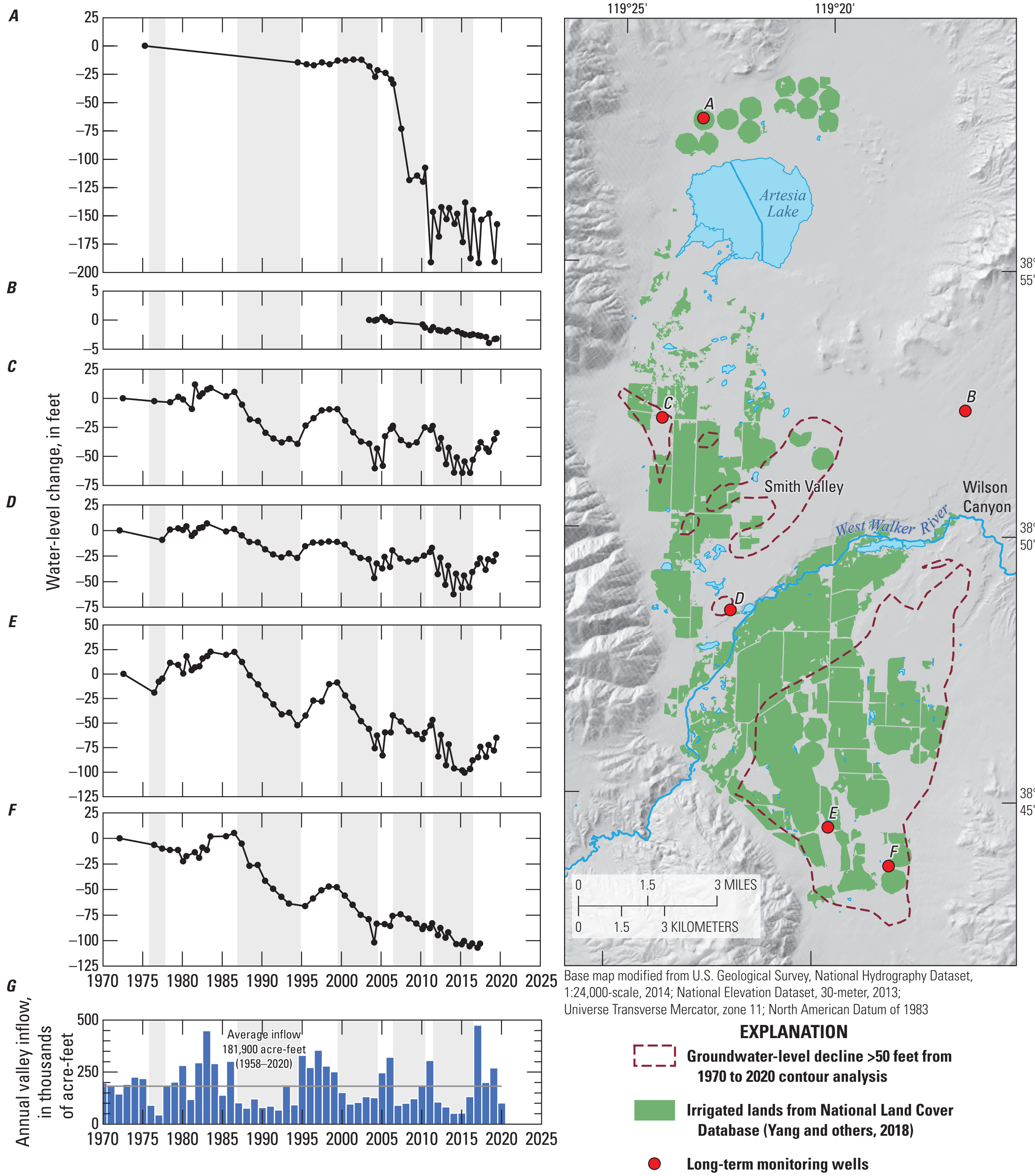


Figure 13. Groundwater-level change and annual valley surface water inflow in Smith Valley (Nevada Division of Water Resources, 2021a; U.S. Geological Survey, 2021). *A*–*F*, Groundwater-level data at long-term monitoring wells and wells near regions with recent change in Smith Valley, Nevada, 1970–2020; and *G*, annual valley inflow to Smith Valley (as measured at Hoye streamgage), Nevada, water years 1970–2020 (U.S. Geological Survey, 2021). Missing values from 1979 to 1994 are due to seasonal operation of U.S. Geological Survey streamgages. Water-level decline great than 50 feet (1970–2020; dashed red line) from groundwater-level change contour analyses (Davies and Naranjo, 2022). Highlighted drought years include 1976–77, 1987–94, 2000–04, 2007–10, 2012–16. Abbreviation: >, greater than.

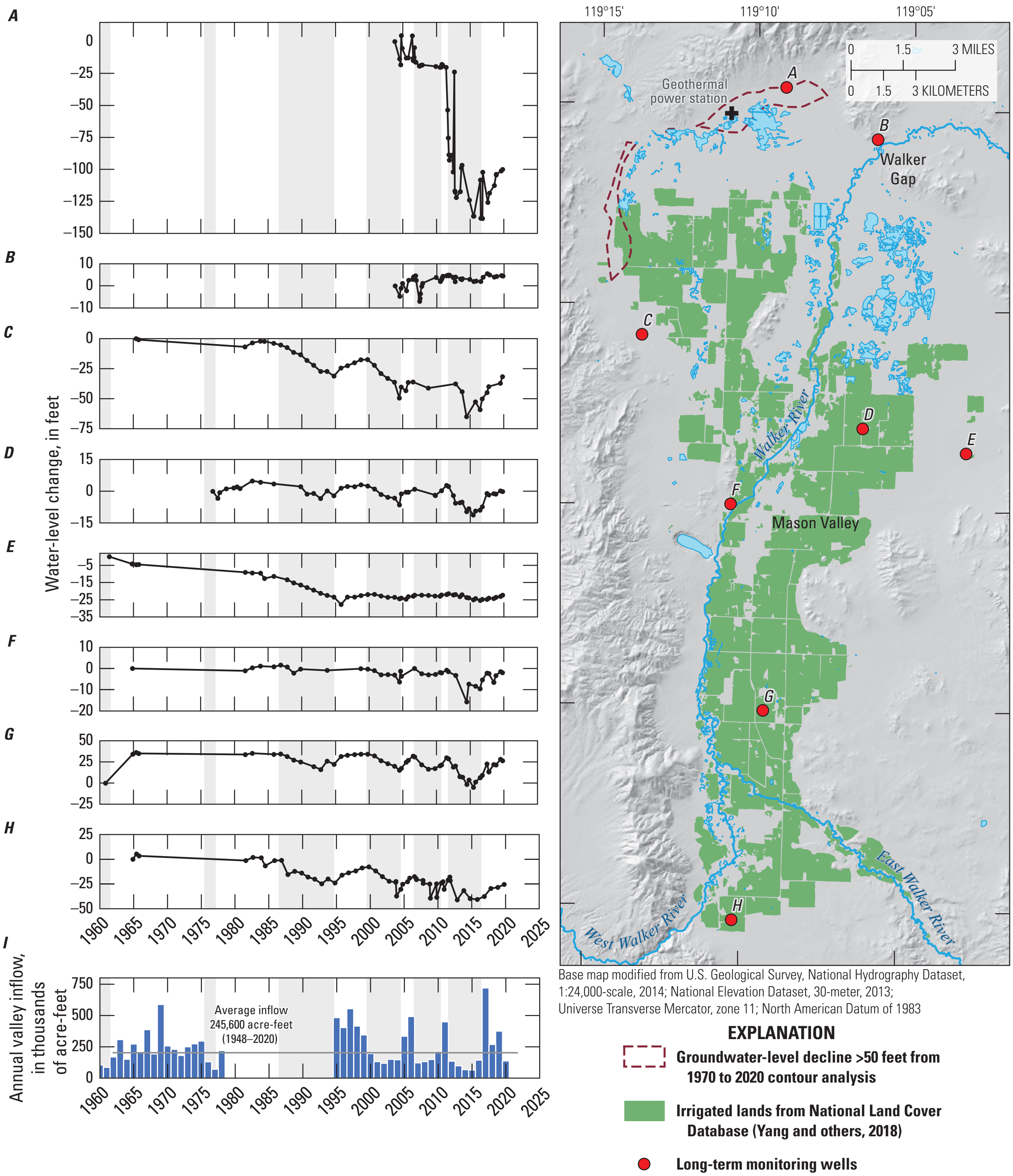


Figure 14. Groundwater-level change and annual valley surface-water inflow in Mason Valley (Nevada Division of Water Resources, 2021a; U.S. Geological Survey, 2021). *A–H*, groundwater-level data at long-term monitoring wells and wells near regions with recent change in Mason Valley, Nevada, 1960–2020; and *I*, annual valley inflow to Mason Valley (as measured at Strosnider and Hudson streamgages), water years 1960–2020 (U.S. Geological Survey, 2021). Missing values from 1979 to 1994 are due to seasonal operation of U.S. Geological Survey streamgages. Groundwater-level decline greater than 50 feet (1970–2020; dashed red line) from groundwater-level change contour analyses (Davies and Naranjo, 2022). Highlighted drought years include 1960–61, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16. Abbreviation: >, greater than.

Walker River Stream Efficiency

The monthly stream efficiency for the West Walker River in Smith Valley and the Walker River in Mason Valley are calculated for the irrigation and non-irrigation seasons of the period with available streamflow and diversion records (1948/1958 to 2020; figs. 15–16). Annual stream efficiencies are compared to average annual valley stream inflow and groundwater pumping (figs. 17–19). Additionally, monthly stream efficiencies and monthly valley inflows are examined during several periods of prolonged drought (fig. 20). Finally, annual streamflow gains and losses are presented for the period of analysis (figs. 21–22). Calculated stream efficiencies are published in the accompanying USGS data release (Davies and Naranjo, 2022).

