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Evapotranspiration from the Lower Walker River Basin, West-Central Nevada, Water Years 2005–07

Scientific Investigations Report 2009–5079

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

Cover: Photograph of U.S. Geological Survey evaporation station on Walker Lake, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, November 9, 2004).

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KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Contents

Contents—Continued

Figures

Figures—Continued

Tables

Conversion Factors, Datums, Abbreviations, and Acronyms

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
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)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Energy	
calorie per second per square foot	45.04	watts per square meter (W/m^2)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	0.0002471	acre
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

SI to Inch/Pound—Continued

Multiply	By	To obtain
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.1450	pound-force per inch (lbf/in)
kilopascal (kPa)	20.88	pound per square foot (lb/ft^2)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Energy	
joule (J)	0.2390	calorie
joule per cubic meter (J/m^3)	0.006767	calorie per cubic foot

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

°C=(°F-32)/1.8.

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

°F=(1.8×°C)+32.

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

Datums

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

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.

Abbreviations and Acronyms

E	evaporation
EAARL	Experimental Advanced Airborne Research Lidar
ESSA	Environmental Science Services Administration
ET	evapotranspiration
GIS	geographic information system
MSAVI	Modified-Soil Adjusted Vegetation Index
NASA	National Aeronautics and Space Administration
NDOW	Nevada Department of Wildlife
NDVI	Normalized Difference Vegetation Index
RAWS	Remote Automated Weather Station
TDS	total dissolved solids
TM	Landsat thematic mapper
USGS	U.S. Geological Survey

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Evapotranspiration from the Lower Walker River Basin, West-Central Nevada, Water Years 2005–07

By Kip K. Allander, J. LaRue Smith, and Michael J. Johnson

Abstract

Evapotranspiration is the ultimate path of outflow of nearly all water from the Lower Walker River basin. Walker Lake is the terminus of the topographically closed Walker River basin, and the lake level has been declining at an average rate of about 1.6 feet per year (ft/yr) since 1917. As a result of the declining lake level, dissolved-solids concentrations are increasingly threatening the fishery and ecosystem health of the lake. Uncertainties in the water budget components of the Lower Walker River basin led the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, to undertake an investigation to refine estimates of the water budget. Evapotranspiration from the Lower Walker River basin represents a major component of this water budget.

The specific objectives of this report are to provide estimates of total and net evapotranspiration for water years 2005–07 for areas in the Lower Walker River basin in which annual evapotranspiration exceeds annual precipitation, and to summarize these results for areas of similar vegetation and soil characteristics, hydrographic subareas, and Walker Lake and Weber Reservoir. The three hydrographic subareas include the area along Walker River north of Walker Lake, the area of and adjacent to Walker Lake, and the area south of Walker Lake.

Areas of annual evapotranspiration exceeding annual precipitation were identified and mapped in the field and were further delineated using remote-sensing analysis. These areas were classified into 10 evapotranspiration units. A network of 11 evapotranspiration stations was operated in natural and agricultural vegetation and on Walker Lake.

Measured evapotranspiration rates ranged from 0.5 ft/yr at a sparsely vegetated desert shrub site to 5.0 ft/yr from Walker Lake. The greatest evapotranspiration rate on land was 4.1 ft/yr at an irrigated alfalfa field, and the greatest rate for natural vegetation was 3.9 ft/yr in a riparian community along Walker River. At an evapotranspiration station in a saltcedar grove, measurements indicated a possible decrease in evapotranspiration of about 50 percent due to defoliation of the saltcedar by the saltcedar leaf beetle.

Total evapotranspiration from the evapotranspiration units identified in the Lower Walker River basin was about 231,000 acre-feet per year (acre-ft/yr). Of this amount, about 45,000 acre-ft/yr originated from direct precipitation, resulting in net evapotranspiration of about 186,000 acre-ft/yr. More than 80 percent of net evapotranspiration in the Lower Walker River basin was through evaporation from Walker Lake. Total evaporation from Walker Lake was about 161,000 acre-ft/yr and net evaporation was about 149,000 acre-ft/yr. Some previous estimates of evaporation from Walker Lake based on water-budget analysis actually represent total evaporation minus ground-water inflow to the lake. Historical evaporation rates determined on the basis of water budget analysis were less than the evaporation rate measured directly during this study. The difference could represent ground-water inflow to Walker Lake of 16,000 to 26,000 acre-ft/yr or could indicate that ground-water inflow to Walker Lake is decreasing over time as the lake perimeter recedes.

Introduction

Walker Lake is a terminal lake in west-central Nevada and is the terminus of the Walker River (fig. 1). Evaporation is the only path of outflow from the lake and the Walker River is the primary source of inflow. Since the late 1800s, there has been increased diversion of water from the Walker River for agricultural use. This has resulted in less water flowing to Walker Lake than is evaporating during most years, and has contributed to an unsteady decline in lake level. The lake has declined an average of 1.6 ft/yr since 1917, a total decline of about 145 ft (fig. 2). Because the only outflow from Walker Lake is by evaporation, all dissolved solids that enter the lake remain there. This has caused a steady increase in concentration of total dissolved solids (TDS) as the volume of the lake decreases (fig. 2). The concentration of TDS in Walker Lake was 3,900 mg/L in 1930 and nearly 16,000 mg/L in September 2007.

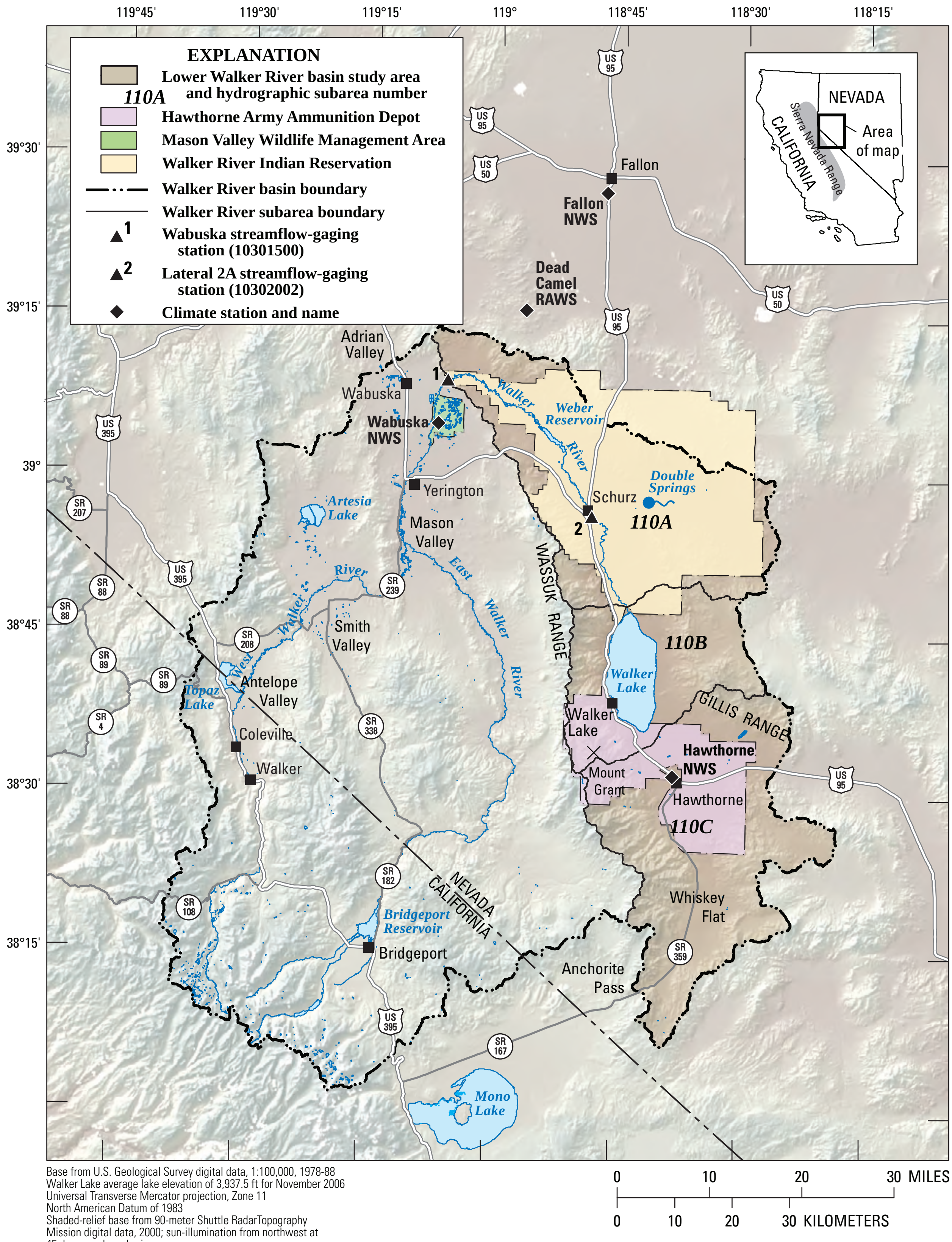


Figure 1. Location and general features of the study area, Walker River basin and Lower Walker River basin, west-central Nevada.

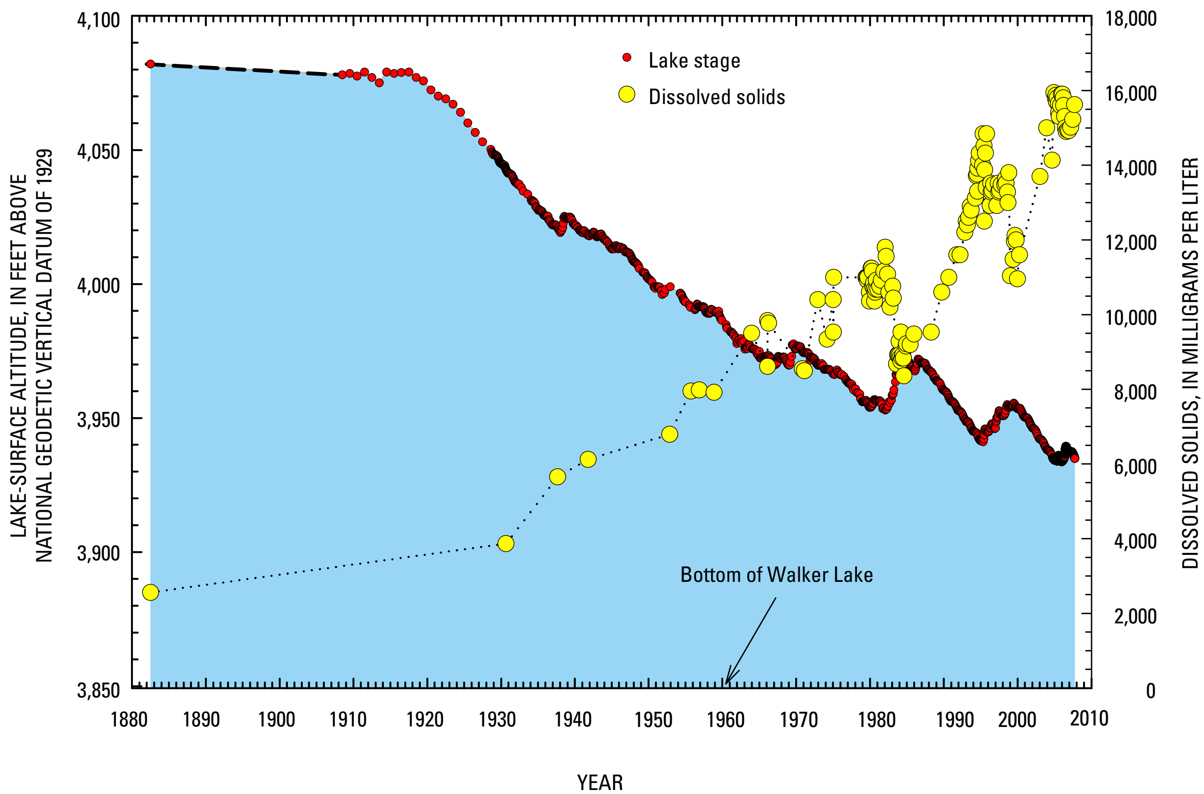


Figure 2. Time-series of dissolved-solids concentrations and lake-surface altitudes for Walker Lake, west-central Nevada, 1882–2007.

The concentration of TDS in Walker Lake has increased to the point at which only 3 of 17 native and non-native fish species are still present in the lake (Koch and others, 1979, p. 107). The Lahontan cutthroat trout had an 80 percent mortality rate after the 2004 stocking, even though the stocked fish had been acclimated in water with TDS concentration of 5,200 mg/L for 2.5 to 7 days before their introduction in Walker Lake (Nevada Division of Environmental Protection, 2005, p. 10). The health of the local fishery is of great concern to local communities and to Native Americans that rely on the fishery for economic and spiritual reasons. Additionally, Walker Lake is a stopover point on the Pacific flyway route for birds migrating within and from outside of the United States. Because International treaties include provisions to protect the integrity and success of the migratory flyways, there are economic, tribal, ecologic, and international reasons to maintain Walker Lake as a viable fishery.

If the Walker Lake fishery and ecology are to be stabilized, TDS concentrations in the lake need to be reduced. The Nevada Division of Environmental Protection (2005, p. 14) has established a Total Maximum Daily Load (or concentration, in this case) for Walker Lake of 12,000 mg/L of TDS. In order for water managers, decisionmakers, and water users in the Walker River basin to make informed water management decisions, they must have accurate information on the water budget of Walker Lake and on the quantity of water that is discharged by evapotranspiration in the Lower Walker River basin.

In response to the concerns and conflicts over water issues within the Walker River basin, the U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation (Reclamation), began the Lower Walker River basin study described in this report. The study was funded under the 2002 Farm Bill amendment to study terminal lakes (Lopes, 2005). Specific objectives of the study are to (1) quantify the volume of natural streamflow in the basin, and determine the percentage of that streamflow by hydrographic area; (2) determine evapotranspiration (ET) losses from riparian vegetation and the lake surface; (3) develop an improved water budget for Walker Lake; and (4) develop the capability to predict how changes in irrigation practices in and below Mason Valley might affect flows in the Lower Walker River. This report is the third in a series of reports prepared for this study. The first two reports were “Bathymetry of Walker Lake, West-Central Nevada” by Lopes and Smith (2007), and “Precipitation Zones of West-Central Nevada” by Lopes and Medina (2007). This report contributes elements to address objectives 3 and 4, and completes objective 2.

Purpose and Scope

The purpose of this report is to provide estimates of the discharge of water from the Lower Walker River basin by ET and net evapotranspiration (ET_n) for water years 2005–07 (October 2004–September 2007; a water year is the 12-month period October 1 through September 30 and is designated by the calendar year in which it ends) for areas with ET exceeding annual precipitation (defined later as ET quantification area), and to summarize these results for (1) areas of similar vegetation and soil characteristics, (2) three hydrographic subareas of the basin, and (3) Walker Lake and Weber Reservoir. In this report, ET represents the discharge to the atmosphere of all water that has entered the ET quantification area, including all surface-water inflows, ground-water inflows, and precipitation. Net ET represents the discharge to the atmosphere of water that has entered the study area through surface-water inflows and ground-water inflows. Net ET does not include the discharge to the atmosphere of water that has entered the study area by direct precipitation. Except for a small quantity of ground-water outflow from the study area near Double Springs (approximately 2,300 acre-ft/yr; T. J. Lopes, U.S. Geological Survey, written commun., 2008), ET_n represents the “net loss” of water from the Lower Walker River basin.

The estimates of ET presented in this report are determined from field measurements of ET and are extrapolated over the area of interest on the basis of vegetation characteristics determined by remote sensing techniques and areas of open water. Annual ET is estimated over the area of interest for each water year of the study and then is used to compute annual ET_n by subtracting annual precipitation. Results are presented year by year as well as summarized for the three hydrographic subareas of the Lower Walker River basin.

Description of Lower Walker River Basin

The 3,950-mi^2 Walker River basin occupies parts of west-central Nevada and eastern California (fig. 1). The study area, which is downstream of the Wabuska streamflow-gaging station in northern Mason Valley, encompasses about 1,350 mi^2 and represents about 34 percent of the entire Walker River basin and is referred to as the Lower Walker River basin throughout this report.

Walker River

The headwaters of the Walker River originate in the eastern Sierra Nevada mountains in California and collect in the West and East Walker Rivers (fig. 1). The two stems of the river join in the southern end of Mason Valley to form the mainstem Walker River, which then flows about 70 mi to its terminus at Walker Lake, Nevada. Streamflow was measured continuously during the study at the Wabuska gaging station, where the Walker River enters the study area, and at the Lateral 2A gaging station, which is about 1 mi downstream of the community of Schurz. No streamflow-gaging stations are downstream of the Lateral 2A station.

The flow of Walker River generally decreases as it traverses the study area toward Walker Lake. For the 30-year period 1971–2000, the mean discharge of the river as it enters the study area at the Wabuska gaging station was 138,000 acre-ft/yr. During the same period, the mean discharge at the Lateral 2A gaging station was 108,000 acre-ft/yr (T. J. Lopes, U.S. Geological Survey, written commun., 2008). This indicates an average loss of streamflow along this reach of about 30,000 acre-ft/yr over this period. This loss is attributed primarily to infiltration of stream water through the channel bottom to the ground-water system and to evapotranspiration from natural and agricultural vegetation. Although there are no permanent-gaging stations downstream of the Lateral 2A station, miscellaneous discharge measurements and data from short-term, temporary gaging stations, indicate that the 30-year mean streamflow entering Walker Lake is about 104,000 acre-ft/yr (T.J. Lopes, U.S. Geological Survey, written commun., 2008). This would indicate a general loss in flow along the lowest reach of the Walker River of about 4,000 acre-ft/yr. This loss also is attributed to loss of stream water to the ground-water system and to evapotranspiration. Following extended periods of no flow along the lowest reach, initial losses of streamflow from Walker River as it rewets the channel and recharges the local ground-water system can be substantial (T.J. Lopes, U.S. Geological Survey, written commun., 2008).

The flow of Walker River during this study was a little greater than the long-term mean flow but strongly varied about the mean. The mean flow entering the study area at the Wabuska gaging station during water years 2005–07 was 160,000 acre-ft/yr, which was about 22,000 acre-ft/yr greater than the 1971–2000 mean. Flow ranged from 299,000 to 40,200 acre-ft in water years 2006 and 2007, respectively, and was 140,000 acre-ft for water year 2005. The mean flow at the Lateral 2A gaging station during this study was 127,000 acre-ft/yr, which was about 19,000 acre-ft/yr greater than the 1971–2000 mean. Flow varied between 254,000 and 31,200 acre-ft in water years 2006 and 2007, respectively, and was 95,000 acre-ft for water year 2005. The average decrease in flow between the Wabuska and Lateral 2A gaging stations during the 3-year study was 33,000 acre-ft/yr, which is similar to the estimated long-term loss of 30,000 acre-ft/yr for this reach.

Walker Lake

Walker Lake is the terminus of the Walker River and is the lowest point in the basin. Walker Lake is a remnant of ancient Lake Lahontan, a large pluvial lake that occupied a large part of the Great Basin most recently during the late Pleistocene (Russell, 1885; Benson, 1988, p. 1). The mean stage of Walker Lake during the study period was 3,935.8 ft. At this stage, the surface area is about 32,200 acres, total water volume is about 1,786,000 acre-ft, and mean depth is 55.4 ft. The stage of Walker Lake during the study ranged from a minimum of 3,933.6 ft in late December 2005 to a maximum of 3,939.4 ft in late July 2006 (fig. 3). The maximum depth ranged from 84.3 to 90.1 ft. The minimum altitude of the bottom of Walker Lake is 3,849.3 ft and is near the center of the lake (Lopes and Smith, 2007, p. 10).

Ground-water altitudes adjacent to and on all sides of Walker Lake were greater than the surface of the lake (T.J. Lopes, U.S. Geological Survey, written commun., 2008), which indicates that the general direction ground-water flow is towards Walker Lake and that ground water generally discharges to the lake. When the level of Walker Lake rises rapidly, such as in years with large runoff in the Walker River, it is likely accompanied by a reversal in gradient near the ground-water/Walker Lake interface, so that lake water flows outward into the ground-water system immediately adjacent to the lake. However, given the long-term, relatively continuous decline in the level of Walker Lake, such an outward component of flow from Walker Lake to the ground-water system probably has occurred only infrequently and only for periods of a few weeks to a few months.

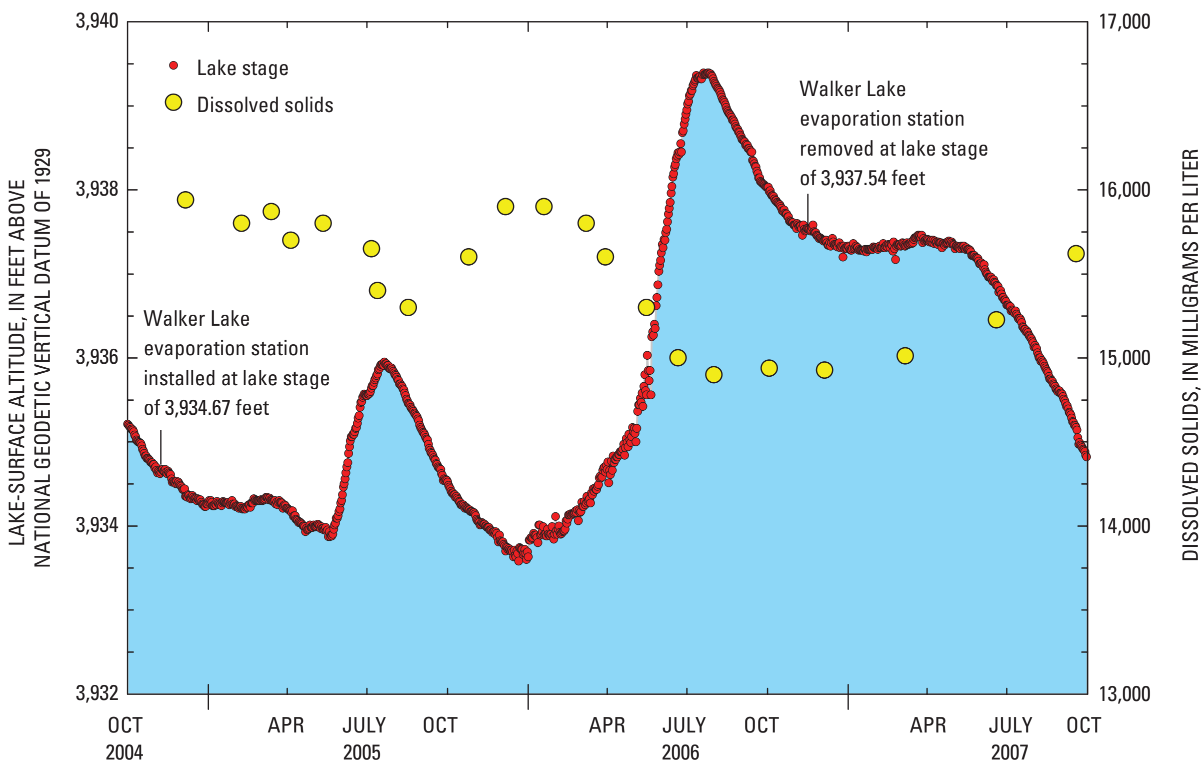


Figure 3. Hydrograph and dissolved-solids concentrations of Walker Lake, west-central Nevada, October 2004–October 2007.

Climate

The climate in the valleys of the study area is typical of the semi-arid great basin desert regime and is classified as mid-latitude desert because of its cold winters and hot summers (Houghton and others, 1975, p. 3). Because most of the area in the Lower Walker River basin in which annual ET exceeds annual precipitation lies within a triangular area defined by the Hawthorne, Wabuska, and Fallon climate station locations (fig. 1), it is assumed that a combination of weather data from these three stations (Western Regional Climate Center, 2007) is more representative of climate conditions in the study area than data from any one of the individual stations. Small amounts of precipitation fall year round (less than 0.8 in. per month), with a slightly uneven monthly distribution (fig. 4*A*). Most of the annual precipitation occurs as rain, with occasional snow, during winter and spring storms. During summer, infrequent but sometimes powerful convective storms produce destructive flash floods (Hess and Glancy, 2000). For the 1971–2000 climate summary period, mean annual precipitation was 5.18 in., average maximum daily temperature was 68.7°F, and average minimum daily temperature was 36.4°F. For comparison purposes, using the 1971–2000 annual normal precipitation relationship for the Walker precipitation zone in Lopes and Medina (2007) and an average altitude of 4,055 ft for the study area valley bottom results in annual precipitation of 4.5 in.

Monthly precipitation during the 3-year study is shown in figure 4*B*. Total precipitation over the study period was 13.05 in., or an average of about 4.35 in/yr, which is less than the long-term mean of 5.18 in/yr (Western Regional Climate Center, 2007). Precipitation during water year 2005 was 6.35 in., which was a little greater than the long-term mean. During water year 2006, precipitation was 4.85 in., which was near normal. During water year 2007, precipitation at about 1.86 in. was much lower than the long-term mean.

Vegetation Communities

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

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

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

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

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

The initial study design was to measure ET from normal and healthy saltcedar. At the time of site installation (March 2005), an experiment with the introduction of an insect called the saltcedar leaf beetle (*Diorhabda elongata*) was taking place. The beetle was released in August 2003 in an attempt to reduce the saltcedar population (R.R. Pattison, U.S. Department of Agriculture, Agricultural Research Service, written commun., 2007). Initially, it was believed that the experiment was unsuccessful and that the beetles were not going to become established nor have the intended effects on the saltcedar. An ET station was established in the saltcedar in early spring 2005 prior to the leafing out of the saltcedar.

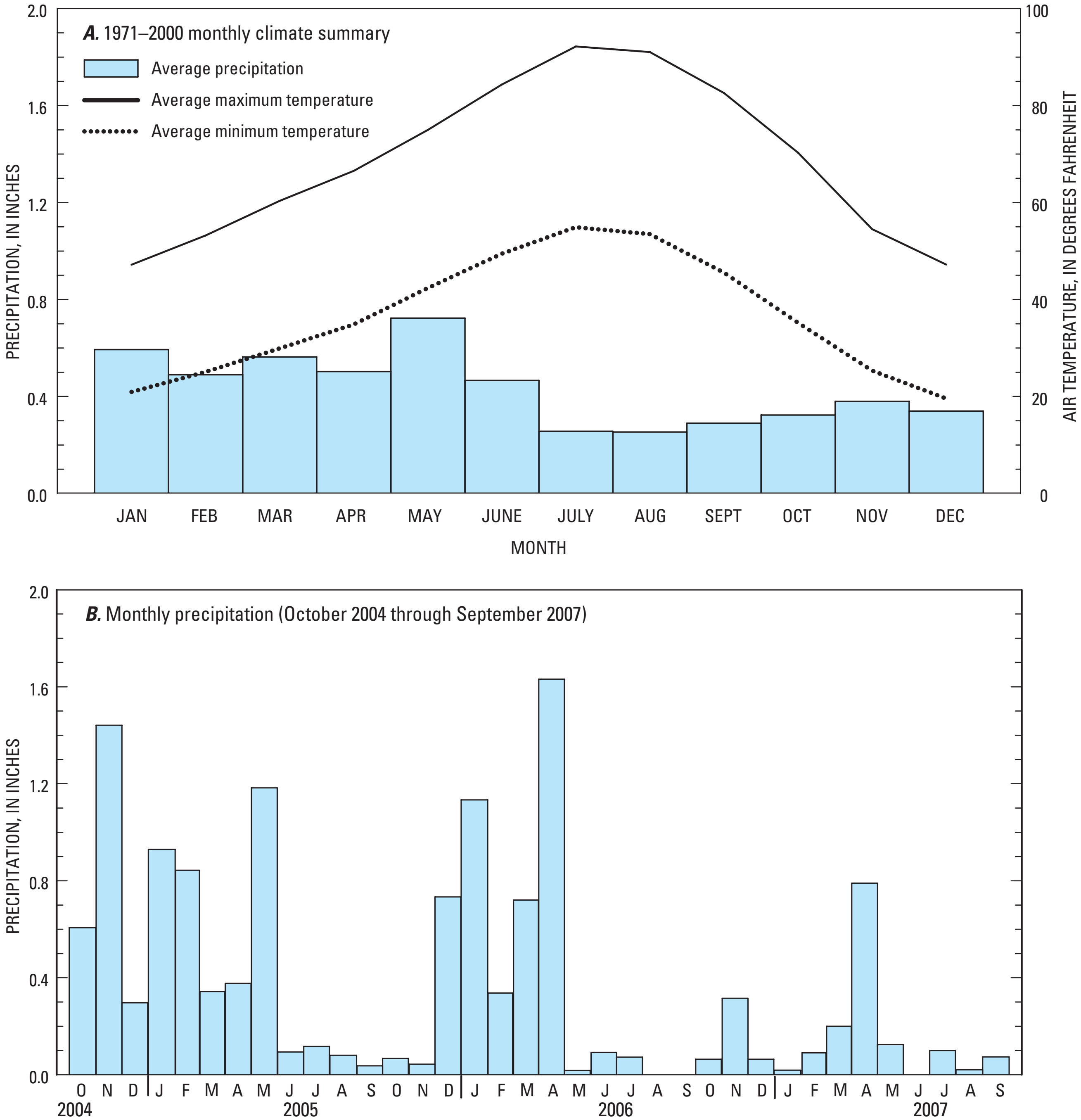


Figure 4. Climate data combined and summarized for Hawthorne, Fallon, and Wabuska weather stations, west-central Nevada. *A*. Monthly climate summary for 1971–2000. *B*. Monthly precipitation during this study (October 2004 through September 2007). Long-term annual mean precipitation for 1971–2000 is 5.18 inches.

