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Estimates of Evapotranspiration from the Ruby Lake National Wildlife Refuge Area, Ruby Valley, Northeastern Nevada, May 1999–October 2000

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Inch-pound units to SI metric units		
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.4	millimeter
inch per day (in/d)	25.4	millimeter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
SI metric units to inch-pound units		
watts per square meter (W/m^2)	10.76	watts per square foot

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)] + 32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F – 32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Note: English units are used throughout this report, except in instances where a measurement has no common English-unit equivalent.

EQUATIONS REFERENCED IN TEXT

Number	Name	Equation
1	Energy budget	$R_n = G + H + \lambda E$
2	Net radiation	$R_n = (R_{Si} - R_{So}) + (R_{Li} - R_{Lo})$
3	Subsurface-heat flux (for soil)	$G = HF_s + \{\delta T_s\, d_{bls}\, \rho_{Bs}\, [C_s + (W\, C_w)]\}$
4	Subsurface-heat flux (for water)	$G = \delta T_w\, d_{bws}\, \rho_w\, C_w$
5	Sensible-heat flux	$H = \rho_a\, C_a\, k_h\, dT/dz_t$
6	Latent-heat flux	$\lambda E = (\lambda\, \rho_a\, \varepsilon\, k_v\, /\, P)\, de/dz_e$
7	Available energy	$E_a = R_n - G$
8	Bowen ratio	$\beta = (H\, /\, \lambda E) = [(P\, C_a)\, /\, (\lambda\, \varepsilon)]\, [(T_l - T_u)\, /\, (e_l - e_u)]$
9	Evapotranspiration	$ET = [E_a / (\lambda\, \rho_w)][(P\, C_a)\, /\, (\lambda\, \varepsilon)]\, [(T_l - T_u)\, /\, (e_l - e_u) + 1]$
10	Latent-heat flux; eddy-correlation method	$\lambda E = \lambda$ covariance $(w\rho_v)$
11	Sensible-heat flux; eddy-correlation method	$H = \rho_a\, C_a$ covariance (wT)
12	Relative closure	$C_r = [(R_n - G - H - \lambda E)/R_n - G]100$

SYMBOLS USED IN EQUATIONS

C_a	Specific heat of air at a constant pressure (energy per mass per temperature)
C_s	Specific heat of dry soil (energy per mass per temperature)
C_w	Specific heat of water (energy per mass per temperature)
d_{bls}	Depth below land surface at which heat flux is measured (length)
C_r	Amount of residual imbalance relative to available energy (percent)
d_{bws}	Depth below water surface at which temperature is measured (length)
de/dz_e	Vapor-pressure gradient near the Earth's surface
dT/dz_t	Temperature gradient near the Earth's surface
$e_{l,u}$	Vapor pressure at lower and upper reference point (force per area)
E_a	Available energy (energy per area per time)
E	Rate of water evaporation (mass per area per time)
ET	Rate of evapotranspiration (length per time)
G	Subsurface-heat flux (energy per area per time)
H	Sensible-heat flux (energy per area per time)
HF_s	Heat flux through soil at some measurement depth (energy per area per time)
k_h	Turbulent transfer coefficient of heat in air (area per time)
k_v	Turbulent transfer coefficient of vapor (area per time)
P	Ambient air (barometric) pressure (force per area)
R_{Li}	Incoming long wave radiation (energy per area per time)
R_{Lo}	Outgoing long wave radiation (energy per area per time)
R_n	Net radiation (energy per area per time)
R_{Si}	Incoming short wave radiation (energy per area per time)
R_{So}	Outgoing short wave radiation (energy per area per time)
T	Instantaneous departure from average temperature
$T_{l,u}$	Temperature at lower and upper reference point
W	Gravimetric soil water content (dimensionless)
w	Instantaneous departure from average wind speed (length per time)
b	Bowen ratio (unitless)
δT_s	Change in soil temperature between surface and soil-heat flux measurement depth (temperature per time)
δT_w	Change in water temperature (temperature per time)
e	Ratio of molecular weight of water to dry air (dimensionless)
l	Latent heat of vaporization for water (energy per mass)
λE	Latent-heat flux (energy per area per time)
ρ_a	Density of air (mass per volume)
ρ_{Bs}	Bulk density of soil (mass per volume)
ρ_w	Density of water (mass per volume)
ρ_v	Instantaneous departure from average vapor density (mass per volume)

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ABSTRACT

The Ruby Lake National Wildlife Refuge in Ruby Valley, Nevada, contains the largest area of perennial wetlands in northeastern Nevada and provides habitat to a large number of migratory and nesting waterfowl. The long-term preservation of the refuge depends on the availability of sufficient water to maintain optimal habitat conditions. In the Ruby Valley water budget, evapotranspiration (ET) from the refuge is one of the largest components of natural outflow. To help determine the amount of inflow needed to maintain wetland habitat, estimates of ET for May 1999 through October 2000 were made at major habitats throughout the refuge.

The Bowen-ratio method was used to estimate daily ET at four sites: over open water, in a moderate-to-dense cover of bulrush marsh, in a moderate cover of mixed phreatophytic shrubs, and in a desert-shrub upland. The eddy-correlation method was used to estimate daily ET for periods of 2 to 12 weeks at a meadow site and at four sites in a sparse-to-moderate cover of phreatophytic shrubs. Daily ET rates ranged from less than 0.010 inch per day at all of the sites to a maximum of 0.464 inch per day at the open-water site. Average daily ET rates estimated for open water and a bulrush marsh were about four to five times greater than in areas of mixed phreatophytic shrubs, where the depth to ground water is less than 5 feet. Based on the seasonal distribution of major habitats in the refuge and on winter and summer ET rates, an estimated total of about 89,000 acre-feet of water was consumed by ET during October 1999–September 2000 (2000 water year). Of this total, about 49,800 acre-feet was consumed by ET in areas of open water and bulrush marsh.

INTRODUCTION

More than half of Nevada's original wetlands have been lost to agricultural and urban development (Dahl, 1990). Wetlands currently account for less than 1 percent of the area of the State (Lico, 1996, p. 267). The only major wetlands in northeastern Nevada are in the Ruby Lake National Wildlife Refuge (Ruby Lake NWR) and nearby Franklin Lake area in the southern half of Ruby Valley (fig. 1). Because of its relative isolation from other wetland areas along the Pacific Flyway, Ruby Valley provides habitat to large numbers of breeding and migratory waterfowl, marsh-dependent birds, and other wildlife. Long-term preservation of wetland in the refuge is tied to the availability of sufficient water to maintain optimal habitat conditions. Not well known, however, is the quantity of water that is needed.

Concerns about the continued viability of the Ruby Lake NWR have prompted the U.S. Fish & Wildlife Service (USFWS) to apply for ground-water rights from the State of Nevada. Although the refuge has existed since 1938, water rights that would ensure its preservation have never been formally acquired. Estimates of evapotranspiration (ET) are needed by USFWS and the State as part of a larger effort to determine a water budget for Ruby Valley, which will be used in future management of the valley's water resources.

In the arid West, water loss by ET typically represents the largest component of natural outflow in a water budget. Evapotranspiration is the combined loss or transfer of water to the atmosphere through transpiration by plants and direct evaporation from surface-water bodies and soil moisture and from shallow ground water in areas of bare soil (Wilson and Moore, 1998).

Evapotranspiration from the Ruby Lake NWR is thought to be the largest source of natural outflow from Ruby Valley (Eakin and Maxey, 1951, p. 82; Nichols, 2000, p. C44). Although preliminary estimates were made of ground-water ET in Ruby Valley (Nichols, 2000), detailed estimates of ET from habitats in the refuge have not been made. Refining the estimate of annual ET from the refuge would aid in determining the amount of inflow required to maintain wetland habitat and would help in quantifying the total outflow from Ruby Valley.

The water resources of Ruby Valley were last investigated in the late 1940's (Eakin and Maxey, 1951). The availability of additional hydrologic data and new technologies, particularly in regional water-budget analysis, presents an opportunity to evaluate in more detail the valley's water resources. In 1999, the U.S. Geological Survey (USGS), in cooperation with the Nevada Division of Water Resources and the USFWS, began a 6-year water-resources investigation to develop an annual water budget for Ruby Valley. The study was planned in terms of two phases of research, each slated to last 3 years. Phase 1 was designed to quantify annual ET from the Ruby Lake NWR, particularly from wetland habitat. The investigation outlined in Phase 2 will develop a water budget for the entire Ruby Valley Hydrographic Area[1] (fig. 1) and will incorporate estimates of ET determined in Phase 1.

[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's 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 Geological Survey scientific reports and Division of Water Resources administrative activities.

Purpose and Scope

This report describes the results of the first phase of study in estimating an annual water budget for Ruby Valley. The report presents ET rates computed from micrometeorological data measured in major habitats of the Ruby Lake NWR. Typical habitats include wetland (consisting of open water and bulrush marsh), meadow, grassland, areas of phreatophytic shrubs, playa, and desert-shrub upland. Estimates are presented of annual ET based on seasonal ET rates and habitat distribution for the 2000 water year. This report also briefly describes the methods and instrumentation used to estimate ET from major habitats.

Beginning in May 1999, micrometeorological data were collected during the next 18 months at four sites that represented habitat in open water, bulrush marsh, mixed phreatophytes, and desert-shrub upland, respectively. Daily ET rates at these sites were estimated using the Bowen-ratio method. Data also were collected from mid-May to mid-September 2000 at five short-term sites that included a meadow habitat and four areas containing a mixture of phreatophytic shrubs, using a different data-collection interval at each site. Daily ET rates at these five sites were estimated using the eddy-correlation method. The eddy-correlation equipment was moved at 2- to 12-week intervals to optimize data collection during the summer season. See the section "Methods of Estimating Evapotranspiration" for descriptions of the Bowen-ratio and eddy-correlation methods.

Previous Investigations

One of the earliest water-resources investigations in Ruby Valley was done by the USGS in the late 1940's (Eakin and Maxey, 1951). The study briefly describes the hydrography of Ruby Valley and presents reconnaissance-level estimates of ground-water recharge and discharge. The hydrogeology of the Ruby Mountains, which border the west side of Ruby Valley, was described by Dudley (1967). Dudley used geomorphic features to infer the hydrology of the Ruby Mountains and their influence on ground-water flow to adjacent valleys. Prudic and others (1995) included Ruby Valley in an evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin. Nichols (2000) included Ruby Valley as part of a regional ground-water study of 16 contiguous valleys in eastern

Nevada. Nichols presents annual estimates of ground-water recharge from precipitation and ground-water discharge by ET in Ruby Valley.

Acknowledgments

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General Description and Setting

Ruby Valley is an elongated, topographically closed basin in northeastern Nevada about 65 mi southeast of Elko, Nev. (fig. 1). The valley occupies a north-south-trending structural basin in the Great Basin region of the Basin and Range physiographic province. The boundary of the Ruby Valley Hydrographic Area (fig. 1), which generally coincides with the drainage-area boundary, encompasses about 1,000 mi^2 in Elko and White Pine Counties.