West Walker River through Smith Valley

During the period of this analysis (1958–2020), the average annual inflow of the West Walker River into Smith Valley at the Hoye streamgage was 181,900 acre-ft/yr, and the average annual diversion volume within the river was 63,200 acre-ft/yr (35 percent of total river inflow; fig. 6*B*; Davies and Naranjo, 2022; U.S. Geological Survey, 2021). The West Walker River through Smith Valley was historically an efficient stream, gaining groundwater discharge throughout the year; however, the river has been influenced by groundwater-level declines associated with groundwater pumping and has become less efficient over time (fig. 15). Historically, the West Walker River was most efficient during non-irrigation season and less efficient during irrigation season when diversions were occurring, indicating a higher percentage of streamflow was supported by groundwater discharge during the non-irrigation season when streamflows were lower and surface water was not diverted. Trend tests for stream efficiency resulted in p-values less than 0.05 ($p<0.05$); therefore, the null hypothesis was rejected and trends were considered statistically significant. Stream efficiency has declined during both seasons over time; however, the river remains a gaining reach. Non-irrigation season stream efficiency declined more rapidly, at a statistically significant rate of −1.1 percent per year ($p<0.05$), compared to stream efficiency during irrigation season, which declined at a statistically significant rate of −0.3 percent per year ($p<0.05$). Average irrigation season stream efficiency values less than 1, which indicate a losing reach rather than gaining reach, first occurred during the 1998 irrigation season and re-occurred during 2015, 2016, and 2018 irrigation seasons (fig. 15*A*). Average non-irrigation season stream efficiency values less than 1 first occurred during the 2005 non-irrigation season and again in 2008 and 2017 (fig. 15*B*). Before 1998, the West Walker River through Smith Valley was always gaining from groundwater. It seems that the West Walker River has recently (2020) reached a point where gains and losses are nearly equivalent during the irrigation season (stream efficiency=1). Stream efficiency fluctuated more substantially during non-irrigation season than during irrigation season.

Trends in stream efficiency generally followed variations in annual valley inflow throughout the period of analysis (figs. 17*A*, 17*C*). During periods of prolonged drought, annual stream efficiency generally declined, although not always. There is an inverse relation between groundwater pumpage and stream efficiency in Smith Valley (figs. 18*A*–18*B*). When annual groundwater pumpage exceeded approximately 30,000 acre-ft, stream efficiency tended to decline. More distinct declines in stream efficiency occurred when increased groundwater pumping occurred for at least two continuous years. The relation between groundwater pumpage and stream efficiency for the following year (n+1) had an R^2=0.32 (fig. 18*C*). During the period of record (1994–2020), average annual groundwater pumpage in Smith Valley was 25,800 acre-ft (Nevada Division of Water Resources, 2021b).

During periods of prolonged drought, low streamflow resulted in increasingly less efficient stream conditions (fig. 20*A*). Drought periods in the late-1950s to the late-1970s routinely resulted in stream efficiencies greater than 1.5, whereas low streamflow during drought periods in the early 2000s to the late-2010s consistently resulted in stream efficiencies less than 1.5. Historically, gaining conditions still occurred with low streamflow; however, more recently, near-neutral or losing conditions occurred more regularly during low streamflow conditions. This change in stream behavior is likely a result of the decline in the groundwater table in response to groundwater pumping occurring near the stream and throughout the valley. Pumping can intercept groundwater that would otherwise discharge into a gaining stream or, at large enough pumping rates, can induce a net seepage loss from the stream to the aquifer (Winter and others, 1998). In western Nevada, projected increases in temperature from climate change are expected to create longer hotter summers with more lengthy droughts (Snyder and others, 2019). Hotter and longer droughts in the future may result in continued declines in stream efficiency at low streamflows.

The total volume of annual streamflow gains declined during the period of analysis (fig. 21*A*). During the first half of the period analysis (1958–78), the average annual gain volume was 30,400 acre-ft/yr (Davies and Naranjo, 2022). During the second half of the period of analysis (1995–2020), the average annual gain volume was less than half of what it was between 1958 and 1978, at only 12,400 acre-ft/yr (Davies and Naranjo, 2022). Similar trends in declining streamflow gains were also observed just during non-irrigation season (fig. 22*A*).

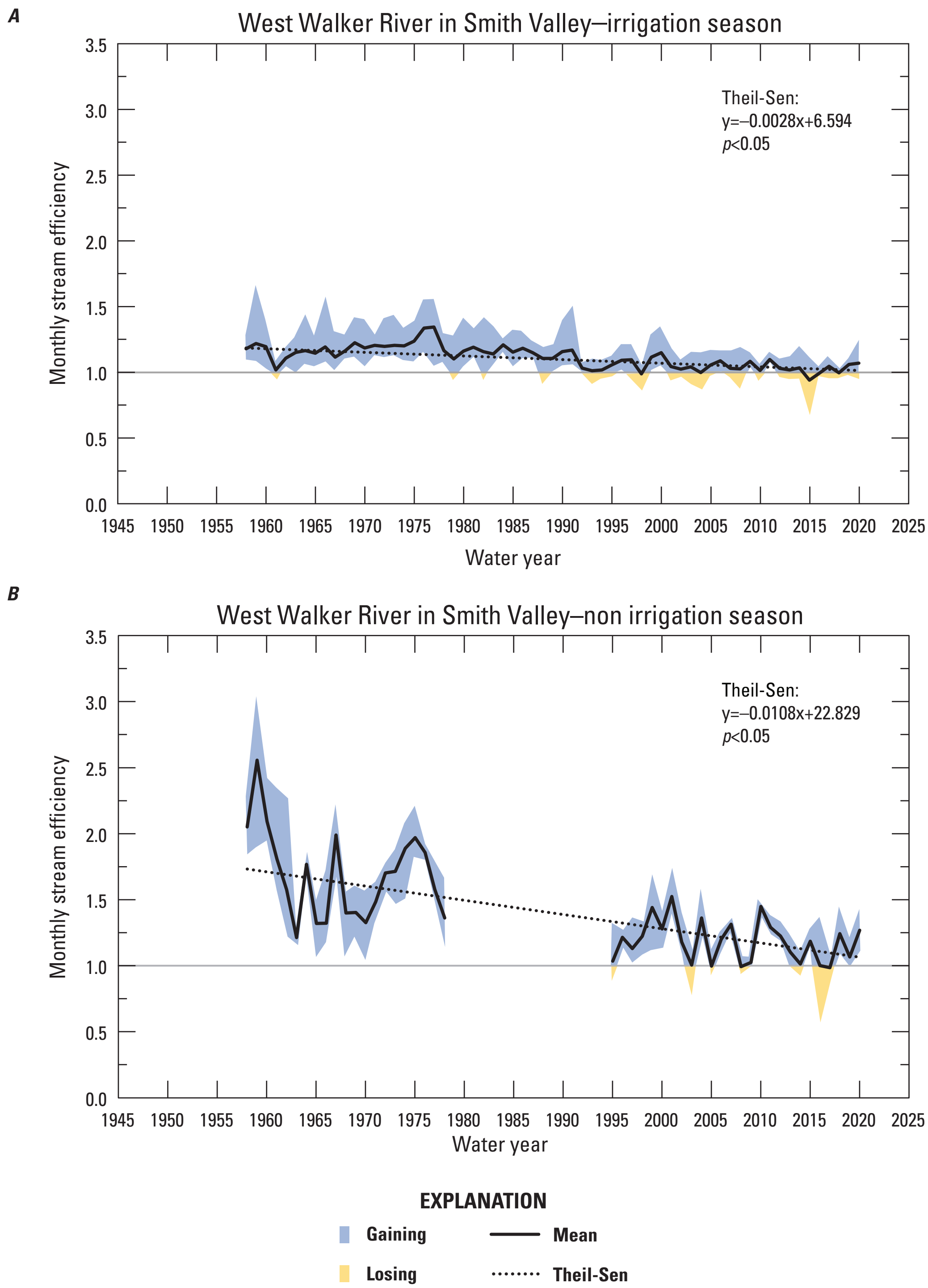


Figure 15. Range of monthly stream efficiencies (blue indicates gaining conditions, yellow indicates losing conditions), seasonal average (solid black line), and Theil Sen (dashed black line; Helsel and others 2020) for Smith Valley, Nevada, 1958–2020 (Davies and Naranjo, 2022), during *A*, irrigation months (April–September); and *B*, non-irrigation months (November–February); Complete streamflow data missing from 1979 to 1994 due to seasonal operation of U.S. Geological Survey streamgages. Abbreviations: =, equals; +, plus; <, less than.