The saltcedar began leafing out in May, and by months' end the saltcedar was full and healthy, following the normal seasonal phenologic development pattern. Then in early to mid-June 2005, the beetle emerged and started defoliating the saltcedar canopy in the vicinity of the ET station. In less than 1 month, the saltcedar canopy was reduced from a full and healthy state to one of almost complete defoliation. This canopy reduction substantially affected ET rates and water use by the saltcedar vegetation (R.R. Pattison, U.S. Department of Agriculture, Agricultural Research Service, written commun., 2007), which is discussed in more detail in the section, "Evapotranspiration Rates."

Agricultural vegetation in the study area is dominated by flood- and sprinkler-irrigated alfalfa and, to a much lesser extent, irrigated turf. Most of the irrigated crops in the study area are on the Walker River Indian Reservation; the remainder are in the Whiskey Flat area. During the 2007 growing season (May–October), the Walker River Paiute Tribe reconstructed the Weber Reservoir dam, and as a consequence, did not irrigate their crops that season. Most of the irrigated turf was at a small community 9-hole golf course adjacent to the Hawthorne Army Ammunition Depot near the city of Hawthorne. Smaller areas of turf were within the city of Hawthorne at schools, government buildings, and private residences.

Physiography

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

Major geographic features of the Lower Walker River basin include the lower Walker River, Weber Reservoir, Walker Lake, Whiskey Flat, Wassuk Mountains, Mount Grant, and Gillis Range (fig. 1). Currently, inhabited communities in the study area are Schurz, the town of Walker Lake, the Hawthorne Army Ammunition Depot, and Hawthorne. The town of Schurz is near the middle of the Walker River Indian Reservation. The highest point in the study area is Mount Grant, at 11,239 ft, and the lowest point is the surface of Walker Lake, which had a mean altitude of 3,935.8 ft during this study. Although the overall length of the study area is approximately 90 mi, the distance between Mount Grant and Walker Lake is only about 5 mi, resulting in a vertical gradient of about 1,460 ft/mi.

Previous Investigations

Several earlier investigators have estimated ET in the Lower Walker River basin on the basis of analysis of water use/consumption by natural and agricultural vegetation. The first attempt was included in a brief appraisal of the water resources of the Walker Lake area by Everett and Rush (1967) as part of the Nevada Department of Conservation and Natural Resources Water-Resources Reconnaissance program. In estimating the water budget and perennial yield of ground water for the Lower Walker River valley, Everett and Rush (1967) mapped and classified different phreatophyte classes and bare soil. Their methods for delineating phreatophyte classes were not described, however, and the ET rates used by Everett and Rush (1967) were obtained from published literature. Schaefer (1980) estimated ET on the Walker River Indian Reservation in the Lower Walker River basin using methodology similar to that used by Everett and Rush (1967) as well as their ET rates for the land covers.

A large body of literature related to ET of natural and agricultural vegetation in the Great Basin is available. The following is a partial summary of work done in and near the Walker River basin. Carman (1989) presents data on ET of phreatophytic areas in Smith Creek Valley and the Carson Desert in west-central Nevada. Nichols and others (1997) estimated ET rates for different densities of saltgrass and a marsh in Ash Meadows in Nye County, Nevada. Laczniak and others (1999) added to this work by measuring ET in additional vegetation communities, by classifying and creating an ET-unit map, and by estimating ground-water discharged by ET in Ash Meadows. Nichols (2000) published methods and results of determining ET estimates using satellite imagery to quantify regional ground-water budgets for valleys in eastern Nevada. Laczniak and others (2001) estimated ground water discharged by ET in the Death Valley Regional Flow System in Nevada and California. Berger and others (2001) made estimates of ET from different vegetation communities in the Ruby Lake National Wildlife Refuge Area in northeastern Nevada. Reiner and others (2002) measured ET in a number of different vegetation communities in Oasis Valley in Nye

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

County, Nevada. DeMeo and others (2003) estimated ground-water discharge from Death Valley, California, using ET estimates for different ET units classified within the Death Valley National Park. Maurer and others (2006) determined ET rates from two desert shrub communities as well as from various irrigated croplands in the Carson Valley of Nevada and California. Thodal and Tumbusch (2006) measured ET of non-phreatophytic vegetation communities representing desert shrub and pinyon-juniper trees in the Tracy-Clark area of the Lower Truckee River. Westenburg and others (2006) studied ET characteristics of riparian vegetation along the Lower Colorado River in the Havasu National Wildlife Refuge in Arizona. As part of the Basin and Range Carbonate-Rock Aquifer System Study, Moreo and others (2007) reported on ET measurements made in different desert vegetation communities of eastern Nevada, and Smith and others (2007) reported on the ET units that were delineated for that study.

Evaporation (E) from open-water surfaces in the Great Basin has been estimated in a number of studies. Westenberg and others (2006, p. 17) used the energy-budget method to estimate 7.5 ft/yr of E from Lake Mead for calendar years 1998–99. Berger and others (2001, p. 16) also used the energy-budget method to estimate 5.3 ft/yr of E for Ruby Lake, Nevada during water year 2000. Laczniak and others (1999, p. 31) used the energy-budget method to derive an E of 8.6 ft for a 1-year period from mid-1996 through mid-1997 for Peterson Reservoir in the Ash Meadows National Wildlife Refuge. Milne (1987) used a water-budget approach similar to that of Harding (1965), to estimate annual E minus ground-water inflow for Pyramid and Winnemucca Lakes of 4.1 ft/yr. Harding (1965), using the same water-budget method he used on Walker Lake, estimated E (minus ground-water inflow) for Pyramid and Winnemucca Lakes of 4.1 ft/yr.

Prior to this study, the evaporation rate most commonly used for Walker Lake was 4.1 ft/yr (Harding, 1965, p. 147; Everett and Rush, 1967, p. 14; Boyle Engineering Corporation, 1976, table 4.2; Koch and others, 1979, p. 48; Myers, 1994, p. 17; Thomas, 1995, p. 3; Nevada Division of Environmental Protection, 2005, p. 8; and Sharpe and others, 2007, p. 14). The original source for this commonly used value, and the methods and data used to develop it, are described in the report by Harding (1965, p. 147). Harding (1965) made estimates of annual evaporation for Walker Lake from 1928 to 1960 using a water-budget approach “based on the record of inflow from Walker River, precipitation on the lake based on the records at Schurz and Hawthorne and the fluctuations of the lake” (p. 143). The basic lake water-budget equation used by Harding in his water-supply studies was $SW_i+P+GW_i–SW_o–E–GW_o+\Delta S=0$, where surface-water inflow (SW_i), precipitation (P), and ground-water inflow (GW_i) were the inflow terms, and surface-water outflow (SW_o), evaporation (E), and ground-water outflow (GW_o) were the outflow terms, and ΔS was the change in lake storage. Harding (1965, p. 8) simplified this equation for Walker Lake by recognizing that “Being enclosed there is no surface outflow” ($SW_o=0$), “there is no known [ground-water] outflow” ($GW_o=0$), and by assuming that ground-water inflow was “too small to supply any material amounts” ($GW_i=0$), and then solved the equation for E to get $E=SW_i+P+\Delta S$.

Harding’s original work on open-water evaporation provided the essential foundation for many water-budget studies that followed. Thus, the following discussion is in no way meant to question the importance and value of that work, but rather offers a frame of reference on why and how estimates of evaporation from Walker Lake could be refined.

The original estimate of evaporation from Walker Lake by Harding (1965) is based on unknown adjustments of the flow records for Walker River and on a possibly oversimplified assumption of no ground-water inflow to Walker Lake. It is unclear which Walker River streamflow record(s) Harding used in his analysis. During the period included in Harding’s analysis (1928–60), the flow of Walker River was measured in Schurz (actually from 1913 to 1933) and at the Wabuska gaging station (from 1928 to 1935 and from 1939 on). However, no single gaging station had a record that that coincided with the full period of his analysis. Additionally, it is unknown whether Harding attempted to adjust the streamflow record for changes in flow between the measurement location(s) and Walker Lake. Because Harding (1965) made the assumption that ground-water inflow to Walker Lake is negligible, his estimate of annual lake evaporation actually represented evaporation minus any ground-water inflow to the lake that may have been occurring. Alternatively stated, the lake water-budget equation that Harding was really solving was $E–GW_i= SW_i+P+\Delta S$. Assuming that ground-water discharge to Walker Lake was greater than zero during the period considered in Harding’s analysis, then his estimated evaporation rate incorporates ground-water inflow to Walker Lake, and the “true” evaporation rate estimated is greater than 4.1 ft/yr by the amount of that inflow.

Several other investigators have made estimates of evaporation for Walker Lake. Kohler and others (1959) produced evaporation maps for the continental United States that were used by Schaefer (1980, p. 14) to derive an evaporation rate of 4.0 ft/yr for Walker Lake. The U.S. Department of Commerce, Environmental Science Services Administration (ESSA) (1968) developed national maps of annual evaporation rates for lakes. The ESSA evaporation map was used by Nevada Department of Conservation and Natural Resources (1973) to estimate evaporation at Walker Lake as 4.0 ft/yr, the same as Schaefer’s (1980) estimate. The ESSA evaporation maps were developed on the basis of pan evaporation data. The use of pan evaporation data to estimate evaporation from Walker Lake may be inappropriate because the lake is not shallow (like a pan), and it is in an area where winter air temperatures frequently fall below freezing. The use of pan evaporation data to estimate lake evaporation can be problematic in lakes that are not shallow because pans do not accurately represent evaporation from lakes in which heat storage is a fundamental part of the evaporation process (Kohler and others, 1959, p. 12). The use of pan evaporation data also can be problematic for estimating lake evaporation in regions where air temperatures go below freezing, because pan data typically are not collected during freezing conditions (Kohler and others, 1959, p. 12).

Milne (1987, p. 35) used a variety of evaporation estimates based on pan evaporation data from Lahontan Dam and Fallon to calibrate a water-budget model for Walker Lake for 1927–86. Milne was not satisfied with the results of the water-budget model in which these evaporation estimates were used as input parameters, and instead combined the evaporation (E) and ground-water inflow (GW_i) terms into a single term ($E–GW_i$), which was set equal to the residual of the water-budget equation. Milne determined that an $E–GW_i$ value of 4.4 ft/yr provided the best solution to her water-budget model. Assuming that ground-water discharge to Walker Lake was greater than zero during this period, then evaporation was 4.4 ft/yr plus the ground-water discharge, resulting in an annual evaporation rate greater than 4.4 ft/yr. Allander and others (2006) estimated annual evaporation as high as 6.0 ft/yr in a preliminary analysis of the data from this study. This estimate was subsequently judged to be too high because the assumptions that all stored heat energy exchange occurred in the top 3.5 m of Walker Lake, and that negative latent heat flux represented zero evaporation rather than condensation, turned out to be incorrect.

Evapotranspiration Units

The water in the Lower Walker River originates as direct precipitation, ground-water inflow, and surface-water inflow. Nearly all this water eventually is discharged to the atmosphere by ET. Ground water and surface water are discharged by ET from areas where annual ET exceeds annual precipitation. This water is evaporated from soils and open-water surfaces and is transpired by a variety of vegetation. Areas of similar soil and vegetation characteristics are assumed to have similar rates of ET.

ET units are defined as areas of similar vegetation type and density and similar soil characteristics where water potentially is being lost to the atmosphere by evaporation or through plant transpiration (Laczniak and others, 1999, 2001, 2006). In general, the more dense and healthy the vegetation and the wetter the soil, the greater the ET. The characteristics of the ET units differ throughout the study area and range from areas of no vegetation, such as open water, to areas dominated by phreatophytic shrubs, grasses, willows, saltcedar, and recently irrigated cropland. For purposes of this study, 10 ET units were defined and delineated (table 1) within the area where annual ET exceeds annual precipitation. These ET units are xerophyte, sparse desert shrubland, moderately dense desert shrubland, dense desert shrubland, saltcedar, grassland, turf, riparian, recently irrigated cropland, and open water.

ET Discharge Quantification Area

An ET discharge quantification area was defined and mapped within the study area (fig. 5) using techniques similar to those used by Nichols (2000) to define areas of phreatophytes in the Great Basin and by Smith and others (2007) to define areas of ground-water discharge in the Basin and Range Carbonate-Rock Aquifer System. This study differs from previous work, however, in that the primary source of water for ET in the study area is provided by surface water (Walker River and Walker Lake). In the studies by Nichols (2000) and Smith and others (2007), precipitation and ground water were the primary sources of water for ET. The ET discharge quantification area defined for the purposes of this study, also referred to as simply the ET quantification area, is the area in which annual ET is greater than annual precipitation. The ET quantification area therefore represents areas in which the water available for ET originates from either a surface-water or ground-water source, or both, in addition to local precipitation. The outer limits of this boundary were determined by the extent of greasewood shrub communities similar to methods by Nichols (2000) and Smith and others (2007). Outside of the ET quantification area, annual ET is assumed to be equivalent to annual precipitation. Mapping the ET quantification area for this study involved field mapping, the use of Lidar (Light Detection and Ranging), and the analysis of high-resolution aerial imagery.

Field Mapping

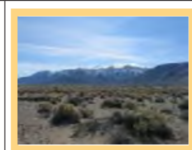
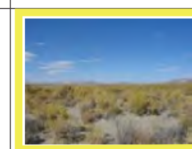
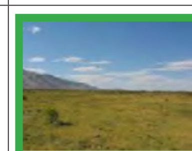
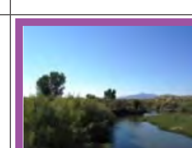
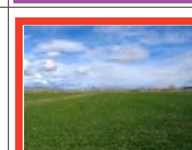
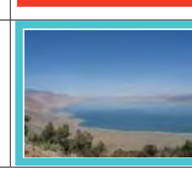
Field mapping of the ET quantification area was conducted during the summers of 2005–07. A total of 49 field points were used to help identify the boundary of the area (fig. 5). At each field point, the location and description of the boundary were noted and photographs were taken. Many field points were not actually on the boundary, but were within visual range of the boundary. The information was entered into a geographic information system (GIS).

Lidar

Lidar is an active remote-sensing technique that was used in this study to accurately measure land-surface altitude. The National Aeronautics and Space Administration's (NASA) Experimental Advanced Airborne Research Lidar (EAARL) was used to map land-surface altitude of the valley floor and adjacent foothills from Hawthorne to Wabuska, Nevada, between May 26 and June 2, 2005 (see last image in Lopes, 2005, for approximate extent of Lidar imagery). Details of the EAARL system used for this study are in Lopes and Smith (2007).

Table 1. Delineated evapotranspiration (ET) units for different vegetation and soil conditions within the ET discharge quantification area of the Lower Walker River basin, west-central Nevada, October 2004–September 2007.

[Locations of evapotranspiration units shown in figure 6. Full scale images of examples of ET units are available by clicking on photograph thumbnails. Landsat image scene date was July 1, 2005. **Abbreviations:** MSAVI, Modified Soil-Adjusted Vegetation Index; TM, Thematic Mapper; ft, foot]

ET-unit name	ET-unit description	Photograph
Xerophyte	Primarily dry open desert with sandy soil and sparse density of desert shrubs. Soil and vegetation characteristics are similar to areas outside of ET quantification area. Scaled MSAVI ranges from 1 to 12. Water table typically is greater than 30 ft below land surface. All vegetation relies on soil moisture originating from precipitation. This unit occupies the area between sparse desert shrubland and the ET quantification boundary.	
Sparse desert shrubland	Area is characterized by a sparse density of desert shrubs in open desert with dry sandy soil. Shrubs primarily include greasewood, rabbitbrush, and saltbush. Scaled MSAVI ranges from 13 to 20. Depth to water can range from about 10 to 50 ft. Vegetation primarily relies on soil moisture originating from precipitation, but can occasionally use ground water when soil moisture from precipitation is not adequate and depth to water is within the plant's root system. This unit primarily occupies the area between moderately dense desert shrubland and xerophyte ET units.	
Moderately dense desert shrubland	Area is characterized by a moderate density of desert shrubs including greasewood, rabbitbrush, and saltbush and may have some saltgrass in the understory. Scaled MSAVI ranges from 21 to 28. Depth to water can range from about 5 to 20 ft. Vegetation uses ground water and soil moisture originating from precipitation. This unit primarily occupies the area between riparian and sparse desert shrubland ET units and between saltcedar and sparse desert shrubland ET units.	
Dense desert shrubland	Area is characterized by a dense mixture of desert shrubs such as greasewood, rabbitbrush, saltbush, and some saltcedar and also may include moderate to dense understory of saltgrass. Scaled MSAVI ranges from 29 to 43. Depth to water can range from a few to 10 feet. Vegetation uses ground water and soil moisture originating from precipitation. This unit primarily occupies area between riparian and other desert shrubland ET units and between saltcedar and other desert shrubland ET units.	
Saltcedar	Area is characterized by saltcedar undergoing oscillating periods of defoliation caused by saltcedar leaf beetle and also may include occasional desert shrubs and light to moderate understory of saltgrass Scaled MSAVI ranges from 29 to 200 and areal extent of unit was mapped using high resolution imagery. Depth to water can range from 5 to 15 ft. Vegetation uses ground water and soil moisture originating from precipitation. Primarily occupies the area adjacent to Walker River below level of 1882 Walker Lake shoreline in sandy and salty soils.	
Grassland	Area is characterized by short, moderately dense perennial grasses. Mainly represents saltgrass. Unit can include moderately dense desert shrubs and occasional cottonwood trees. Scaled MSAVI ranges from 44 to 200 and areal extent of unit was mapped using high resolution imagery. Depth to water can range from a few to 10 feet. Vegetation uses ground water and soil moisture originating from precipitation. This unit primarily occupies the area adjacent to the saltcedar on the north side of Walker Lake, and adjacent to shoreline on the south side of Walker Lake.	
Turf	Area is characterized by irrigated short, moderate to high density of perennial grasses (lawns). Unit is dominated by turf and can include cottonwood trees as well as ornamental coniferous and deciduous trees. Soil moisture varies with irrigation practice, but typically alternates from very moist to semi-dry during growing season. Vegetation was mapped using Landsat data and high resolution imagery. Depth to water typically is greater than 10 ft. Vegetation uses soil moisture originating from irrigation. This unit primarily covers much of the Hawthorne Golf Course and scattered lawns within the city of Hawthorne.	
Riparian	Area is characterized by willow shrubs and other riparian vegetation including cottonwood trees. Can include moderately dense desert shrubs and saltgrass. Scaled MSAVI ranges from 29 to 200 and areal extent of unit was mapped using high resolution imagery. Depth to water can range from land surface to 10 ft. Vegetation uses ground water. This unit primarily occupies the area along perennial river corridor upstream of saltcedar ET unit.	
Recently irrigated cropland	Area dominated by irrigated cropland. Soil moisture varies with irrigation practice, but typically alternates from very moist to semi-dry during growing season. Irrigated cropland areas were determined from photograph interpretation of Landsat TM imagery. Depth to water typically is greater than 5 ft. Vegetation uses soil moisture originating from irrigation. This unit primarily occupies area in and near Schurz and Whiskey Flat.	
Open water	Area of open water, including lakes, reservoirs, and ponds. Reservoir water bodies vary in size seasonally. Size of Walker Lake was relatively constant during study period. Unit represents an unlimited source of water available for evaporation. This unit consists solely of Walker Lake and Weber Reservoir.	

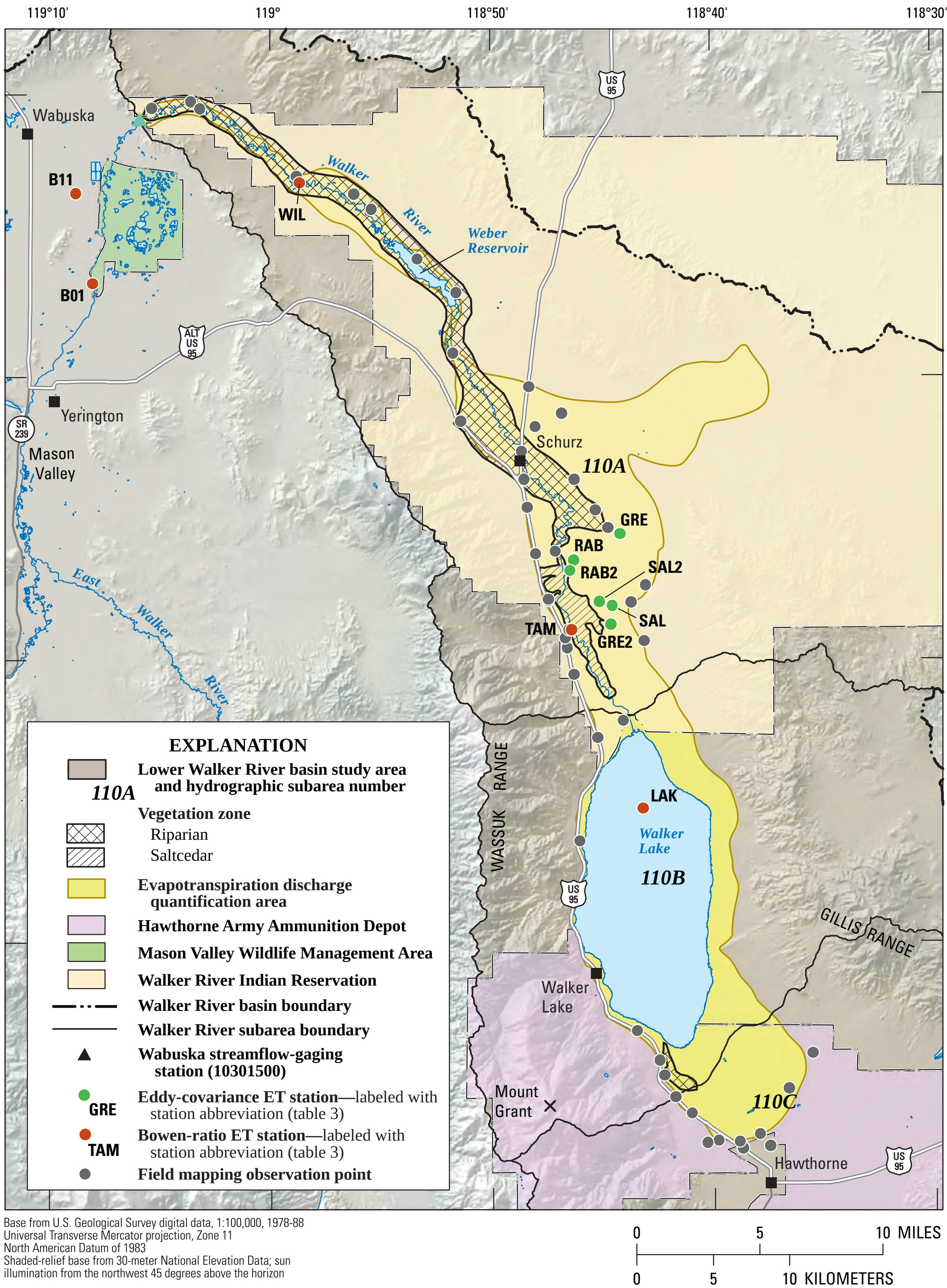


Figure 5. Boundary of evapotranspiration (ET) discharge quantification area and locations of (ET) stations and field mapping observation points, Walker River basin, west-central Nevada.

High Resolution Aerial Imagery

High resolution aerial imagery was collected in the Walker Lake area by EarthData International, LLC, on June 28, 2005. Natural color and color infrared ortho-images were produced at about 3-ft pixel resolution over an area of 1,364 mi^2 (see last image in Lopes, 2005, for approximate extent of high resolution imagery). Details of the high resolution aerial imagery used for this study are in Lopes and Smith (2007).

Mapping the ET Discharge Quantification Area

The final boundary of the ET quantification area was determined in the GIS using information collected at the field mapped points, Lidar data, and high resolution aerial imagery (fig. 5). Using the high resolution aerial imagery, a polygon was described using the field mapped points, which acted as guides for the delineation of the polygon. Generally, the high resolution aerial imagery clearly identified where the outer boundary occurred. In areas where greasewood was mixed with other desert shrubs or where the greasewood was very sparse, the boundary was more difficult to define. The boundary of greasewood generally occurs at or near the same altitude in a given area due to similar depths to ground water. Where this boundary was not easily defined on the basis of data from the field mapped points and high resolution aerial imagery, it was extended from defined boundaries using equal altitude contours determined from the Lidar data.

Delineation of Evapotranspiration Units

The ET-unit map (fig. 6) was created on the basis of analyses and interpretation of Landsat data from 2005 and the high resolution aerial imagery of 2005. Landsat data from 2000 also was used to delineate recently irrigated cropland. The open-water ET unit was dominated by Walker Lake and Weber Reservoir. Their acreages were determined using relations between lake stage and surface area. An explanation of the data and the techniques used to determine the land ET units are described in the following sections.

Landsat Thematic Mapper Imagery

Landsat Thematic Mapper (TM) imagery was used to delineate certain ET units in the study area and to characterize the health, density, and vigor of vegetation around the land ET stations and within the ET units for each year of this study. Landsat satellites orbit the Earth such that they acquire data over the same area at the same time every 16 days. These Earth-orbiting satellites are equipped with sensors to detect and acquire solar-reflected and earth-emitted radiation. Spectral reflectance, as acquired by Landsat sensors, represents an average value over a pixel (picture element) that measures about 100 by 100 ft. These pixel dimensions define the spatial resolution of the imagery.

Landsat data are available as scenes that image an area measuring about 115 by 115 mi. Six Landsat scenes were analyzed: (1) entity-id lt7042033000009750 acquired April 6, 2000; (2) entity-id lt70042033000019350 acquired July 11, 2000; (3) entity-id lt7042033000027350 acquired September 29, 2000; (4) entity-id lt5042033000518210 acquired July 1, 2005; (5) entity-id lt5042033000616910 acquired June 18, 2006; and (6) entity-id lt5042033000717210 acquired June 21, 2007. These scenes were selected for various reasons. The April, July, and September scenes of 2000 were used to delineate recently irrigated crops as those dates span the growing season. The optimum period for delineating ET units and for characterizing an annual representation of vegetation health and vigor is between late June and early July—between the summer solstice, which has the longest daylight hours (peak solar radiation), and early July, the approximate date when transpiration from phreatophytes peak. The July 2005 Landsat scene was used to help define the size and extent of the ET units, and was then used in conjunction with the 2006 and 2007 scenes to characterize vegetation health and vigor for the land ET stations and the ET units for each year of the study. Because the recently irrigated cropland ET unit was determined from the Landsat scenes acquired in 2000, some minor adjustments were necessary to make the extent of this unit reflect conditions during the study period. The high-resolution imagery from the 2005 and 2007 Landsat scenes was used to help adjust the irrigated cropland delineations for the study period.

All Landsat imagery was georeferenced to allow geospatial evaluations and direct comparison with other spatially referenced datasets. Image standardization was performed to normalize the spectral data for differences in sun illumination geometry, atmospheric effects, and instrument calibration. Smith and others (2007) provide the details of this procedure.

Delineation of ET Units Using Modified-Soil Adjusted Vegetation Index

The Modified-Soil Adjusted Vegetation Index (MSAVI; Qi and others, 1994), developed on the basis of analyses of the normalized Landsat image data, was used to delineate many of the ET units. The MSAVI also was used to characterize vegetation in areas of land ET stations and to adjust ET rates for the ET units. These latter applications will be discussed in more detail later in this report.

A vegetation index is a number that is generated by the combination of the visible red and near-infrared remote sensing bands and thus has some relation to the vegetation in a given image pixel. The MSAVI removes soil influences from the vegetation index, which makes this index more applicable to areas of sparse vegetation densities than other, similar vegetation indices (for example: Normalized Difference Vegetation Index, Rouse and others, 1973; Enhanced Vegetation Index, Huete and others, 2002). Thus, the MSAVI is an appropriate index to use to map changes in the sparse plant cover in the Nevada desert landscape. MSAVI values are dimensionless and range from -1.0 to 1.0. For this study, MSAVI was rescaled by multiplying MSAVI values between 0 and 1 by 200 to get the values on a scale between 0 and 200 and are referred to as scaled MSAVI. Values less than 0 were set to 0.

The use of a vegetation index to map vegetation cover is based on the assumption that the greener, denser, and more vigorous the vegetation, the greater the vegetation index. Nichols (2000) observed that in some areas of phreatophytes in the Great Basin, medium and short shrubs generally are the dominant vegetation type where plant cover is less than about 35 percent, and grasses, tall shrubs, and trees dominate where plant cover is greater than 35 percent. Xerophytic areas are those in which phreatophytes are absent and bare soil dominates, and generally are defined as areas in which plant cover is less than about 7 percent.