Entrance to Ruby Valley is provided by two paved and several dirt roads. Under most weather conditions, access is by numerous gravel-surfaced roads. The residential population is distributed among several ranches around the west, north, and northeast sides of the valley. The principal industry is ranching, supported by large acreages of irrigated hay meadows. Near the center of the valley is Franklin Lake (fig. 2), 3,200 acres of which are managed by the Nevada Division of Wildlife. The Ruby Lake NWR headquarters and Gallagher State Fish Hatchery are located along the east flank of the Ruby Mountains adjacent to Ruby Lake, in the southern part of the valley. Shanty Town, a seasonal community, is about 3 mi south of the refuge headquarters.

Physiography

Named for the red garnets found in the area (Harolds Club, 1951), the Ruby Mountains form the entire western border of Ruby Valley. This mountain range is a narrow, asymmetrical fault block that extends nearly 100 mi to the south from its northern extension near Wells, Nev. Along nearly its entire length, the east slope of the Ruby Mountains is steeper than the west slope; in many places, the crest of the range is west of the drainage divide (Sharp, 1940, p. 343). Several peaks in the range have altitudes that exceed 11,000 ft. The Ruby Mountains merge in the north with the East Humboldt Range (fig. 1), which forms the northeast border of the valley. Summit altitudes of the East Humboldt Range are between 8,000 ft and 11,000 ft. The Ruby Mountains and the East Humboldt Range are the most dominant features in the study area and are the principal source areas for inflow water to Ruby Valley. The eastern border of the valley is composed of low hills and alluvial divides in the north and the Maverick Springs Range (fig. 1), which reaches altitudes of nearly 8,000 ft, in the south.

The floor of Ruby Valley lies just above an altitude of 5,900 ft, making it one of the higher valleys in the Great Basin. The valley is divided into two internally drained basins separated by an alluvial ridge at an altitude of about 6,000 ft. The lowest parts of these two basins are occupied by Franklin Lake in the north and Ruby Lake in the south. Wave action of the two lakes, aided by sediment from Harrison Pass Creek (fig. 2), probably built the alluvial ridge that separates the two lakes (Sharp, 1938, p. 318). The altitude of the valley floor increases northward from Franklin Lake to about 6,100 ft and southward from Ruby Lake to about 6,300 ft. Streams issuing from the east side of the Ruby Mountains north of Harrison Pass Creek and from the southwest flank of the East Humboldt Range terminate in Franklin Lake. Franklin Lake is an intermittent lake that was completely dry for 6 of the 26 years from 1960 to 1986 (Csuti, 1987). The Franklin Lake drainage area covers the northern two-thirds of the Ruby Valley Hydrographic Area. Streams south of and including Harrison Pass Creek and those issuing from the Maverick Springs Range terminate in Ruby Lake. Most of these streams are perennial only in the canyons and along the uppermost parts of the alluvial slopes.

Ruby Lake, in the southern third of Ruby Valley, is the site of the Ruby Lake NWR (fig. 2). The refuge covers nearly 38,000 acres of wetland and adjacent areas consisting of meadow, grassland, and shrub upland. The wetland area is divided into numerous marsh management units that are separated by earthen dikes (visible in fig. 2 as linear features crossing open water). During years of average precipitation, the wetland area covers about 14,000 acres in the spring and declines to about 11,000 acres in the fall. After several years of below-average precipitation, the area of the wetland decreases to about 1,000 acres that generally are located in the southern part of the refuge. The predominant water source for the refuge is spring discharge along the western edge of Ruby Lake. Ruby Lake is thought to have never dried up during any historic droughts (Thompson, 1992, p. 2).

Hydrogeology

The existence of Ruby Lake and associated wetlands stems in large part from the unusual hydrogeology of the southern Ruby Mountains (Eakin and Maxey, 1951, p. 82–83; Dudley, 1967). The southern Ruby Mountains (south of Harrison Pass Creek) consist of a nearly complete Paleozoic section (more than 17,000-ft thick) of mostly carbonate rock ranging in age from Cambrian to Mississippian (?) (Sharp, 1942, p. 651). This Paleozoic section is dominated by two cavernous limestone units with high permeability that are separated by carbonate rocks of low-to-moderate permeability (Dudley, 1967, p. 13). Because limestone can be dissolved by ground water that contains carbon dioxide, springs capable of discharging large quantities of ground water have developed along enlarged fissures within the carbonate rocks of the southern Ruby Mountains.

The movement of ground water toward Ruby Lake from the west is controlled by the permeability and stratigraphic positions of these carbonate rocks. Movement of ground water is significantly enhanced by their eastward dip. Sharp (1942, p. 685) suggests that the large and uniform discharge from Cave Spring, and presumably the discharge from other springs issuing from carbonate rocks along the east side of the southern Ruby Mountains (fig. 2), is primarily interbasin flow originating in areas west of the topographic divide. The highly permeable, eastward-dipping carbonate rocks may transmit large quantities of ground water from infiltrated streamflow originating on the west slope of the Ruby Mountains (Rush and Everett, 1966, p. 13). This infiltrated streamflow appears as springs that discharge from the alluvium along the west margin of and possibly beneath Ruby Lake, thereby providing a substantial portion of inflow to the Ruby Lake NWR.

The floor of Ruby Valley has been downdropped relative to the adjacent mountains, forming a structural basin that is filled with interbedded deposits of gravel, sand, silt, and clay derived primarily from adjacent mountains. These deposits form the basin-fill aquifer, which is bounded and underlain by consolidated rock. According to water-level data collected in September 2000, ground water in the basin-fill aquifer beneath the southern part of Ruby Valley moves toward Ruby Lake from recharge source areas in adjacent mountains (fig. 2). Water-level data also suggest that ground water moves northward from Ruby Lake toward Franklin Lake under a gradient of about 5 ft/mi.

Climate

Ruby Valley is in a middle-latitude desert and steppe climate that is dominated by tropical air masses in the summer and continental polar air masses in the winter (Houghton and others, 1975, p. 13, 69–70). In the Ruby Mountains and East Humboldt Range, average annual precipitation, based on Snowpack Telemetry (SNOTEL) data (1961–90) from five stations (fig. 1) at altitudes ranging from 7,700 to 8,500 ft, is about 32 in. (Greenlee, 1992). Precipitation data collected at the headquarters of Ruby Lake NWR (altitude = 6,012 ft) and a weather station at Arthur in the northern part of Ruby Valley (altitude = 6,300 ft) suggest that average annual precipitation on the valley floor during a 30-year reference period (1961–90) ranged from about 13 to 15 in. During the period of data collection for this study (May 1999–November 2000), total precipitation at the Ruby Lake NWR was about 53 percent of the 30-year average (fig. 3). Average annual precipitation for the 3 years preceding this study (1997–99) was about 12 percent greater than the 30-year average.

Temperature data collected at the refuge headquarters for 1961–90 indicate that daily maximum temperatures in the summer typically exceed 85°F and reach 100°F on only 1 or 2 days during late July or early August. The average daily minimum summer temperature is about 40°F. Daily maximum temperatures during the winter range between 30°F and 50°F and daily minimum temperatures typically range from about 0 to 30°F but have been recorded as low as -15°F in January. Evaporation measurements collected from 1978 through 2000 at the refuge headquarters indicate that pan evaporation from April through October is about 48 in.

Plant Communities

Habitats in Ruby Lake NWR include perennial wetlands and adjacent drier areas that support a wide variety of plant communities. The diversity of plants

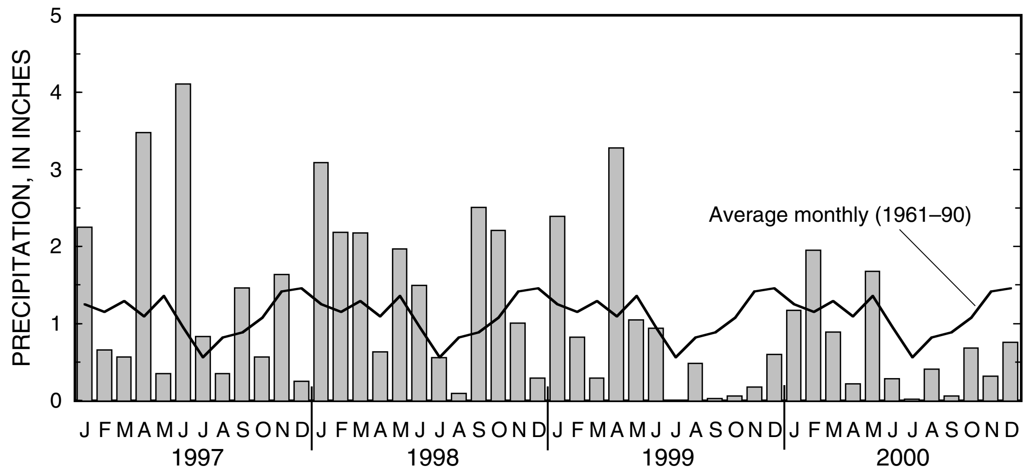

Figure 3. Monthly precipitation for 1997–2000 and average monthly precipitation for 1961–90, Ruby Lake National Wildlife Refuge, northeastern Nevada.

in these communities reflects, in large part, the hydrogeologic setting of the southern part of Ruby Valley. For purposes of this study, the most aerially extensive habitats found on the refuge are grouped by general plant communities and by the source of water consumed by ET.

Wetlands in the refuge consist of areas of open water that contain submerged aquatic vegetation as well as areas of dense bulrush marsh and scattered stands of cattails. Dispersed within the wetlands are small islands covered with grasses and bare soil. Seasonally flooded playas occupy large areas along the north and east sides of the refuge. During prolonged dry periods the playas become sparsely colonized by grasses.

Changes in the type of plant community occur with increasing distance from the wetland as soils become drier and depths to ground water increase. In general, wetland is bordered by meadow in places where the water table rises periodically and causes flooding, or is very near the land surface. Along the west margin of the wetlands a transition occurs from meadow and grassland to desert-shrub upland as land-surface altitudes increase toward the Ruby Mountains. The numerous springs along the western and southern parts of the refuge create areas of lush meadow and riparian habitat. In contrast, the meadows on the eastern side of the refuge are much less extensive and are bordered by large areas of sparse grasses, mixed phreatophytic shrubs, and associated areas of bare soil. These habitats eventually merge with desert-shrub upland along the western flanks of the Maverick Springs Range (fig. 2).

METHODS OF ESTIMATING EVAPOTRANSPIRATION

Seasonal and annual ET rates were determined by estimating site-specific daily ET rates in major habitats and applying these rates to similar areas throughout the refuge. Instrumentation was installed at nine sites to collect micrometeorological data for estimating ET using the Bowen-ratio and eddy-correlation methods. The sites represented wetland, meadow, areas of mixed phreatophytic shrubs and associated bare soil, and desert-shrub upland (table 1).

Year-round accessibility was a factor in the selection of ET sites. In warm weather, access to the wetland sites was by non-motorized canoe. During the winter, when much of the wetland is covered by surface ice, access was by an air boat. The remaining sites were easily reached with field vehicles.