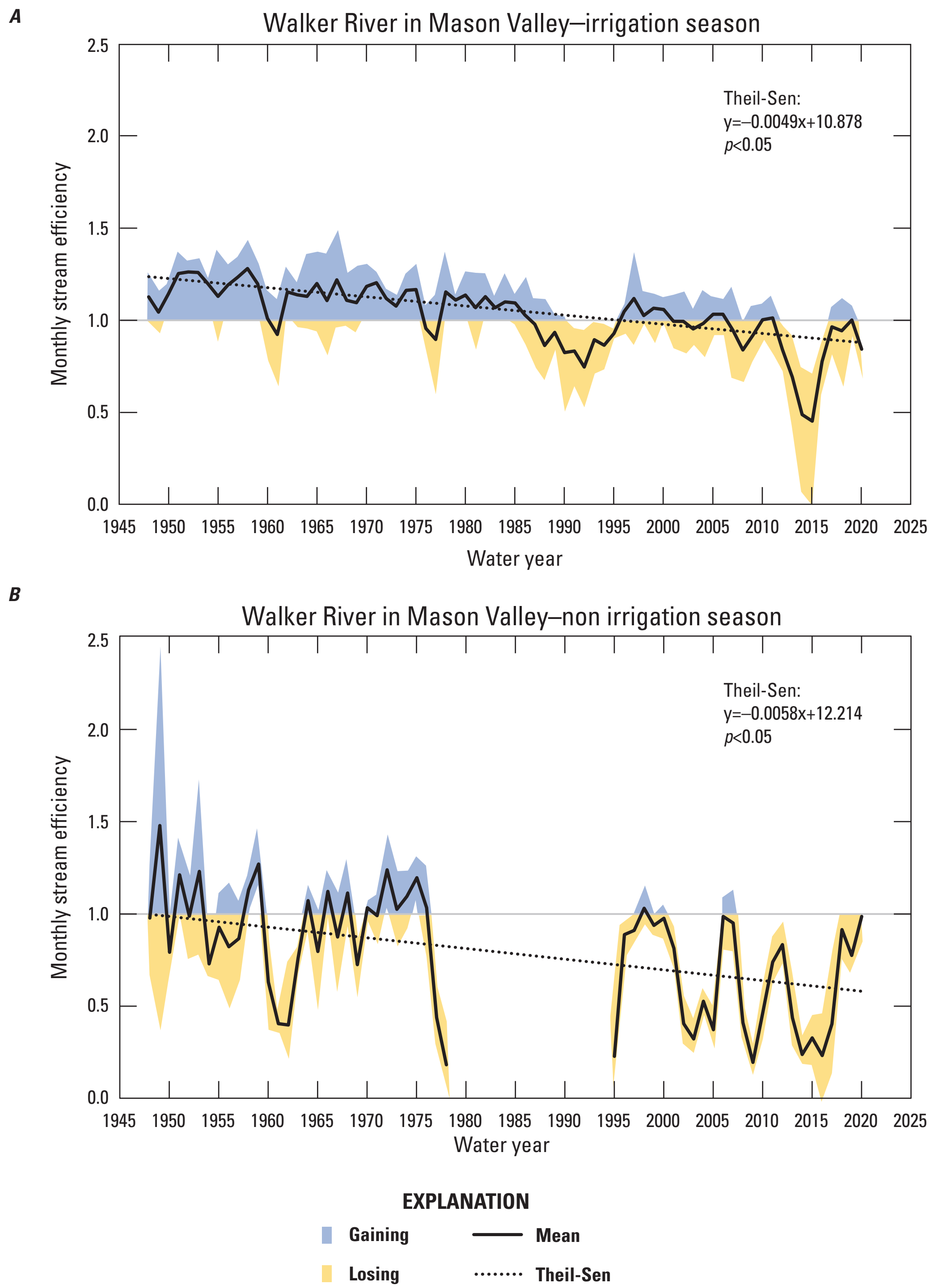


Figure 16. Range of monthly stream efficiencies (blue indicates gaining conditions, yellow indicates losing conditions), seasonal average (solid black line), and Thiel Sen (dashed black line; Helsel and others, 2020) for Mason Valley, Nevada, 1948–2020 (Davies and Naranjo, 2022), during *A*, irrigation season (April–September); and *B*, non-irrigation season (November–February); Complete streamflow data missing from 1979 to 1994 due to seasonal operation of U.S. Geological Survey streamgages. Abbreviations: =, equals; +, plus; <, less than.

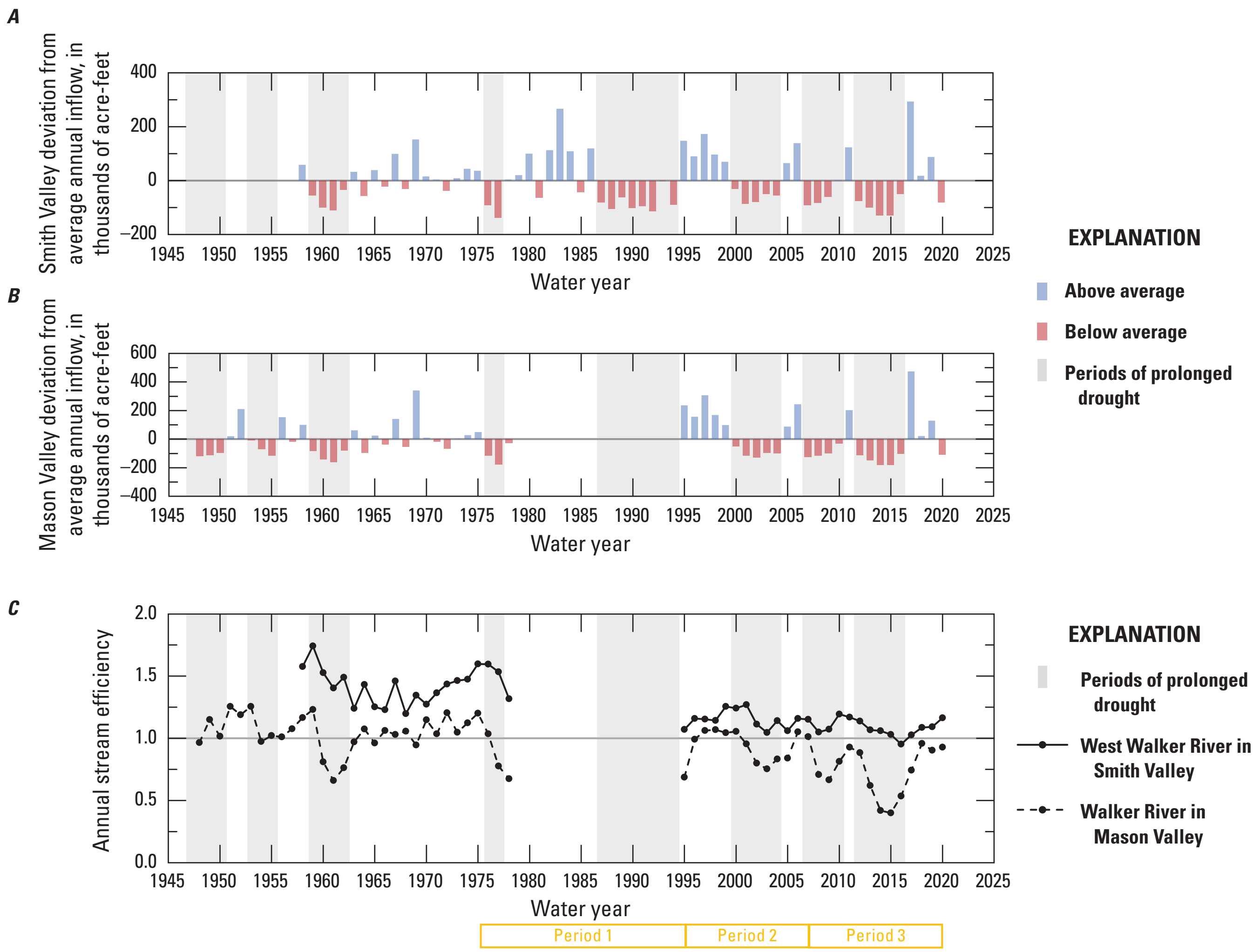


Figure 17. Variability in streamflow and stream efficiency during the period of analysis (U.S Geological Survey, 2021; Davies and Naranjo, 2022). *A*, Deviation from average annual inflow into Smith Valley, as measured at the Hoye streamgage water years 1958–2020; *B*, Deviation from average annual inflow into Mason Valley, as measured at the Strosnider and Hudson streamgages, water years 1948–2020; and *C*, Annual stream efficiency for Smith and Mason Valley reaches. Periods 1–3 of groundwater storage change analysis shown in yellow. Highlighted drought years include: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16.

Walker River through Mason Valley

During the period of analysis (1948–2020), the average annual inflow into Mason Valley (sum of Hudson and Strosnider streamgages) was 245,600 acre-ft, and the average annual diversion volume within the river was 134,500 acre-ft (55 percent of river inflow; fig. 6*C*; Davies and Naranjo, 2022). The Walker River through Mason Valley generally was an inefficient stream, losing streamflow to the aquifer most years. Similar to Smith Valley, a declining (worsening) trend in monthly stream efficiency was apparent during irrigation and non-irrigation seasons in Mason Valley (fig. 16). The river typically was most efficient during irrigation season and inefficient during non-irrigation season (the opposite of Smith Valley), indicating a lower percentage of river flow was derived from groundwater discharge during the non-irrigation season. Trend tests for stream efficiency resulted in p-values less than 0.05 ($p<0.05$); therefore, the null hypothesis was rejected and trends were considered statistically significant. Non-irrigation season stream efficiency declined at a statistically significant rate of −0.6 percent per year ($p<0.05$), comparable to irrigation season at a statistically significant rate of −0.5 percent per year ($p<0.05$). Average stream-efficiency values less than 1 occurred during both seasons throughout the period of analysis; however, stream efficiencies less than 1 began occurring more frequently in the late 1980s (fig. 16). During the entire period of analysis, streamflow at the Wabuska streamgage ceased flowing for at least one full month in WYs 2015 and 2016, resulting in a stream efficiency of zero. Similar to Smith Valley, stream efficiency in Mason Valley fluctuated more substantially during the non-irrigation season compared to the irrigation season.