Most of the ET units were iteratively determined by using field reconnaissance and high-resolution imagery to identify the ranges in scaled MSAVI that adequately segregated vegetation characteristics into units that could be readily described as in table 1. The initial scaled MSAVI ranges and ET-unit descriptions used in this iterative process were taken from Smith and others (2007). The scaled MSAVI ranges were adjusted until the ET quantification area was effectively and consistently delineated into areas of open water, areas dominated by xerophytes, areas dominated by desert shrublands, and areas dominated by riparian and tall shrub vegetation and saltgrass. The scaled MSAVI range for desert shrubland was further divided to break the desert shrubland into three general density classes: sparse, moderate, and dense. ET-unit descriptions in table 1 then were modified to better describe the conditions observed in the field for the classified ET units. This process was iterated several times until a satisfactory agreement was established between the classified ET units and the ET-unit descriptions.

Areas with a scaled MSAVI of 0 were identified as water, those with values from 1 to 12 as xerophyte, with values from 13 to 20 as sparse desert shrubland, with values from 21 to 28 as moderately dense desert shrubland, and those with values greater than 29 as either dense desert shrubland, grassland, riparian, or saltcedar.

Delineation of the Riparian, Saltcedar, Grassland, and Dense Desert Shrubland ET Units

The riparian, saltcedar, grassland, and dense desert shrubland ET units were delineated on the basis of the MSAVI determined from Landsat imagery, as well as by field identification of zones where riparian and saltcedar vegetation dominates. The riparian and saltcedar vegetation zones were delineated from field observations and examination of the high resolution aerial imagery (fig. 5). Areas with scaled MSAVI values of 29 to 200 within the riparian and saltcedar vegetation zones were classified as the riparian and saltcedar ET units, respectively. The areas outside of the riparian and saltcedar vegetation zones with scaled MSAVI values of 29 to 43 were classified as dense desert shrubland, and the areas with scaled MSAVI values of 44 to 200 were classified as grassland.

Riparian vegetation and saltcedar shrubs dominate the vegetation types along the riparian corridor of the Lower Walker River. The riparian vegetation zone is the Walker River riparian corridor above the 1882 shoreline of Walker Lake in Lopes and Smith (1882 shoreline is presented in plate 1 in Lopes and Smith, 2007; fig. 5). This area is dominated by willow shrubs and occasional cottonwood trees, but also can include dense shrubs and grasses. Although the riparian vegetation zone is largely classified as riparian ET unit, substantial areas within that unit are classified as desert shrubland of varying density and xerophyte ET units. The saltcedar vegetation zone is the area along the Walker River riparian corridor below the 1882 shoreline (Lopes and Smith, 2007; fig. 5) and is dominated by saltcedar and other desert shrubs but also can include some saltgrass. Although the saltcedar vegetation zone is classified primarily as the saltcedar ET unit, substantial areas within it are classified as desert shrubland of varying density and xerophyte ET units. The grassland ET unit dominates the flat areas adjacent to the Walker River riparian corridor below the 1882 shoreline and consists of nearly continuous beds of saltgrass with an occasional mix of varying densities of shrub canopy.

Delineation of the Turf Evapotranspiration Unit

The turf ET unit represents irrigated short, moderate to high density perennial grasses such as lawns and golf courses. The turf ET unit was delineated using the high resolution aerial imagery. This unit was identified only in hydrographic subarea 110C, within the Hawthorne and Hawthorne Army Ammunition Depot areas, as the area of turf in the other hydrographic subareas was negligible. The 100-ft spatial resolution of Landsat imagery did not allow identification of the relatively small lawns and fields. The 3-ft spatial resolution of the high resolution aerial imagery, however, did make possible the identification and delineation of such small areas of turf. The high resolution aerial imagery also has data in the visible red and near infrared spectrum, and these two spectral bands were used to determine the Normalized Difference Vegetation Index (NDVI) (Rouse and others, 1973), the ratio of the difference of the red and infrared bands over their sum. The NDVI is similar to the MSAVI in that it also can provide an indication of vegetation vigor and density. The NDVI was used instead of MSAVI because the imagery could not be standardized and converted to percent reflectance, which is necessary for computing MSAVI. The NDVI data were computed and rescaled between 0 and 255. The data were then interactively viewed in a GIS, and the best minimum value that delineated lawns and fields was a scaled NDVI of 126. Pixels with scaled NDVI greater than this value were classified as turf and then summed in order to estimate the area of the turf ET unit.

Assembly of Evapotranspiration-Unit Map

A map showing the spatial distribution of ET units was assembled (fig. 6) and was layered according to ET-unit priorities. The base level of the ET-unit map was assembled first, using the ET units determined from scaled MSAVI values. ET units within the riparian and saltcedar vegetation zones were superimposed on the base level, recently irrigated cropland ET units were then added, and lastly, the turf ET unit was added.

All ET units, except recently irrigated cropland and turf, were filtered—pixels were added and removed on the basis of a minimum mapping unit. The minimum mapping unit for this filter was set at four adjacent pixels, which is an area of about 35,000 ft^2 or 0.8 acre in the source imagery. An area this size was found to provide sufficient resolution within the source areas of similar land ET stations in a study by Moreo and others (2007). If an ET unit encompassed less than 0.8 acre, it was replaced with the value of the ET unit that was closest to it.

Total ET-unit acreage and ET-unit acreage listed by hydrographic subarea are presented in table 2 and figure 7. The desert shrubland ET units are the most prominent units within the ET quantification area and constituted about 50 percent of the total area. Sparse desert shrubland dominates the shrubland units and occurs across large areas to the north, east, and south of Walker Lake. The xerophyte ET unit is the next largest land ET unit with about 14 percent of the ET quantification area. The open-water ET unit accounts for 27 percent of the ET quantification area. The open-water ET unit includes Walker Lake and Weber Reservoir. Riparian and saltcedar ET units together make up nearly 5 percent of the ET quantification area and occur primarily along the river corridor. The turf ET unit is the smallest unit, making up less than 1 percent of the ET quantification area. Recently irrigated cropland makes up only 3 percent of the ET quantification area.

Selection of ET Stations and Site Characteristics

Eleven ET stations were installed and maintained in the Lower Walker River basin (fig. 5, table 3). One of the stations was on open water (Walker Lake), and 10 were on land. Four of the land-based stations were Bowen-ratio energy-budget stations, and 6 were eddy-covariance stations. The Walker Lake station also was a Bowen-ratio energy-budget station. Two ET stations were in irrigated agriculture fields and 8 stations were in areas of natural vegetation. The 6 eddy-covariance stations were all established in natural vegetation areas. The 10 land-based ET stations were used to compute ET in natural and agricultural vegetation in the Lower Walker River basin (table 3, fig. 5).

The land-based ET stations were initially located using a general field reconnaissance technique. The site for each of the stations was qualitatively assessed for adequacy of the fetch and visual homogeneity of vegetation characteristics. Fetch is the horizontal distance between the ET measurement site and the upwind edge of the environment of influence, and generally implies a homogeneous combination of vegetation and soil characteristics. Stations were located so that fetch distance was at least 100 times greater than the instrument height above the top of the vegetation canopy (Campbell, 1977).

The adequacy of ET station placement to represent the general density and health of the vegetation units was assessed after the high-resolution imagery became available and after more than one growing season of data was collected. It was determined that two of the shrubland stations and a single grassland station were adequately representing the low density and vigor fraction of their associated vegetation communities. A decision was made to diversify the ET measurement environments within these vegetation communities, however, to better represent the actual range of ET within them. Therefore, these three stations were moved during the summer of 2006 to areas of greater vigor and density within their respective vegetation communities and operated for slightly more than 1 year, to the end of water year 2007.

The TAM ET station (fig. B1 in appendix B) was installed in a large stand of saltcedar adjacent to the Walker River a few miles downstream of Schurz. The canopy coverage of the saltcedar at this site had been substantially reduced by the successful introduction of the saltcedar leaf beetle (R.R. Pattison, U.S. Department of Agriculture, Agricultural Research Service, written commun., 2007). The reduction in the ET rates in the vicinity of this station caused by the introduction of the saltcedar leaf beetle is discussed in the section, “Evapotranspiration Rates.”

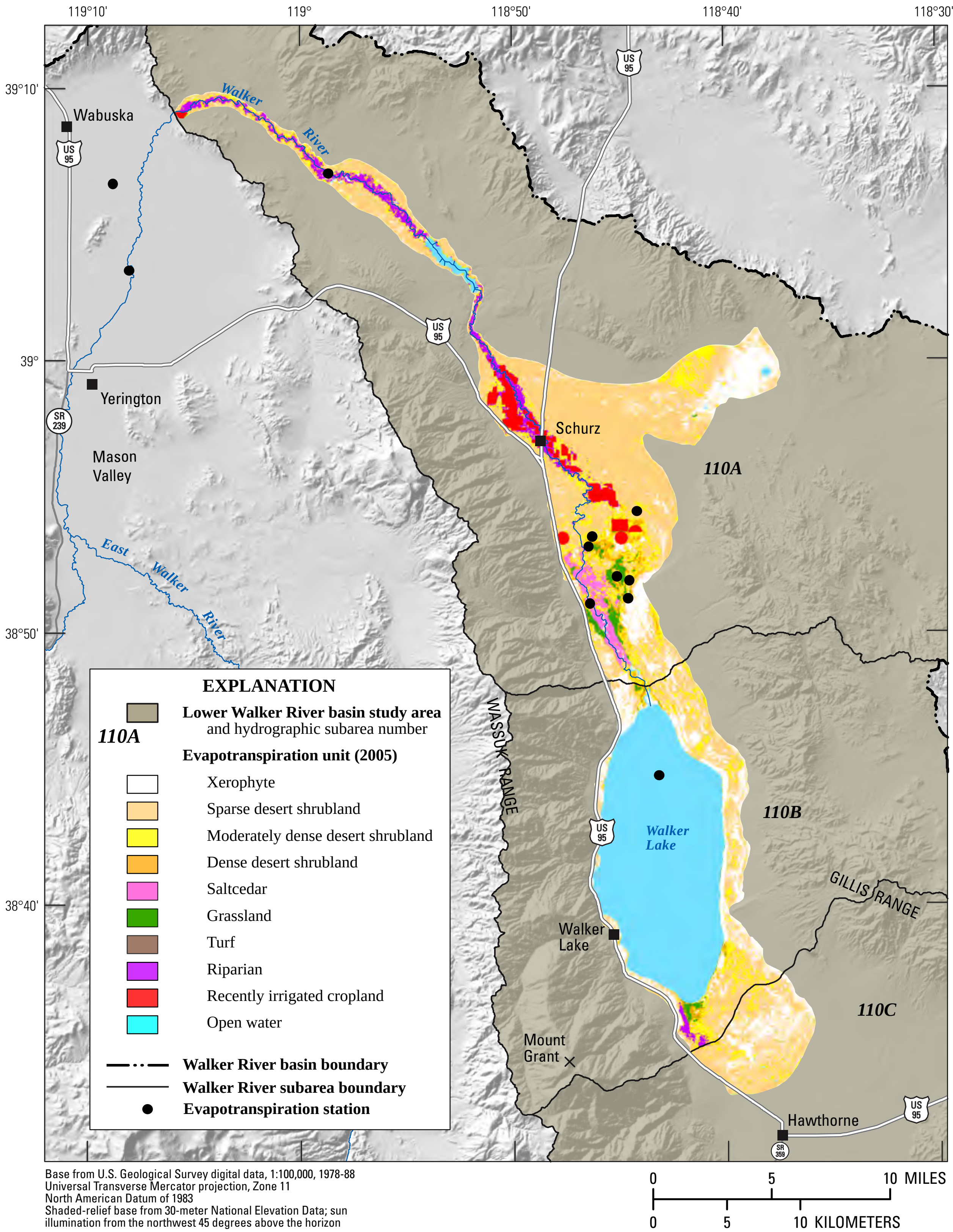


Figure 6. Spatial distribution of evapotranspiration units in the Lower Walker River basin, west-central Nevada.

Table 2. Evapotranspiration-unit acreage by hydrographic subareas in the Lower Walker River basin, Nevada.

[Locations of evapotranspiration units shown in figure 6. **Total area:** The open-water area assigned to hydrographic subarea 110A is the average lake area for Weber Reservoir over the 3-year study. The open-water area assigned to hydrographic subarea 110B is the average lake area for Walker Lake over the 3-year study.]

Hydrographic subarea	Evapotranspiration-unit acreage										
	Xerophyte	Sparse desert shrubland	Moderately dense desert shrubland	Dense desert shrubland	Saltcedar	Grassland	Turf	Riparian	Recently irrigated cropland	Open water	Total area
110A	7,550	34,080	6,680	1,480	1,870	1,040	0	3,710	2,870	580	59,880
110B	7,220	9,520	2,070	530	0	260	0	300	0	32,330	51,920
110C	3,020	6,650	540	30	0	0	390	10	550	0	11,190
Total	17,790	50,250	9,290	2,040	1,870	1,300	390	4,020	3,420	32,910	123,290

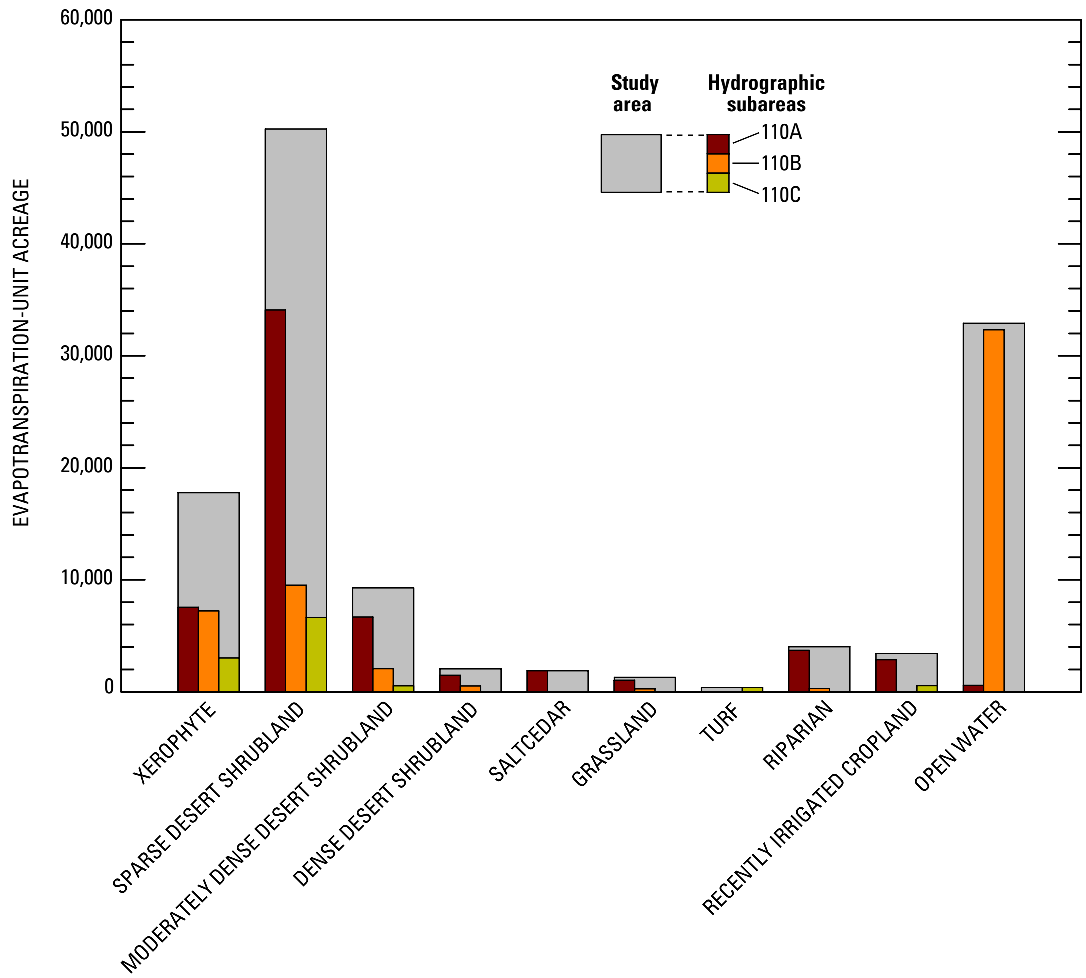


Figure 7. Acreage of each evapotranspiration unit in each hydrographic subarea, Lower Walker River basin, west-central Nevada.

Table 3. Location and description of evapotranspiration (ET) stations in the Lower Walker River basin, west-central Nevada.

[**ET Station name:** Locations are shown in figure 5. **Latitude and Longitude** are DDMMSS.S and DDDMMSS.S referenced to North American Datum of 1983**. Altitude** is referenced to National Geodetic Vertical Datum of 1929]

ET station name	Station No.	Latitude	Longitude	Altitude (feet)	Description of land cover	ET unit
			Bowen-ratio ET stations			
LAK	384443118430901	384442.8	1184309.0	[1]3,936	Open-water body. North-central part of Walker Lake.	Open Water
TAM	385103118462201	385103.4	1184622.3	4,010	Moderately dense saltcedar intermittently defoliated by saltcedar leaf beetle. Soil typically is dry.	Saltcedar
WIL	390653118583901	390652.7	1185839.2	4,236	Moderate to dense stand of willows next to river with varying density of saltgrass in understory. Soil typically is moist to very moist with occasional flooding.	Riparian
B01	390319119080201	390319.1	1190802.4	4,350	Flood irrigated alfalfa intermittent with non-irrigated alfalfa and weeds. Soil is moist when field is irrigated, mostly dry at other times.	Recently irrigated cropland
B11	390630119084701	390630.2	1190847.2	4,320	Flood irrigated alfalfa. Soil is moist during the growing season and mostly dry the rest of the year.	Recently irrigated cropland
			Eddy-covariance ET stations			
SAL	385154118443001	385153.8	1184429.9	4,008	Sparse cover of saltgrass. Soil typically is slightly moist.	Moderately dense desert shrubland
SAL2	385203118450601	385202.6	1184506.5	4,015	Moderate cover of saltgrass. Soil typically is slightly moist.	Grassland
GRE	385426118440801	385425.5	1184408.4	4,087	Sparse cover of greasewood. Soil typically is very dry.	Sparse desert shrubland
GRE2	385114118443401	385113.9	1184434.4	4,015	Sparse to moderate cover of greasewood. Soil typically is dry.	Moderately dense desert shrubland
RAB	385330118461601	385330.3	1184615.9	4,068	Sparse cover of rabbitbrush. Soil typically is very dry.	Sparse desert shrubland
RAB2	385308118462501	385307.8	1184625.3	4,042	Moderate to dense cover of rabbitbrush. Soil typically is slightly moist.	Grassland

[1]Mean lake stage for Walker Lake during this study (rounded). Actual altitude for LAK ET varied with lake stage (fig. 3).

The WIL ET station (fig. B2 in appendix B) was installed in a moderate to dense grove of willow shrubs along the Walker River, about 3 mi upstream of Weber Reservoir. This site had varying densities of saltgrass in the willow understory. The greater than normal runoff for Walker River during the spring melt periods for water years 2005–06 caused flooding in the area of the WIL station. The flooding of this riparian zone in 2005–06 was coincident with the Landsat image used to produce the ET-unit map, and resulted in scaled MSAVI that was not representative at this site or for the riparian ET unit. The operation of this station was interrupted because of loss of power and the inability to access the site over a 10-month period from mid-October 2005 through mid-August 2006, during the middle of the data-collection period (appendix B2). Thus, the period of analysis for this station incorporates two periods of data collection: from February 4, 2005, through October 13, 2005, and from August 15, 2006, through March 19, 2007.

The B01 and B11 ET stations (fig. B3 and B4 in appendix B, respectively) were installed near the middle of irrigated alfalfa fields at the Mason Valley Wildlife Management Area. Although the B01 station was operated for more than 2 years, from March 22, 2005, through April 9, 2007, only the 1-year period of March 22, 2005, through March 21, 2006 was used in analysis of ET rates because the field was not in production and was not irrigated during the 2006 growing season.

The SAL and SAL2 ET stations were installed in saltgrass communities. The SAL station (fig. B5 in appendix B) was installed in an area with a sparse cover of saltgrass that was classified as being in the higher end of a moderately dense desert shrubland. The SAL2 station (fig. B6 in appendix B) was installed in an area with a much healthier moderate cover of saltgrass. This station was classified as being in a grassland ET unit. The period of record for the SAL station was less than 1 year, from March 10, 2005, through January 1, 2006, so that it was necessary to estimate data for the remainder of the year in order to calculate total annual ET.

The GRE, GRE2, RAB, and RAB2 ET stations were installed in desert shrub communities. The GRE and GRE2 stations (fig. B7 and B8 in appendix B, respectively) were installed in relatively continuous communities of greasewood that were classified as sparse desert shrubland and moderately dense desert shrubland ET units, respectively, in the vicinity of the stations. The RAB and RAB2 stations (fig. B9 and B10 in appendix B, respectively) were both installed in communities of rabbitbrush. However, the ET-unit classifications in the vicinity of these two stations were quite different. The RAB station had a sparse cover of rabbitbrush with low vigor in its vicinity, and was classified as being in sparse desert shrubland, while the RAB2 station was installed in a community of very dense and highly vigorous rabbitbrush that had saltcedar mixed in and a relatively dense understory of saltgrass. The RAB2 station was classified as being in the grassland ET unit.

Evapotranspiration from Land

ET is the process by which liquid water is transferred from the Earth's surface to the atmosphere. ET is the combination of two processes: evaporation, the physical conversion of water molecules in a liquid state to a vapor state; and transpiration, the evaporation of water that has moved through a plant and exits through its stomata. Energy is required for water to change its physical state from liquid to vapor, and this energy consumption serves as the basis for the energy-budget methods used to measure ET. Two methods were used to compute ET at the land ET stations: the eddy-covariance method and the Bowen-ratio energy-budget method.

In addition to energy, water must be available in order for ET to occur on land. Water supplied for ET can come from a variety of sources: surface water, ground water, and local precipitation. For this report, ET is actual total ET from the above sources. Net ET (ET_n) is ET less local precipitation and originates from a combination of surface- and ground-water sources. Evapotranspiration of water from a ground-water source (ET_g) is ET_n less any ET originating from surface water, and for this study, generally occurs in areas where ET_n is greater than zero and surface water flooding or discharge is negligible.

Estimation of ET by Eddy-Covariance Method

The eddy-covariance method was used to measure ET at 6 of the 10 land-based ET stations. Descriptions and basic mathematical formulations of the eddy-covariance method are given in Berger and others (2001), Sumner (2001), and Moreo and others (2007).

In the eddy-covariance method, the transfer of latent-heat flux (γ) and sensible-heat flux (H) from the Earth's surface to the atmosphere is measured by monitoring atmospheric air turbulence above the land surface (Swinbank, 1951; Businger and others, 1967; Brutsaert, 1982; and Tanner and Greene, 1989). Both vapor and heat are transported between the Earth's surface and the atmosphere by turbulent, highly irregular rotational air flows called eddies. Eddies are generated by the wind moving air advectively across the Earth's surface, creating mechanical air turbulence from the frictional effects of the underlying land surface, and by the upward movement of warmed lighter air into the atmosphere, creating thermal air turbulence from convective heat flow. Convective heat flow is a result of solar radiation warming air near the Earth's surface, which creates unequal air density and vertical air buoyancy (Rosenberg and others, 1983). When water vapor in the upward moving eddies is greater than in downward moving eddies, water is discharged to the atmosphere and ET occurs. Likewise, when heat or thermal energy in upward moving eddies is greater than in downward moving eddies, sensible heat is lost to the atmosphere. This accumulated difference in moisture between ascending and descending eddies over a period of time defines the water-vapor flux density (*E*) from which ET is derived.

Instrumentation

A diagram showing the layout of the eddy-covariance site instrumentation is provided in figure 7 of Moreo and others (2007). Instrumentation consists of a three-dimensional sonic anemometer, a fine-wire thermocouple, and a krypton hygrometer to measure variations in vertical wind speed, air temperature, and vapor density, respectively. These instruments measure two of the main energy-budget components: the transfer of water vapor (latent-heat flux) and the transfer of heat (sensible-heat flux) through the atmosphere. The sonic anemometer measures wind speed and the speed of sound on three non-orthogonal axes using facing pairs of sealed transducers that emit and receive sound waves. From these measurements, orthogonal wind speed and sonic temperature are computed. The anemometer uses the Doppler Effect (phase shift of emitted frequencies) to measure wind speed between opposing transducer pairs. The sonic anemometer also measures the instantaneous change in air temperature with a minimal temperature-loading, fine-wire thermocouple (type E). The hygrometer relies on the attenuation of ultraviolet radiation, emitted from a source tube, by water vapor in the air along the path to the detector tube. The anemometer and the hygrometer sensors are separated from each other to avoid sensor interference, but close enough to each other so that both sensors attempt to measure the same eddies. By minimizing sensor separation, frequency-response corrections (Moore, 1986; Massman, 2002) are less of a concern. Typically, evaluation of frequency-response corrections in similar environments (Moreo and others, 2007; D.I. Stannard, U.S. Geological Survey, oral commun., 2007) indicated that without corrections, a loss of about 5 percent in latent-heat values could be expected. In this study, no frequency-response corrections were applied. Conditions that may produce larger frequency-response corrections (10–15 percent) are larger sensor separation, very low instrument height, very large wind speeds, and small sampling frequency or averaging time. The water-vapor flux (*E*) values are corrected for oxygen effects when using the krypton hygrometer (Tanner and Green, 1989) and for density differences caused by heat and vapor transfer (Webb and others, 1980).

Additional sensors were added to this instrumentation to document the two other principal energy-budget components, net radiation and soil-heat flux; as well as measure some additional basic properties of air. Net radiation is measured by a net radiometer. Soil-heat flux is calculated by measurements obtained from ground sensors consisting of two heat-flow transducer plates, an averaging soil-temperature probe, and a water content reflectometer. The eddy-covariance system uses a temperature and relative humidity sensor to derive other necessary variables needed for the eddy-covariance technique such as vapor and air densities.

Soil samples were collected and sealed during periodic field trips to calibrate the soil moisture probe and were analyzed for soil moisture content at the USGS Nevada Water Science Center soils laboratory within a few days of collection.

Data Reduction Procedure

The eddy-covariance fluxes are computed over a 20-minute covariance period based on a 0.1-second execution or sampling interval. The 20-minute covariance period was selected so that time-series data were collected on the same interval as data collected at the Bowen-ratio stations. It is acknowledged that this results in loss of frequency response of the eddy-covariance system to eddies with periods greater than 20 minutes. Other sensors generally sample data over a 1-second sampling interval and average the 1-second data over every 20-minute period. Energy fluxes and ET were computed for each 20-minute period and summed over each full day to compute daily ET. Daily ET was summed over a 1-year period (365 days) to obtain annual ET. Ideally, all annual summation periods would be the same — begin and end on the same dates — and coincide with a water year, but due to timing limitations of the study, and some site access issues, annual summation periods were variable (appendix B). However, all annual summation periods included a full year of data and the full growing season (typically early April to October) for that year.

Twenty-minute instrument and energy-flux values were reviewed for quality and completeness. Questionable or spurious data were identified and removed. Appendix B shows the periods for which ET was estimated for each ET station. Breaks in the continuity of recorded data occurred for a number of reasons, including hygrometer reading interruptions due to rain, wires chewed by animals, and equipment failure. Some prolonged data gaps, from October 1, 2005, through mid summer of 2006, were because access to the sites was denied.

For periods in which only the hygrometer data record was interrupted, latent heat flux was computed as the residual in the energy budget equation, and ET still was computed for 20-minute periods. Daily ET was computed by summing the 20-minute values over each day. For the SAL2 ET station, net radiation and hygrometer data were missing for a 10-day period, and daily ET was estimated by using a weighted linear interpolation method of daily ET data from either side of the data gap. In the weighted linear interpolation method, 5 days of data on each side of the data gap were used as the end reference for interpolating the daily ET data. For the SAL ET station, net radiation data and hygrometer data were missing for 16 days. For this period, net radiation was estimated by using an average of net radiation from two nearby ET stations (RAB and GRE ET stations) normalized to this station. The energy-budget approach then was used to compute ET over this period.

To have a complete annual record of daily ET data and to have it correspond with monthly precipitation, some daily ET values had to be replicated to get a full year of data or to have the record break evenly at the beginning of a month. The replication of ET data occurred on the tail ends of some of the annual summation curves (appendix B), and simply was completing the annual summation curve by using daily ET data for the dates of interest but from a different year. Such a substitution of data results in minimal error in estimation of annual ET because the tail ends of the annual summation periods occur during the dormant vegetation season, when daily ET is typically at or near its minimum.

Energy-budget ratios were computed for each eddy-covariance site for all available 20-minute values and averaged over the data reporting periods. Energy-budget ratios are the ratio of turbulent flux (latent-heat flux plus sensible-heat flux) to available energy (net radiation less soil-heat flux). Energy-budget ratios give an indication of the bias in ET values computed by the eddy-covariance and Bowen-ratio method (described below), but it is unclear which method, if either, provides a more reliable estimate of ET (Wilson and others, 2002).