Also considered was fetch, which was deemed adequate at each ET site. Fetch, the horizontal distance from the ET measurement site to a change in surface conditions in the direction of prevailing winds, is assumed to be adequate at 100 times the instrument height (Campbell, 1977). Prevailing winds on the refuge typically came from the southwest during the data-collection period. Adequate fetch implies that the surface is uniform so that the profile of air flow across the area of interest is approximately constant.

Table 1. Location and general description of evapotranspiration sites, Ruby Lake National Wildlife Refuge, northeastern Nevada

Site name	Latitude [1]	Longitude[1]	Altitude[1] (feet above sea level)	Method used to estimate ET [2]	Period of data collection	Site description [3]
Open water	40°04′49″	115°30′26″	5,965	Bowen ratio	May 22, 1999–November 13, 2000	Open water; submerged aquatic vegetation; water depth varies seasonally from 3 to 5 ft.
Bulrush marsh	40°13′34″	115°28′04″	5,964	Bowen ratio	May 21, 1999–November 13, 2000	Moderate-to-dense cover of bulrush and cattails; depth to ground water varies seasonally from 1 to 3 ft.
Meadow	40°04′40″	115°31′00″	5,968	Eddy correlation	May 26, 2000–August 29, 2000	Dense cover of mixed sedges, rushes, and grasses; surface periodically floods; depth to ground water less than 2 ft.
Phreatophyte-1	40°10′13″	115°27′19″	5,967	Bowen ratio	May 28, 1999–November 5, 2000	Moderate cover of saltgrass, rubber rabbitbrush, basin wildrye, and greasewood; depth to ground water less than 5 ft.
Phreatophyte-2	40°17′31″	115°25′00″	5,970	Eddy correlation	August 31, 2000–September 19, 2000	Moderate cover of rubber rabbitbrush, basin wildrye, greasewood, and big sagebrush; depth to ground water about 5 ft.
Phreatophyte-3	40°08′34″	115°26′48″	5,970	Eddy correlation	May 26, 2000–July 19, 2000	Moderate cover of rubber rabbitbrush, basin wildrye, greasewood, and big sagebrush; depth to ground water about 10 ft.
Phreatophyte-4	40°10′16″	115°27′17″	5,967	Eddy correlation	July 21, 2000–August 29, 2000	Moderate cover of saltgrass, rubber rabbitbrush, basin wildrye, and greasewood; depth to ground water less than 5 ft.
Phreatophyte-5	40°10′13″	115°26′39″	5,980	Eddy correlation	August 31, 2000–September 18, 2000	Sparse-to-moderate cover of greasewood, rubber rabbitbrush, basin wildrye, and big sagebrush; depth to ground water about 17 ft.
Desert-shrub upland	40°04′25″	115°32′04″	6,080	Bowen ratio	June 20, 1999–November 12, 2000	Moderate cover of black sagebrush and green rabbitbrush; depth to ground water greater than 80 ft.

[1] Latitude and longitude determined using global positioning systems based on 1983 datum. Altitudes estimated from U.S. Geological Survey 1:24,000-scale maps: Ruby Lake NW, 1968; Franklin Lake SW, 1968; Sherman Mountain, 1985.

[2] See section "Methods of Estimating Evapotranspiration" for description of each method.

[3] Plant cover: sparse, 5 to less than 25 percent; moderate, 25 to less than 75 percent; dense, 75 percent or greater. Only dominant plants are listed in order of relative abundance. Water depths are for period of ET data collection and were estimated from water levels measured in selected wells (fig. 2).

Energy Budget and the Bowen-Ratio Method

During the ET process, energy is used to convert water from liquid to vapor and transfer the vapor to the atmosphere. The Bowen-ratio and eddy-correlation methods, which were used in this study to estimate ET, are based on characteristics of the energy budget associated with atmospheric fluxes. The symbols and forms of the equations used in these methods are listed on pages V and VI (see "Contents" section) and generally follow the nomenclature of Laczniak and others (1999). Detailed information on the equations and methods used in this study to estimate ET is in Nichols (1992) and Laczniak and others (1999).

The balance between incoming and outgoing energy fluxes can be mathematically expressed by the one-dimensional form of the energy-budget equation (eq. 1). In the environment, energy is partitioned by the energy budget into four principal flux components: (1) net radiation, (2) subsurface-heat flux, (3) sensible-heat flux, and (4) latent-heat flux. The term flux refers to flux density, which represents the amount of energy that flows through a horizontal surface of unit area per unit time. Energy terms related to biological processes, such as photosynthesis and the storage of heat in plant biomass, are considered negligible, thus are not included in the energy budget. Energy terms related to the horizontal transfer of heat also are not included because they are assumed to be small compared to the vertical transfer of heat.

Net radiation, which depends on the temperature and reflectivity of the surface exposed, is the major energy source that drives ET processes. Net radiation, the sum of all incoming and outgoing radiation at the surface of the Earth, is considered positive when the sum of incoming radiation exceeds the sum of outgoing radiation (eq. 2).

The subsurface-heat flux is the amount of energy stored in the soil or water column. Because one site was set up over water, the usual soil-heat flux term in the energy-budget equation was replaced with the term subsurface-heat flux (Laczniak and others, 1999, p. 20). The subsurface-heat flux associated with the soil is a function of the change in soil temperature with depth and the thermal and physical properties of the soil (eq. 3). For water, the subsurface-heat flux is a function of the change in temperature of water with depth and the specific heat and density of the water (eq. 4).

Sensible-heat flux is the amount of energy that heats the air directly above the soil, plant canopy, or water surface (eq. 5). Sensible-heat flux is temperature-driven and directly relates to the turbulent transfer of heat.

Energy that is consumed by ET is the latent-heat flux, which is related to the vapor-pressure gradient and the turbulent transfer of vapor (eq. 6). At the Earth's surface, the difference between net radiation and subsurface-heat flux is the energy available (eq. 7) for sensible- and latent-heat fluxes (often called turbulent fluxes).

Net radiation and subsurface-heat flux can be measured in the field using available instrumentation. Sensible-heat and latent-heat fluxes are not easily estimated because turbulent transfer coefficients (k_h and k_v in eqs. 5 and 6, respectively) are difficult to determine. However, Bowen (1926) determined that if the transfer coefficients are assumed to be equal, the ratio of sensible-heat flux to latent-heat flux is proportional to the ratio of the vertical gradients of temperature and vapor pressure above a surface. This ratio between sensible-heat flux and latent-heat flux is known as the Bowen ratio (eq. 8; Bowen, 1926) and can be approximated from measurements of air temperature and relative humidity at two different heights. Under certain conditions, the Bowen ratio approaches -1 and application of the method is invalidated. When this happens, the calculated value of latent-heat flux (eq. 6) loses numerical meaning (Ohmura, 1982, p. 596). This condition seldom occurred. When it did, however, an average of latent-heat flux from the previous and subsequent time periods was used. In most instances, this condition took place during periods of low ET and probably had little effect on the daily ET computation. The ratio of sensible-heat flux to latent-heat flux was used in a modified form of the energy-budget equation (eq. 9) along with micrometeorological data to compute ET at the four Bowen-ratio sites in the refuge (table 1).

Instrumentation and sensors that could operate for long periods under such adverse weather conditions as high winds, freezing rains, and possible accumulations of snow and ice were required to collect data continuously for application of the Bowen-ratio method. Variations of Bowen-ratio instrumentation also were required to accommodate the differences between sites on land and those over water or bulrush-marsh areas. Solar panels were installed at all sites to recharge batteries used to power the instruments. Energy fluxes and ET were computed every 20 minutes based on a

10- or 30-second sampling interval and were summed to compute daily ET. A schematic of the typical instrument arrangements used to collect micrometeorological data over land and over open water or bulrush marsh is in figure 4.

Instrumentation at the Bowen-ratio land sites (fig. 4*A*) consisted of:

- two solid-state temperature and relative-humidity probes mounted on an exchange mechanism to measure air temperature and relative humidity at two heights;
- two anemometers to measure wind speed;
- a net radiometer to measure net radiation;
- a set of soil-heat flux plates, thermocouples, and a water-content reflectometer to compute the subsurface-heat flux; and
- two infrared temperature sensors to measure plant-canopy and soil temperatures.

Instrumentation at the open-water and bulrush-marsh sites (fig. 4*B*) was similar to that of the land sites but with a slightly different arrangement. To compute the subsurface-heat flux to or from the water, three thermistor temperature probes extending downward through the water column replaced the heat-flux plates and themocouples. At the open-water site, the temperature and relative humidity of the air were measured at only one height above the water surface. A single anemometer was used to measure wind direction. A floating thermistor measured water-surface temperature, from which (saturated) vapor pressure was calculated. Temperature and vapor pressure differences were computed between the water surface and the elevated sensor. Staff gages were installed at the wetland sites to determine changes in water depth. Data were stored at the Bowen-ratio sites on data loggers and could be retrieved through telecommunication systems.

Eddy-Correlation Method

Eddies are turbulent, highly rotational air flows that move across the surface of the earth transporting water vapor and heat between the surface and the atmosphere. In turbulent air flow, fluxes of water vapor and heat vary irregularly in time and space; for this reason, statistical analyses are used to represent turbulent flow. Covariances between two fluctuating variables such as vertical wind speed and water vapor or vertical wind speed and temperature are directly related to turbulent flux (Arya, 1988, p. 118). The eddy-correlation method consists of determining the turbulent fluxes of latent and sensible heat from the covariance of vertical wind speed with vapor density and with air temperature. Latent-heat flux is determined by the covariance of instantaneous departures from the average values of wind speed and vapor density (eq. 10). Latent-heat flux is corrected for oxygen effects (Tanner and Greene, 1989) and for density differences caused by heat and vapor transfer (Webb and others, 1980). Sensible-heat flux is determined by the covariance of instantaneous departures from the average values of wind speed and air temperature (eq. 11).

Net radiation and subsurface-heat flux also are measured at each eddy-correlation site; together with measurements of latent- and sensible-heat flux, these measurements allow an energy budget to be estimated. Evaluation of the energy budget using data collected at eddy-correlation sites provides an indication of instrument efficiency in measuring the available energy. A nonzero energy-budget closure typically suggests instrumentation problems; however, the source of the discrepancy usually is difficult to determine. The uncertainty in computing ET rates by the eddy-correlation method can be inferred from the size of the closure residual. Relative closure of the energy budget is the amount of imbalance relative to the available energy and indicates the amount of available energy that is not accounted for by measurements of turbulent fluxes (eq. 12; Johnson, 1995, p. 7). Although the eddy-correlation method is the most reliable and direct measurement of turbulent fluxes, the method requires sophisticated fast-response instrumentation.