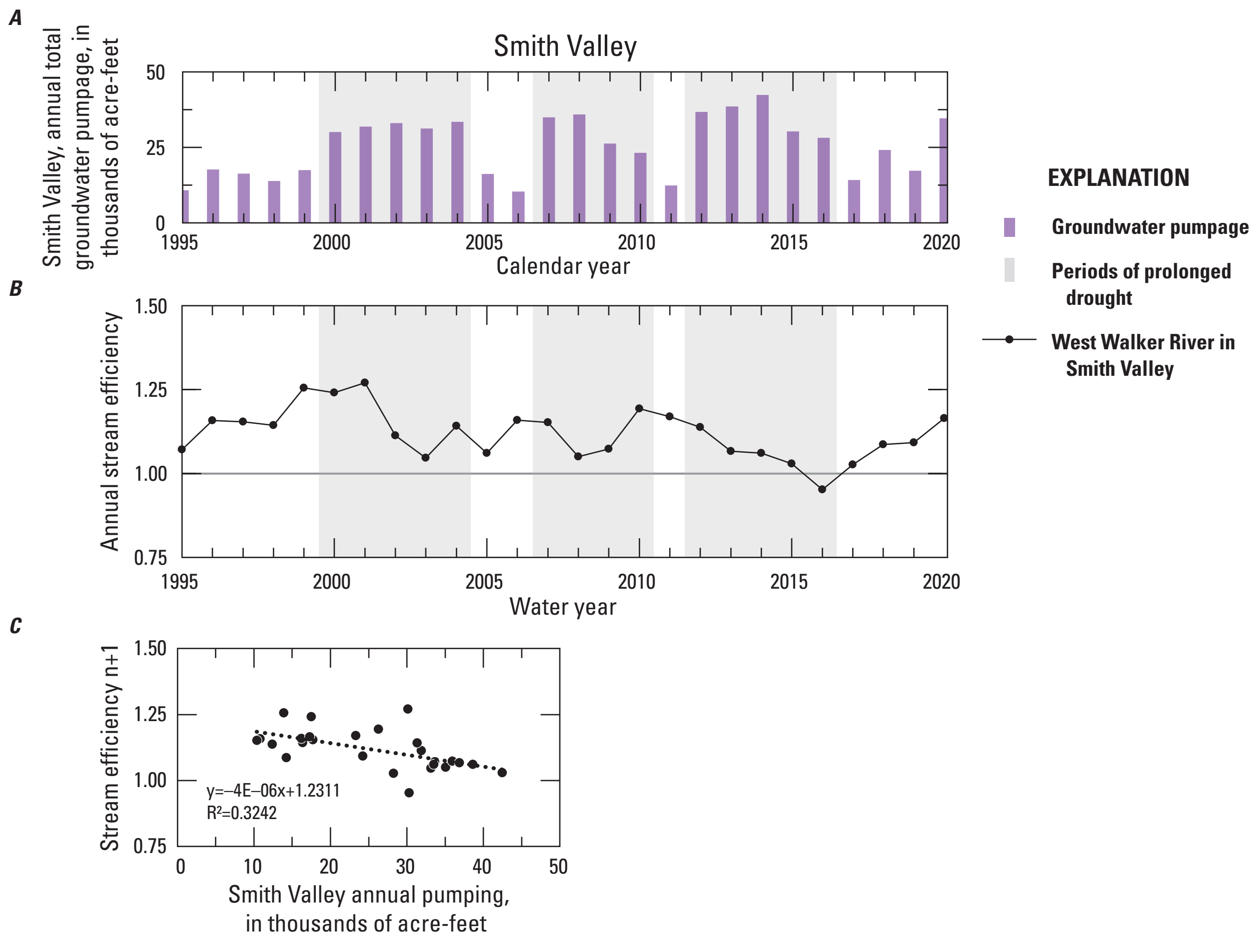


Figure 18. Variability in groundwater pumpage and stream efficiency during periods with available pumpage data. *A*, Annual total groundwater pumpage in Smith Valley in acre-feet, calendar years 1995–2020 (Nevada Division of Water Resources, 2021b); and *B*, Annual stream efficiency of the West Walker River in Smith Valley, water years 1995–2020 (Davies and Naranjo, 2022). Highlighted drought years include: 2000–04, 2007–10, 2012–16; and *C*, linear regression of Smith Valley annual pumpage and stream efficiency for the following year (n+1). Abbreviations: =, equals; -, minus; +, plus.

Trends in stream efficiency closely followed variations in annual valley inflow throughout the period of analysis (figs. 17*B*–17*C*). During periods of prolonged drought, stream efficiency generally declined. Year-to-year variation in stream efficiency closely followed variations in valley inflow with about a 1-year lag time. Above average valley inflow tended to elevate annual stream efficiency for 1–2 years when followed by average or below average annual inflows. For example, during the transitions between wet and dry periods in 1999–2000, 2006–07, 2011–12, and 2017–18, stream efficiency remained elevated in the first dry year and then began to decline after two or more consecutive dry or average years (figs. 17*B*–17*C*). There is an inverse relation between annual groundwater pumpage and stream efficiency in Mason Valley (figs. 19*A*–19*B*). When annual groundwater pumpage exceeded approximately 80,000 acre-ft, stream efficiency steadily declined. Notable declines in stream efficiency resulted when increased annual groundwater pumping occurred for at least 2 continuous years. The relation between groundwater pumpage and stream efficiency for the following year (n+1) had an R^2=0.68 (fig. 19*C*). The relation between total groundwater pumpage and stream efficiency was more apparent in Mason Valley compared to Smith Valley. During the available period of record (1994–2020), average annual groundwater pumpage in Mason Valley was 79,200 acre-ft/yr (Nevada Division of Water Resources, 2021b).

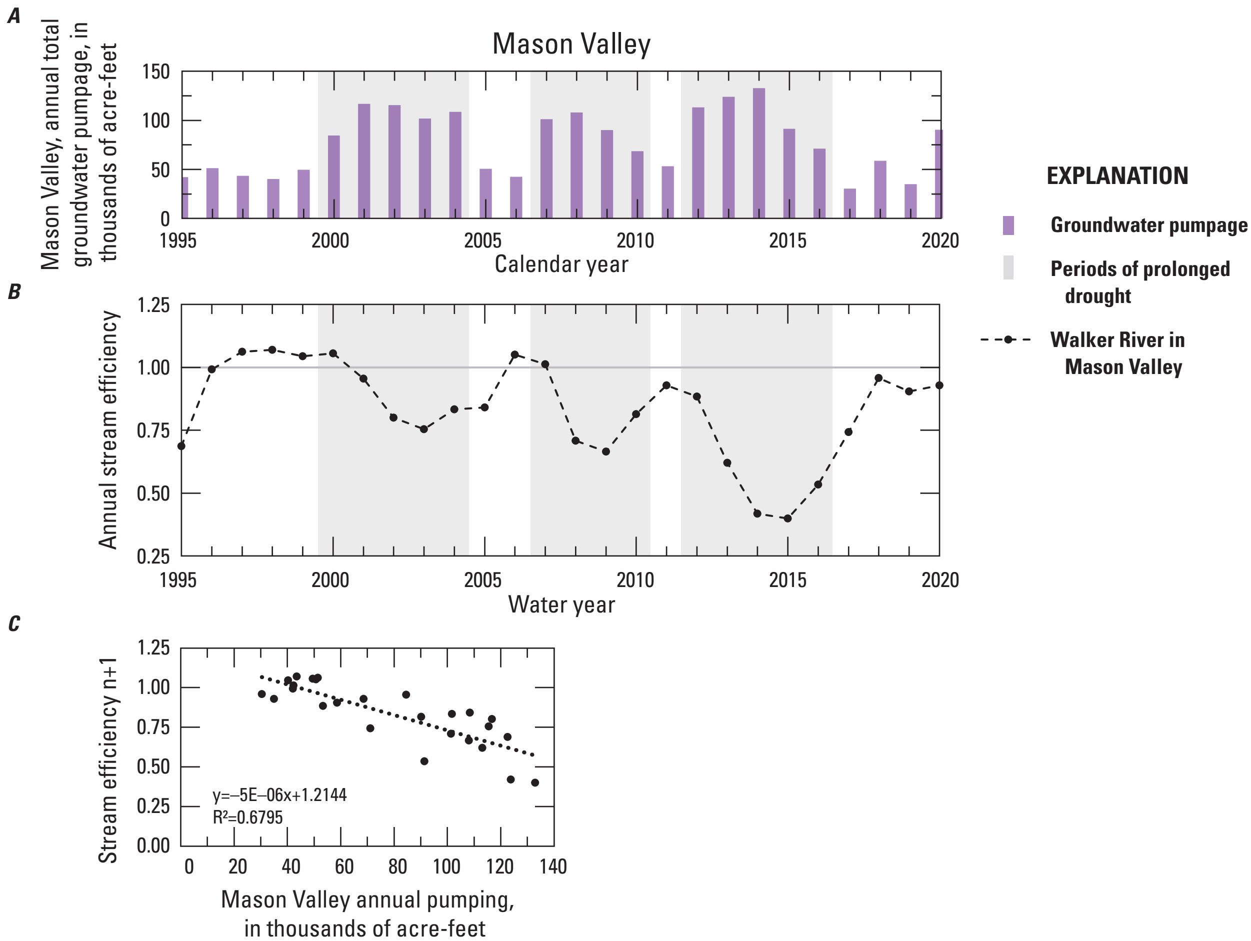


Figure 19. Variability in groundwater pumpage and stream efficiency during periods with available pumpage data. *A*, Annual total groundwater pumpage in Mason Valley, calendar years 1995–2020 (Nevada Division of Water Resources, 2021b); *B*, Annual stream efficiency of the Walker River in Mason Valley, water years 1995–2020 (Davies and Naranjo, 2022). Highlighted drought years include: 2000–04, 2007–10, 2012–16; and *C*, linear regression of Mason Valley annual pumpage and stream efficiency for the following year (n+1). Abbreviations: =, equals; -, minus; +, plus.

Prolonged drought resulted in worsening stream efficiency over time (fig. 20*B*). Low streamflow during drought periods in the late-1950s to the early 2000s routinely resulted in stream efficiencies greater than 1.0, whereas low streamflow during drought periods in the 2010s consistently resulted in stream efficiencies less than 1.0.

Annual stream volume gains declined during the period of analysis (fig. 21*B*). During the first half of the period (1948–78), the average annual gain in volume was 28,600 acre-ft/yr (Davies and Naranjo, 2022). During the second half of the period (1995–2020), gains in streamflow largely changed to losses with an average annual loss of 13,500 acre-ft/yr. Similar trends in declining streamflow gains were also observed just during non-irrigation season (fig. 22*B*). Large losses occurred in wet years, following periods of prolonged drought (particularly in 1995 and 2017; fig. 21*B*). During these years, seepage resulting from the record high (and sustained) streamflow helped replenish the aquifer. Streamflow gains in the years following large recharge events (1996–2000, 2018) were short-lived (fig. 21*B*). During non-irrigation season, the Walker River in Mason Valley loses more flow than the West Walker River in Smith Valley (fig. 22). This demonstrates how the Walker River in Mason Valley provides greater recharge to the aquifer than the West Walker in Smith Valley.