Estimation of ET by Bowen-Ratio Energy Budget Method

The Bowen-ratio energy-budget method was used to calculate ET at 4 of the 10 land-based ET stations and the ET station on Walker Lake (LAK evaporation station). Detailed description and mathematical formulation of the Bowen-ratio energy-budget method used to estimate ET at the land-based stations is given in Laczniak and others (1999). The method used to estimate evaporation at the Walker Lake station is described in more detail in section, "Evaporation from Walker Lake."

The energy-budget method is an accounting system of the total energy at the Earth's surface. This energy can be partitioned into four main components: (1) net radiation, (2) subsurface heat flux, (3) sensible-heat flux, and (4) latent-heat flux.

Net radiation is the sum of all incoming and outgoing radiation, with incoming radiation being positive energy and outgoing radiation being negative energy. If the total daily incoming radiation exceeds the total daily outgoing radiation, then there is net positive energy into the system for that day. Net radiation is the main driver of the energy interactions at the Earth's surface, and ultimately is the energy that controls the ET process. Typically, daily net radiation is positive because a certain amount of the incoming energy is used to convert liquid water to vapor, making less energy available to return to the sky as radiation.

Subsurface heat flux is the energy that transfers through the ground (or water) surface, and is measured as the change in energy stored in the subsurface. Subsurface heat flux is positive when energy is transferring into the subsurface (subsurface is warming) and negative when it is moving out (subsurface is cooling). For land stations, the average daily subsurface heat flux typically is very small because soil has a relatively low heat capacity, and the total heat stored is nearly equal to the heat lost each day. For the open-water station, daily subsurface heat flux can be much larger because water has a relatively large heat capacity and tends to store heat during spring and summer and releases it slowly during autumn and winter. Over an annual period, the subsurface heat flux for land and water sites is near zero.

Sensible-heat flux is the energy that is used in heating the air. Sensible heat is proportional to the temperature gradient and the turbulent transfer of the heat. Sensible-heat flux is positive when energy is being used to heat the air.

Latent-heat flux is the energy that is used in ET and is proportional to the vapor pressure gradient and the turbulent transfer of water vapor. Latent-heat flux is positive when energy is being used to convert water from a liquid to water vapor. On some occasions, latent-heat flux is negative, which could indicate that condensation is occurring, and energy is being released. Condensation is infrequent in the desert setting of this study, but it can happen during storms, or when night time air temperature drops below the dew point and dew forms.

Net radiation and subsurface heat flux are the only two components of energy that can be measured directly in the field with the Bowen-ratio energy-budget method. The turbulent flux terms in the sensible- and latent-heat energy flux components are not measured; however, they are assumed to be equal, which makes it possible to use the method developed by Bowen (1926). This method divides the sensible-heat flux by the latent-heat flux to cancel out the turbulent flux terms, and results in a ratio that is proportional to the temperature gradient divided by the vapor-pressure gradient. This ratio, which can be readily calculated in the field, is called the Bowen ratio. The Bowen ratio is used to compute the component of latent-energy flux. ET rates are readily computed from the latent-energy flux values.

Instrumentation

At the Bowen-ratio method ET stations, sensors were installed to measure (a) air temperature and vapor density at two different heights above the vegetation canopy, (b) net radiation and wind speed, and (c) subsurface heat fluxes. The layout of the Bowen-ratio station instrumentation is similar to that in figure 4*A* of Berger and others (2001) except that in this study, infrared temperature sensors were not used to measure soil-surface and canopy temperatures. Air temperature and vapor density were monitored by two solid-state temperature and relative-humidity sensors mounted at two heights with 3.3 ft spacing between them, the bottom sensor typically set at or slightly higher than 3.3 ft above the vegetation canopy. These sensors were mounted on a mechanism that interchanged the sensor positions midway between each measurement in order to minimize measurement biases, and to provide the best possible temperature and vapor pressure gradient data to compute the Bowen-ratio. Net radiation was measured using a net radiometer, and wind speed was measured using either a 3-cup rotor or marine-grade propeller type anemometer. Wind speed was used to correct net radiation measurements for bias introduced by the wind. Subsurface temperatures at the land stations were measured using a pair of thermocouples, subsurface heat flux was measured using a pair of soil-heat flux plates, and soil moisture was measured using a water content reflectometer. These subsurface instruments were used to compute the subsurface heat flux at the land stations. Soil samples were periodically collected and sealed during site visits and were used as a quality control check on subsurface soil moisture measurements. The soil samples were analyzed in the USGS Nevada Water Science Center soil laboratory within a few days of collection.

Data Reduction Procedure

Instrument readings were recorded every 10 seconds and then averaged every 20 minutes to compute 20-minute mean values. Energy fluxes and ET were computed for each 20-minute period and summed over each full day to obtain daily ET. Daily ET was summed over a 1-year period (365 days) to obtain annual ET. Ideally, all the annual summation periods would be the same — begin and end on the same dates — and coincide with a water year, but due to timing limitations of the study, and some site access issues, annual summation periods were variable (appendix B). However, all annual summation periods included a full year of data and the full growing season (typically early April to October) for that year.

Twenty-minute instrument and energy-flux values were reviewed for quality and completeness. Questionable or spurious data were identified and excluded from the analysis. If more than 10 percent of the 20-minute values were missing or were considered “bad” data, ET was estimated for that day. Appendix B shows the periods that ET was estimated for each ET station. Breaks in the continuity of recorded data occurred for a number of reasons, including equipment failure, battery failure, wires chewed by animals, and field operation error. Some prolonged data gaps occurred from October 1, 2005, through mid-summer of 2006, because access to the sites was denied.

Several methods were used to estimate missing daily ET values. The preferred and most frequently used method was similar to that used by Maurer and others (2006), in which a linear regression between measured daily net radiation and corresponding natural log transform of daily ET was developed. If net radiation data were not available for an ET station, it was estimated using net radiation data from a nearby station after normalizing the data to the station of interest. A weighted linear interpolation method was used for short data gaps (typically less than 10 days), or when a good relation between net radiation and natural logarithm transformed ET could not be obtained. The weighted linear interpolation method used the average of measured daily ET data on each side of the data gap as the end references for the interpolation. The number of days of measured data used in the average was equal to one-half the length of the data gap. This allowed for more dynamic scaling of the reference for the interpolation so that it better reflected the trend of the daily ET curve.

Just as with the eddy-covariance ET data, in order to have complete annual record of daily ET data that breaks at the beginning of a month, some data was transposed on the tail ends of the annual summation curves (appendix B).

Evaporation from Open Water

Evaporation from the open-water ET unit in the Lower Walker River basin was measured on Walker Lake. The only other substantial open-water ET unit in the study area was Weber Reservoir. Evaporation rates measured on Walker Lake were applied to Weber Reservoir.

Evaporation from Walker Lake

Evaporation from Walker Lake was monitored over a 2-year period from mid-November 2004 through mid-November 2006 using a Bowen-ratio ET station in the north central part of the lake (LAK in fig. 5; WLET in fig. 8). The station was installed at a point on a depth contour of 60 ft as close to center of the lake as possible. The instrumentation was mounted to an 8×12 ft floating platform secured by a four-point mooring system (cover photograph).

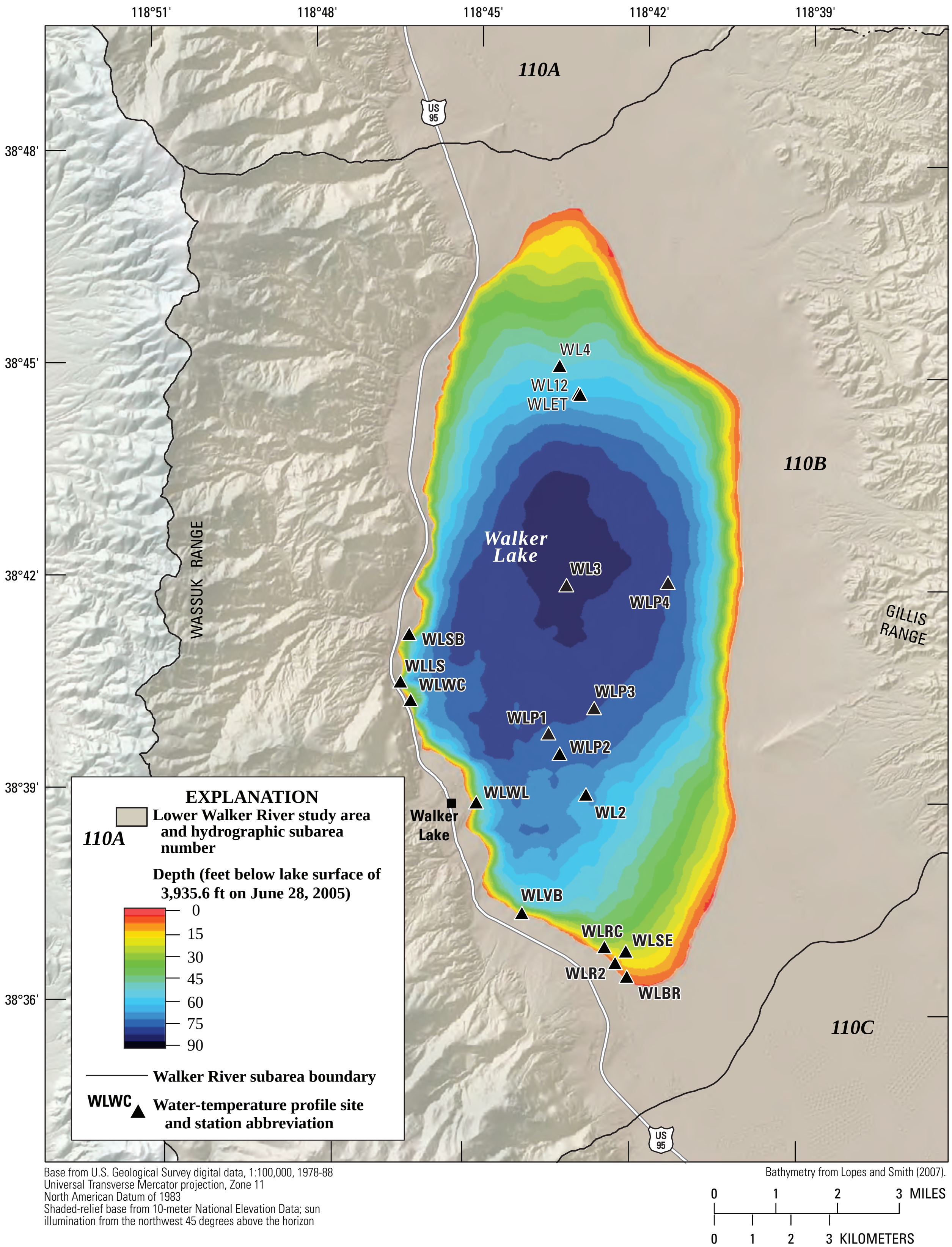


Figure 8. Bathymetry and water-temperature profile sites on Walker Lake, west-central Nevada.

Energy Budget of Walker Lake

For open-water sites, the energy-budget method generally is considered to be the most accurate method of estimating evaporation for periods of a week or longer (Winter, 1981, p. 90). The energy budget for an open body of water is (Sturrock and others, 1992):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w + Q_b = Q_x \ , \qquad (1)$$

where

Q_s is incoming short-wave radiation,
Q_r is reflected short-wave radiation,
Q_a is incoming long-wave radiation,
Q_{ar} is reflected long-wave radiation,
Q_{bs} is long-wave radiation emitted from the body of water,
Q_v is net energy advected to the lake,
Q_e is energy used for evaporation,
Q_h is energy conducted from the water body as sensible heat,
Q_w is energy advected from the body of water by the evaporated water,
Q_b is energy transferred from lake-bed sediments to the lake, and
Q_x is change in energy stored in the lake, hereafter called heat storage energy flux.

All Q terms are in watts per square meter (W/m^2). For this study, the radiation terms of Q_s, Q_r, Q_a, Q_{ar}, and Q_{bs} were all measured with a single instrument as net radiation (Q_n):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} = Q_n \ . \qquad (2)$$

The net energy advected (Q_v) to Walker Lake is the energy advected from all water inflows. Energy is advected into Walker Lake with surface-water inflows, ground-water inflows, and precipitation. In most lakes, Q_v also includes energy advected away from the water body through outflow components. But because Walker Lake is a terminal lake, the only path of outflow is evaporation. The energy advected away by evaporation (Q_w) is incorporated into the energy budget equation separately because it requires knowing the evaporative flux, which is the unknown variable for which the equation is being solved.

Net energy advection to Walker Lake is computed using the equation

$$Q_v = c\rho \sum F_x (T_x - T_b) \, , \qquad (3)$$

where

c is specific heat of water (4,190 J/kg),
ρ is density of evaporated water (1,000 kg/m^3),
F_x is flux of inflow component (m/s),
T_x is temperature of the inflowing water (°C), and
T_b is arbitrary base temperature (0°C).

Net energy advection to Walker Lake is from three sources: Direct precipitation, ground-water inflow, and surface-water inflows. The energy advected to Walker Lake by direct precipitation and ground water is assumed to be negligible. The assumption for direct precipitation was tested by calculating energy advection from a hypothetical heavy precipitation event during the summer, when temperature of the precipitation would be high. Every inch of precipitation (at 25°C) over a 30-day period would contribute 1 W/m^2 of energy to the lake. Because average annual precipitation at Walker Lake is about 5 in., this demonstrates that heat advection due to precipitation is negligible. Following a similar exercise for ground water: a 1 W/m^2 of energy contribution over a 1-year period would require an annual ground-water inflow of more than 50,000 acre-ft (assumes a lake area of 32,000 acres and ground-water temperature of 15°C). This indicates the assumption of negligible net energy advection from ground water also is a reasonable one. Energy advected to Walker Lake by surface inflows was dominated by Walker River, and the streamflow and water temperature measured at the Lateral 2A site (10302002) is representative of the heat advected to Walker Lake from this source.

The energy transfer between Walker Lake and lake-bed sediments (Q_b) is assumed to be negligible. Energy-budget studies of lakes commonly do not measure Q_b (Winter, 1981, p. 89; Rosenberry and others, 2007, p. 152), and in the few studies in which it has been measured, those measurements indicate that it was very small in comparison to major energy terms (Sturrock and others, 1992, p. 1612; Winters and others, 2003, p. 999; Rosenberry and others, 2007).

Three of the terms in equation (1) were not measured directly and are a function of the evaporation rate (E). These terms are Q_e, Q_h, and Q_w, and are related to E as follows (Sturrock and others, 1992):

$$Q_e = \rho E L \, , \qquad (4)$$

$$Q_h = R Q_e \text{ , and} \qquad (5)$$

$$Q_w = c\rho E (T_e - T_b) \, , \qquad (6)$$

where

E is energy-budget evaporation rate (m/s),
L is latent heat of vaporization of water (2,450,000 J/kg/°C),
R is Bowen ratio (dimensionless), and
T_e is temperature of the evaporated water (taken as surface temperature T_0; °C).

Substitution of equation (4) into equation (5) and then substitution of equations (2), (4), (5), and (6) into equation (1) and elimination of Q_v and Q_b yields the equation used to calculate evaporation by the energy-budget method in this study:

$$E = \frac{Q_n + Q_v - Q_x}{\rho\left[L(1+\beta) + cT_0\right]}, \quad (7)$$

where the term (Q_n + Q_v - Q_x) is the *available energy*, and is the energy available for latent and sensible heat flux processes.

The Bowen ratio (β) is defined as:

$$\beta = \frac{c_b P\left(T_1 - T_2\right)}{(e_1 - e_2)}, \quad (8)$$

where

c_b is an empirical constant (0.000663°C^{-1}),
P is atmospheric pressure at altitude of Walker Lake (88,700 Pa),
$T_1 - T_2$ is air temperature difference (°C) between 1.5 and 2.5 m above lake surface, and
$e_1 - e_2$ is vapor pressure difference (Pa) between 1.5 and 2.5 m above lake surface.

The Bowen ratio is a unitless quantity and was calculated on site using data from two temperature, humidity, and atmospheric pressure sensors (THP sensors) that were 1 m apart with the bottom sensor positioned 1.5 m above the water surface. The THP sensors were mounted on an automatic exchanging device that would swap their positions every 10 minutes in order to minimize any potential measurement bias between the two instruments. The sensors measured temperature directly but not vapor pressure. Vapor pressure was computed from the temperature and humidity data.

Similar to the procedure followed at the land-based ET stations, each of parameters was measured every 10 seconds and the accumulated 10-second readings were averaged every 20 minutes. This resulted in about 72 values per parameter per day (unit values). For each of the parameters, the 72 values were averaged from midnight to midnight to obtain a daily mean value. On occasion, fewer than the full 72 values were available for a particular day because of instrument failures or interruptions of power to the station. If greater than 10 percent of unit values were missing in a day, a daily mean value was not calculated for that day.

Computation of Q_x on time scales of less than a week is not common for energy-budget studies on lakes (Winter, 1981, p. 90). This is due to large fluctuations of Q_x caused by small errors in temperature measurement over short periods (daily or smaller time scales), which in turn can cause large errors in estimates of evaporation (Rosenberry and others, 1993, p. 2481; Swancar and others, 2000, p. 38). In this study, Q_x was measured manually during site visits, generally every 4 to 6 weeks. Because of the intermittent measurement of Q_x, analyses of E for Walker Lake are over what are termed energy-budget periods, which are the time intervals between the thermal-profile measurements used to compute Q_x. Because Q_x values represent the change of heat stored over the energy-budget periods, the other energy-budget terms also had to be computed for those same periods. Each of the energy-budget terms were determined for the energy-budget periods by computing daily mean values and averaging the daily mean values over the periods. For some energy-budget periods, some daily mean values were missing. If more than 15 percent of mean daily values for any of the energy-budget terms were missing, the evaporation for that energy-budget period was estimated. On the basis of these criteria, evaporation could be computed directly for 12 of the 18 energy-budget periods.

Heat Storage

The heat storage energy flux of Walker Lake was computed using the following equation:

$$Q_x = \frac{C_w d_e \Delta T}{t} \quad , \quad (9)$$

where

Q_x is heat storage energy flux (W/m^2),
C_w is volumetric heat capacity of water, a constant (4.187 million J/m^3/°C),
d_e is mean lake depth (m),
ΔT is change in volume-weighted temperature (°C), and
t is time span of energy-budget period (seconds).

Heat storage energy flux (Q_x) was computed for each energy-budget period. Volumetric heat capacity of water (C_w) is a constant. The mean depth of the lake (d_e) is the average of the mean depth of the lake at the start and end of each energy-budget period. The mean depth of the lake was computed by dividing the total lake volume by the lake-surface area, and can be conceptualized as the uniform depth the lake would be if it had vertical sides and a flat bottom, while still having the same surface area and volume.

The change in volume-weighted temperature (ΔT, in °C) over an energy-budget period is the difference between volume-weighted temperatures measured during each site visit. Volume-weighted temperature was determined from thermal-profile measurements. The lake was divided into horizontal layers of representative temperature. The temperature and volume of each layer were multiplied and their products summed. The sum was then divided by the total volume of the lake to obtain the volume-weighted temperature.

The volumes of each layer, total volume of Walker Lake, and lake-surface area were determined by interpolation of values from the lake-storage volume, surface area, and surface altitude data in Lopes and Smith (2007).

Thermal-profile data were collected during each site visit at approximately 1-m depth intervals from the surface to the bottom at the LAK evaporation station (384443118430901; table 3; fig. 5). However, thermal-profile data were not collected when the site was initially installed or during the first site visit (November 10 and December 6, 2004, respectively). This required the use of other temperature data for these two dates in order to estimate ΔT and Q_x for the first energy-budget periods. For the December 6, 2004, site visit, data from the Nevada Department of Wildlife's (NDOW) Walker Lake 4 North station was used (WL4 in appendix A; fig. 8). The WL4 station is just over a one-half mile to the north and west of the lake-evaporation station and conditions at WL4 are assumed to accurately represent those at LAK . On November 10, 2004, site visit, it was assumed that Walker Lake was well mixed and that the temperature measured in the top 3.5 m at the evaporation station on this date was representative of the entire water column. This assumption was tested by constructing a time-series temperature profile contour plot of the thermal structure of Walker Lake (fig. 9). Figure 9 was constructed using data from NDOW thermal-profile measurements on September 7, 2004, and November 10, 2004, as well as all subsequent thermal-profile measurements by USGS at the evaporation station LAK, and shows that Walker Lake generally is well mixed by mid-November of each year. Thermal-profile measurements at the LAK evaporation station reached only to within about 8 m of the absolute bottom of Walker Lake. However, because bottom temperature measurements at this location typically are in the hypolimnion (fig. 9), it was assumed that the deepest temperature measurement at this site adequately defined the temperature of the bottom layer of water in the lake. Temperature-profile data collected by the USGS and used to compute heat storage energy flux are listed in appendix A (site ID is 384443118430901).

A summary of the terms used to compute heat-storage energy flux for Walker Lake is given in table 4. The heat storage energy flux rate ranged from a minimum of -151 W/m² during the first energy-budget period (November 11–December 6, 2004) to a maximum of 111 W/m² during the 12th energy-budget period (March 31–May 16, 2006).

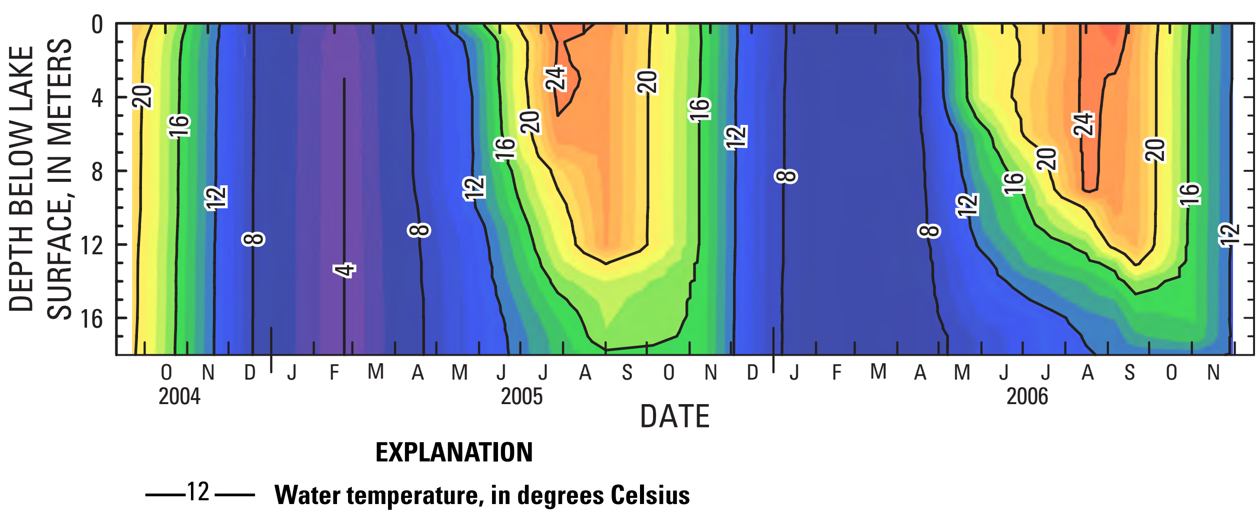


Figure 9. Contour plot of temperature-profile data beneath evaporation station LAK on Walker Lake, west-central Nevada, September 2004–November 2006.

Table 4. Heat storage energy flux and other terms used in its computation, Walker Lake, west-central Nevada, November 2004–November 2006.

[All periods start at 0000 hours and end at 2359 hours on indicated dates. Observation is on end date of energy budget period for lake stage, lake volume, and lake-surface area. **Lake stage:** In feet above National Geodetic Vertical Datum of 1929. **Lake volume**: Interpolated from lake stage/volume curve in Lopes and Smith (2007). **Lake-surface area**: Interpolated from lake stage/area relation curve in Lopes and Smith (2007). **Abbreviations:** T, volume weighted lake temperature, in degrees Celsius (°C); ΔT, change in volume weighted lake temperature; d_e, mean depth (lake volume/lake area, in meters (m); J/m², joules per square meter; Q_x, heat-storage energy flux, in watts per square meter (W/m²); e, estimate; –, data not available]

Energy budget period	Start date	End date	Days in period	Lake stage (feet)	Lake volume (acre-feet)	Lake-surface area (acres)	T (°C)	ΔT (°C)	d_e (m)	Change in heat storage (×10⁶ J/m²)	Q_x (W/m²)
0		11-10-04	0	3,934.7	1,719,500	32,250	[1]e12.7	–	–	–	–
1	11-11-04	12-06-04	25	3,934.4	1,708,900	32,190	[2]7.7	-5.0	16.2	-340	-151
2	12-07-04	02-08-05	64	3,934.2	1,704,300	32,160	4.0	-3.7	16.2	-248	-45
3	02-09-05	04-05-05	56	3,934.2	1,703,300	32,160	8.3	4.3	16.1	291	60
4	04-06-05	05-12-05	37	3,934.0	1,696,500	32,120	11.4	3.1	16.1	210	66
5	05-13-05	07-13-05	62	3,935.8	1,757,300	32,470	19.7	8.3	16.3	566	106
6	07-14-05	08-17-05	35	3,935.5	1,745,600	32,410	21.0	1.2	16.5	85	28
7	08-18-05	10-25-05	69	3,934.2	1,703,700	32,160	15.9	-5.1	16.3	-347	-58
8	10-26-05	12-06-05	42	3,933.7	1,687,600	32,060	9.4	-6.4	16.1	-433	-119
9	12-07-05	01-19-06	44	3,933.9	1,693,800	32,100	6.0	-3.4	16.1	-232	-61
10	01-20-06	03-08-06	48	3,934.3	1,706,300	32,180	6.1	0.1	16.1	4	1
11	03-09-06	03-30-06	22	3,934.6	1,718,500	32,250	7.1	1.0	16.2	70	37
12	03-31-06	05-16-06	47	3,935.6	1,748,900	32,420	13.7	6.6	16.3	451	111
13	05-17-06	06-21-06	36	3,938.4	1,845,900	32,980	16.1	2.5	16.7	173	56
14	06-22-06	08-01-06	41	3,939.3	1,875,000	33,150	19.2	3.0	17.2	219	62
15	08-02-06	08-22-06	21	3,938.8	1,859,200	33,060	19.6	0.4	17.2	29	16
16	08-23-06	09-06-06	15	3,938.5	1,849,000	33,000	19.3	-0.3	17.1	-18	-14
17	09-07-06	10-19-06	43	3,937.7	1,822,100	32,850	14.6	-4.8	17.0	-338	-91
18	10-20-06	11-15-06	27	3,937.5	1,815,400	32,810	11.9	-2.7	16.9	-188	-81

[1]Volume weighted lake temperature measurement for November 10, 2004, is estimated from daily mean temperature of the top 3.5 meters of water at evaporation station, based on assumption that lake is well mixed and 12.7°C represents entire water column.

Evaporation Rates

Data were sufficient for direct computation (using equation 7) of evaporation from Walker Lake for 14 of the 18 energy-budget periods. Evaporation rates for energy-budget periods with insufficient daily data had to be estimated for the remaining four energy-budget periods (1, 2, 4, and 9 in table 5). A relation between energy-budget period available energy and evaporation rates was developed (fig. 10). For energy-budget periods with insufficient daily data, net radiation also was limited and needed to be estimated. Net radiation was estimated by using a relation between net radiation at Walker Lake and total solar radiation data from a Remote Automated Weather Station (RAWS) in the Dead Camel Mountains (fig. 1; data obtained from Western Regional Climate Center at http://www.wrcc.dri.edu/ accessed July 27, 2007). Agreement between these terms was excellent, and net radiation during the four energy-budget periods with missing data was estimated using the relation in figure 11. Energy-budget period evaporation rates were then estimated from the available energy during those periods using the relation in figure 10.

A summary of energy-budget components and evaporation rates by energy-budget period is listed in table 5. The maximum evaporation rate was 6.8 mm/d over the 43-day energy-budget period September 7 through October 19, 2006 (period 17). The minimum evaporation rate measured was 1.8 mm/d over the 56-day energy-budget period February 9 through April 5, 2005 (period 3). The distribution of evaporation rates is shown in figure 12, which also shows that the maximum evaporation rates typically occurred in late summer to early autumn (mid-August to early October) and the minimum evaporation rates generally occurred in late winter (February and March). This seasonal pattern is similar to that observed in other lake evaporation studies (Swancar and others, 2000, p. 39; Winter and others, 2003, p. 1001) as well as to the seasonal pattern for Walker Lake described by Harding (1965).

Table 5. Summary of energy-budget components and calculated evaporation rates for energy-budget periods, Walker Lake, Nevada.