Two similar sets of eddy-correlation instrumentation were used for data collection at five sites. A typical instrumentation configuration for the eddy-correlation method consists of:

- a sonic anemometer with a fine-wire thermocouple to measure instantaneous changes in vertical wind speed and air temperature, respectively, which are used to determine sensible-heat flux;

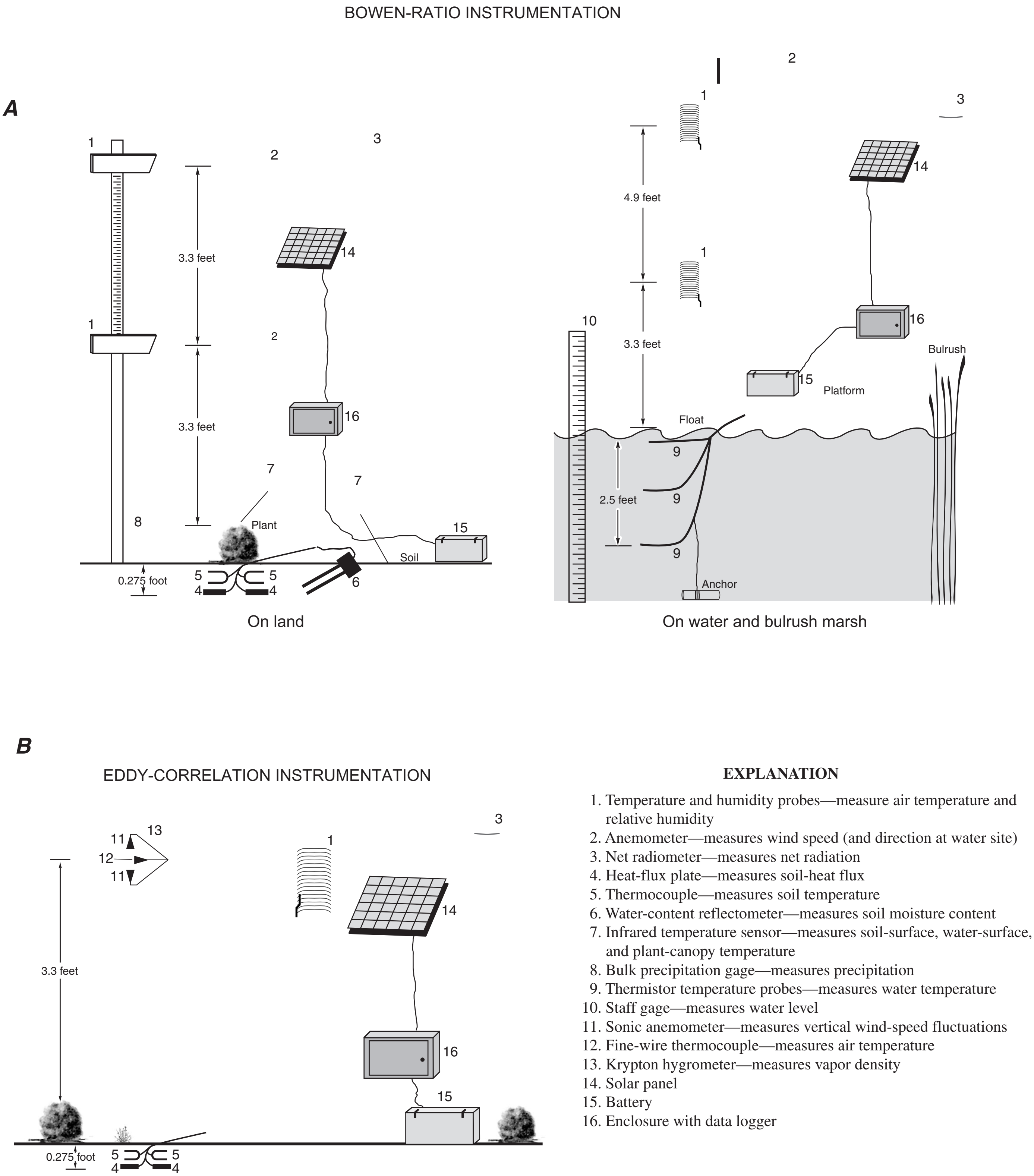

Figure 4. Schematic diagram of typical instrumentation used to collect micrometeorological data for computing the energy budget and estimating evapotranspiration: (*A*) Bowen-ratio instrumentation over land, open water, and bulrush marsh; and (*B*) eddy-correlation instrumentation over land.

- a krypton hygrometer to measure instantaneous changes in air-vapor density in combination with changes in vertical wind speed, which are used to determine latent-heat flux;
- a net radiometer to measure net radiation;
- a set of soil-heat flux plates and thermocouples to compute subsurface-heat flux; and
- a solid-state temperature and relative humidity probe to measure air temperature and relative humidity, respectively, at one height (fig. 4*B*).

Data were stored on data loggers and were retrieved during site visits.

EVAPOTRANSPIRATION FROM HABITATS

Micrometeorological data used in estimating the energy budget were collected at nine sites that represented five of the most aerially extensive habitats in the refuge (table 1). The source and amount of water consumed by ET, in part, is a function of the conditions at each site. Daily ET rates, computed by summing ET calculations made for each 20-minute period, are given in appendices 1–5. The period of data collection at Bowen-ratio sites began in early summer 1999 and ended in November 2000. Data at eddy-correlation sites were acquired at different times during the summer of 2000.

Site Locations and Conditions

The open-water and bulrush-marsh sites were selected primarily to measure the amount of water consumed by ET in the wetland area (fig. 2). The Bowen-ratio method was used to estimate daily ET for more than 540 consecutive days at both sites (apps. 1 and 2). Ruby Lake is the primary source of water for ET in the wetland. Water within the lake is derived principally from springs discharging along the west and southwest side of the refuge and beneath the lake, and from precipitation that falls directly on the lake.

The open-water site was located in the extreme southern part of the South Marsh (figs. 2 and 5*A*; table 1). Historically, the South Marsh has remained at least partially flooded during prolonged dry periods while other water bodies in the refuge desiccate. In June 1985, open water covered about 1,030 acres in the South Marsh (Nichols, 2000, C17). During this study, the water level at the open-water site initially was 4.3 ft in May 1999, but fell 1.5 ft by September 1999. During the winter (October 1999–April 2000) the water level rose about 1.0 ft, but dropped 2.3 ft by September 2000. The bulrush-marsh site was located in a moderately dense stand of bulrush (*Scirpus robustus*) with scattered cattails (*Typha* spp.) in the southern part of the North Marsh (figs. 2 and 5*B*; table 1). The initial water level at the bulrush-marsh site was about 3.0 ft in May 1999 and declined by 1.6 ft in September 1999. In March 2000 the water level was about 2.8 ft and dropped 1.6 ft by September 2000. The extent of the wetland area decreased by about 4,500 acres between March and September 2000.

In general, surface-water levels throughout the wetland were 1.0 ft lower in the summer of 2000 (May–September) than in the summer of 1999 (USFWS, written commun., 2000). This decline in water level is largely due to the smaller amount of precipitation during the 1999–2000 winter (October 1999–April 2000) than during the preceding winter (October 1998–April 1999; fig. 3).

Meadows along the western and southern parts of the refuge are found in association with springs and areas of frequent flooding from rising ground water. Eddy-correlation instrumentation was set up in a meadow in the southern part of the refuge, less than 1/4 mi from the South Marsh (figs. 2 and 6*A*; table 1). Daily ET at the meadow site was computed from data collected continuously from May 26 through August 29 except for 19 days at the end of July when the data logger malfunctioned (app. 5). Plants at the meadow site consist primarily of sedges (*Carex* spp.), rushes (*Juncus* spp.), and some grasses and herbaceous species. Depth to ground water beneath the site was estimated to be less than 2 ft during the period of data collection and the soil generally was moist. Although the meadow site has been subject to periodic flooding in years of above-average precipitation, the site was not flooded during this study.

Mixed phreatophytic shrubs and associated areas of bare soil are found in a broad expanse along the east, northeast, and southeast sides of the refuge that is not subject to flooding (fig. 7). ET typically exceeds seasonal precipitation in these areas because the plants have access to ground water for transpiration. Five sites were selected to estimate ET from various mixtures of phreatophytic shrubs using both the Bowen-ratio and eddy-correlation methods (fig. 2; table 1). The plant species of interest at the phreatophyte sites include

Table 2. Average, maximum, minimum, and seasonal daily evapotranspiration rates, and seasonal and annual total evapotranspiration, computed using Bowen-ratio method, September 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Site name	Evapotranspiration (inches)							
	Average daily	Maximum daily	Minimum daily	Winter daily average (Oct. 1999–April 2000)	Summer daily average (May 2000–Sept. 2000)	Winter total	Summer total	Annual total [1]
Open water	0.174	0.464	0.001	0.112	0.260	23.85	39.99	63.64
Bulrush marsh	.137	.396	.008	.062	.242	13.18	37.06	50.24
Phreatophyte-1	.043	.146	.006	.028	.065	5.96	9.93	15.89
Desert-shrub upland	.033	.160	.003	.029	.035	6.17	5.78	11.96

[1] Annual total based on 2000 water year (October 1999–September 2000).

saltgrass (*Distichlis stricta*), rubber rabbitbrush (*Chrysothamnus nauseosus*), basin wildrye (*Elymus cinereus*), greasewood (*Sarcobatus vermiculatus*) and big sagebrush (*Artemesia tridentada* spp. *tridentada*). At each phreatophyte site about 30 to 35 percent of the area was vegetated and the remaining area was bare soil. During data collection the depth to ground water at the five phreatophyte sites ranged from less than 5 ft to nearly 20 ft (table 1). Ground-water levels measured in wells near the phreatophyte sites dropped on average about 2.4 ft between March and September 2000.

Bowen-ratio instrumentation was set up at the phreatophyte-1 site (fig. 7*A*) and daily ET was computed continuously for 502 days (app. 3). Data were collected at the remaining four phreatophyte sites using two similar sets of eddy-correlation instrumentation (app. 5). In late August, the eddy-correlation instrumentation initially set up at the meadow site was moved to the northeastern part of the refuge (phreatophyte-2) until mid-September; data was collected there for 20 days. The second set of eddy-correlation instrumentation began collecting data in late May at the phreatophyte-3 site, then was moved in late July to the phreatophyte-4 site in the same area as the phreatophyte-1 site to compare daily ET rates with those computed using the Bowen-ratio method. The second set of eddy-correlation instrument again was moved in late August to the phreatophyte-5 site (fig. 7*B*), where it remained until mid-September, providing daily ET rates for 19 days.

The desert-shrub upland habitat occupies the higher areas, mostly on the west and northeast sides of the refuge where the depth to ground water is too great to support phreatophytes (fig. 2). In the desert-shrub upland, the source of water for ET is soil moisture derived from precipitation. The depletion of soil moisture typically is equal to ET when precipitation does not occur. The desert-shrub upland site was located in the southwestern part of the refuge on a piedmont slope at an altitude of about 6,080 ft (fig. 6*B*). The Bowen-ratio method was used and daily ET was computed for 512 consecutive days. Dominant plants include black sagebrush (*Artemisia nova*) and green rabbitbrush (*Chrysothamnus viscidiflorus*). The soils at this site were dry and depth to ground water probably was greater than 80 ft. Although ET in the desert-shrub upland area is minor compared to the wetter habitats, it significantly reduces the amount of annual precipitation available for deep percolation and ground-water recharge.