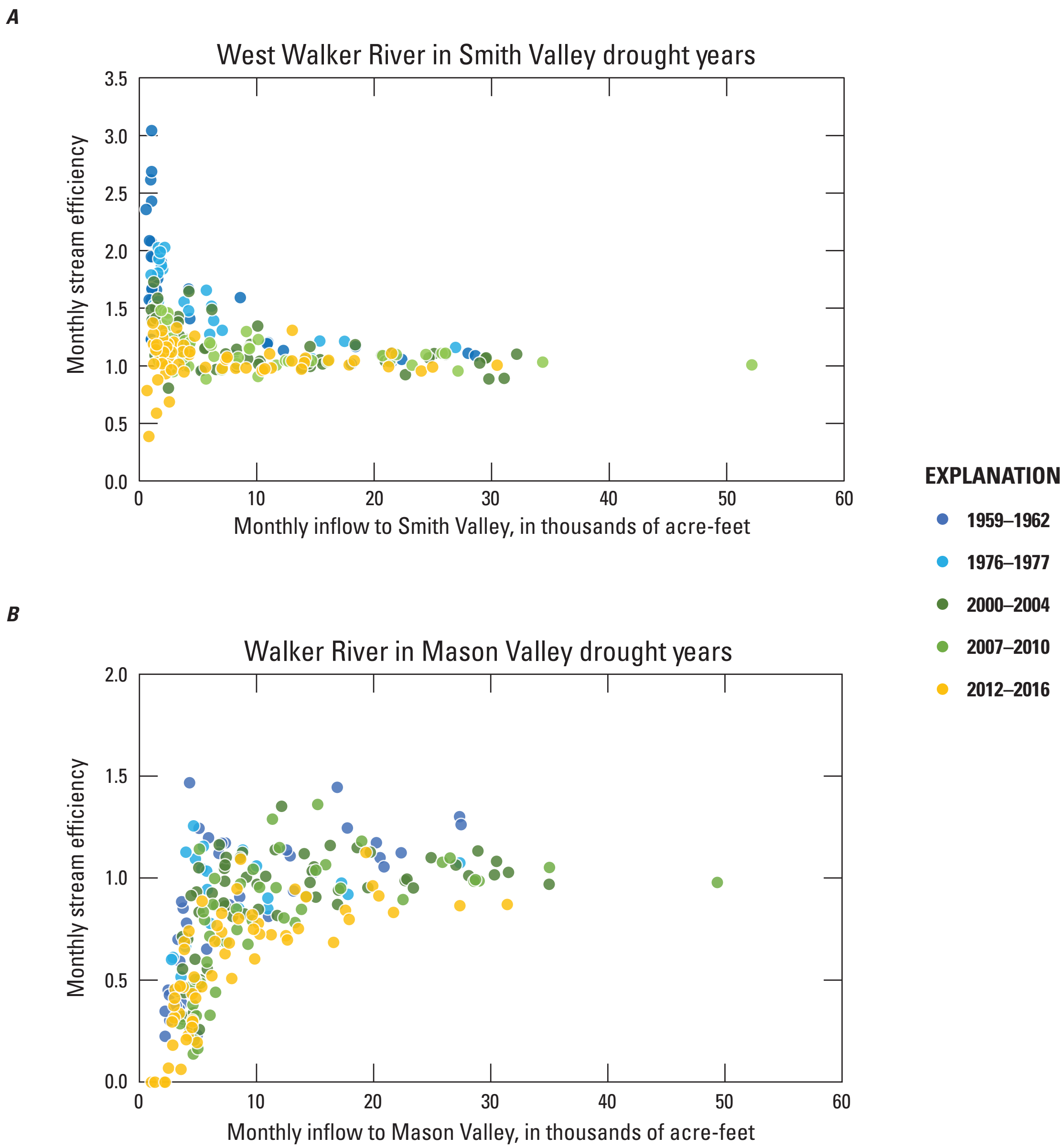


Figure 20. Monthly valley inflow and monthly stream efficiency for selected periods of prolonged drought for *A*, Smith Valley, Nevada, as measured at the Hoye streamgage (U.S. Geological Survey, 2021; Davies and Naranjo, 2022); and *B*, Mason Valley, Nevada, as measured at the Strosnider and Hudson streamgages (U.S. Geological Survey, 2021; Davies and Naranjo, 2022).

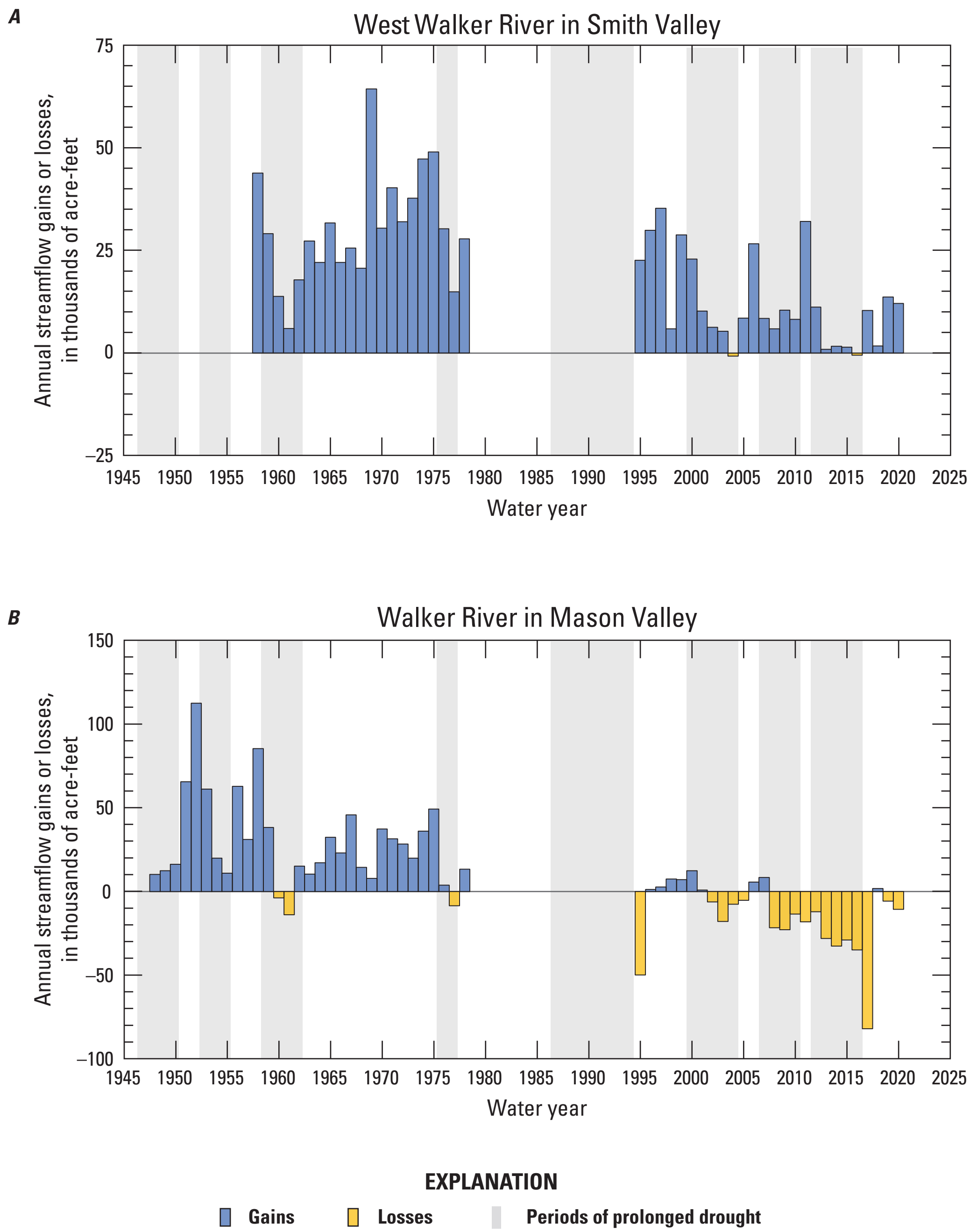


Figure 21. Annual streamflow gains or losses for *A*, Smith Valley, Nevada, water years 1958–2020; and *B*, Mason Valley, Nevada, water years 1948–2020 (U.S. Geological Survey, 2021; Davies and Naranjo, 2022). Complete streamflow data missing from 1979 to 1994 due to seasonal operation of U.S. Geological Survey streamgages. Highlighted drought years include: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16. Blue indicates gains and yellow indicates losses.