[All periods start at 0000 hours and end at 2359 hours on indicated dates; all units are daily mean values and are in watts per square meter (W/m^2) unless otherwise noted. **Percentage of days represented**: If fewer than 85 percent of the days in an energy-budget period have complete data, then energy-budget terms of Q_x, *E*, and Total *E* are estimated for that period. Q_x is measured independently and therefore did not need to be estimated. **Abbreviations:** $\boldsymbol{Q_n}$, net radiation; $\boldsymbol{Q_x}$, heat storage energy flux; **β**, Bowen ratio; $\boldsymbol{T_0}$, water-surface temperature, in degrees Celsius (°C); ***E***, energy budget period evaporation rate, in millimeter per day (mm/d); **Total *E***, total evaporation during energy budget period, in inches (in.); mm, millimeter; e, estimated value; –, insufficient data to calculate]

Energy budget period	Start date	End date	Days in period	Percentage of days represented	Q_n	Q_v	Q_x	β (unitless)	T_o (°C)	*E* (mm/d)	Total *E* (in.)
1	11-11-04	12-06-04	25	65	e20	0	-151	–	–	e6.1	e6
2	12-07-04	02-08-05	64	25	e4	0	-45	–	–	e1.7	e4.3
3	02-09-05	04-05-05	56	98	105	0	60	-0.12	7.1	1.8	3.9
4	04-06-05	05-12-05	37	38	e144	0	66	–	–	e2.7	e3.9
5	05-13-05	07-13-05	62	95	222	13	106	-0.12	18.5	5.0	12.2
6	07-14-05	08-17-05	35	91	203	3	28	-0.08	25.1	6.5	9.0
7	08-18-05	10-25-05	69	91	142	0	-58	0.03	20.0	6.6	18.0
8	10-26-05	12-06-05	42	98	46	1	-119	0.35	13.1	4.3	7.1
9	12-07-05	01-19-06	44	48	e1	0	-61	–	–	e2.1	e3.6
10	01-20-06	03-08-06	48	98	60	1	1	0.10	5.9	1.9	3.6
11	03-09-06	03-30-06	22	100	96	2	37	0.02	6.6	2.1	1.8
12	03-31-06	05-16-06	47	98	169	6	111	-0.18	11.9	2.7	5.0
13	05-17-06	06-21-06	36	97	200	26	56	-0.08	19.3	6.3	9.0
14	06-22-06	08-01-06	41	88	200	14	62	-0.09	24.5	5.6	9.1
15	08-02-06	08-22-06	21	100	197	1	16	-0.05	24.4	6.4	5.3
16	08-23-06	09-06-06	15	100	167	0	-14	-0.05	23.2	6.5	3.8
17	09-07-06	10-19-06	43	98	120	0	-91	0.07	19.2	6.8	11.4
18	10-20-06	11-15-06	27	96	54	1	-81	0.24	13.9	3.8	4.0

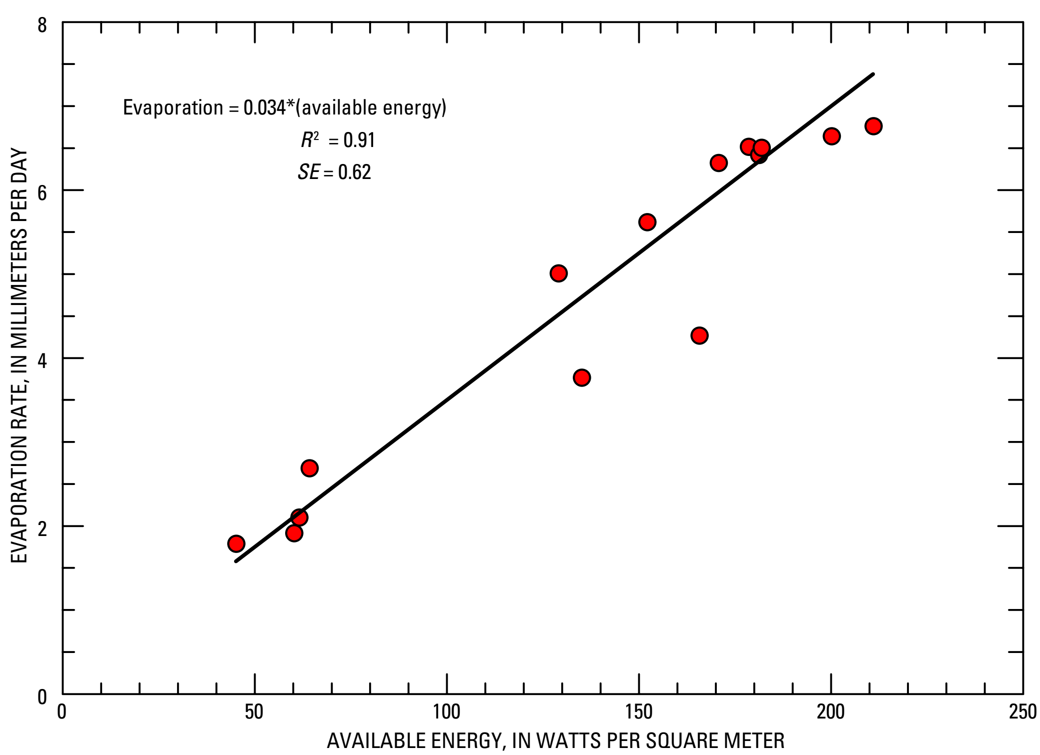


Figure 10. Relation between available energy and evaporation rates for Walker Lake, west-central Nevada (averaged over energy-budget periods, represented by red dots on graph).

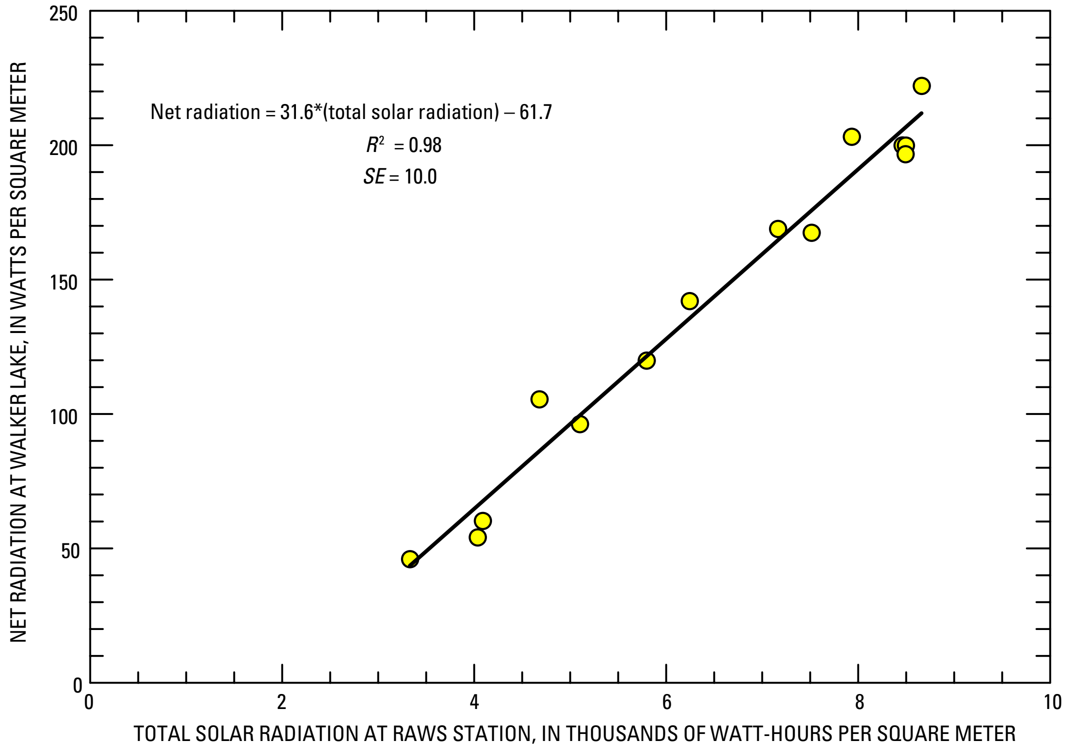


Figure 11. Relation between total solar radiation at Dead Camel Mountain Remote Automated Weather Station (RAWS) and net radiation at Walker Lake, west-central Nevada (averaged over energy-budget periods, represented by yellow dots on graph).

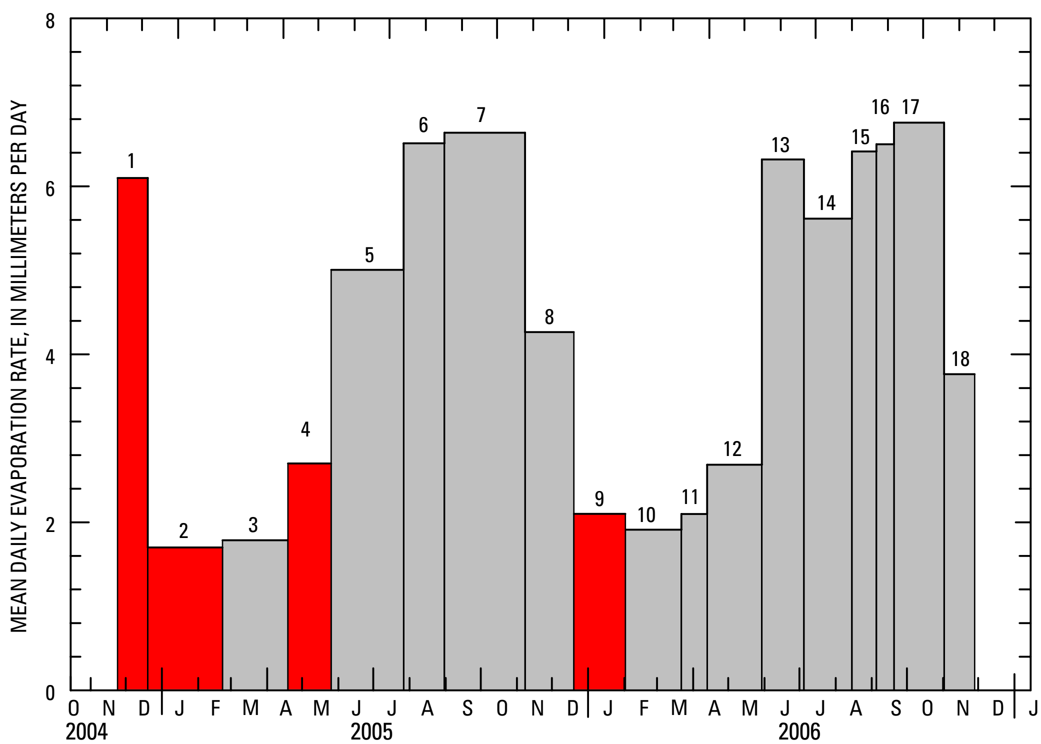


Figure 12. Evaporation rates for the energy-budget periods, Walker Lake, west-central Nevada, 2004-06. Numbers above bars are energy-budget periods. Red bars are periods for which evaporation was estimated.

The mean daily evaporation rate for each energy-budget period (table 5) is used to compute monthly evaporation (table 6 and fig. 13). Monthly evaporation is determined by applying the energy-budget period evaporation rate to each day within the period. Then daily evaporation values are summed over their respective months to obtain total monthly evaporation. Monthly evaporation values are summed over the entire year to obtain total annual evaporation. Using this method, the computation of total annual evaporation is the same whether determined by summation of energy-budget period evaporation or monthly period evaporation. Monthly and annual evaporation are reported in inches rather than in metric units. Measured monthly evaporation was determined for the period December 2004 through October 2006. Monthly average evaporation was determined by calculating the average of the two available months of data except for November, for which only a single value was available (table 6).

The distribution of monthly evaporation for Walker Lake was similar in 2005 and 2006 (fig. 13 and table 6). Maximum monthly evaporation was 8.0 in. in August 2005, and minimum monthly evaporation was 1.9 in. in February 2005. The total annual evaporation was 58.8 in. for calendar year 2005 and 60.5 in. for calendar year 2006. In determining the calendar year 2006 evaporation rate, the average November and December evaporation was used because evaporation was not measured from mid-November to the end of 2006. The average annual evaporation rate for the 2 years of measurement was 59.7 in. (5.0 ft).

Table 6. Mean monthly and annual evaporation, lake area, and evaporative losses for Walker Lake, west-central Nevada.

[**Evaporation**: Monthly rate determined from energy-budget period evaporation rate data. Mean lake area was computed from mean stage of Walker Lake for each of the months and using stage-area relation in Lopes and Smith (2007). **Volume evaporated**: Obtained by multiplying monthly mean lake area by monthly evaporation. –, data not computed]

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Evaporation, in inches													
2004	–	–	–	–	–	–	–	–	–	–	–	3.1	–
2005	2.1	1.9	2.2	3.0	5.0	5.9	7.2	8.0	7.8	7.5	5.0	3.1	58.8
2006	2.5	2.1	2.5	3.2	5.4	7.2	6.9	7.8	7.9	6.8	–	–	[1]60.5
2007	–	–	–	–	–	–	–	–	–	–	–	–	–
Mean	2.3	2.0	2.4	3.1	5.2	6.6	7.0	7.9	7.9	7.2	5.0	3.1	59.7
Mean lake area, in acres													
2004	–	–	–	–	–	–	–	–	–	32,080	32,010	31,970	–
2005	31,950	31,950	31,950	31,910	31,890	32,100	32,240	32,170	32,060	31,950	31,890	31,860	31,990
2006	31,870	31,910	31,990	32,060	32,240	32,900	33,050	33,020	32,940	32,870	32,820	32,780	32,540
2007	32,750	32,780	32,780	32,780	32,750	32,680	32,520	32,240	32,110	–	–	–	–
Volume evaporated, in acre-feet													
2004	–	–	–	–	–	–	–	–	–	[2]19,220	[2]13,440	8,300	–
2005	5,520	5,170	5,800	8,000	13,340	15,820	19,280	21,490	20,950	20,080	13,570	8,460	157,000
2006	6,570	5,610	6,730	8,470	14,570	19,780	18,880	21,550	21,750	18,720	[2]13,780	[2]8,450	164,900
2007	[2]6,210	[2]5,530	[2]6,430	[2]8,440	[2]14,250	[2]17,880	[2]19,020	[2]21,290	[2]21,090	–	–	–	–
Mean	6,100	5,440	6,320	8,300	14,050	17,830	19,060	21,440	21,260	19,400	13,590	8,310	161,000

[1]Mean evaporation rates for November and December were used in computing calendar year 2006 evaporation.

[2]Mean evaporation rates were used in computation of monthly volume evaporated for Walker Lake.

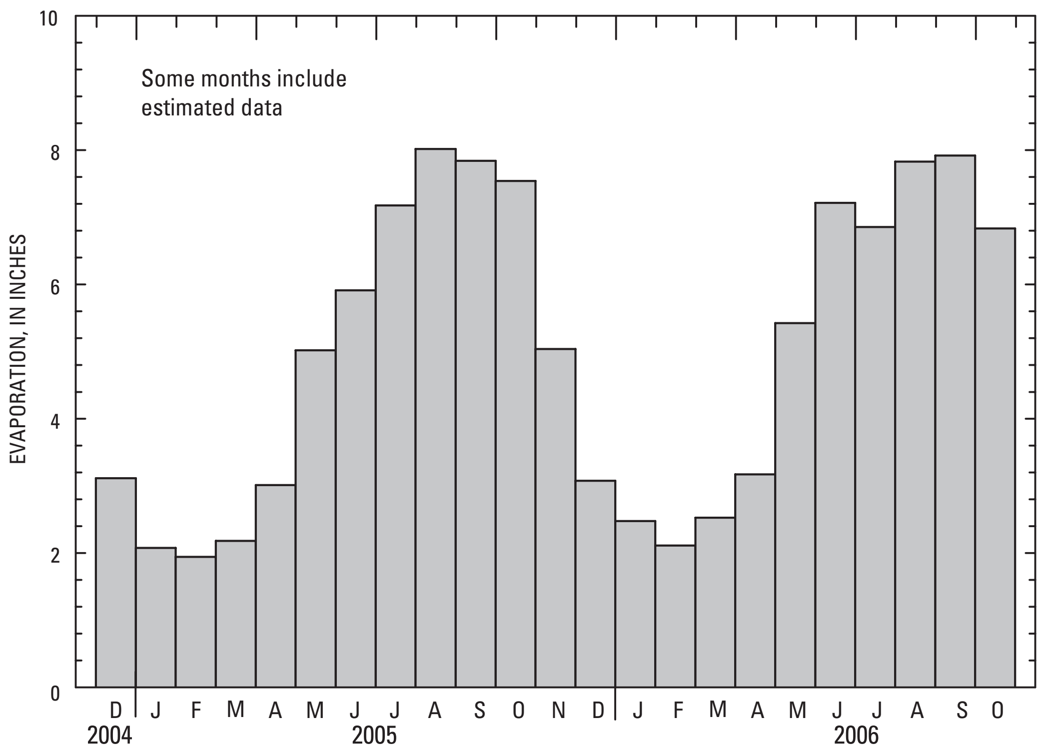


Figure 13. Monthly evaporation from Walker Lake, west-central Nevada.

Discharge by Evaporation

In order to accurately quantify the total volume of water evaporating from Walker Lake, the surface area at time of evaporation must be known. Because monthly evaporation is being reported, monthly average lake-surface areas were used to compute monthly evaporation volumes. These areas were determined by applying the mean stage for each month to the stage-area tables in Lopes and Smith (2007).

The monthly lake-surface areas used in the computation of evaporative discharge from Walker Lake are listed in table 6. During the 3-year study, the surface area of Walker Lake expanded and contracted according to the stage hydrograph in figure 3. The surface area varied by just more than 1,000 acres during the study. The largest monthly average surface area was 33,050 acres in July 2006, and the smallest was 31,860 acres in December 2005. The mean surface area over the 3 years was about 32,200 acres.

For months with measured evaporation (December 2004 through October 2006), the monthly volume of water evaporated from Walker Lake was determined by multiplying measured monthly evaporation by the lake-surface area. For the months in which evaporation was not measured (October and November 2004, and November 2006 through September 2007), the monthly volume of water evaporated was determined by multiplying the mean monthly evaporation by lake-surface area (table 6).

The total monthly volume of water discharged from Walker Lake by evaporation ranged from a minimum of 5,170 acre-ft in February 2005 to a maximum of 21,750 acre-ft in September 2006 (table 6). The total annual discharge from Walker Lake by evaporation did not differ greatly in the 2 years it was measured: 157,000 acre-ft in calendar year 2005 and 164,900 acre-ft in calendar year 2006. For calendar years 2005 and 2006, the average annual discharge was 161,000 acre-ft.

Evaporation rates, lake-surface areas, and total volume of water discharged from Walker Lake by evaporation are summarized by water year in table 7. Annual evaporation rates of 58.5, 61.2, and 59.3 inches (4.9, 5.1, and 4.9 ft) for water years 2005–07 (respectively) were determined. The annual average lake area for each of the water years was 32,020, 32,310, and 32,660 acres, and the total volume of water evaporated was 156,300, 165,500, and 161,100 acre-ft for each of the 3 water years. The maximum variability in evaporation from Walker Lake was about 6 percent, between the 2005 and 2006 water years. The average rate at which water evaporated from Walker Lake over the 3 water years was 161,000 acre-ft/yr, which is the same as the result of the analysis by calendar year.

Although water evaporates from Walker Lake throughout the year, nearly 80 percent of the annual evaporation occurs in the 7-month period May through November (table 6). This seasonal lag in evaporation rate with respect to incident solar radiation is characteristic of deeper lakes in general (Sacks and others, 1994). A deep lake has a lag in peak evaporation compared to that in a shallow lake, because of the greater amount of heat that is seasonally stored and released in the deep lake (Sacks and others, 1994). Lakes and reservoirs in the western Great Basin region generally are considered deep and will have evaporation patterns similar to that at Walker Lake. Weber Reservoir, which is relatively shallow–just over 8 m at its deepest point (Katzer and Harmsen, 1973)–is an exception.

Previous estimates of evaporation for Walker Lake by Harding (1965) and Milne (1987) were 4.1 and 4.4 ft/yr, respectively. However, these estimates actually represented total evaporation less any ground-water inflow to Walker Lake. If the long-term ground-water inflow rate to Walker Lake is relatively constant, then the difference between these earlier studies and this study would indicate between 0.5 and 0.8 ft of ground-water inflow to Walker Lake each year. This translates to between 16,000 and 26,000 acre-ft/yr of water, assuming a lake area of 32,200 acres. Harding and Milne used similar approaches but different variations of the water budget method for their analyses. Harding's period of analysis was 1928–60 and Milne's was 1927–86. Because they used a similar approach, however, it is possible that had they both used the same period of analysis, they would have had ended up with similar results. But because they used different periods of analysis, the difference between their results may be due to decreasing ground-water inflows to Walker Lake. Decreasing ground-water inflows to Walker Lake during a period of shrinking surface area would be expected because the decrease in shoreline length over time results in a decreasing area over which ground-water can directly discharge to the lake.

Table 7. Summary of evaporation rate, lake-surface area, and total evaporation for Walker Lake, west-central Nevada, by water year.

[All values were obtained by summarizing data in table 6 by water year; therefore, computation of evaporation directly by multiplying evaporation rate by lake-surface area does not necessarily agree with evaporation listed in this table]

Water year	Evaporation rate		Lake-surface area (acres)	Total evaporation (acre-feet)
	Inches	Feet		
2005	58.5	4.9	32,020	156,300
2006	61.2	5.1	32,310	165,500
2007[1]	59.3	4.9	32,660	161,100
Mean[2]	59.9	5.0	32,330	161,000

[1]2007 evaporation rate was computed by summing mean monthly evaporation rates.

[2]Mean annual evaporation rate was computed by taking average of 2005 and 2006 measured annual evaporation rates.

Evaporation from Weber Reservoir

Evaporation from Weber Reservoir was estimated by applying annual evaporation rates determined for Walker Lake to a representative surface area for Weber Reservoir. The representative surface area for Weber Reservoir was weighted for the period during which most of the evaporation was occurring. Because most of the evaporation on Walker Lake (80 percent) occurred over a 7-month period, the surface area used for Weber Reservoir was the mean lake area over a 7-month period. The 7-month period of analysis chosen for Weber Reservoir was April through October, a lag 1-month earlier than that observed on Walker Lake (May through November), because Weber Reservoir is less than one-half as deep as Walker Lake and the peak monthly evaporation should occur earlier than at Walker Lake (Sacks and others, 1994). The representative surface area used in the analysis for Weber Reservoir was determined from observed stage data and bathymetric reconnaissance data in Katzer and Harmsen (1973).

Estimated evaporation data for Weber Reservoir for water years 2005–07 is summarized in table 8. The mean stage for the 3-year study was about 4,200 ft above mean sea level and the mean surface area was about 580 acres. Lake stage and surface area for Weber Reservoir were lowest in water year 2007. This is partly due to the reconstruction of Weber Dam during the summer of 2007 and partly due to water year 2007 being a dry year with less than normal runoff in

Table 8. Evaporation from Weber Reservoir, Walker River basin, west-central Nevada, water years 2005–07.

[**Representative stage:** About 80 percent of evaporation from Weber Reservoir was assumed to occur between April 1 and October 31 in any given year; therefore, the representative stage was the mean stage for April 1 through October 31]

Water year	Evaporation rate		Representative stage (feet)	Lake-surface area (acres)	Total evaporation (acre-feet)
	Inches	Feet			
2005	58.5	4.9	4,200.1	603	2,900
2006	61.2	5.1	4,201.0	647	3,300
2007	59.3	4.9	4,197.9	497	2,500
Mean	59.9	5.0	4,199.7	582	2,900

the Walker River. Additionally, the mean stage, surface area, and evaporation from Weber Reservoir during the study was lower than normal due to reservoir operations amid dam safety concerns and likely not representative of future reservoir levels for similar hydrologic years (Carol Greiner, Bureau of Reclamation, written commun., 2008). Total evaporation from the reservoir for water years 2005–07 was 2,900, 3,300, and 2,500 acre-ft, respectively, a variability of about 28 percent over the 3-year period. This shows that evaporation from Weber Reservoir is highly influenced by the reservoir's operation and surface areas. The total evaporation from Weber Reservoir over the 3-year study was about 8,700 acre-ft, or an average of about 2,900 acre-ft/yr.

Evapotranspiration Rates

ET rates were extrapolated to the ET units and adjusted each year to account for variability in ET resulting from variability in climate, streamflows, irrigation practices, and health and vigor of the vegetation. Annual ET for each ET unit was adjusted using the scaled MSAVI (Modified Soil Adjusted Vegetation Index) of the unit as a surrogate and was based on a relation between measured annual ET and scaled MSAVI of each ET station.

ET rates for the ET stations are summarized in table 9. Measured annual ET rates at land ET stations ranged from a low of 6.0 in/yr at the GRE ET station to a maximum of 48.8 in/yr at the B11 ET station. The site on Walker Lake (LAK) had the greatest ET rate, about 59.7 in/yr. Annual ET was the lowest at the sparse desert shrubland ET stations (GRE, RAB). The greatest measured annual ET for land-based stations was at the riparian and alfalfa sites.

A negligible proportion of the ET observed at the ET stations originates from antecedent soil moisture. This is indicated by very little net change in soil water storage for ET stations with measured annual ET less than 40 in. (table 9). Additionally, for ET stations with annual ET greater than 40 in., net changes in soil water storage account for only a very small fraction of the overall ET because ET is large. This indicates that the primary sources of water for the ET measured during this study are surface water, ground water, and local precipitation, and that antecedent soil moisture is an insignificant source.

In order to determine how the ET rates for the ET stations are related to the health and vigor of the vegetation, the relative size of the source area, or footprint, of the ET stations was needed. The source areas contributing to the ET flux observed at the ET stations were determined using a method described by Schuepp and others (1990). Determining the size of the footprint of an ET station relies on variables such as surface roughness, sensor height, vegetation height and density, windspeed, and assumptions on degree of atmospheric stability. The procedures outlined by Schuepp and others (1990) apply to ET measured at a single height, as is the case for the eddy-covariance stations but not for the Bowen-ratio stations (which have sensors at two heights with 1 m spacing between them). The separation of sensors at the Bowen-ratio stations adds a level of complexity to the analysis of the data because the sensors are 'sensing' different source areas (Stannard, 1997). However, Horst (1999) found that the source area for the sensors at the Bowen-ratio stations is similar to that at eddy-covariance stations when the eddy-covariance measurements are made at a height equal to the arithmetic or geometric mean of the Bowen-ratio instrument heights for stable or unstable atmospheric conditions, respectively. The arithmetic and geometric means of the Bowen-ratio sensor heights for each station used in this study were nearly identical, allowing for source area to be computed by using the method of Schuepp and others (1990), and with the results being representative of both stable and unstable atmospheric conditions.

For this study, the footprint for the ET stations was defined as the area contributing approximately 85 percent of the measured ET flux. This resulted in footprints for the land ET stations equivalent to circular areas with radii ranging from 100 to 400 ft. The mean scaled MSAVI for the footprint of each land ET station then was computed from the respective Landsat image for the year in which the annual ET measurement was made. The sensitivity of the mean scaled MSAVI to possible errors in the estimate of the size of the footprints was tested by comparing changes in mean scaled MSAVI for footprint radii of 200, 400, and 600 ft for each land ET station. For all 10 land ET stations, the mean scaled

Table 9. Annual evapotranspiration (ET) rates and mean scaled MSAVI measured at ET stations in the Lower Walker River basin, west-central Nevada, for various periods of analysis in water years 2005–07.

[ET station locations shown in figure 5. Mean scaled Modified Soil-Adjusted Vegetation Index (MSAVI) was not used in computation of evaporation rates or volumes on open water ET units. **Energy budget ratio**: By method of computation, energy-budget ratio is always 100 percent for Bowen-ratio ET stations. **Abbreviations:** NA, not applicable; –, data not available]

ET station name	Period of analysis	Annual ET		Mean scaled MSAVI (unitless)	Energy budget ratio (percent)	Soil-water content (unitless)	
		Inches	Feet			Starting	Ending
Bowen-ratio ET stations							
LAK	01-01-05 – 12-31-05	58.8	4.9	NA	NA	NA	NA
	01-01-06 – 12-31-06	60.5	5.0				
TAM	04-01-05 – 03-31-06	13.0	1.1	23.5	NA	0.13	0.12
	04-01-06 – 03-31-07	10.4	0.9	22.1		0.12	0.07
WIL	02-01-05 – 01-31-06	46.2	3.9	[1]85.2	NA	0.14	–
B01	04-01-05 – 03-31-06	40.1	3.3	81	NA	0.19	0.42
B11	03-01-05 – 02-28-06	48.7	4.1	137.9	NA	0.22	0.58
	03-01-06 – 02-28-07	48.8	4.1	144.2		0.58	0.11
Eddy-covariance ET stations							
SAL	03-01-05 – 02-28-06	10.6	0.9	23.7	52	0.32	0.25
SAL2	10-01-06 – 09-30-07	20.2	1.7	48.6	67	0.04	0.07
GRE	03-01-05 – 02-28-06	6.0	0.5	13.9	70	0.07	0.09
GRE2	10-01-06 – 09-30-07	7.3	0.6	17.4	77	0.02	0.02
RAB	03-01-05 – 02-28-06	6.9	0.6	17.4	58	0.04	0.05
RAB2	10-01-06 – 09-30-07	37.8	3.1	58.8	75	0.06	0.10

[1]Mean MSAVI at WIL ET station was calculated from Landsat imagery obtained on July 11, 2000, because the site was flooded in the 2005 and 2006 scenes. The flooding artificially reduced the MSAVI by covering the understory vegetation with water, which decreased the spectral reflectance of this site.