Results and Analysis

Daily and monthly ET rates computed at the four Bowen-ratio sites are presented graphically in figures 8–11. Fluctuations in daily and monthly estimated ET are much more pronounced at the open-water and bulrush-marsh sites (figs. 8 and 9) than at the phreatophyte-1 and desert-shrub upland sites (figs. 10 and 11). Daily fluctuations in ET at a given site are caused by changes in cloud cover and other short-term changes in weather patterns. Differences in ET estimates among sites are, in part, a function of the spatial and temporal differences in the availability of water for ET. The annual variability in daily estimates of ET at the Bowen-ratio sites during the 2000 water year (October 1999–September 2000) are given in table 2.

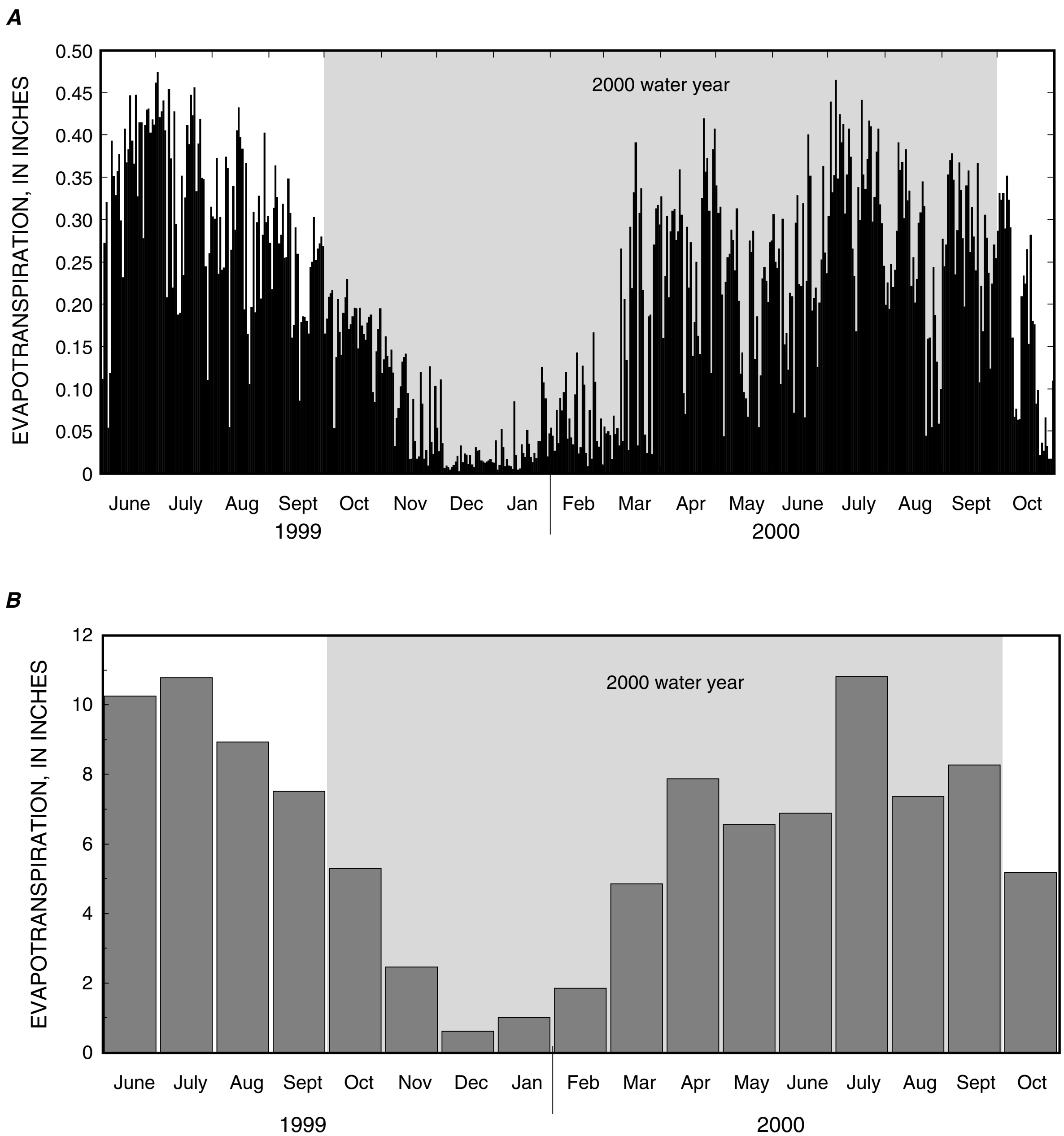

Figure 8. (*A*) Daily, and (*B*) monthly evapotranspiration at the open-water site, June 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

The lowest average rates of daily ET among the Bowen-ratio sites during the 2000 water year were estimated at the phreatophyte-1 and desert-shrub upland sites. In comparison, the average daily ET rates estimated at the open-water and bulrush-marsh sites, where standing water was continuously available for evaporation, were about four to five times greater (table 2). Daily ET at the phreatophyte-1 and desert-shrub upland sites ranged from less than 0.010 in/d during the winter to a maximum of about 0.146 in/d and 0.160 in/d, respectively, in May (apps. 3 and 4). At the open-water and bulrush-marsh sites minimum daily ET rates also were less than 0.010 in/d in the winter, but maximum rates of 0.464 in/d and 0.396 in/d, respectively, occurred in July. The timing of the maximum daily ET rates at the phreatophyte-1 and desert-shrub upland sites

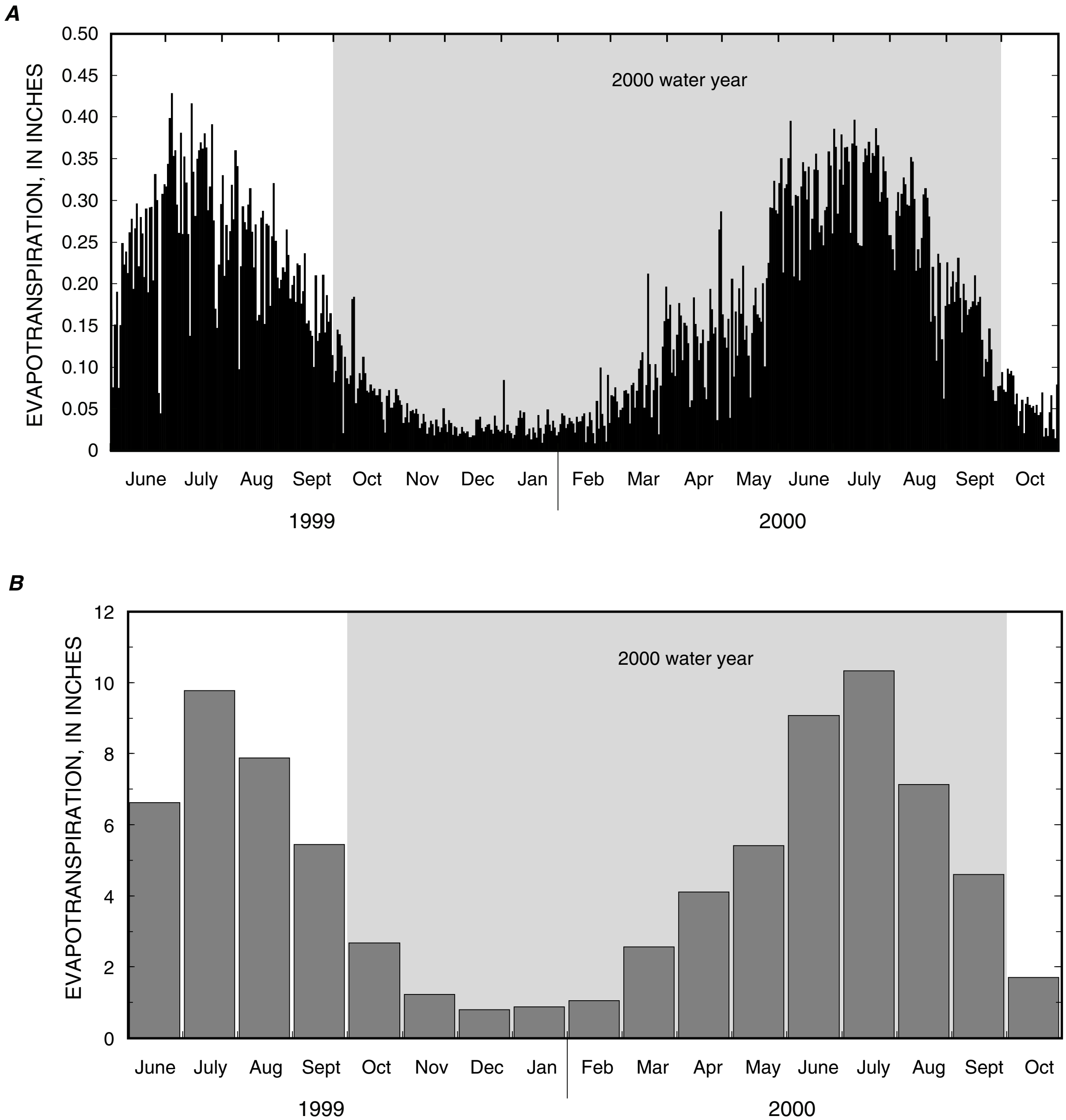

Figure 9. (*A*) Daily, and (*B*) monthly evapotranspiration at the bulrush-marsh site, June 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

reflects the above-average precipitation that occurred during May, which was preceded by two months of below-average precipitation (fig. 3).

A comparison of daily average ET rates (fig. 12) and monthly totals (figs. 8*B* and 9*B*) for the open-water and bulrush-marsh sites shows that ET increased more rapidly from February through April at the open-water site than at the bulrush-marsh site. This less-rapid increase in ET at the bulrush-marsh site is attributed to shading by dead plant material from previous years. Shading can reduce evaporative losses by partitioning energy to sensible heat at the expense of latent heat (Bidlake, 2000, p. 1315). Shading effects also are apparent in the comparison of winter to summer ET (table 2). The winter ET estimate at the open-water site (23.85 in.) is almost twice that at the bulrush-marsh site (13.18 in.);