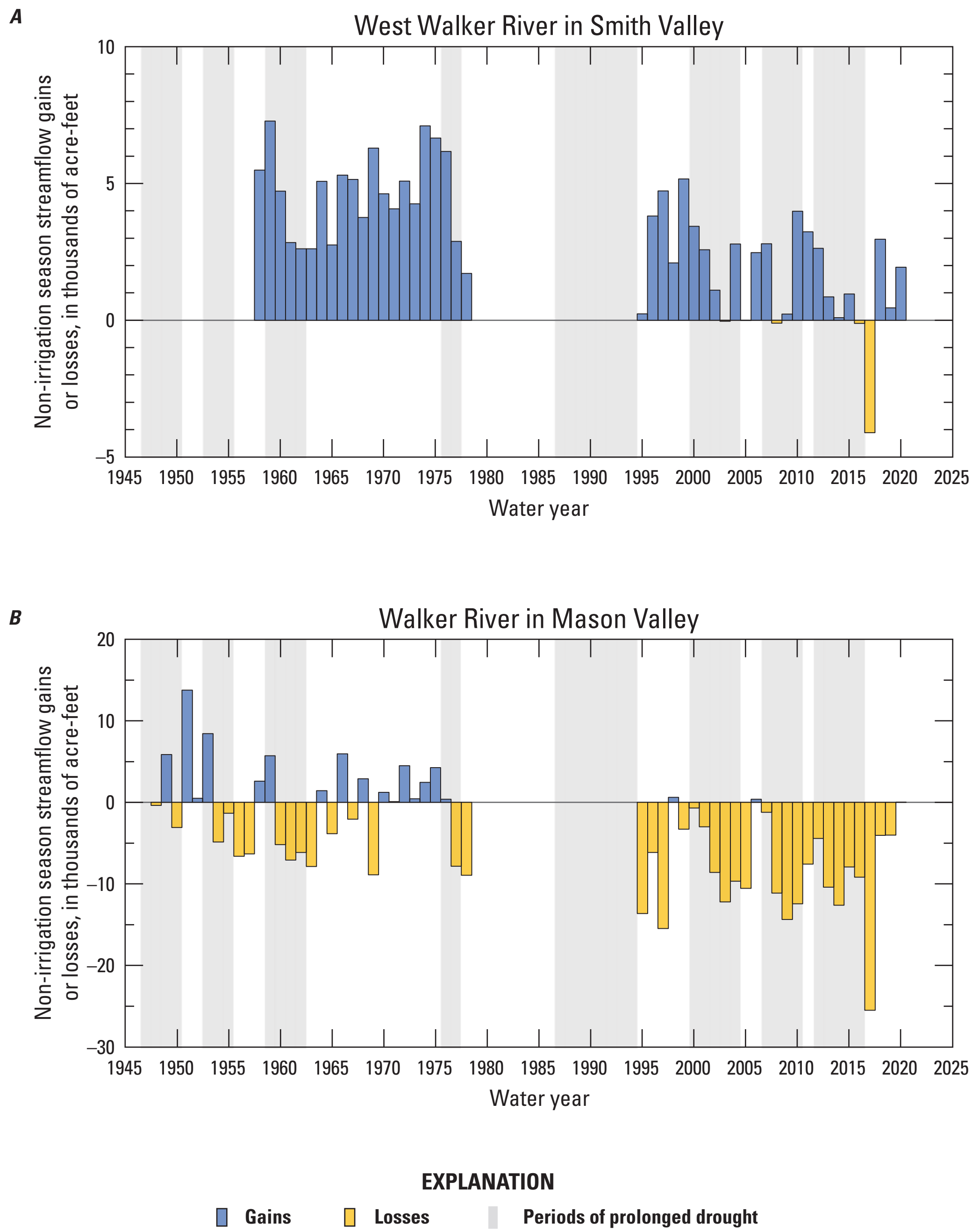


Figure 22. Non-irrigation season (November–February) streamflow gains or losses for *A*, Smith Valley, Nevada, water years 1958–2020; and *B,* Mason Valley, Nevada water years 1948–2020 (U.S. Geological Survey, 2021; Davies and Naranjo, 2022). Complete streamflow data missing from 1979 to 1994 due to seasonal operation of U.S. Geological Survey streamgages. Highlighted drought years include: 1947–50, 1953–55, 1959–62, 1976–77, 1987–94, 2000–04, 2007–10, 2012–16. Blue indicates gains and yellow indicates losses.

Relation of Groundwater Storage Change and Stream Efficiency

During the study period, the total amount of irrigated acreage remained relatively fixed (Welborn, 2017). Annual streamflows and irrigation diversions vary considerably, depending on snowpack conditions, runoff characteristics, and reservoir storage. During drought years, groundwater pumpage approximately doubles in magnitude to offset the shortfalls in surface-water deliveries in order to meet irrigation demands. The latter half of the study period (1987–2020) experienced more severe droughts, which were of longer extent than the first half (1948/58–1987). A summary of groundwater storage-volume change, groundwater pumpage, and stream efficiency analyses is presented in table 8.

Groundwater storage-volume change during period 1 (1970–95) was substantial in Smith and Mason Valleys (−191,700 and −176,100 acre-ft, respectively; table 6). During this period, the Walker River Basin experienced a severe 7-year drought between 1987 and 1994. Stream efficiency could only be calculated for part of this period due to seasonal operation of streamgages; however, a sharp decline in efficiency was seen in Smith and Mason Valleys in the late 1970s (fig. 17*C*). Considerable groundwater-level declines occurred between 1987 and 1994 across both valleys (figs. 13 and 14).

Groundwater storage-volume change during period 2 (1996–2006) was close to negligible in Smith Valley (−3,700 acre-ft) and increased in Mason Valley (+19,100 acre-ft; table 6). This period experienced above average streamflow from 1996 to 1999, which recharged the groundwater system sufficiently to sustain elevated groundwater levels into the early 2000s; however, recovery was not sufficient to bring groundwater levels to levels seen before the 1987–94 drought. The overall declining trend in groundwater levels continued despite experiencing several of the wettest years on record. Stream efficiency temporarily increased following years with above average streamflow but quickly dropped off to less efficiency with the onset of another drought period from 2000 to 2004.

Groundwater storage-volume change during period 3 (2007–20) decreased substantially in Smith and Mason Valleys compared to the previous period (−92,200 and −112,000 acre-ft, respectively; table 6). Period 3 experienced severe drought collectively for 7 years between 2007–10 and 2012–16 but also experienced above average streamflow in 2011, 2017, and 2019. Stream efficiencies reached their lowest consecutive values in the period of analysis between 2013 and 2015. The above average WYs in 2011, 2017, and 2019 increased stream efficiency for several years but not to levels seen earlier in the period of analysis. Groundwater levels declined sharply during the drought periods and rebounded quickly following the above average WYs in 2011, 2017, and 2019. However, the rebound from 2017 and 2019 was not sufficient to fully recover to the groundwater levels seen during the 1995–99 rebound, when a similar extensive multi-year drought was followed by several years of above average streamflows.

Table 8. Summary of groundwater storage-volume change, groundwater pumpage, and average non-irrigation season stream efficiency for all periods of analysis,1970–2020 (Nevada Division of Water Resources, 2021b; Davies and Naranjo, 2022).

[For the groundwater storage change column, positive value indicate storage increase and negative values indicate storage decline. **Abbreviations**: acre-ft, acre-feet; —, no data]

Period	Smith and Mason groundwater storage-volume change, contour approach (acre-ft)	Smith and Mason groundwater pumpage (acre-ft)	Average non-irrigation season stream efficiency (unitless)	
			Smith Valley	Mason Valley
Period 1: 1970–95	−367,800	—[1]	[2]1.66	[2]0.92
Period 2: 1996–2006	+15,400	1,056,200	1.23	0.75
Period 3: 2007–20	−204,200	1,568,000	1.16	0.57
Overall: 1970–2020	–556,600	—	—	—

[1]Pumpage data not available during this period.

[2]Average of years 1970–78 because Strosnider and Hudson gages operated seasonally from 1979 to 1994.

In Smith and Mason Valleys, total groundwater storage-volume decline during the 1970 to 2020 period of analysis was similar in magnitude despite Mason Valley containing more irrigated land and diverting a larger part of its river flow for irrigation than Smith Valley. The comparable groundwater storage-volume decline is, in part, because of proximity of agricultural land to the river and differing groundwater surface-water interactions in the different valleys. In Smith Valley, the West Walker River intersects the valley from west to east, across the valley's shortest diameter. In Mason Valley, the East Walker, West Walker, and Walker Rivers intersect the valley from south to north, across the valley's longest diameter (fig. 2). This spatial difference results in more agricultural land located in close proximity to the river in Mason Valley, in comparison to Smith Valley. Additionally, the network of irrigation canals and ditches in Mason Valley is more extensive than in Smith Valley, further extending the physical proximity of agricultural lands to the river in Mason Valley. Because stream efficiency of the Walker River in Mason Valley is consistently low (the river loses flow to the aquifer), the aquifer receives stream recharge, which has prevented sizable groundwater decline. The stream efficiency of the West Walker River in Smith Valley is consistently higher (the river gains flow from the aquifer), which provides little to no stream recharge to the aquifer and therefore, sizable groundwater decline (more than 50 ft) has occurred across much of the valley.

During the period of analysis, with each successive drought period, annual groundwater levels and stream efficiencies have declined. Following a wetter period with 1–5 years of above average streamflow, annual groundwater levels and stream efficiencies rebound, but not to the levels that they were before the respective drought periods. Depleted groundwater storage and reduced stream efficiencies over time indicate the river does not fully replenish groundwater storage while simultaneously supplying groundwater and surface-water withdrawals of the current year. On the basis of more than a half century of observation, if annual surface-water inflows and groundwater pumpage trends continue into the future, groundwater levels and stream efficiencies are expected to continue to decline. The consistent slope of decline of annual stream efficiency during the period of analysis suggests the river system is still hydraulically connected to the aquifer (in other words, the groundwater/surface-water interface is fully saturated). If the groundwater levels continue to lower, eventually the stream system will reach a transitional or hydraulically disconnected state (in other words, an unsaturated zone between the streambed and groundwater-table exists). Once the river is in a hydraulically disconnected state, stream efficiency will stabilize at a fixed low value and further groundwater-level decline will not substantially alter stream infiltration rates or stream efficiencies (Brunner and others, 2009). An inefficient stream system will result in the continued loss of flow from the stream to the alluvial aquifer. The decreasing ability to convey surface water (low stream efficiency) while concurrently replenishing groundwater storage may result in the increased use of supplemental groundwater to compensate for increasing surface-water deficits, which may further intensify the groundwater storage deficit. Above average streamflow combined with decreased groundwater pumping may allow groundwater levels and stream efficiencies to rebound.

Summary

This report documents changes in groundwater storage-volume and trends in Walker River stream efficiency in the two largest agricultural valleys in the Walker River Basin, Smith, and Mason Valleys, for a multi-decade period. Extraction of groundwater for agricultural use first became prevalent in the Walker River Basin in the late 1950s and early 1960s to supplement irrigation demands not met by surface-water diversions during times of drought; however, over the past 60 years, the reliance on supplemental groundwater has resulted in widespread groundwater storage-volume decline and decreased stream efficiency of the Walker River. If usage patterns continue, groundwater withdrawals within the Walker River Basin may further contribute to the depletion of groundwater storage-volume and reduced streamflow conveyance efficiencies of the East Walker, West Walker, and Walker Rivers through Smith and Mason Valleys.

Groundwater-level change was investigated using previously published groundwater-level maps from 1965–72 and 2006 (Huxel and Harris, 1969; Rush and Schroer, 1976; Lopes and Allander, 2009a) and two newly developed groundwater-level maps. A 1995 map, representing contoured groundwater-level altitudes, was developed using median groundwater-level measurements from 96 wells between water years (WYs) 1991 and 1995. A 2020 map representing contoured groundwater-level altitudes was developed using median groundwater-level measurements from 165 wells between WYs 2016 and 2020. Groundwater-level change and groundwater storage-volume change was calculated for the periods 1970–95, 1996–2006, 2007–20 and for the overall period between 1970 and 2020. Groundwater hydrographs were compiled from the few wells that have a long-term record dating from the 1960s to 1970s. Long-term groundwater-level changes were examined by considering proximity of wells to the river and trends in annual streamflow. Using data from U.S. Geological Survey (USGS) streamgages (U.S. Geological Survey, 2021) and monthly irrigation diversion totals (Pahl, 2000; C. Garner, Desert Research Institute, written commun., 2020; B. Bryan, Walker River Irrigation District, written commun., 2021), stream efficiency, a metric that quantifies the relative gain or loss in streamflow, was calculated from 1958 to 2020 in Smith Valley and from 1948 to 2020 in Mason Valley. Trends in annual stream efficiency were evaluated considering periods of prolonged drought, deviation from average annual streamflow, and annual groundwater pumpage volumes.