MSAVI decreased by about 6 percent when the footprint radius was increased from 200 to 400 ft, and decreased by another 3 percent when the footprint radius was increased from 400 to 600 ft. This indicated that changes in the size of the footprints within a radius of 600 ft for these ET stations generally did not have a substantial effect on the mean scaled MSAVI, and that the footprint radii used are adequate and fairly robust for characterizing the scaled MSAVI for these ET stations.

The mean scaled MSAVI was computed for the footprints of all land ET stations using the respective early summer Landsat scenes (table 9). Other studies suggest that late June or early July is the most representative period to use Landsat scenes to characterize peak health and vigor of vegetation in the desert environment of the Great Basin (Laczniak and others, 1999; Smith and others, 2007). This study assumes that these image dates are the most representative for estimating annual ET rates for vegetation sites and land ET units. The mean scaled MSAVI values for each of the land ET station footprints ranged from a low of 13.9 at the GRE ET station to a high of 144.2 at the B11 ET station. The mean scaled MSAVI's for the TAM ET station footprint were 23.5 and 22.1 from the 2005 and 2006 Landsat images, respectively. To give an indication of the overall effect, the saltcedar leaf beetle may have had on the vegetation characteristics of the saltcedar, the mean scaled MSAVI for the TAM station on July 11, 2000, was 36.3. Assuming that the reduction in MSAVI from 2000 to 2006 is due entirely to the effects of the saltcedar leaf beetle, then the beetles caused a reduction in mean scaled MSAVI of about 39 percent within the footprint of the TAM ET station. The mean scaled MSAVI for the WIL ET station footprint was misleading due to flood conditions at the site (and throughout the ET unit) during the early summer Landsat image scenes that were used to compute the MSAVI's. The flooding artificially reduced the measured MSAVI by covering the understory vegetation with water, which decreased the spectral reflectance at this site. To estimate a more representative MSAVI for the WIL ET station, mean scaled MSAVI of 85.2 was computed for the station footprint from a Landsat scene imaged on July 11, 2000 (when Walker River was not flooding).

Several factors caused variations in the relative health, vigor, and density of vegetation in the ET units during this study. For example, annual precipitation across the study area was much less in 2007 than in 2005 and 2006, which contributed to decreased vigor in the vegetation in 2007 compared to that in the preceding 2 years. Success of the introduced saltcedar leaf beetle in defoliating the saltcedar shrub caused the vigor of the saltcedar in the saltcedar ET unit to decrease during successive years in this study. The suspension of irrigation in hydrograph subarea 110A in 2007 during reconstruction activity on Weber Reservoir caused the formerly irrigated crops to change from a healthy and vibrant condition to a struggling and sparse one. Many biophysical parameters can affect the spectral features of vegetation (American Society of Photogrammetry, 1999, p. 196). Leaf area and plant vigor decreases as plants are stressed or begin to die. This influences the rate at which the ET-unit communities transpire water, which influences their annual ET rate. In general, when plants are stressed, they transpire less water, which is reflected by a decrease in MSAVI.

To characterize how the relative health of vegetation in the ET units varied each year, the mean scaled MSAVI for each ET unit was computed for each year using the Landsat scenes from early summer. This use of MSAVI for this computation is separate from the determination of ET-units discussed earlier in this report. The mean scaled MSAVI varied from year to year in each of the ET units (table 10) and some ET units had greater variability than others. The smallest annual variations occurred in the xerophyte and turf ET units, with the mean MSAVI's for these units varying by less than 9 percent over the 3-year period. Mean MSAVI for the grassland ET unit varied the most, by as much as 62 percent, although mean MSAVI in the saltcedar and irrigated cropland ET units varied by about 55 and 30 percent, respectively. However, the maximum mean scaled MSAVI for the irrigated cropland ET unit (72; table 10) was less than the minimum

Table 10. Mean scaled MSAVI for each evapotranspiration (ET) unit, Walker River basin, west-central Nevada, water years 2005–07.

[Mean scaled Modified Soil-Adjusted Vegetation Index (MSAVI) was computed from Landsat imagery from the early summer for the indicated water years, unitless. **Xerophyte:** ET rates applied to ET units cannot be less than annual precipitation, by definition. Compared ET rates for these values were less than annual precipitation so annual precipitation was used instead. **Riparian:** MSAVI observations in the riparian ET unit in hydrographic subarea 110A were misleading due to flood conditions in the unit during the Landsat imaging scenes used; therefore, a constant ET rate of 45.1 inches per year (the ET computed for the riparian ET station), was applied to this ET unit each year. **Abbreviations:** NA, not applicable, usually no area associated with ET unit in the particular subarea or is open water ET unit; –, no data presented]

Water year	Mean scaled MSAVI, unitless									
	Xerophyte	Sparse shrub	Moderate shrub	Dense	Saltcedar	Grassland	Turf	Riparian	Recently irrigated cropland	Open water
Hydrographic Subarea 110A										
2005	10.0	15.8	23.7	34.0	43.3	64.2	NA	–	54.2	NA
2006	11.8	15.4	19.3	22.1	27.6	36.3	NA	–	50.4	NA
2007	12.0	13.7	18.1	20.2	25.7	33.4	NA	–	37.5	NA
Mean	11.3	15.0	20.4	25.4	32.2	44.6	NA	–	47.4	NA
Hydrographic Subarea 110B										
2005	9.8	15.8	23.6	34.1	NA	56.6	NA	48.5	NA	NA
2006	9.9	12.5	16.9	26.3	NA	41.3	NA	42.5	NA	NA
2007	10.1	12.3	16.6	28.0	NA	41.8	NA	43.4	NA	NA
Mean	9.9	13.5	19.0	29.5	NA	46.6	NA	44.8	NA	NA
Hydrographic Subarea 110C										
2005	10.3	15.6	22.9	31.8	NA	NA	80.6	36.7	64.7	NA
2006	11.1	13.0	15.6	23.7	NA	NA	78.7	31.9	72.3	NA
2007	10.6	12.6	14.3	21.5	NA	NA	75.3	32.7	59.5	NA
Mean	10.7	13.7	17.6	25.7	NA	NA	78.2	33.8	65.5	NA
Lower Walker River basin										
2005	10.0	15.8	23.7	34.0	43.3	62.7	80.6	–	55.9	NA
2006	10.9	14.5	18.5	23.3	27.6	37.3	78.7	–	53.9	NA
2007	11.0	13.3	17.5	22.2	25.6	34.8	75.3	–	41.0	NA
Mean	10.6	14.5	19.9	26.5	32.2	44.9	78.2	–	50.3	NA

mean scaled MSAVI for the irrigated cropland ET station footprints (B01 and B11) on the MVWMA (81; table 9). The variability of mean scaled MSAVI in the saltcedar ET unit is partly explained by the effects of the saltcedar leaf beetle, which caused a large decline of the mean scaled MSAVI, from 43 in 2005 to 28 in 2006 to 26 in 2007. The irrigated cropland ET unit in hydrographic subarea 110A had a substantial decrease in MSAVI in 2007 because there was no irrigation during the 2007 growing season. The mean scaled MSAVI for this unit decreased from 54 in 2005 to 38 in 2007, a decrease of about 30 percent. MSAVI was not used in computations of ET for the open-water ET unit.

The ET rates applied to the ET-unit areas were determined by adjusting the annual ET rates measured at the land-based ET stations using scaled MSAVI as a surrogate. A relation between annual ET at the stations and mean scaled MSAVI for their footprints was developed using data from table 9. The guidelines followed in developing this curve were the relation could not decrease with increasing scaled MSAVI, and the relation was not to be extended beyond the maximum observed ET or scaled MSAVI. The relation developed on the basis of these guidelines that resulted in the best coefficient of determination (closest to 1) while minimizing standard error was a quadratic relation with a maximum dependent variable equal to the maximum measured ET of 48.8 in. The best fit occurred with the 48.8 maximum occurring at scaled MSAVI of 126. This relation had a coefficient of determination (R^2) of 0.96 and a standard error of 3.5 in/yr (fig. 14):

$$ET = -0.0035\text{MSAVI}^2 + 0.89\text{MSAVI} - 7.33, \qquad (10)$$

where

ET is total annual ET rate (in/yr), and

MSAVI is mean scaled MSAVI computed from Landsat imagery collected in early summer.

This relation applies to scaled MSAVI's up to 126 (fig. 14), which is much greater than any of the mean scaled MSAVI's computed for the ET units (table 10). This relation requires the assumption that annual ET from vegetation in the Lower Walker River basin can be adequately scaled using MSAVI from a single date during the early summer. Although this relation could have been used to calculate ET pixel by pixel rather than by ET unit (assuming that ET rates for scaled MSAVI greater than 126 are equal to 48.8 in.), it was developed and intended to be used only to adjust the annual ET rates of ET units based on the measured ET rates in this study, and should not be applied to areas outside of this study or to timeframes outside of water years 2005–07.

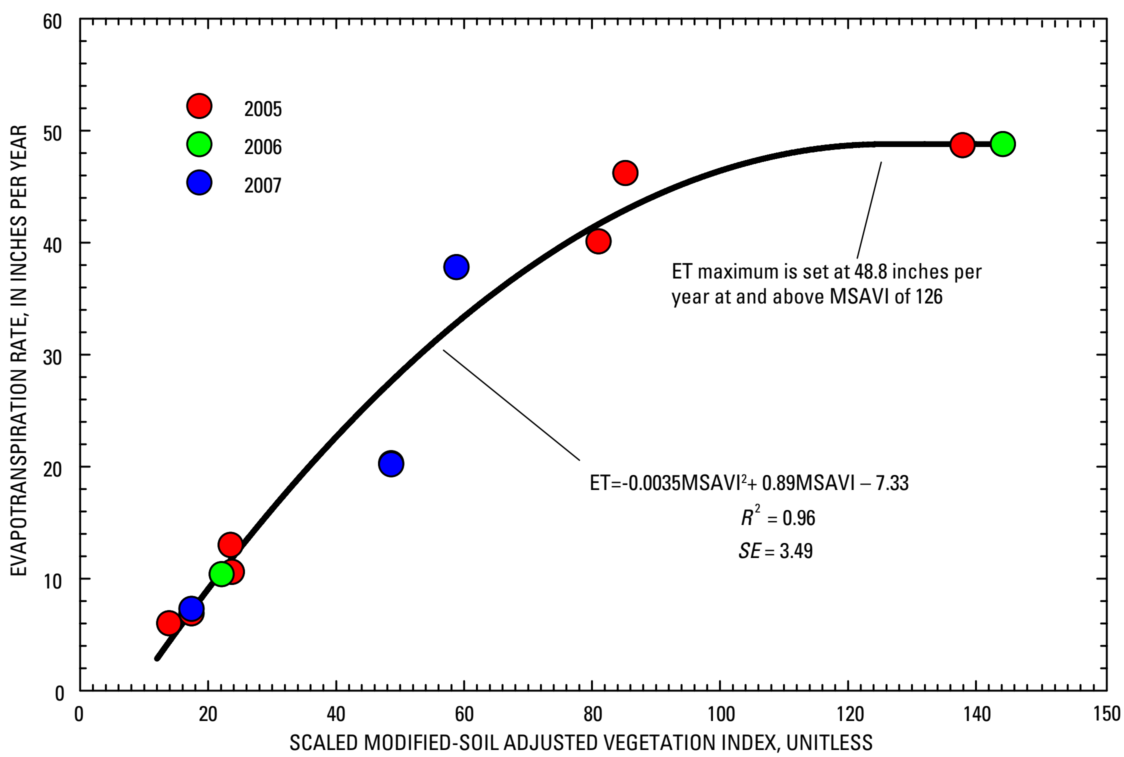


Figure 14. Relation between scaled MSAVI and annual evapotranspiration rate for the land evapotranspiration stations, Walker River basin, west-central Nevada, water years 2005–07.

Because equation 10 was used to determine ET rates for the ET units, the patterns of variability of the ET rates for the land ET units were similar to patterns of variability in MSAVI (table 10). The greatest ET rates assigned to land ET units were for the riparian ET unit, followed by the turf unit and the recently irrigated cropland unit. The irrigated cropland in the Lower Walker River basin had ET rates of 21–39 in/yr which is less than measured ET rates at the B01 and B11 ET stations on the MVWMA (40–49 in/yr; table 9). Because of the problem with the MSAVI measured in the riparian ET unit discussed earlier, a constant ET rate equal to the observed ET rate at the WIL ET station (46.2 in/yr; table 9) was used for this ET unit in hydrographic subarea 110A for each year.

Total ET from any of the ET units must be greater than or equal to the annual precipitation on the unit. Therefore, the annual ET of the xerophyte unit was the same as annual precipitation: 6.3 in. in water year 2005, 4.8 in. in 2006, and 1.9 in. in 2007. Similarly, the sparse desert shrubland unit had the same annual ET as the xerophyte unit in the wetter water years of 2005 and 2006 (6.3 and 4.8 in., respectively), but had ET greater than the xerophyte unit during the dryer water year 2007 (3.9 in.). This indicates that precipitation in water years 2005 and 2006 was sufficient to support the vegetation within the sparse desert shrub ET unit, but was not sufficient in water year 2007 when this vegetation relied, in part, on ground water for some of its water needs.

Equation 10 can be used to estimate roughly how much effect the saltcedar leaf beetle may have had on reducing ET of the saltcedar in the vicinity of the TAM ET station. This estimate is based on a comparison of measured ET_n at the TAM ET station in 2005 and 2006 with an estimate of ET_n for 2000, prior to the introduction of the beetle. ET_n for 2000 was estimated by using mean scaled MSAVI for the same footprint area from early summer 2000 Landsat data and equation 10 to calculate ET and then subtracting annual precipitation for 2000. The measured annual ET at the TAM ET station was 13.0 and 10.4 in/yr during the 2005 and 2006 growing seasons. Annual precipitation in the same 2 years was 4.9 and 2.6 in., respectively. Therefore, the ET_n for 2005 and 2006 was about 8 in. each year. The mean scaled MSAVI values for the footprint of this ET station over the same 2 years were 23.5 and 22.1, respectively. Using these scaled MSAVI values in equation 10 yields ET values of 11.7 and 10.6 in. for 2005 and 2006, which is similar to the measured rates. Using scaled MSAVI data for this same area but for July of 2000 (36.3), equation 10 yields an ET of 20.4 in for 2000. The average precipitation at nearby climate stations for water year 2000 was 3.35 in. The resulting estimate of ET_n for water year 2000 is thus about 17.0 in. This results in a rough estimate of the reduction in ET_n from 17 in/yr to about 8 in/yr for the saltcedar, which is a reduction of about 9 in/yr, or roughly a 50 percent reduction in water use. This compares with an estimate of 22 percent reduction in water use for the 2005 growing season made by Allander (2006) using a normalized curve method. The 50 percent reduction in water use estimate relies on the assumption that equation 10 adequately describes the relation between ET and scaled MSAVI for a time period outside of the period for which it was developed.

Discharge by Evapotranspiration

Total discharge in the Lower Walker River basin by evapotranspiration was determined by multiplying ET rates by the number of acres for each of the ET units in each of the hydrographic subareas (table 2) for each year of the study (table 11 and fig. 15). The ET_n for each of the ET units for each year of the study was determined by subtracting the volume of precipitation (annual precipitation from figure 4 multiplied by ET-unit acreage in table 2) from the ET discharge in table 11 (table 12 and fig. 16).

Annual ET and ET_n from the ET quantification area in the Lower Walker River basin varied each year of the study. For the 3-year study, the mean annual water discharged by ET was about 231,000 acre-ft. The ET discharge was greatest for water year 2005, was less in water year 2006, and was the least in water year 2007. The mean annual discharge by ET_n was about 186,000 acre-ft for the 3-year period. The ET_n discharge was greatest in water year 2007, was less in water year 2006, and was the least in water year 2005.

Total discharge by ET decreased in each successive year of the study, while ET_n discharge increased. Total ET discharge decreased because annual precipitation decreased each year and ET is strongly influenced by annual precipitation. The ET_n discharge increased each year primarily because of the expansion of the Walker Lake surface area during 2006 (fig. 3), which allowed the open-water evaporation to occur over a greater area. The sparse desert shrub ET unit also was able to rely more fully on local precipitation in water years 2005–06, but had a greater reliance on ground water for its water consumption needs in water year 2007, resulting in an increase in ET_n from that ET unit.

Annual ET and ET_n varied among each of the hydrographic subareas. Hydrographic subarea 110B had the greatest volume of water discharged by ET and ET_n, subarea 110C had the least with and subarea 110A was in between. Hydrographic subareas 110A and 110C had their greatest ET during water year 2005 and ET was progressively less for water years 2006–07. This pattern for ET again was influenced largely by annual precipitation. For ET_n, hydrographic areas 110A and 110C had similar discharge in water years 2005–06 and greater discharge for water year 2007. The maximum ET in subarea 110B occurred in water year 2006 and maximum ET_n occurred in water year 2007. This was primarily due to the area of Walker Lake (table 7) being greater in water years 2006–07 and direct precipitation on Walker Lake (fig. 4) being greater in 2006 than in 2007.

Table 11. Total discharge from evapotranspiration (ET) in the study area by hydrographic subarea, Lower Walker River basin, west-central Nevada, water years 2005–07.

[ET unit locations shown in figure 6. ET is total ET that has not been corrected or adjusted for direct precipitation on any of the ET units]

Water year	Discharge by ET, in acre-feet/year										
	Xerophyte	Sparse shrub	Moderate shrub	Dense	Saltcedar	Grassland	Turf	Riparian	Recently irrigated cropland	Open water	Total
Hydrographic Subarea 110A											
2005	3,990	18,030	6,570	2,330	3,840	3,070	0	[1]14,280	7,320	3,000	62,430
2006	3,050	15,750	4,760	1,310	2,270	1,760	0	14,280	6,850	3,200	53,230
2007	1,170	11,950	4,250	1,140	2,060	1,600	0	14,280	5,050	2,400	43,900
Mean	2,740	15,240	5,190	1,590	2,720	2,140	0	14,280	6,410	2,900	53,210
Hydrographic Subarea 110B											
2005	3,820	5,040	2,020	840	0	690	0	690	0	156,300	169,400
2006	2,920	3,840	1,160	600	0	510	0	600	0	165,500	175,100
2007	1,120	2,450	1,120	660	0	510	0	620	0	161,100	167,600
Mean	2,620	3,780	1,430	700	0	570	0	640	0	161,000	170,700
Hydrographic Subarea 110C											
2005	1,600	3,520	500	40	0	0	1,350	20	1,630	0	8,660
2006	1,220	2,690	260	30	0	0	1,330	10	1,770	0	7,310
2007	470	1,840	210	30	0	0	1,290	20	1,520	0	5,380
Mean	1,090	2,680	320	30	0	0	1,330	20	1,640	0	7,120
Lower Walker River basin											
2005	9,410	26,590	9,090	3,210	3,840	3,760	1,350	14,990	8,950	159,300	240,500
2006	7,190	22,280	6,180	1,940	2,270	2,270	1,330	14,890	8,620	168,700	235,700
2007	2,760	16,240	5,580	1,830	2,060	2,110	1,290	14,920	6,570	163,500	216,900
Mean	6,450	21,700	6,940	2,320	2,720	2,710	1,330	14,940	8,050	163,900	231,100

[1]Because MSAVI observations in the riparian ET unit in hydrographic subarea 110A were misleading due to flood conditions in the unit during the Landsat scenes, a constant ET rate of 46.2 inches per year (the ET computed for the riparian ET station), was applied to the riparian ET unit in hydrographic subarea 110A each year.

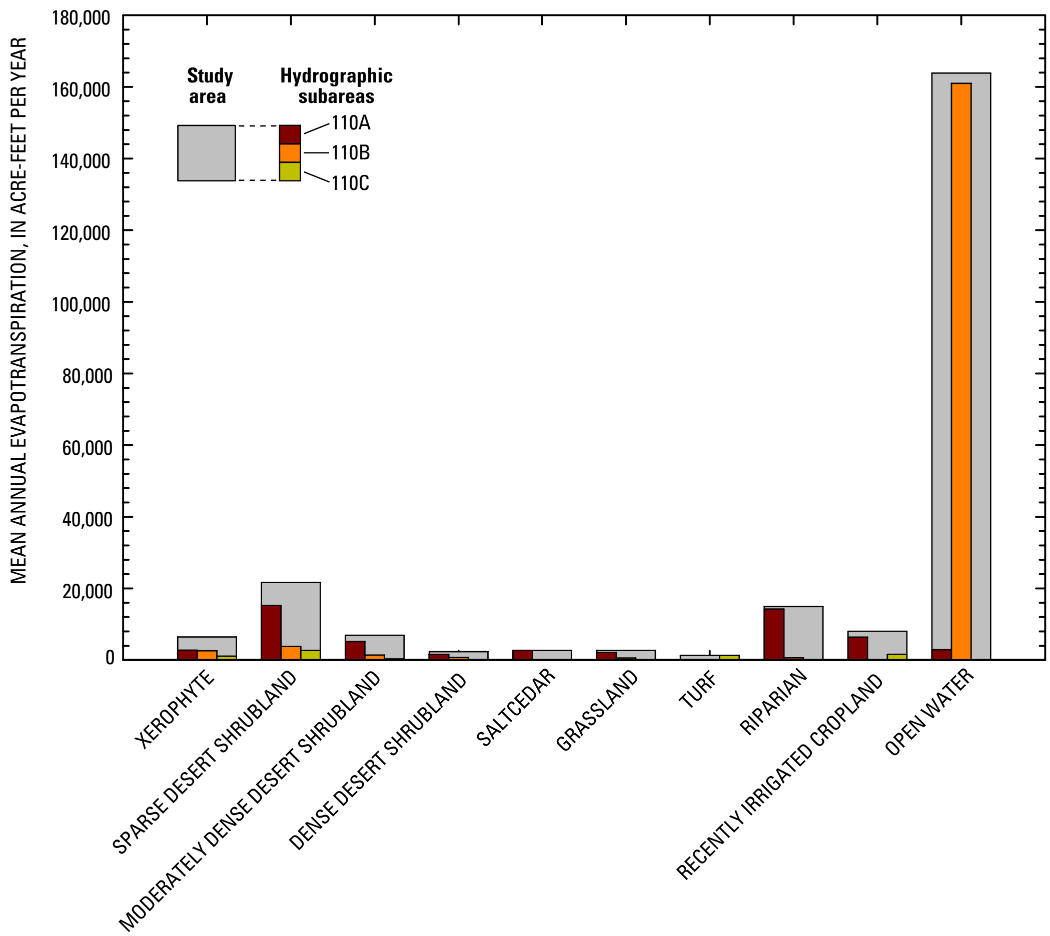


Figure 15. Total discharge by evapotranspiration in the Lower Walker River basin, west-central Nevada, water years 2005–07.

Table 12. Net discharge from evapotranspiration (ET) in the study area by hydrographic subarea, Lower Walker River basin, west-central Nevada, water years 2005–07.

[ET is net ET that has been adjusted by subtracting direct precipitation from total ET on each of the ET units]

Water year	Net discharge by ET, in acre-feet per year										Total
	Xerophyte	Sparse shrub	Moderate shrub	Dense	Saltcedar	Grassland	Turf	Riparian	Recently irrigated cropland	Open water	
Hydrographic Subarea 110A											
2005	0	0	3,030	1,550	2,850	2,520	0	12,320	5,810	2,600	30,680
2006	0	1,990	2,060	710	1,510	1,340	0	12,790	5,690	3,000	29,090
2007	0	6,670	3,210	910	1,770	1,440	0	13,710	4,610	2,400	34,720
Mean	0	2,890	2,770	1,060	2,040	1,770	0	12,940	5,370	2,700	31,540
Hydrographic Subarea 110B											
2005	0	0	930	560	0	550	0	530	0	139,400	142,000
2006	0	0	320	390	0	400	0	480	0	152,600	154,200
2007	0	980	800	570	0	470	0	570	0	156,000	159,400
Mean	0	330	680	510	0	470	0	530	0	149,300	151,900
Hydrographic Subarea 110C											
2005	0	0	220	30	0	0	1,150	10	1,340	0	2,750
2006	0	0	40	20	0	0	1,180	10	1,550	0	2,800
2007	0	820	130	20	0	0	1,230	10	1,440	0	3,650
Mean	0	270	130	20	0	0	1,190	10	1,440	0	3,060
Lower Walker River basin											
2005	0	0	4,180	2,140	2,850	3,070	1,150	12,860	7,150	142,000	175,400
2006	0	1,990	2,420	1,120	1,510	1,740	1,180	13,280	7,240	155,600	186,100
2007	0	8,470	4,140	1,500	1,770	1,910	1,230	14,290	6,050	158,400	197,800
Mean	0	3,490	3,580	1,590	2,040	2,240	1,190	13,480	6,810	152,000	186,400

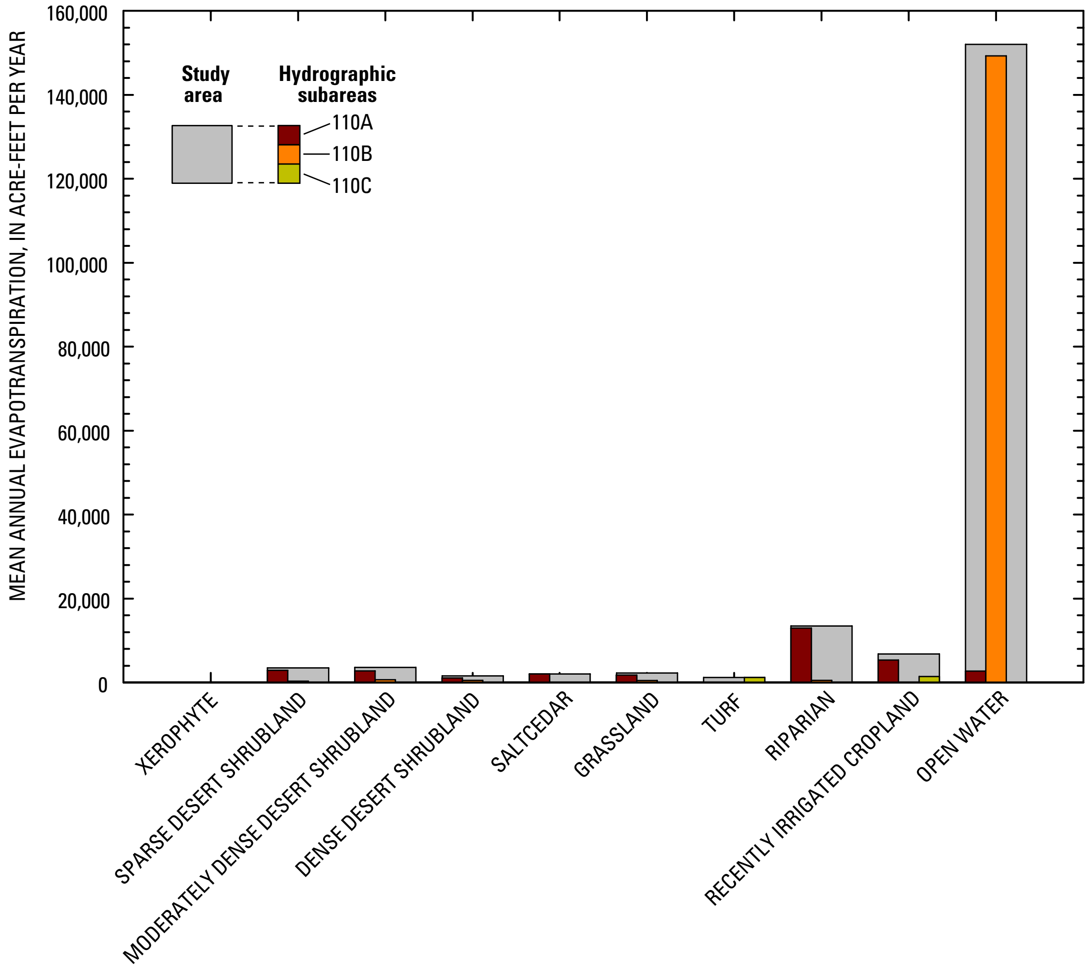


Figure 16. Net discharge from evapotranspiration in the Lower Walker River basin,west-central Nevada, water years 2005–07.

Annual ET and ET_n discharge varied for each of the ET units with the open-water ET unit contributing the greatest of these amounts in the Lower Walker River basin. About 70 percent of the total discharge by ET within the ET quantification area in the Lower Walker River basin is by direct evaporation from Walker Lake, and the remaining 30 percent is from elsewhere. However, Walker Lake is responsible for just more than 80 percent of the overall ET_n discharge from the Lower Walker River basin, and all other area accounts for the remainder. Even though the sparse desert shrub ET unit has a relatively low annual ET rate, it is the next largest contributor of total annual ET discharge because it occupies the largest area within the ET quantification area (table 2). Most of this water, however, originates as local precipitation, as the annual ET_n was only about 3,500 acre-ft/yr. This indicates that about 3,500 acre-ft/yr of the ET discharge from the sparse desert shrub unit is from ground-water discharge. The riparian ET unit had the third greatest total ET discharge, but had the second greatest ET_n discharge. The water for the ET_n from the riparian ET unit originates from ground water and surface water due to flooding of Walker River. Total ET and ET_n discharge was the least in the turf, saltcedar, grassland, and dense desert shrub ET units.