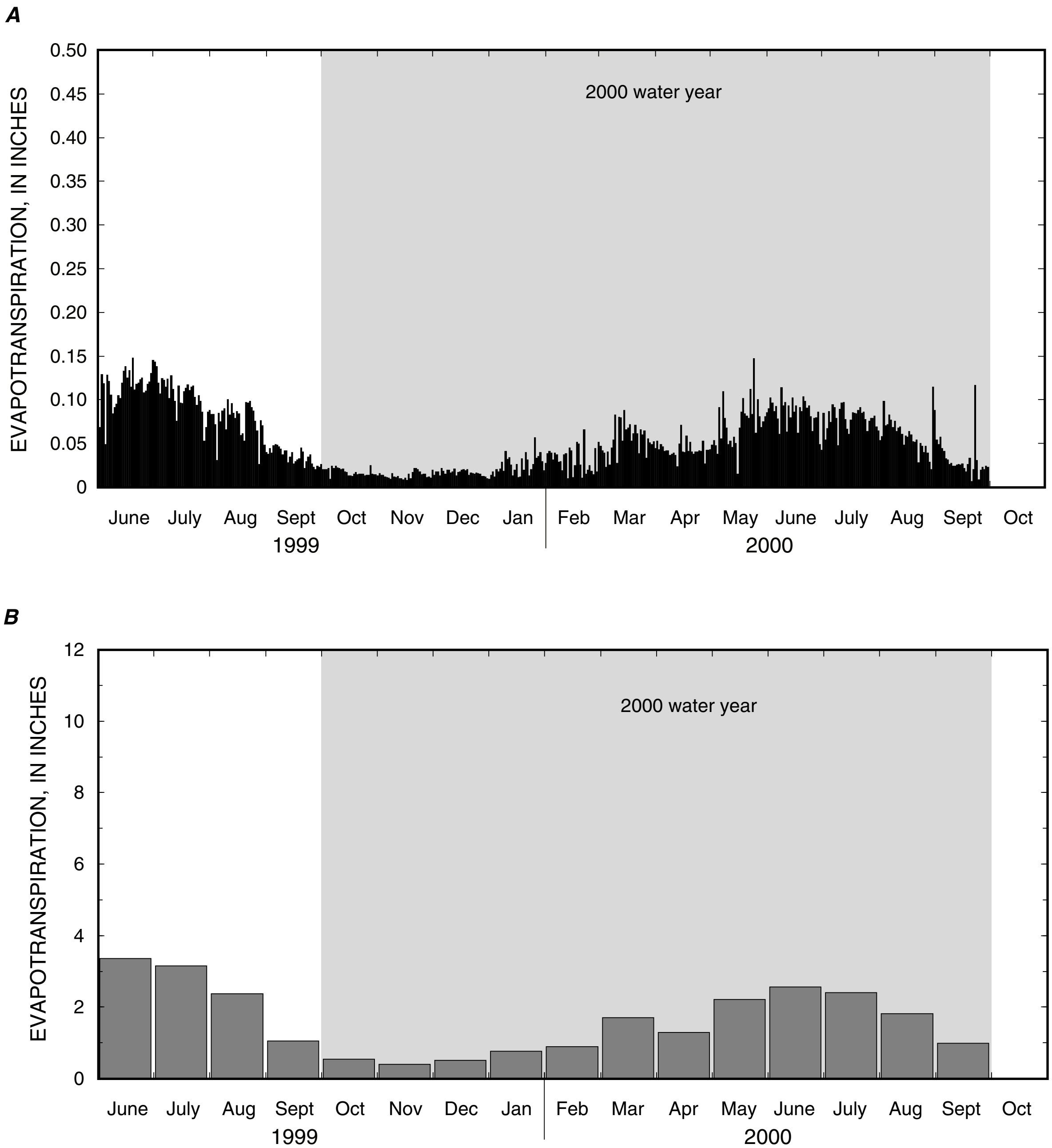

Figure 10. (*A*) Daily, and (*B*) monthly evapotranspiration at the phreatophyte-1 site, June 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

however, ET is similar at the two sites during summer. Laczniak and others (1999, p. 33) suggest that, in vegetated areas, shading by dead vegetation reduces winter evaporation by maintaining relative humidity near saturation and decreasing air exchange. Shading also is somewhat decreased in the summer by the higher angle of the sun, allowing direct evaporation from the water to make up more of the summer ET.

Temporal differences in water source and availability also appear to cause variations in daily ET between those sites where plants rely solely on soil moisture and those that use a combination of soil moisture and ground water. Beginning in November 1999 and up through May 2000 estimates of average daily ET were similar at the phreatophyte-1 and desert-shrub upland sites (fig. 12). Average daily ET nearly

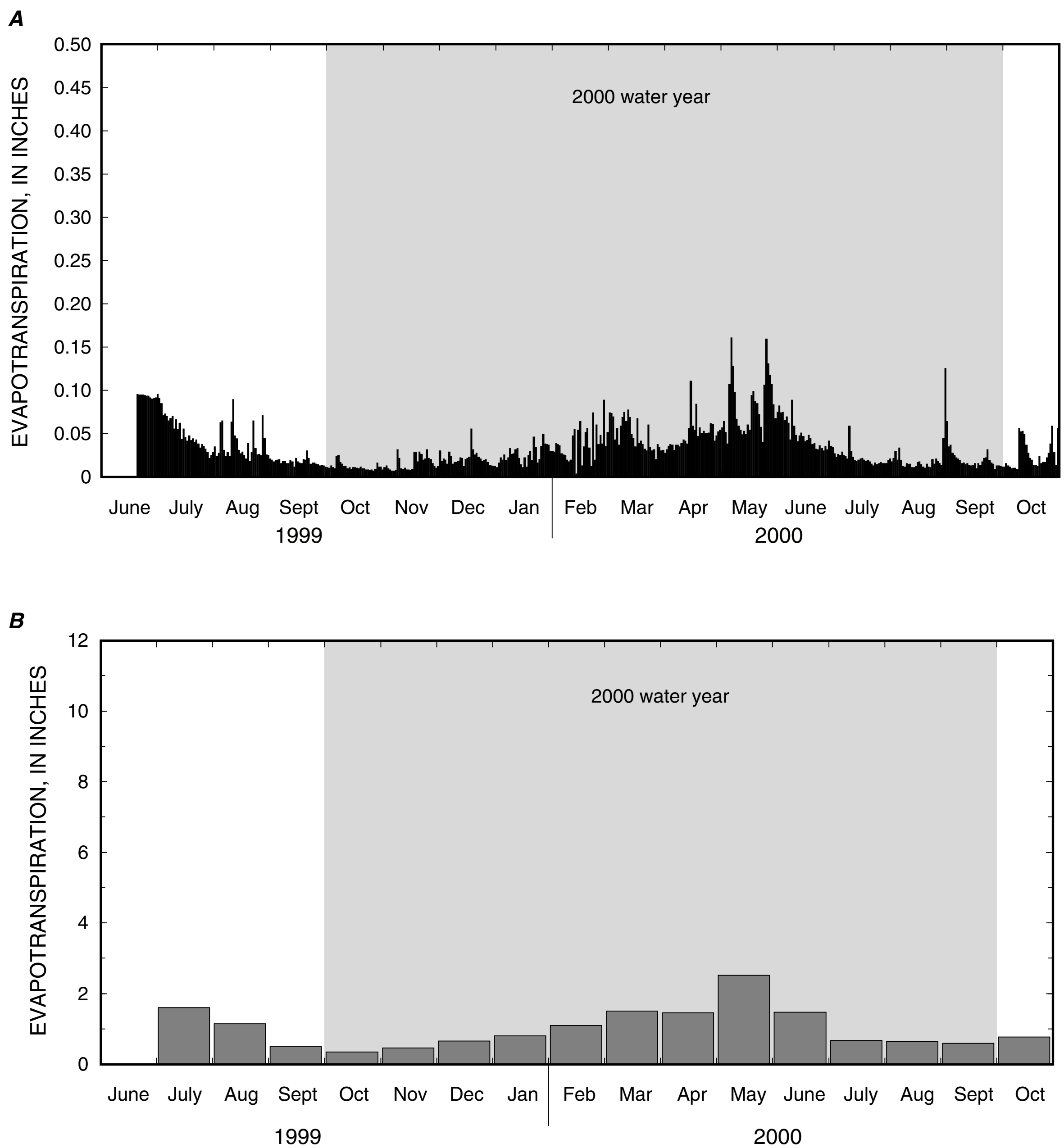

Figure 11. (*A*) Daily, and (*B*) monthly evapotranspiration at the desert-shrub upland site, June 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

doubled at both sites in May as a result of increased soil moisture from precipitation (fig. 13). As the moisture content in the shallow soils decreased following the May precipitation, average daily ET at the upland site also decreased while average daily ET at the phreatophyte-1 site reached a summer maximum in June (fig. 12). At phreatophyte-1, where the water table is shallow, plants are able to use ground water directly to supplement the soil moisture available for transpiration. Daily ET at the phreatophyte-1 site remained relatively constant through July and gradually decreased as available energy decreased (fig. 14).

Although daily ET data estimated at the eddy-correlation sites are limited in duration, some general statements and comparisons can be made. Total ET estimated at the meadow site for a span of 84 days,

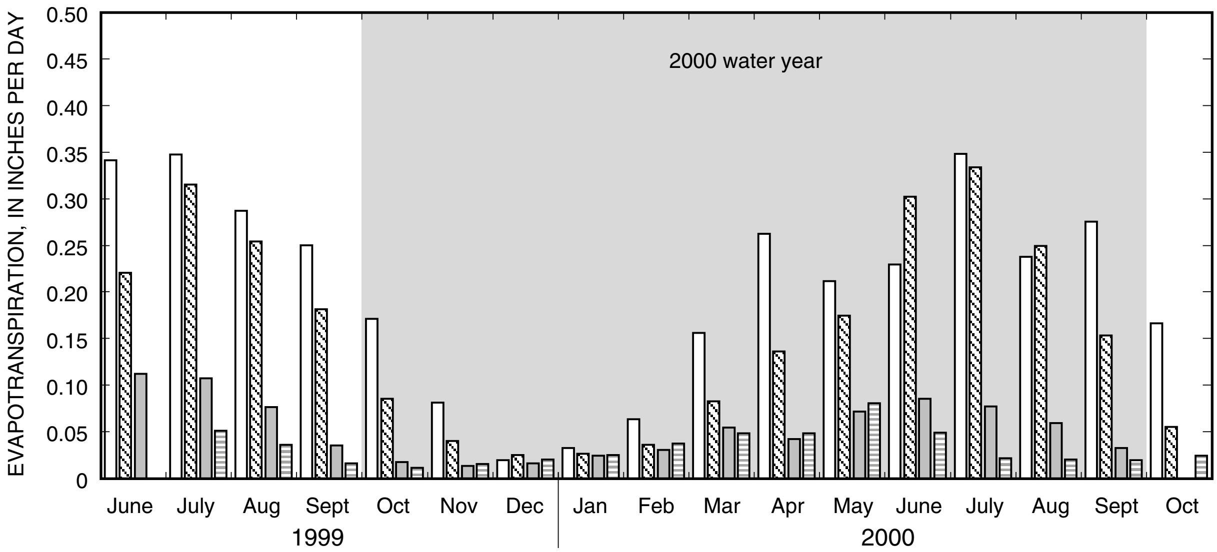

Figure 12. Average daily evapotranspiration at Bowen-ratio sites, June 1999–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

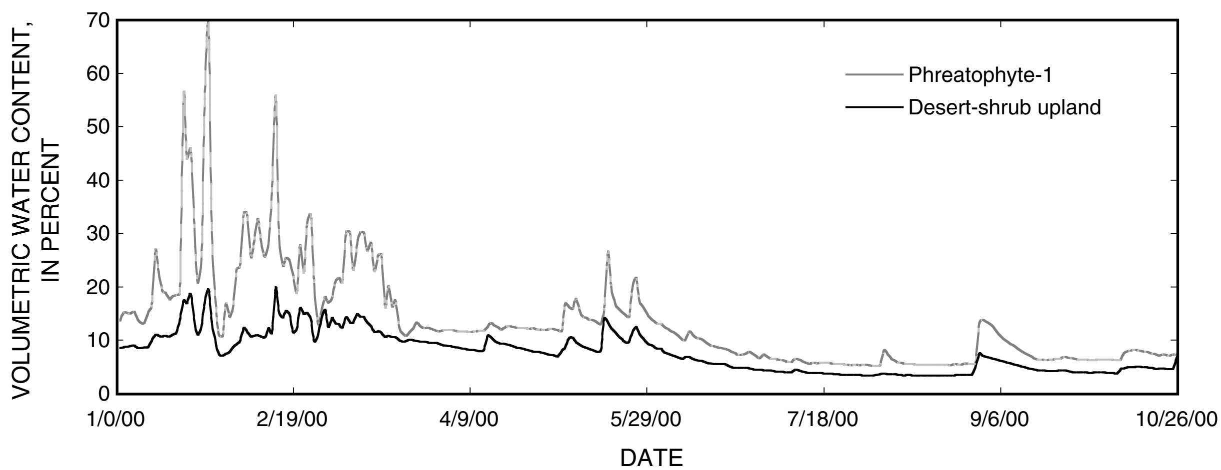

Figure 13. Daily average volumetric water content of shallow soils at phreatophyte-1 and desert-shrub upland sites, January–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

about 55 percent of the summer period, was 10.73 in., more than two-thirds of the annual ET of 15.89 in. estimated at the phreatophyte-1 site (table 2). The daily energy budget closure at the meadow site, calculated as the difference between available energy and turbulent fluxes, averaged 23.9 W/m^2 (table 3). This residual suggests that about 17.2 percent of the available energy at the meadow site was not accounted for by measurements of the turbulent fluxes and the imbalance is due either to measurement or computational error.