Evaluation of groundwater-level conditions in Smith Valley from 1970 to 2020 indicates that the groundwater contribution to streamflow has been affected by the lowering of groundwater levels. The West Walker River in Smith Valley, historically a gaining reach throughout the valley, is changing to a losing reach on the west side of the valley and to a progressively more neutral reach on the east side of the valley. Stream-efficiency analysis of the West Walker River in Smith Valley confirmed that the river is becoming less efficient at conveying water at a rate of −1.1 percent per year during the non-irrigation season. Before 1998, the West Walker River through Smith Valley gained measurable streamflow from groundwater discharge. Since 1998, the river has experienced consistent periods of inefficiency, losing streamflow to groundwater. During periods of prolonged drought and below average annual valley inflow and increased groundwater pumpage, stream efficiency in Smith Valley generally declined. Analysis of monthly stream efficiency, as it relates to valley inflow during periods of prolonged drought, demonstrated that historically, gaining conditions in Smith Valley still occurred at low streamflow. However, in the past 20 years, near-neutral or losing conditions occur more regularly during low streamflow in times of drought. Groundwater-level contour analysis from 1970 to 2020 in Smith Valley highlighted an average groundwater-level decline across the valley of 52 feet (ft). Groundwater-level declines were most dramatic at the southern extent of Smith Valley, whereas the fluvial deposit units making up the river corridor experienced the least decline. Hydrographs from wells with long-term monitoring data confirmed the largest groundwater-level decline in Smith Valley occurred in the region north of Artesia Lake (157 ft) and the southern valley at least 3-miles south of the West Walker River (103 ft). Most hydrographs from long-term monitoring wells mirrored groundwater-level change with annual valley inflow. Groundwater levels in wells adjacent or near to the river rebounded promptly with the river, whereas groundwater levels in wells 3–5 miles from the West Walker River experienced more steady decline during the period of analysis. The total groundwater storage-volume decline in Smith Valley between 1970 and 2020 was 287,600 acre-feet (acre-ft).

Evaluation of groundwater-level conditions in Mason Valley from 1970 to 2020 indicates that the groundwater contribution to streamflow also has been affected by the lowering of the groundwater table. The West Walker River in Mason Valley changed from a gaining reach to a neutral reach between 1970 and 1995 and maintained neutral conditions through 2020. The East Walker River in Mason Valley changed from a neutral reach to a losing reach between 1970 and 1995 and has maintained losing conditions through 2020. The Walker River below the confluence in Mason Valley maintained losing conditions throughout 1970–2020. Stream-efficiency analysis of the Walker River in Mason Valley confirmed that the reach changed from neutral conditions to losing conditions, with stream efficiency declining at a rate of 0.6 percent per year during non-irrigation season. Beginning in 1976, less efficient conditions occurred more frequently. During periods of prolonged drought with below average annual valley inflow and increased groundwater pumpage, stream efficiency in Mason Valley generally declined. The relation between total groundwater pumpage and stream efficiency was more apparent in Mason Valley than in Smith Valley. Above average annual valley inflow tended to elevate stream efficiency in Mason Valley for 1–2 years when followed by average or below average inflows. Analysis of monthly stream efficiency, as it relates to valley inflow during periods of prolonged drought, demonstrated that historically, gaining or near-neutral conditions in Mason Valley still occurred at low streamflows. However, during the past 10 years, near-neutral or losing conditions occurred more regularly during low streamflow in times of drought. In Mason Valley, groundwater-level contour analysis from 1970 to 2020 demonstrated an average groundwater-level decline across the valley of 14 ft. The greatest groundwater-level decline occurred at the north-northwest periphery of the valley, near Adrian Gap, and at the north end of the valley near the geothermal power station. Groundwater-level rise occurred at the Mason Valley Wildlife Management Area and at the various discharge regions associated with the geothermal power station. The fluvial deposit units along the river corridor experienced the least amount of groundwater-level change in the valley. Hydrographs from long-term monitoring wells confirmed the greatest groundwater-level change in Mason Valley occurred in the region near the geothermal power station (34–100 ft). Most hydrographs from long-term monitoring wells also showed groundwater-level changes that mirror changes in annual valley inflows. Groundwater levels in wells adjacent to the Walker River rebounded promptly in years with above average (or high) streamflow, whereas groundwater levels in wells 1–5 miles from the Walker River showed a more muted response. The total groundwater storage-volume decline in Mason Valley between 1970 and 2020 was 269,000 acre-ft.

The combined groundwater storage-volume decline in Smith and Mason Valleys between 1970 and 2020 was 556,600 acre-ft. The estimated groundwater storage-volume decline in Smith and Mason Valleys could be considered a conservative estimate because the geographic extent used for analysis was limited to valley floor and fluvial deposit units and excluded the alluvial slopes to maintain an acceptable level of confidence. Seasonal groundwater-level monitoring in the alluvial slopes at the edges of the valleys could allow for more accurate definition of the region of maximum groundwater-level decline. Seasonal groundwater-level monitoring in areas closer to the river could improve understanding of the effects of groundwater pumping on groundwater and surface-water interactions along the river corridor. Notably, above average wet periods had a marginal and short-lived effect on groundwater level recovery outside the river corridor in Smith and Mason Valleys. Recent wet periods, particularly WYs 2006, 2011, and 2017, resulted in only minor and temporary recoveries to groundwater levels.

Using groundwater storage-volume decline and annual groundwater pumpage rates, a maximum groundwater pumpage rate can be estimated at which the effects of groundwater pumpage on groundwater levels and streamflow appear to be minimized. In Smith Valley, groundwater pumping in excess of 22,300 acre-feet per year (acre-ft/yr) appears to result in groundwater storage decline. In Mason Valley, groundwater pumping in excess of 75,200 acre-ft/yr appears to result in groundwater storage decline.

Declining stream efficiency of the Walker River in Smith and Mason Valleys from 1948/58 to 2020 is primarily a result of stream capture and induced seepage losses from decades of groundwater pumping. Pumping has lowered groundwater levels to the extent that groundwater gradients now dominantly support streamflow loss from the river to the aquifer. In years with average streamflow conditions, decreased stream efficiency could result in reduced surface-water deliveries downstream during irrigation season. In drought years, this may result in the inability to deliver surface water to the most senior surface-water users located downstream from Mason Valley. Decreased stream efficiency during non-irrigation season results in larger losses of streamflow to the aquifer, which would result in less available streamflow to recharge the aquifer farther downstream and, in turn, would further decrease downstream stream efficiency in the following irrigation seasons.

The continued declining groundwater level and stream-efficiency trends indicate that the groundwater system is becoming less able to recover after periods of drought. With each successive drought cycle, the groundwater system has become more depleted, reducing the East Walker, West Walker, and Walker Rivers' ability to sustain flows and deliver surface water for downstream uses. In western Nevada, projected increases in temperature from climate change are expected to create longer hotter summers with more lengthy droughts. Extended droughts in the future may result in unreliable streamflow and continued dependence on supplement groundwater pumping for irrigation, further intensifying the groundwater storage deficit.

References Cited

Allander, K.K., Niswonger, R.G., and Jeton, A.E., 2014, Simulation of the Lower Walker River Basin hydrologic system, west-central Nevada, using PRMS and MODFLOW models: U.S. Geological Survey Scientific Investigations Report 2014–5190, 93 p. [Available at https://doi.org/10.3133/sir20145190.]

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. [Available at https://doi.org/10.3133/cir1376.]

Beutel, M.W., Horne, A.J., Roth, J.C., and Barratt, N.J., 2001, Limnological effects of anthropogenic desiccation of a large, saline lake, Walker Lake, Nevada: Hydrobiologia, v. 466, p. 91–105. [Available at https://doi.org/10.1023/A:1014569521381.]

Boyle, D., Pohll, G., Bassett, S., Minor, T., Garner, C., Carroll, R., McGraw, D., Knust, A., and Barth, C., 2010, Project F—Development of a decision support tool in support of water right acquisitions in the Walker River Basin, *in* Collopy, M.W., and Thomas, J.M., eds., Restoration of a desert lake in an agriculturally dominated watershed—The Walker Lake Basin: Desert Research Institute. [Available at http://water.nv.gov/hearings/past/National%20Fish%20and%20Wildlife%20Foundation/Exhibits/NFWF/NFWF_Exh%20086%20-%202010%20UNR-DRI%20Walker%20Basin%20Report.pdf.]

Brunner, P., Cook, P.G., and Simmons, C.T., 2009, Hydrogeologic controls on disconnection between surface water and groundwater: Water Resources Research, v. 45, no. 1. [Available at https://doi.org/10.1029/2008WR006953.]

Buto, S.B, Evetts, D.M., Smith-Sager, S., 2006, Water-table contours of Nevada, U.S. Geological Survey data release, https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2006-5100_wanv_l.xml.

California Department of Water Resources, 1992, River chronologies and atlases—Walker River atlas: California Department of Water Resources, accessed June 28, 2021, at http://images.water.nv.gov/images/publications/River%20Chronologies/Walker_River_Atlas.pdf.

Carroll, R.W.H., Pohll, G., McGraw, D., Garner, C., Knust, A., Boyle, D., Minor, T., Bassett, S., and Pohlmann, K., 2010, Mason Valley Groundwater Model—Linking surface water and groundwater in the Walker River Basin, Nevada : Journal of the American Water Resources Association, v. 46, no. 3, p. 554–573. [Available at https://doi.org/10.1111/j.1752-1688.2010.00434.x.]

Carroll, R.W.H., Pohll, G.M., and Fereday, W., 2014, Streamflow gain-loss analysis—Walker River Basin, Nevada: Reno, Nev., Desert Research Institute, Publication no. 41258, 37 p.

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, book 1, chap. A1, 151 p. [Available at https://doi.org/10.3133/tm1A1.]

Davies, G.E., and Naranjo, R.C., 2022, Supplemental data—Estimated effects of pumping on groundwater storage and Walker River stream efficiencies in Smith and Mason Valleys, west-central Nevada: U.S. Geological Survey data release, https://doi.org/10.5066/P9LI9XY7.