In hydrographic subarea 110A, the riparian and sparse desert shrub ET units had the greatest ET discharge and the riparian ET unit had the greatest ET_n discharge. Recently irrigated cropland had the third greatest total ET discharge and the second greatest ET_n discharge. Evaporation from Weber reservoir was about 2,900 acre-ft/yr (table 8) and net evaporation was about 2,700 acre-ft/yr. Total ET discharge from the saltcedar ET unit was less than the total ET discharge from the riparian, irrigated cropland, sparse desert shrub, and moderate desert shrub ET units, and was similar to the total evaporation from Weber Reservoir. The ET_n discharge from the saltcedar ET unit also was less than ET_n from the riparian, irrigated cropland, sparse desert shrub, and moderate desert shrub ET units, but was less than the net evaporation from Weber Reservoir. Because the saltcedar ET unit was present only within hydrographic subarea 110A, the results for this ET unit in subarea 110A represent the entire study area. The ET_n discharge from this unit may have been reduced by as much as 50 percent due to the introduction of the saltcedar leaf beetle.

ET discharge from hydrographic subarea 110B was dominated by Walker Lake; the lake accounted for about 94 percent of the total ET discharge and about 98 percent of ET_n discharge while all other ET units accounted for the remainder within this subarea.

ET discharge from hydrographic subarea 110C was the smallest of the three subareas. The greatest ET was from the sparse desert shrubs, recently irrigated cropland, and turf ET units. The only substantial ET_n discharge was from the recently irrigated cropland and turf ET units.

Limitations of Methodology

The methods for estimating ET discharge used in this study and described in this report are not without uncertainties and limitations. This section discusses some of the limitations and attempts to provide a general qualitative assessment of some of these uncertainties. Limitations associated with the measurement of ET on land are different from those associated with the measurement of evaporation from open water and are addressed separately. Generally, the uncertainties associated with the analyses in this report can be broadly classified into errors of measurement and errors of scaling.

Uncertainties and limitations with the estimates of ET over land are a result of inaccuracies associated with the instrumentation used to measure ET and the methods and assumptions used to scale point measurements to the study area. There is debate on whether the Bowen-ratio method or eddy covariance method provides a more accurate and reliable estimate of ET (Dugas and others, 1991; Bidlake, 1996; Tomlinson, 1996; Wilson and others, 2002; Brotzge and Crawford, 2003; Tumbusch and Johnson, 2005). The eddy covariance method is suspected of possibly underestimating latent energy fluxes due to possible instrument biases with the sonic anemometer, not sampling very large or very small eddies, and not accounting for regional advection (Wilson and others, 2002). Likewise, because the Bowen-ratio method does not directly measure latent and sensible heat fluxes, it is suspected of possibly overestimating the energy available for these processes (Wilson and others, 2002). It generally is agreed, however, that there is a slight systematic difference between the two methods, with the eddy-covariance method providing estimates of ET that generally are less than estimates from the Bowen-ratio method (10 to 20 percent less).

The energy budget ratio provides an estimate of the potential bias between the two methods and was computed for each of the eddy-covariance stations (table 9). Estimates of energy-budget ratio for the Bowen-ratio stations are not presented because by definition, energy budget ratios are always unity. The energy budget ratio estimates ranged from 52 to 77 percent with an average of 67 percent for the six eddy-covariance stations. These are relatively poor energy-budget closures and indicate a fairly substantial bias between the two methods. It is unclear why closure was not better and is more than likely an indication of the difference between the two methods rather than problems with either of the methods alone. Because it is unclear which ET measurement method provides the most representative estimate of ET (Wilson and others, 2002), no attempts were made to correct the bias between estimates of ET made with the Bowen-ratio energy budget and eddy-covariance methods in this study. Annual point estimates of ET in similar vegetation environments in western Nevada and the Great Basin from similarly instrumented ET stations have produced estimates of uncertainty between 10 and 12 percent (Maurer and others, 2006; Moreo and others, 2007). Uncertainties in annual ET estimates for individual ET stations may be greater than 10 to 12 percent depending on how much daily ET data was missing and how data gaps were filled in order to produce an annual ET estimate. In general, the greater the number of estimated daily ET values for a given ET station, the greater will be the uncertainty of the annual ET estimate for that station.

Errors and limitations with scaling point ET measurements to the study area scale are associated with the methods and assumptions used to do this. ET was quantified only for areas interpreted as having annual ET exceeding annual precipitation. It is likely that some areas in which annual ET exceeded annual precipitation were outside of this mapped boundary. It is known that some small strips of riparian vegetation exist along perennial streams in the Wassuk Mountains but were not included within the discharge boundary. It was assumed that these areas contributed an insignificant amount of ET relative to the overall discharge by ET. Point ET measurements were scaled based on a computed vegetation index of the source area of vapor flux observed during the early summer and a relation between that index and annual ET for that year. The basic assumptions involved in this scaling were (1) an ET station footprint contributing 85 percent of the measured ET flux is adequate for characterizing a vegetation point ET rate and the vegetation over that source area is relatively homogeneous with regard to ET discharge, and (2) the Landsat images used to compute MSAVI can be used to adequately characterize annual ET discharge for vegetation in the study area. The first assumption was initially addressed by locating ET stations within vegetation communities having an adequate radius of relatively homogeneous vegetation characteristics. This assumption was tested by computing MSAVI over circular areas of varying radii (200, 400, and 600 ft) and observing the change in MSAVI among those areas. This showed that although no ET stations were in areas of truly homogeneous vegetation, MSAVI did not vary substantially over the different circular areas, indicating that the stations were adequately located and the MSAVI estimate was reasonable for the source area of ET flux for each of the stations. The second assumption is more difficult to test or quantify. The uncertainty in this assumption is that vegetation characteristics observed on a single day of the year may not adequately characterize conditions for the entire year's ET. However, it has been reported that single scene satellite-based ET estimates do work best in dry climate, vegetated, shallow ground-water environments (Groeneveld and others, 2007), which describes the environment of this study well. Furthermore, the relation used to scale point observations of ET to study-scale values of ET was developed using data and observations from many ET stations operating in the study area and representing a broad distribution of MSAVI values that span the expected MSAVI range for the ET units identified in the study area. Because this scaling was performed using data from within the area of study, collected during the period of study, and spanning a wide range of ET rates, the use of single scene satellite images to scale annual ET should provide reasonable and valid results.

Estimates of ET_n discharge rely on the difference between annual ET and precipitation. Therefore, the uncertainties associated with both annual ET and precipitation factor into the uncertainty of ET_n. Precipitation in the study area was estimated as the average of data from three precipitation stations in and near the area. The uncertainty in the estimate is thus a combination of the uncertainties of precipitation measured at each of the three stations as well as the actual variability of precipitation across the study area. The maximum difference in annual precipitation among the three stations over the 3-year study period was 3.2 in., which is assumed to be the potential maximum error for precipitation estimates for the study area. Thus, for areas of greater ET rates such as the riparian or recently irrigated cropland ET units, the uncertainty introduced in the estimates of ET_n by the precipitation values are a much smaller fraction of the ET_n than for areas with smaller ET rates, such as the sparse desert shrubland ET unit.

Errors and limitations in the estimates of evaporation over water are a result of inaccuracies associated with the measurement of evaporation and the estimated areas of Walker Lake and Weber Reservoir. Winter (1981) summarized errors reported in various studies of open-water evaporation in which the energy-budget method was used and concluded the errors generally were about 10 percent. Furthermore, Winters (1981) considered the energy-budget method the most accurate method of estimating evaporation on lakes for periods of a week or longer. For this study, many of the same uncertainties associated with the instrumentation used to measure ET over land also apply to the instrumentation over water, resulting in an estimated uncertainty from instrumentation of around 10 to 12 percent. However, different uncertainties arise from measurements of lake heat storage due to incorporation of lake temperature, stage, volume, and area into the computations. Walker Lake temperatures primarily were measured at a single location at the evaporation station. According to Crow and Hottman (1973), the ideal number of lake-water temperature stations required to minimize error in their study of Lake Hefner, Oklahoma, while also minimizing operational time and expense, was about five stations. Crow and Hottman (1973) compared lake evaporation that was computed using data for a single lake-water temperature station to lake evaporation that was computed using data from a network of 19 lake-temperature stations and found the resulting error to be about 8 percent, which is less than the estimated error associated with the instrumentation discussed earlier.

The lake-stage data used to estimate areas of Walker Lake and Weber Reservoir and the volumes of Walker Lake are considered accurate. The lake-stage data has an uncertainty of about 0.02 ft, which equates to uncertainties in Walker Lake area and volume of about 10 acres and 640 acre-ft, respectively (not taking into consideration the additional uncertainties of the lake stage/area/volume relations). Uncertainties in estimates of lake volume and area from lake-stage/area/volume relations for Walker Lake are summarized and discussed in Lopes and Smith (2007). The uncertainties in the lake stage/area relations for Weber Reservoir are unknown, but some error likely is due to changes with Weber Reservoir bathymetry since the bathymetric survey in 1973 (Katzer and Harmsen, 1973). Katzer and Harmsen (1973) had reported that Weber Reservoir was filling in with sediment at a rate of about 60 acre-ft/yr at that time.

Summary

The level of Walker Lake has been declining at an average rate of about 1.6 feet per year (ft/yr) since 1917. With this decline, there has been an associated increase in total dissolved-solids concentration. Total dissolved-solids concentration in Walker Lake was near 16,000 milligrams per liter at the end of water year 2007 and is an increasing threat to the viability and health of the fishery and ecology of the lake. A substantial amount of water use in the Walker River basin is to support agriculture upstream of Walker Lake and is part of the lifeblood of the upstream economies.

A need for a comprehensive study on the hydrology of the Lower Walker River basin and development of an improved water budget for Walker Lake were identified so that decisions on management of the Walker River water system would be guided by updated and relevant science. This study focuses on the distribution and quantities of water that are discharged to the atmosphere in the Lower Walker River basin through the process of evapotranspiration (ET).

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, started a 3-year study of ET in the Lower Walker River basin downstream of Mason Valley. The period of this study was water years 2005–07. The study area was divided into three hydrographic subareas so that results could be further refined. Climate within the study area during this period was wetter than normal the first year, nearly average the second year, and very dry the third year. The overall level of Walker Lake was virtually the same at the beginning and end of this study, but varied considerably during the study period.

The areas in which annual ET exceeded annual precipitation were identified and defined as the ET discharge quantification area. This area was classified into 10 ET units according to vegetation and soil characteristics to represent areas of similar ET rates. An ET-unit map was developed using a combination of techniques and tools that included field mapping, remote sensing using Landsat imagery, high resolution imagery, and Lidar data. ET rates were measured in varying types and densities of vegetation and on open water at 11 ET stations. Data collected at these stations were used in either a Bowen-ratio energy-budget method or eddy-covariance method to compute ET. ET rates at land ET stations were correlated with scaled Modified-Soil Adjusted Vegetation Index (MSAVI), which was used to adjust the ET rates for each ET unit for each year and for each hydrographic subarea. ET rates for the ET units were then applied to their respective areas to compute ET discharge.

Evaporation from Walker Lake was measured using an energy-budget method in combination with a Bowen-ratio station located in the north-central part of the Lake. Evaporation from Walker Lake varied little over the 2 years of measurements and averaged 5.0 ft/yr. The average area for Walker Lake was about 32,200 acres. Total evaporation from the lake was about 161,000 acre-feet per year (acre-ft/yr) over the 3-year period and varied by a maximum of 6 percent from year to year. Net evaporation was about 149,000 acre-ft/yr. Nearly 80 percent of all evaporation on Walker Lake occurred within the 7-month period May through November. Previous estimates of evaporation minus ground-water inflow to Walker Lake from 1965 and 1987 were 4.1 and 4.4 ft/yr, respectively. The difference between the evaporation rate measured in this study and those estimated in earlier studies suggest either that ground-water inflow to Walker Lake of between 16,000 and 26,000 acre-ft/yr was unaccounted for in previous work, or that ground-water inflow to Walker Lake is decreasing with the long-term recession of the lake, or some combination thereof.

The evaporation rates determined for Walker Lake were applied to Weber Reservoir, where total evaporation was more variable than for Walker Lake because reservoir operations affected the surface area. The average surface area of Weber Reservoir was about 580 acres and total evaporation was about 2,870 acre-ft/yr. Annual evaporation varied by as much as 28 percent over the 3-year period. The reservoir stage, surface area, and ET were lower than normal during this study for similar hydrologic conditions in other years due to reservoir operations amid dam safety concerns.

Evaporation rates were greatest for the open-water ET unit and were progressively less for each of the following land-based ET units: riparian, turf, recently irrigated cropland, grassland, saltcedar, dense shrub, moderately dense shrub, sparse shrub, and xerophyte. ET rates from irrigated agriculture varied substantially due to the suspension of irrigation by the Walker River Paiute Tribe during the 2007 growing season. ET from saltcedar also varied during the study as a consequence of the success of the saltcedar leaf beetle in defoliating saltcedar trees starting in June 2005. The beetle may have reduced the water use of the saltcedar tree by as much as 50 percent in the first 2 years of their appearance at the ET station within the saltcedar ET unit. Net ET rates at this station went from a roughly estimated 17.0 inches per year (in/yr) prior to the introduction of the saltcedar leaf beetle (in 2000) to about 8.0 in/yr after the first 2 years of their success (2005–06).

Total ET from the ET quantification area in the Lower Walker River basin was about 231,000 acre-ft/yr during the 3-year study. Of this total, about 45,000 acre-ft/yr originated from direct precipitation, resulting in net evapotranspiration (ET_n) of about 186,000 acre-ft/yr. A little more than 80 percent of the ET_n discharge in the Lower Walker River basin can be attributed to evaporation from Walker Lake, which was about 149,000 acre-ft/yr, while the remainder of the ET_n originated from elsewhere in the study area. The land ET units with the greatest ET discharge were the sparse desert shrub unit, followed by the riparian unit, with about 22,000 and 15,000 acre-ft/yr, respectively. Of the 22,000 acre-ft/yr of ET by the sparse desert shrub unit, 3,500 acre-ft was from ground-water discharge and the remainder originated from direct precipitation. Of the 15,000 acre-ft/yr of ET from the riparian ET unit, about 13,000 acre-ft was from ground- and surface-water sources, and 2,000 acre-ft originated from direct precipitation.

Hydrographic subarea 110B (Walker Lake area), which includes all of Walker Lake, had the greatest ET of the three hydrographic subareas, with about 171,000 acre-ft/yr. Hydrographic subarea 110A (study area north of Walker Lake) had the next greatest ET with about 53,000 acre-ft/yr, and hydrographic subarea 110C (study area south of Walker Lake) had the least with only about 7,100 acre-ft/yr of ET. ET_n from these three hydrographic subareas was approximately: 32,000 acre-ft/yr in subarea 110A; 152,000 acre-ft/yr in subarea 110B; and 3,100 acre-ft/yr in subarea 110C.

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Appendix A. Site Information and Water-Quality Profile Data for Lake Stations on Walker Lake, West-Central Nevada, 2005–06

Appendix is data files stored in Microsoft© Excel and are available for download at http://pubs.usgs.gov/sir/2009/5079.

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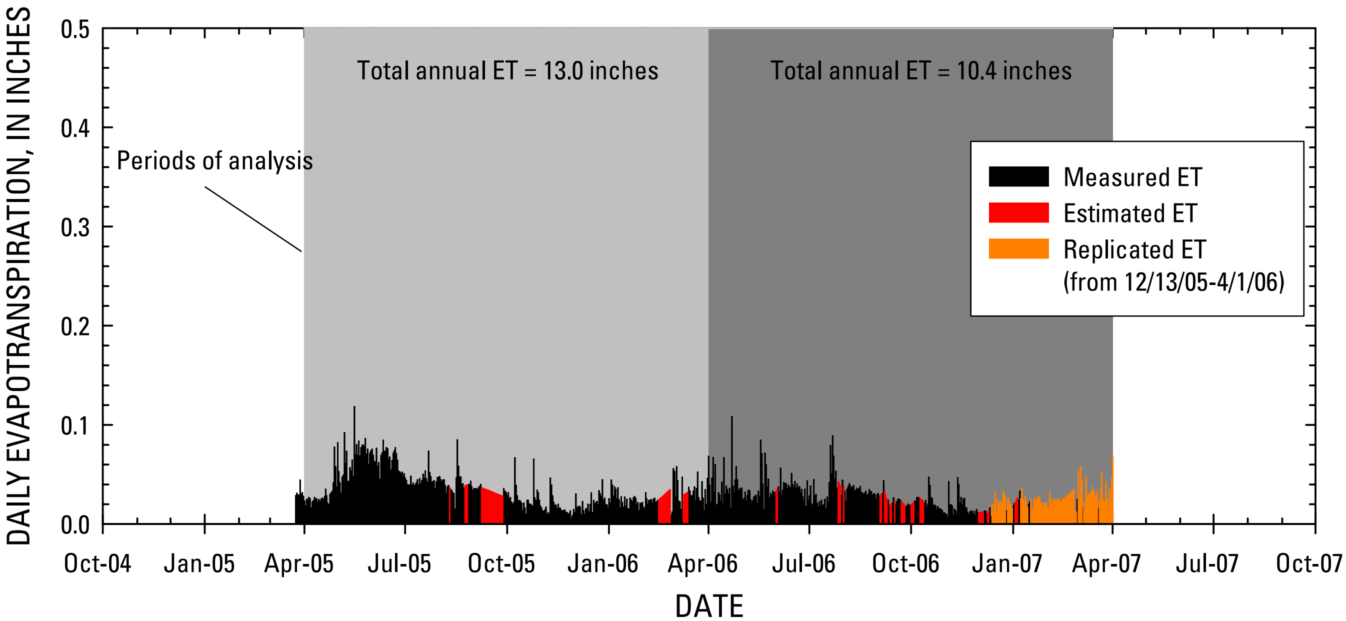
Appendix B. Individual Data Summary Plots and Photographs for Land Evapotranspiration Stations.



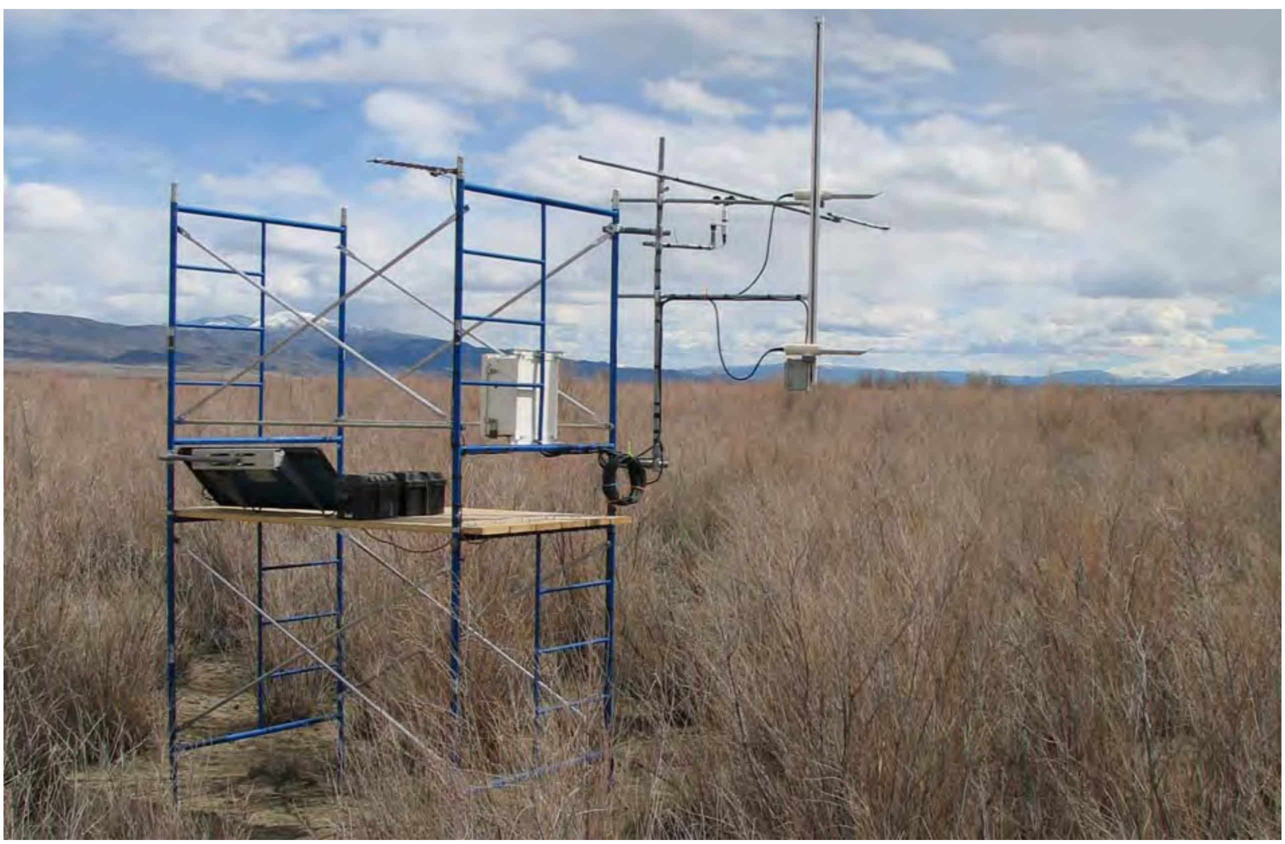
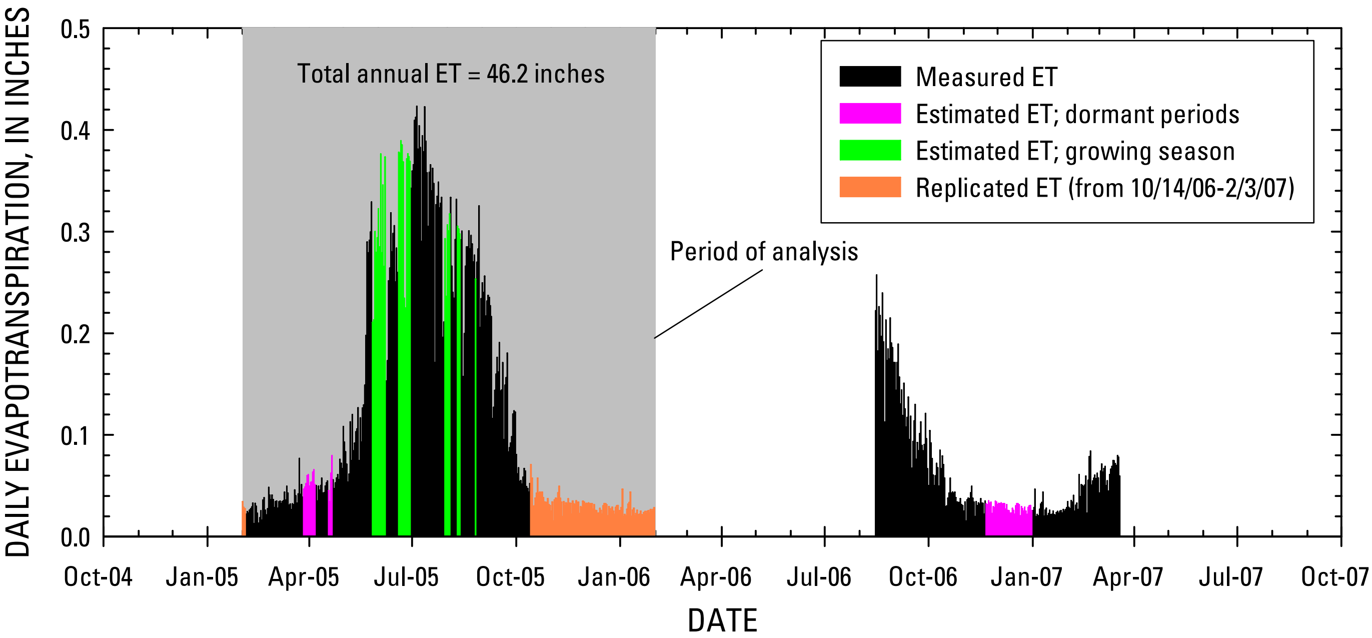


Figure B1. Daily evapotranspiration curves over study period and site photograph for TAM evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 23, 2005.)



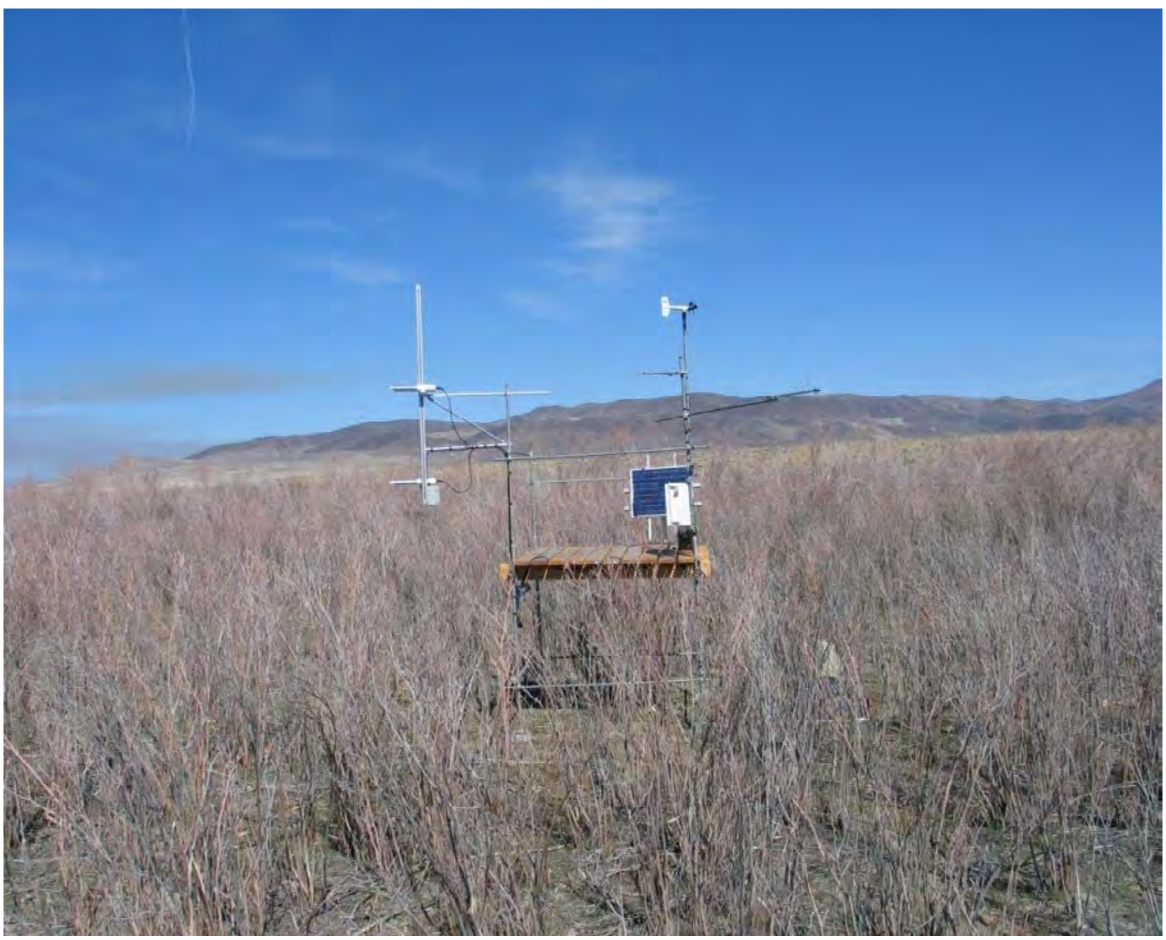


Figure B2. Daily evapotranspiration curves over study period and site photograph for WIL evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 9, 2005.)