The remaining eddy-correlation sites provided daily estimates of ET for periods of 19 to 51 days from areas with various mixtures of phreatophytic shrubs (table 1). In a comparison of average daily

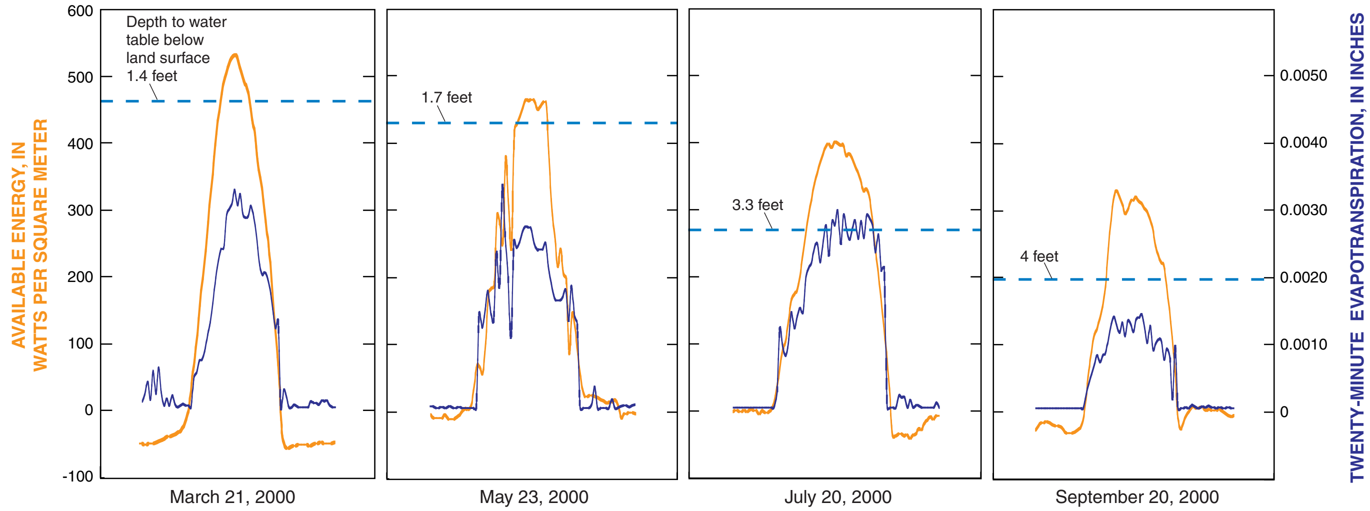

Figure 14. Available energy and 20-minute evapotranspiration computed from micrometeorological data collected at phreatophyte-1 site, and depth to water collected at nearby well, March 21, May 23, July 20, and September 20, 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

ET computed at the phreatophyte sites, the eddy-correlation method generally provided a lower value for ET than was provided by the Bowen-ratio method (fig. 15). On corresponding days, average daily ET at the phreatophyte-2 site was 0.012 in/d less than at the phreatophyte-1 site. At the phreatophyte-3 site, ET was 0.021 in/d less than at phreatophyte-1. At the phreatophyte-5 site, ET was 0.009 in/d less than at phreatophyte-1.

The best correlation between methods was at the phreatophyte-1 and phreatophyte-4 sites; on corresponding days, ET computed at the phreatophyte-4 site was only 0.001 more than at phreatophyte-1. Although the two sites were about 100 ft apart, the average difference in available energy was 3 percent, suggesting that similar available-energy conditions existed at both sites. Energy-budget closure at phreatophyte-4 was 20.1 W/m^2 with a 16.3-percent relative closure (table 3). The average energy-budget closure for the remaining three eddy-correlation sites ranged from 33.1 W/m^2 computed at phreatophyte-5 to 61.4 W/m^2 computed at phreatophyte-2. The energy-budget closure generally was positive, indicating that either available energy was overestimated or turbulent fluxes were underestimated (Sumner, 1996, p. 18).

ET rates presented represent total ET at a given site and as such include the volume of precipitation that fell during the data-collection period at each site that was consumed by plants. ET rates estimated for one particular habitat are assumed, in this study, to be representative of ET rates in similar habitats throughout the refuge. The uncertainty in ET computed by the Bowen-ratio method is a composite of errors introduced in measuring net radiation and subsurface-heat flux, and in measuring air temperature and relative humidity at two heights. One potential source of error is the instrumentation used to measure the variables needed to compute the flux components. Tomlinson (1995, p. 15) suggests, based on instrument error analysis, that about a 12-percent change in the final ET estimate would be expected if all instruments varied by a maximum amount. Analysis of energy-budget closure data computed at the eddy-correlation sites (table 3) indicates that the measured turbulent fluxes were not sufficient to account for the measured available energy. Although there are techniques to account for these discrepancies in the energy budget (Bidlake and others, 1993; Sumner, 1996, p. 13), they were not applied to the eddy-correlation-estimated ET in this study.

ANNUAL EVAPOTRANSPIRATION IN RUBY LAKE NATIONAL WILDLIFE REFUGE

Seasonal estimates of ET and the corresponding extent of habitat areas were used to compute annual ET (October 1999–September 2000) in the Ruby Lake

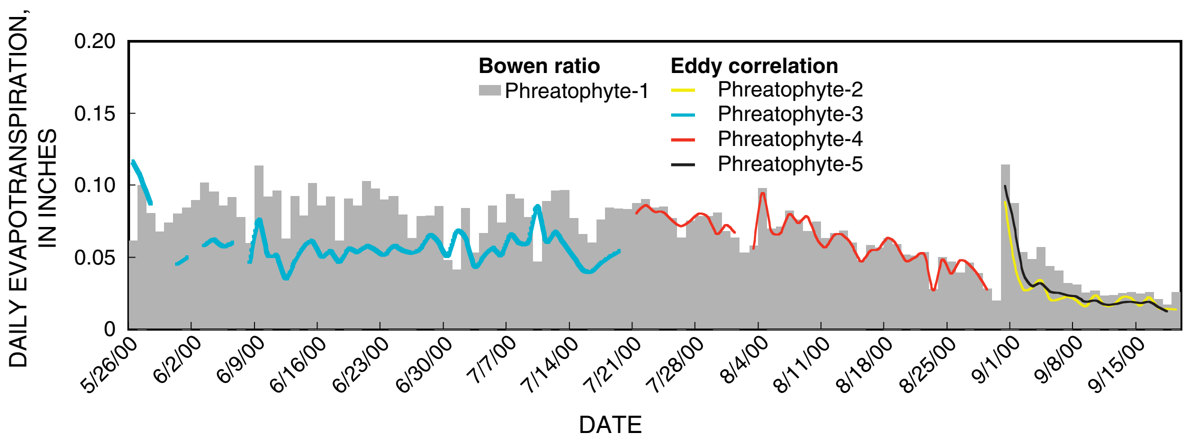

Figure 15. Daily evapotranspiration computed from micrometeorological data collected at five sites in mixed phreatophytic-shrub habitat, May–October 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada.

Table 3. Average, maximum, and minimum daily evapotranspiration rates and total evapotranspiration for days of data collection computed using the eddy-correlation method, and summary of daily energy-budget closure for eddy-correlation sites, May–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Site name	Number of days of data collection	Daily evapotranspiration (inches)				Absolute energy-budget closure [1] (watts per square meter)		Relative energy-budget closure [2] (percent)
		Average	Maximum	Minimum	Total	Range	Average	
Meadow	84	0.126	0.233	0.046	10.73	28.0–65.6	23.9	17.2
Phreatophyte-2	20	.024	.088	.013	.502	2.3–105.9	61.4	19.5
Phreatophyte-3	51	.058	.116	.035	2.95	12.6–54.5	36.0	22.4
Phreatophyte-4	24	.062	.094	.027	2.43	-.9–28.9	20.1	16.3
Phreatophyte-5	19	.028	.099	.012	.540	12.0–48.8	33.1	26.4

[1] Difference between available energy and turbulent-flux energy.

[2] Equation 12.

NWR (table 4). Because the area of wetland typically decreases during the summer, seasonal estimates of ET were applied to compute an annual estimate.

Major habitats on the Ruby Lake NWR are regularly inventoried by USFWS as part of the refuge's annual water-management plan. Areas of major habitats were determined from field mapping and observation by USFWS personnel in March 2000, when the maximum extent of the wetland occurred during this study. Total wetland area was estimated by determining the percentage of open water and bulrush marsh in each management unit (fig. 2). Habitat areas were determined once more in September 2000 during the minimum extent of the wetland. As the wetland area diminishes during the summer, additional playa areas become exposed. Between March and September 2000, the wetland area decreased by about 4,500 acres and the area of playa increased (table 4). During prolonged dry periods, these playas often become vegetated. Generally, habitat areas other than open water, bulrush marsh, and playas do not change, except during years of above-normal precipitation when flooding occurs in the lower-lying areas.

Summation of monthly ET totals for October 1999 through April 2000 at representative sites was used to compute winter ET for habitats in the wetland, areas of

Table 4. Area and estimated annual evapotranspiration for major habitats within Ruby Lake National Wildlife Refuge, September 1999–October 2000, northeastern Nevada

Habitat	Area (acres) [1]		Evapotranspiration (feet) [2]		Evapotranspiration (acre-feet per year) [3]
	Winter	Summer	Winter	Summer	
Open water	5,700	3,700	1.99	3.32	23,600
Bulrush marsh	8,100	5,600	1.10	3.09	26,200
Meadow	4,100	4,100	1.08	2.11	13,100
Grassland	3,100	3,100	.87	1.49	7,320
Mixed phreatophytes	5,500	5,500	.50	.83	7,320
Desert-shrub upland	4,800	4,800	.51	.48	4,750
Playa and bare soil	6,300	10,800	.46	.34	6,570
Total	**37,600**	**37,600**			**89,000**

[1] Area in winter (October 1999–April 2000) determined in March 2000 during maximum extent of wetland; area in summer (May 2000–September 2000) determined in September 2000 during minimum area of wetland.