Eakin, T.E., Maxey, G.B., Robinson, T.W., Fredericks, J.C., and Loeltz, O.J., 1951, Contributions to the hydrology of eastern Nevada: Water Resources Bulletin 12, 171 p.

Environmental Systems Research Institute, 2019, ArcMap 10.7, Technical Support: Environmental Systems Research Institute, accessed September 28, 2021, at https://support.esri.com/en/products/desktop/arcgis-desktop/arcmap/10-7-1.

Gallagher, T.K., 2005, Estimated annual ground-water pumpage, 1994–2003, Smith Valley and Mason Valley, Lyon County, Nevada: Nevada Division of Water Resources, accessed January 1, 2021, at http://images.water.nv.gov/images/Pumpage%20Inventories/107-108%20Smith-Mason%20Valley/107-108%20-%201994-2003%20-%20Smith-Mason%20Valley.pdf.

Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods, book 6, chap. A16, variously paged. [Available at https://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf.]

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., and Gilroy, E.J., 2020, Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chap. A3, 458 p., https://doi.org/10.3133/tm4a3. [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chap. A3, version 1.1.].

Horton, G., 1996, Walker River chronology—A chronological history of the Walker River and related water issues: Carson City, Nev., Nevada Division of Water Planning.

Huxel, C.J., Jr., and Harris, E.E., 1969, Water resources and development in Mason Valley, Lyon and Mineral Counties, Nevada, 1948–65: Nevada Division of Water Resources Bulletin 38, 77 p.

Loeltz, O.J. and Eakin, T.E., 1953, Geology and water resources of Smith Valley, Lyon and Douglas counties, Nevada: U.S. Geological Survey Water-Supply Paper 1228, 89 p. [Available at https://doi.org/10.3133/wsp1228.]

Lopes, T.J., and Evetts, D.M., 2004, Ground-water pumpage and artificial recharge estimates for calendar year 2000 and average annual natural recharge and interbasin flow by hydrographic area, Nevada: U.S. Geological Survey Scientific Investigations Report 2004–5239, 81 p. [Available at https://doi.org/10.3133/sir20045239.]

Lopes, T.J., and Smith, J.L., 2007, Bathymetry of Walker Lake, west-central Nevada: U.S. Geological Survey Scientific Investigations Report 2007–5012, 26 p. [Available at https://doi.org/10.3133/sir20075012.]

Lopes, T.J., and Allander, K.K., 2009a, Hydrologic setting and conceptual hydrologic model of the Walker River basin, California and Nevada: U.S. Geological Survey Scientific Investigations Report 2009–5155, 84 p. [Available at https://doi.org/10.3133/sir20095155.]

Lopes, T.J., and Allander, K.K., 2009b, Water budgets of the Walker River basin and Walker Lake, California and Nevada: U.S. Geological Survey Scientific Investigations Report 2009–5157, 44 p. [Available at https://doi.org/10.3133/sir20095157.]

Malmberg, G.T., 1967, Hydrology of the valley-fill and carbonate-rock reservoirs, Pahrump Valley Nevada-California: U.S. Geological Survey Water-Supply Paper 1832, 47 p. [Available at https://doi.org/10.3133/wsp1832.]

Medina, R. L., Lopes, T.J., and Little, B.D., 2022, Data for the 2009 report Hydrologic Setting and Conceptual Hydrologic Model of the Walker River Basin, west-central Nevada: U.S. Geological Survey data release, https://doi.org/10.5066/P9US1B3S.

Mauer, D.K., Lopes, T.J., Medina, R.L., and Smith, J.L., 2004, Hydrogeology and hydrologic landscape regions of Nevada: U.S. Geological Survey Scientific Investigations Report 2004–5131, 35 p. [Available at https://doi.org/10.3133/sir20045131.]

Meinzer, O.E., 1923, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p. [Available at https://doi.org/10.3133/wsp494.]

Milne, W., 1987, A comparison of reconstructed lake level records since the mid-1800s of some Great Basin lakes: Golden, Colo., Colorado School of Mines, Master's thesis in Engineering.

Mohammadi, A., Parvaresh Rizi, A., and Abbasi, N., 2019, Field measurement and analysis of water losses at the main and tertiary levels of irrigation canals—Varamin Irrigation Scheme, Iran: Global Ecology and Conservation, v. 18. [Available at https://doi.org/10.1016/j.gecco.2019.e00646.]

National Fish and Wildlife Foundation, 2022, Desert terminal lakes restoration fund: National Fish and Wildlife Foundation, accessed October 19, 2022, at https://www.nfwf.org/programs/walker-basin-restoration-program/desert-terminal-lakes-restoration-fund.

National Oceanic and Atmospheric Administration, 2021, The National Climatic Data Center—North American drought monitor indices: National Oceanic and Atmospheric Administration, accessed April 26, 2021, at https://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/indices.php.

Natural Resources Conservation Service, 2021, The National Water and Climate Center snow water equivalent and snow depth report: Natural Resources Conservation Service, accessed April 26, 2021, at https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring/snowpack/.

Naranjo, R.C., and Smith, D.W., 2016, Quantifying seepage using heat as a tracer in selected irrigation canals, Walker River Basin, Nevada, 2012 and 2013: U.S. Geological Survey Scientific Investigations Report 2016–5133, 169 p. [Available at https://doi.org/10.3133/sir20165133.]

Nevada Division of Water Resources, 2019, Chapter 534, Underground water and wells, Nevada Division of Water Resources, accessed June 28, 2021, at http://water.nv.gov/documents/WD_Regs_2019.pdf.

Nevada Division of Water Resources, 2021a, Water use and availability—Water level data: Nevada Division of Water Resources, accessed April 28, 2021, at http://water.nv.gov/WaterLevelData.aspx.

Nevada Division of Water Resources, 2021b, Water use and availability—Pumpage inventories: Smith Valley (107) and Mason Valley (108), Nevada Division of Water Resources, 2011, 2017, 2019 reports, accessed June 28, 2021, at http://water.nv.gov/PumpageInventoryFiles.aspx.

Pahl, R., 2000, Walker River Basin irrigation diversions—Summary of historic surface water irrigation diversions—APPENDICES: State of Nevada. [Available at https://doi.org/10.13140/RG.2.1.2421.0648.]

R Core Team, 2022, R—A language and environment for statistical computing, R Project for Statistical Computing: Vienna, Austria, R Core Team, accessed July 21, 2022, http://www.R-project.org/.

Rush, F.E., and Schroer, C.V., 1976, Geohydrology of Smith Valley, Nevada, with special reference to the water-use period, 1953–72: U.S. Geological Survey Water Resources Bulletin no. 43. [Available at http://images.water.nv.gov/images/publications/water%20resources%20bulletins/Bulletin43.pdf.]

Sharpe, S.E., Cablk, M.E., and Thomas, J.M., 2008, The Walker Basin, Nevada and California—Physical environment, hydrology, and biology: Desert Research Institute Publication no. 41231, 62 p. [Available at http://water.nv.gov/hearings/past/National%20Fish%20and%20Wildlife%20Foundation/Exhibits/NFWF/NFWF_Exh%20089%20-%20080501%20DRI%20Walker%20Basin%20Pub%20No%2041231.pdf.]

Simonds, F.W. and Sinclair, K.A., 2002, Surface water-ground water interactions along the lower Dungeness River and vertical hydraulic conductivity of streambed sediments, Clallam County, Washington, September 1999–July 2001: U.S. Geological Survey Water-Resources Investigations Report 2002–4161, 69 p. [Available at https://doi.org/10.3133/wri024161.]

Skinner, K.D., Bartolino, J.R., and Tranmer, A.W., 2007, Water-resource trends and comparisons between partial development and October 2006 hydrologic conditions, Wood River Valley, south-central, Idaho: U.S. Geological Survey Scientific Investigations Report 2007–5258, 30 p. [Available at https://doi.org/10.3133/sir20075258.]

Snyder, K.A., Evers, L., Chambers, J.C., Dunham, J., Bradford, J.B., and Loik, M.E., 2019, Effects of changing climate on the hydrological cycle in cold desert ecosystems of the Great Basin and Columbia Plateau: Rangeland Ecology and Management, v. 72, no. 1, p. 1–12. [Available at https://doi.org/10.1016/j.rama.2018.07.007.]

U.S. Geological Survey, 2020, USGS National Map 3DEP, 1/3 Arc-second digital elevation models: U.S. Geological Survey, accessed April 28, 2021, at https://data.usgs.gov/datacatalog/data/USGS:3a81321b-c153-416f-98b7-cc8e5f0e17c3.

U.S. Geological Survey, 2021, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed April 28, 2021, at https://waterdata.usgs.gov/nwis.

Welborn, T.L., 2017, Irrigated acreage delineated from Landsat-derived maximum normalized difference vegetation index (NDVI) 1975–2010, Walker River Basin Nevada and California: U.S. Geological Survey data release, https://doi.org/10.5066/F7XD10MK.

Welborn, T.L., and Medina, R.L., 2022, Data for the 1976 report Geohydrology of Smith Valley, Nevada, with special reference to the water-use period 1953–72: U.S. Geological Survey data release, https://doi.org/10.5066/P9KK0KZW.

Weldon, F.W., 2003, History of water law in Nevada and the western states: Background paper 03-2, Nevada Legislature Counsel Bureau Research Division, 15 p.

Wilberg, D.E., Swenson, R.L., Slaugh, B.A., Howells, J.H., and Christiansen, H.K., 2001, Seepage investigation for Leap, South Ash, Wet Sandy, and Leeds Creeks in the Pine Valley Mountains, Washington County, Utah, 1998: U.S. Geological Survey Scientific Investigations Report 2001–4237, 42 p. [Available at https://doi.org/10.3133/wri014237.]

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water—A single resource: U.S. Geological Survey Circular 1139, 79 p. [Available at https://doi.org/10.3133/cir1139.]

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S.M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Grannemann, B., Liknes, G.C., Rigge, M., and Xian, G., 2018, A new generation of the United States National Land Cover Database—Requirements, research priorities, design, and implementation strategies: ISPRS Journal of Photogrammetry and Remote Sensing, v. 146, p.108–123. [Available at https://doi.org/10.1016/j.isprsjprs.2018.09.006.]

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