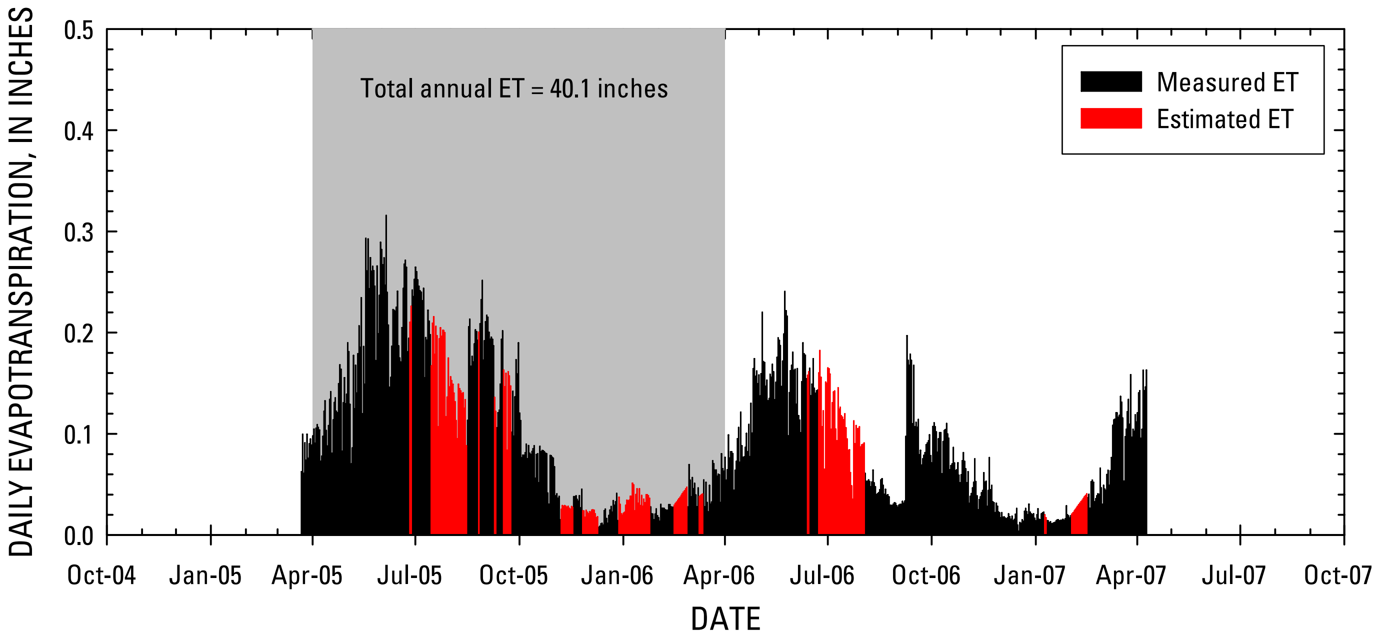


Figure B3. Daily evapotranspiration curves over study period and site photograph for B01 evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 21, 2005.)

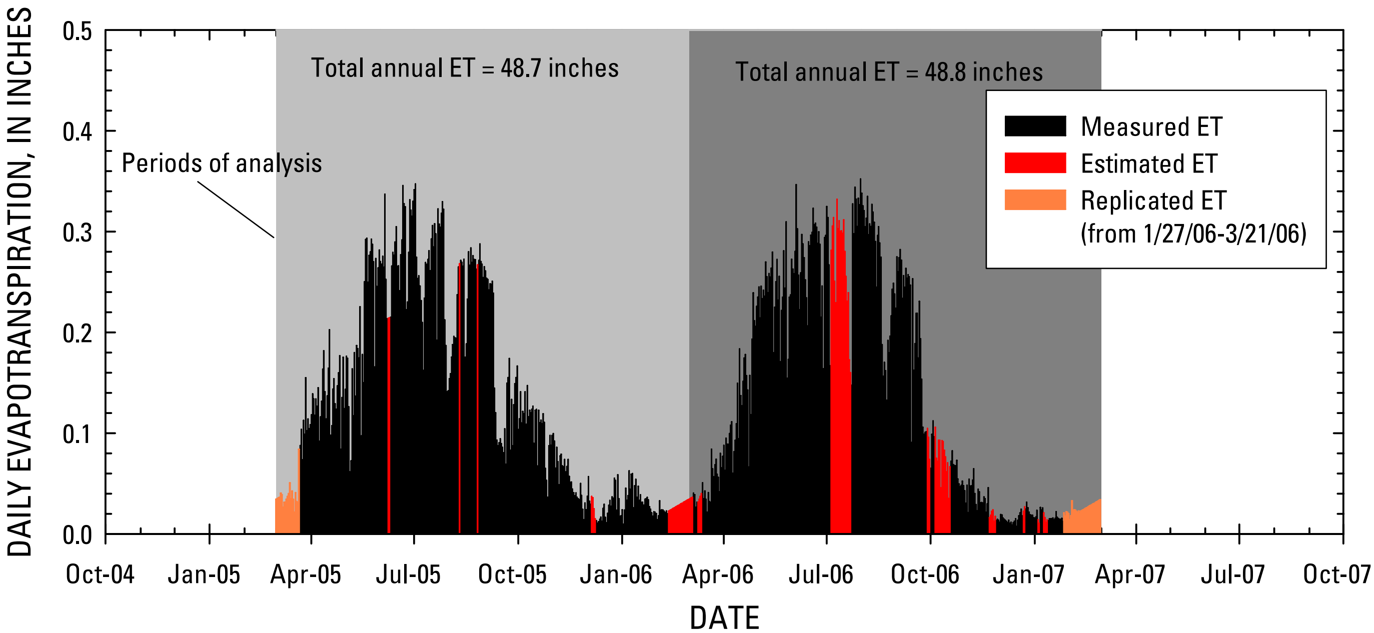


Figure B4. Daily evapotranspiration curves over study period and site photograph for B11 evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 23, 2005.)

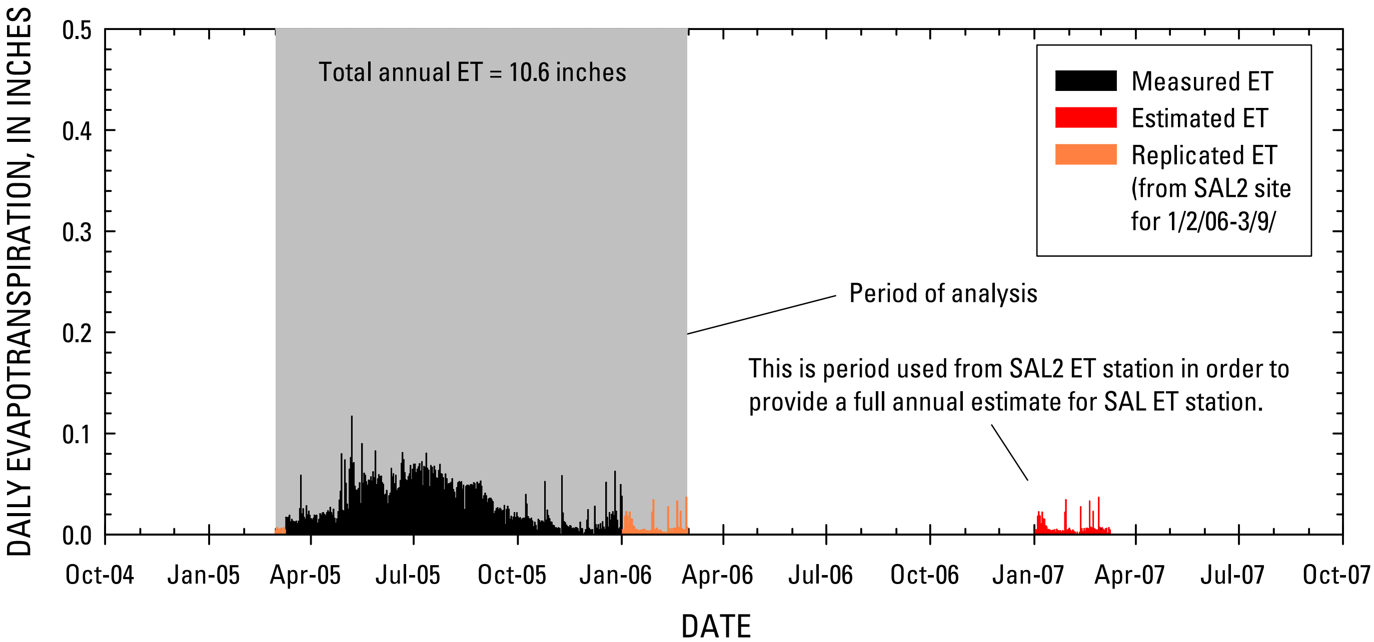
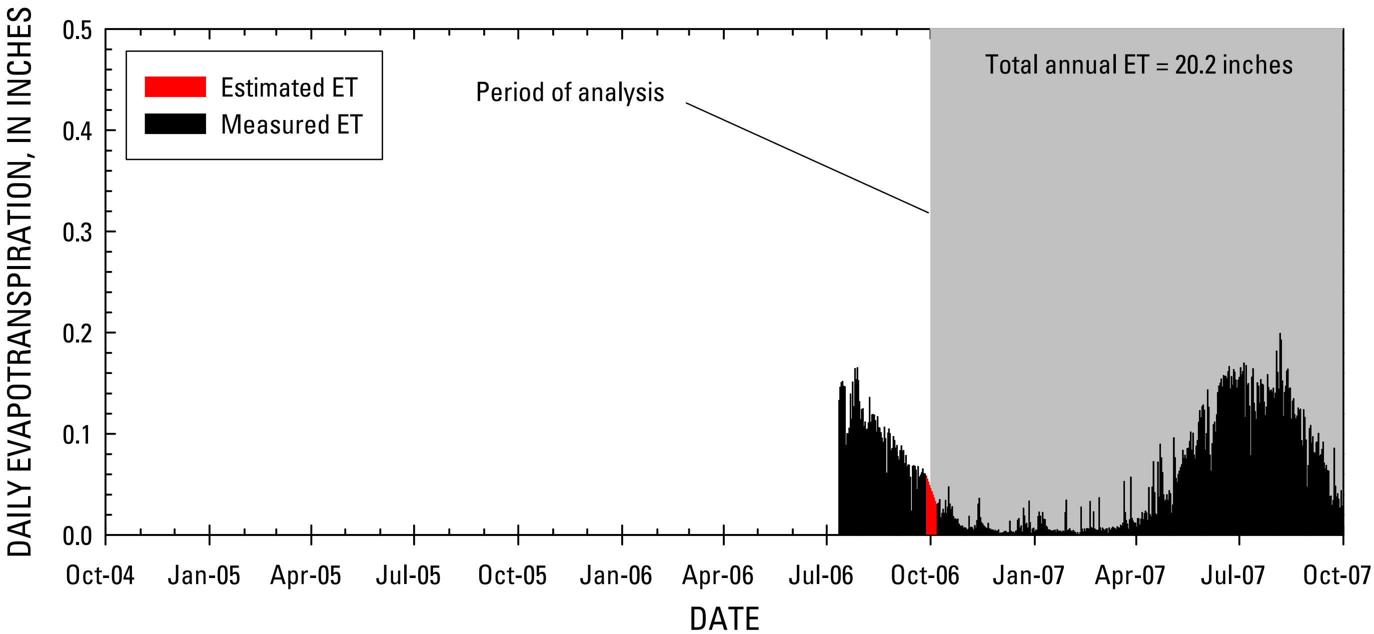


Figure B5. Daily evapotranspiration curves over study period and site photograph for SAL evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 10, 2005.)



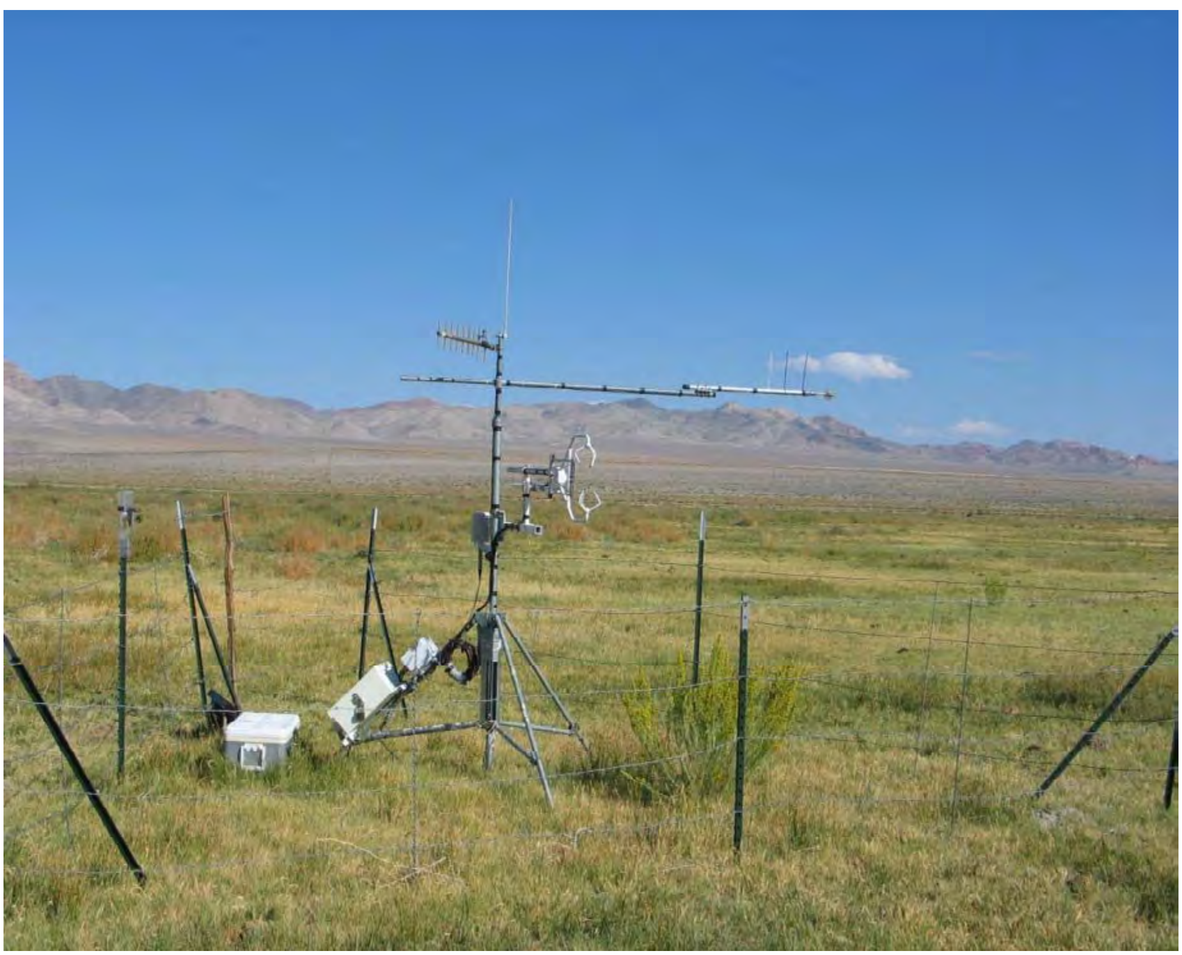
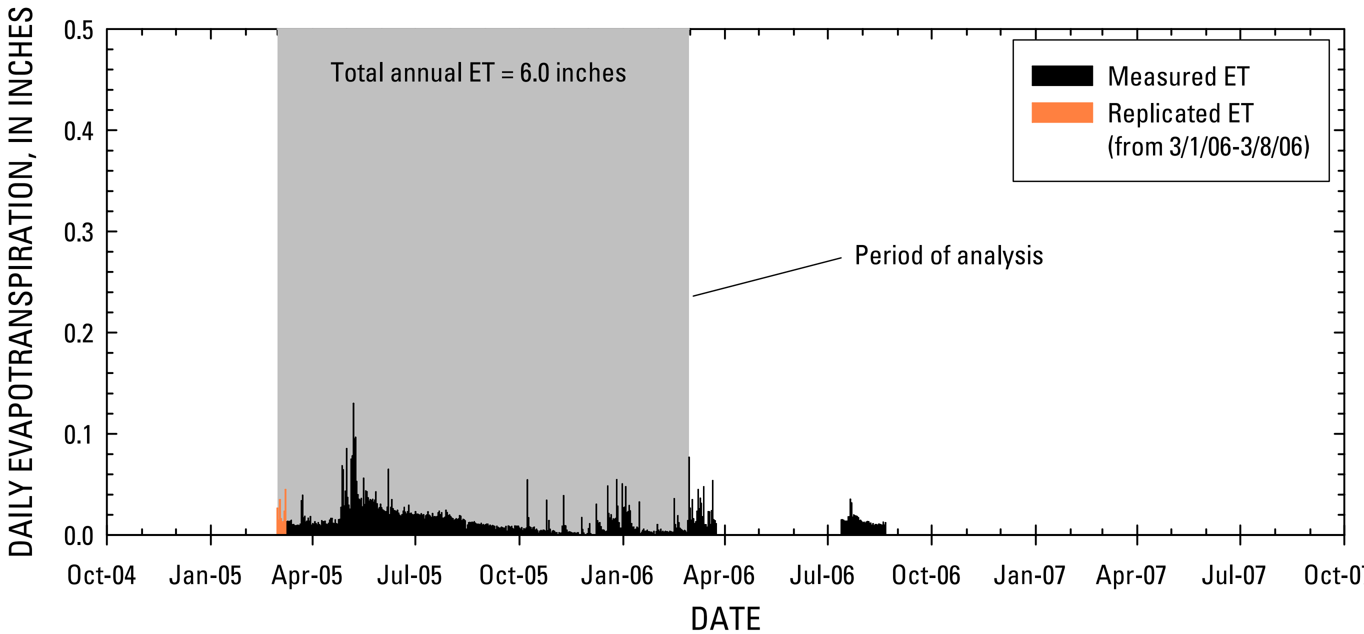


Figure B6. Daily evapotranspiration curves over study period and site photograph for SAL2 evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 18, 2005.)



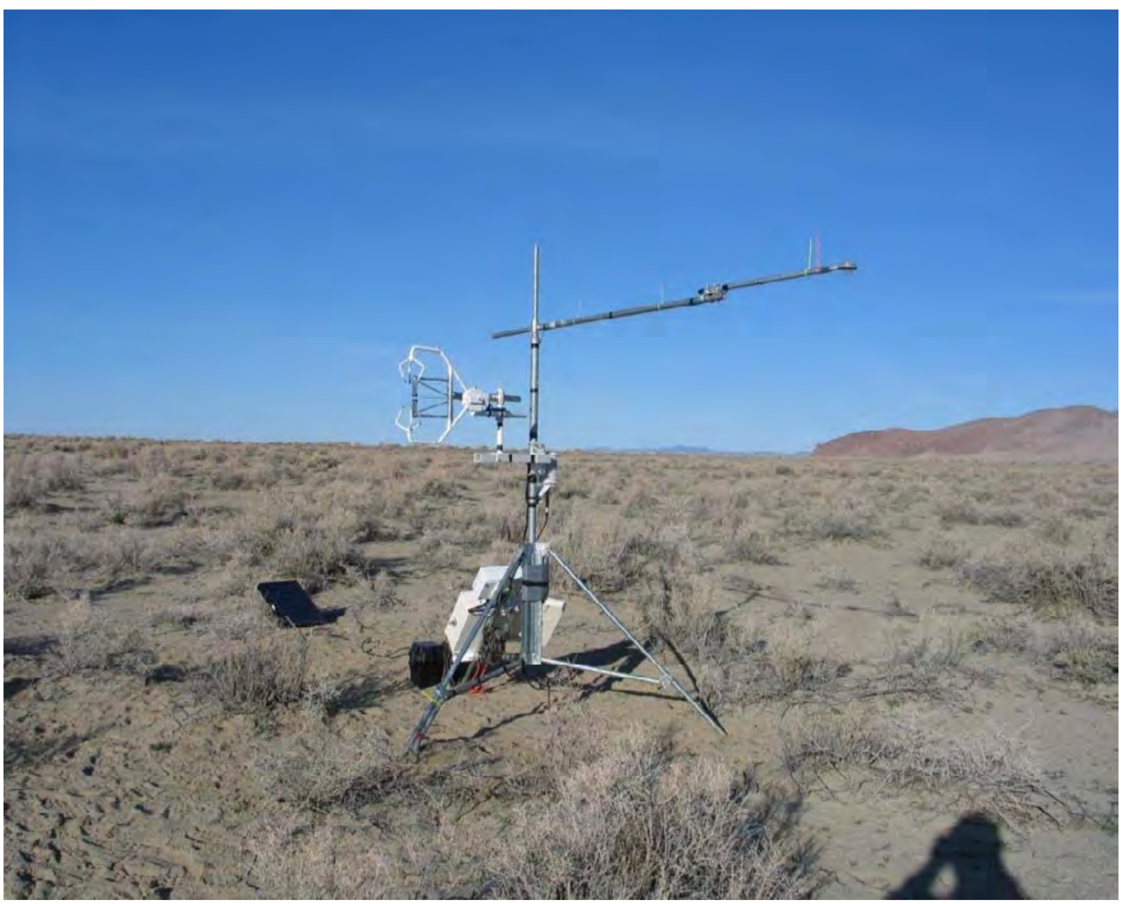


Figure B7. Daily evapotranspiration curves over study period and site photograph for GRE evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 1, 2005.)

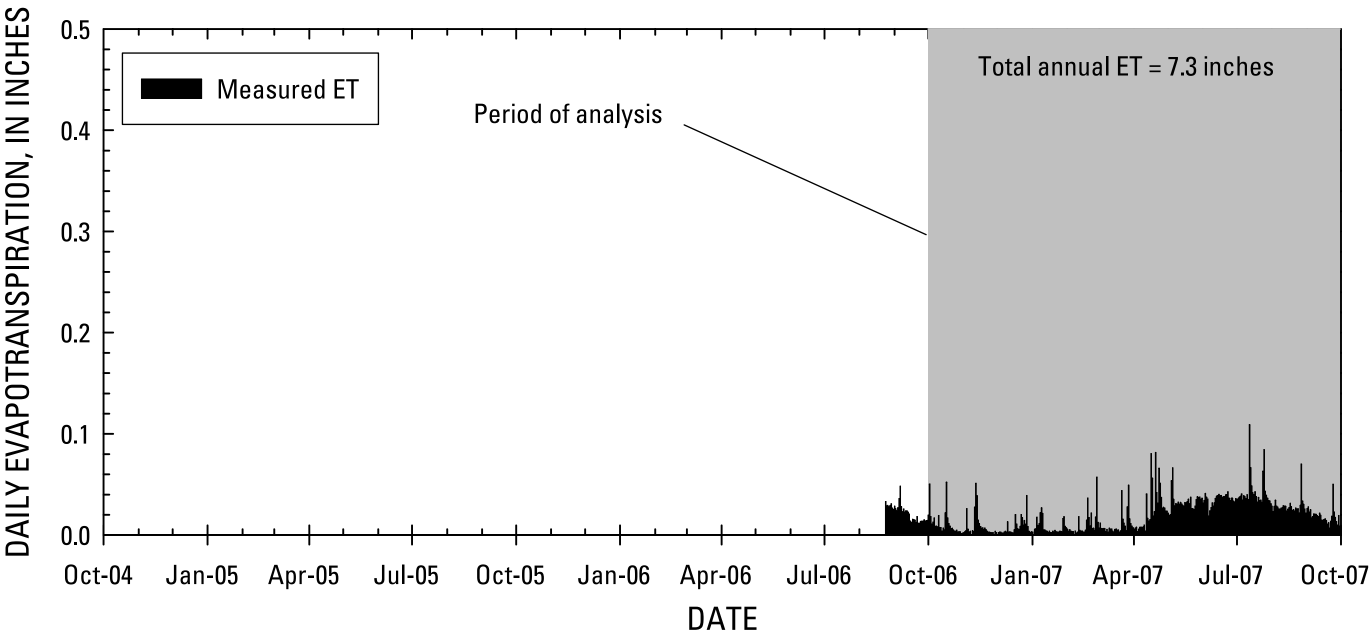


Figure B8. Daily evapotranspiration curves over study period and site photograph for GRE2 evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, September 18, 2005.)

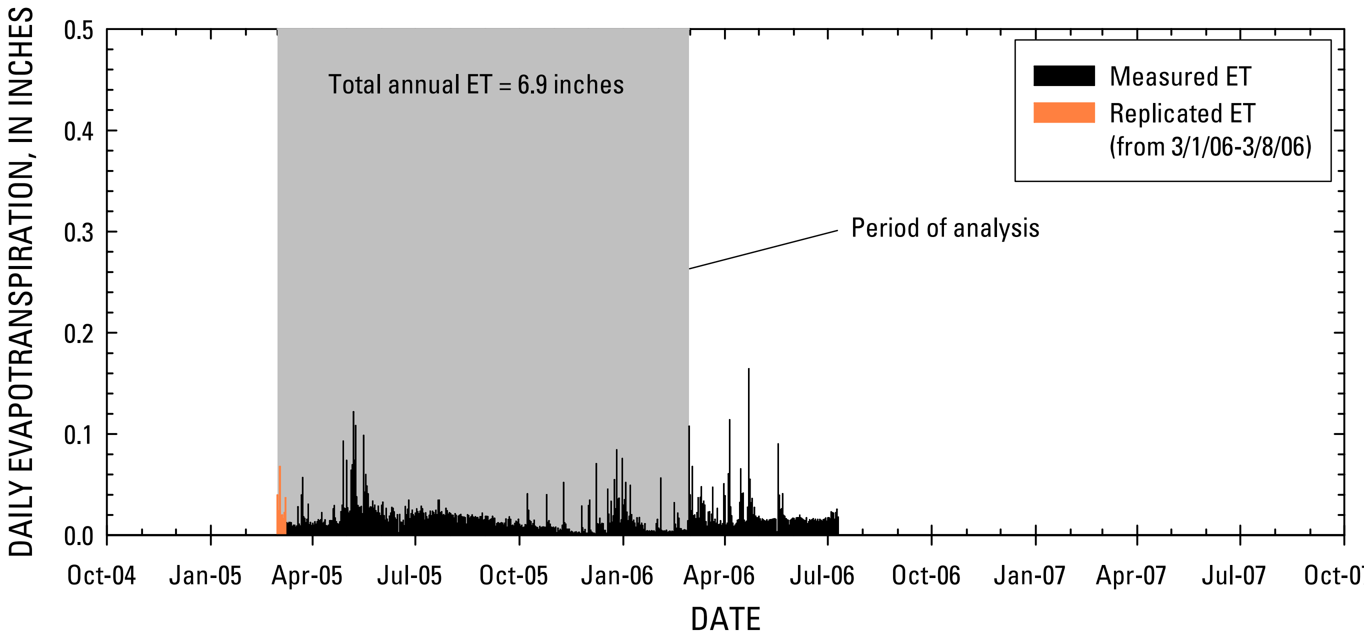


Figure B9. Daily evapotranspiration curves over study period and site photograph for RAB evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, March 8, 2005.)

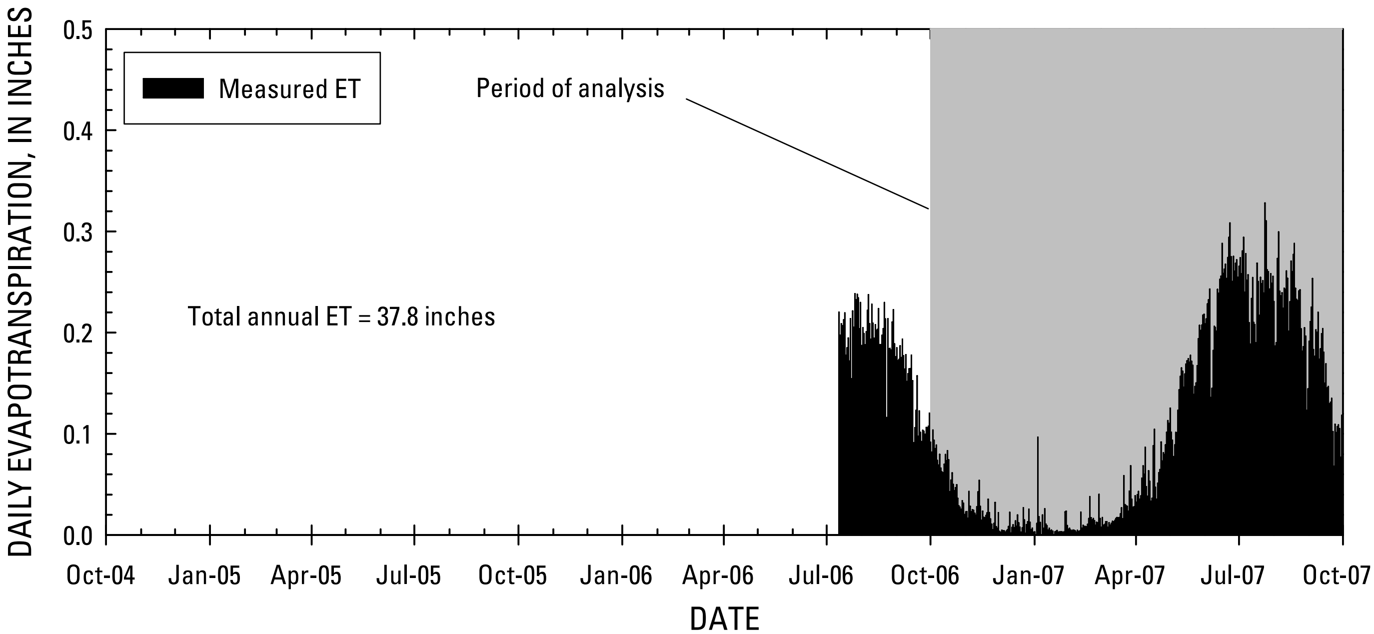


Figure B10. Daily evapotranspiration curves over study period and site photograph for RAB2 evapotranspiration station, Walker Lake basin, Nevada. (Photograph taken by Kip K. Allander, U.S. Geological Survey, August 9, 2005.)

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