[2] See table 2 for seasonal ET rates for open water, bulrush marsh, mixed phreatophytes, and desert-shrub upland. Annual ET rates for other habitats equal sum of seasonal precipitation (winter, 0.42 ft; summer, 0.23 ft) measured at Ruby Lake NWR and annual ground-water ET rate of 2.54 ft/yr for meadow; 1.71 ft/yr for grassland; and 0.15 ft/yr for areas of playa and bare soil determined from Landsat data (Nichols, 2000) and proportioned seasonally based on 26 percent of annual ET occurring during winter and 74 percent occurring during summer (Nichols, 2000, p. C12).

[3] Computed as sum of products of estimated seasonal habitat area and seasonal evapotranspiration.

phreatophytic shrubs, and desert-shrub uplands (table 4). Similarly, summation of monthly totals for May 2000 through September 2000 was used to compute summer ET rates. To determine total ET for the remaining major habitats (meadow, grassland, and playa and bare soil), annual ground-water ET rates were derived on the basis of satellite data, adjusted to reflect total ET by adding precipitation, and seasonally proportioned to correspond with changes in habitat area.

Satellite data recently has been used in east-central Nevada to estimate regional ground-water ET based on relations between vegetation indices derived from Landsat data and measured plant cover (Nichols, 2000). Nichols (2000, p. A6, eq. 3) determined that ground-water ET could be estimated as a function of plant cover. Plant cover, in turn, can be determined on a regional scale from Landsat data using easily calculated vegetation indices (Nichols, 2000, p. B6, eqs. 9 and 10). The relation between vegetation indices and plant cover was used together with the relation between plant cover and ground-water ET to determine annual estimates of ground-water ET for meadow, grassland, and areas of playa and bare soil in Ruby Lake NWR. Satellite data used to derive plant cover and compute annual ET rates were obtained on June 10, 1985, and June 29, 1989. Based on this analysis, annual ground-water ET in Ruby Lake NWR is 2.54 ft/yr for meadow, 1.71 ft/yr for grassland, and 0.15 ft/yr for areas of playa and bare soil.

Nichols (2000, p. C12) suggests that winter ground-water ET by vegetation in east-central Nevada accounts for about 26 percent of the annual ground-water ET. Applying this percentage to the annual estimates derived from the Landsat data produces a winter ground-water ET of about 0.66 ft/yr for meadow, about 0.45 ft/yr for grassland, and about 0.04 ft/yr for areas of playa and bare soil. Similarly, estimates of summer ground-water ET are about 1.88 ft/yr for meadow, about 1.26 ft/yr for grassland, and about 0.11 ft/yr for areas of playa and bare soil. Finally, the seasonal rates of ground-water ET were adjusted to account for the volume of precipitation that fell during the data-collection period to arrive at total annual ET.

Total annual ET for meadow, grassland, and playa and bare soil were computed by adding the seasonal amount of precipitation measured at the refuge headquarters to the estimated rate of seasonal ground-water ET. Limited bulk-precipitation gage data, which was collected at the Bowen-ratio sites, suggest some spatial variability in precipitation on the valley floor, particularly during the summer. However, the data set is incomplete due to problems with vandalism and with evaporation of precipitation at the bulk-precipitation gage. Consequently, precipitation measured at the refuge headquarters (fig. 2) was used in the computation of total annual ET. Annual precipitation for the 2000 water year measured at the refuge headquarters was 0.65 ft (7.74 in.), which represents about 58 percent of the long-term annual average (13.3 in.) based on a 30-year record (1961–90). Of the total precipitation, 0.42 ft occurred during the winter (October 1999–April 2000) and 0.23 ft occurred during the summer (May–September 2000). Adjusting the seasonal ground-water ET rates to account for seasonal precipitation results, for meadow, in total winter ET during the data-collection period of about 1.08 ft/yr and total summer ET of about 2.11 ft/yr (table 4). Total winter ET for grassland is about 0.87 ft/yr and in summer about 1.49 ft/yr. Total winter ET for areas of playa and bare soil is about 0.46 ft/yr and in summer about 0.34 ft/yr (table 4). The product of the seasonal habitat areas and ET rates for each habitat was summed to compute an annual ET.

Based on the seasonal distribution of habitats and computed winter and summer ET rates, an estimated 89,000 acre-ft of water was consumed by ET on the refuge during the 2000 water year (table 4). Of this total, more than 55 percent (49,800 acre-ft) is accounted for by ET in the wetland areas. Assuming that the precipitation measured at the refuge headquarters equals the average over the wetland area, about 7,960 acre-ft (16 percent) of the annual ET from the wetland was derived from precipitation and about 41,800 acre-ft was derived from sources other than precipitation during the 2000 water year.

The amount of annual inflow water required to maintain the refuge can be determined, in part, from estimates of annual ET from the wetland. Results of this study suggest that about 49,800 acre-ft were consumed by ET from the wetland based on the seasonal extent of open water and bulrush marsh during the 2000 water year (table 4). The extent of the refuge that is flooded is directly related to the amount of annual precipitation that falls on Ruby Lake, and more importantly, to the annual amount of snow accumulation in the southern Ruby Mountains that ultimately discharges to Ruby Lake. Several years of below-average precipitation can decrease the wetland area. Conversely, several years of above-average precipitation can increase the wetland area. In 1989, after 3 years of near- to below-average precipitation, the open-water area of the wetland covered about 1,030 acres in the South Marsh (fig. 2). For 1989 conditions, Nichols (2000, C17) estimated about 26,800 acre-ft of ET from open water, marsh vegetation, and bare soil that previously was flooded. Although seasonal ET rates were not considered in this estimate, it does provide a probable lower limit of water consumed by ET in the wetland. Comparison of Nichols' preliminary estimate with results of this study suggest that annual variations of ET in the wetland area resulting from climatic variation could be on the order of 20,000 acre-ft.

SUMMARY

The Ruby Lake NWR in the southern part of Ruby Valley is the largest perennial wetland area in northeastern Nevada. The long-term preservation of the refuge depends on the availability of sufficient water to maintain optimal habitat conditions. ET from the refuge is thought to be the largest natural outflow component of the water budget for Ruby Valley. To refine the estimate of the annual water budget for Ruby Valley and to facilitate water management on the refuge, estimates of ET were made at nine sites that represented the major habitats found in the Ruby Lake NWR.

Ruby Valley is about 65 mi southeast of Elko, Nev., and encompasses about 1,000 mi^2 in Elko and White Pine Counties. The Ruby Lake NWR includes about 38,000 acres of the southern part of Ruby Valley and consists of wetland and adjacent areas of meadow, grassland, and shrub upland. The existence of Ruby Lake stems in large part from the permeability and stratigraphic positions of the carbonate rocks that make up the Ruby Mountains, which form the western border of Ruby Valley. The predominant water source for Ruby Lake and associated wetland is spring discharge that originates in the southern Ruby Mountains.

Micrometeorological data were collected during an 18-month period at nine sites. These sites represented five of the most aerially extensive habitats in the refuge. The Bowen-ratio method was used to estimate daily ET for more than 500 consecutive days, from mid-May 1999 to mid-November 2000, over an open-water site, in a moderate-to-dense cover of bulrush marsh, in a moderate cover of mixed phreatophytic shrubs, and in a desert-shrub upland. The eddy-correlation method was used to estimate daily ET for periods of 2 to 12 weeks during May–September 2000 at a meadow site and at four sites in sparse-to-moderate cover of phreatophytic shrubs.

Daily ET rates ranged from less than 0.010 in/d at all of the sites to a daily maximum of 0.464 in/d at the open-water site. Average daily ET rates estimated at the open-water and bulrush-marsh sites were about four to five times greater than at the phreatophyte-1 and desert-shrub upland sites. Winter ET at the open-water site was almost twice that at the bulrush-marsh site due to the effect of shading from dead plant material. ET, computed for 84 days during the summer at the meadow site, was more than two-thirds of the annual estimate of ET at the phreatophyte-1 site. Differences in average daily ET for corresponding days between the phreatophyte-1 and the other four phreatophyte sites, where the eddy-correlation method was used, ranged from 0.001 to 0.021 in/d.

Seasonal estimates of ET derived from daily ET rates, along with corresponding habitat areas, were used to compute annual ET for the 2000 water year (October 1999–September 2000). Annual ET rates for habitats with limited ET data were derived from basis of satellite data, adjusted to reflect total ET by adding precipitation, and seasonally proportioned to correspond with changes in habitat area. An estimated 89,000 acre-ft of water was consumed by ET on the refuge during the 2000 water year based on seasonal distribution of habitats and computed winter and summer ET rates. Of this total, 49,800 acre-ft is accounted for by ET in the wetland area.

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APPENDICES

Appendix 1. Daily evapotranspiration at the open-water site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Symbol: —, no data; *, no monthly total or daily average, maximum, and minimum given for partial month]

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1999						
1	—	—	—	—	—	0.292	0.461	0.303	0.272	0.164	0.117	0.053
2	—	—	—	—	—	.111	.474	.300	.217	.182	.134	.025
3	—	—	—	—	—	.271	.420	.372	.312	.207	.161	.110
4	—	—	—	—	—	.320	.427	.235	.363	.211	.138	.034
5	—	—	—	—	—	.053	.440	.302	.325	.216	.125	.006
6	—	—	—	—	—	.117	.405	.239	.271	.052	.145	.008
7	—	—	—	—	—	.392	.207	.242	.281	.136	.118	.006
8	—	—	—	—	—	.350	.453	.373	.317	.205	.031	.003
9	—	—	—	—	—	.327	.371	.360	.254	.166	.065	.006
10	—	—	—	—	—	.356	.218	.053	.254	.139	.076	.009
11	—	—	—	—	—	.376	.426	.263	.347	.189	.102	.013
12	—	—	—	—	—	.298	.294	.339	.306	.207	.131	.020
13	—	—	—	—	—	.231	.186	.287	.159	.229	.137	.001
14	—	—	—	—	—	.407	.189	.404	.174	.169	.141	.032
15	—	—	—	—	—	.366	.351	.431	.290	.175	.093	.012
16	—	—	—	—	—	.382	.233	.396	.259	.184	.016	.023
17	—	—	—	—	—	.446	.325	.383	.085	.195	.016	.021
18	—	—	—	—	—	.392	.410	.193	.178	.194	.087	.010
19	—	—	—	—	—	.365	.388	.365	.185	.146	.037	.020
20	—	—	—	—	—	.446	.446	.163	.184	.194	.016	.009
21	—	—	—	—	—	.326	.422	.105	.179	.174	.019	.006
22	—	—	—	—	0.376	.414	.455	.195	.164	.164	.119	.030
23	—	—	—	—	.229	.414	.332	.308	.243	.157	.081	.026
24	—	—	—	—	.290	.277	.389	.189	.249	.177	.016	.027
25	—	—	—	—	.319	.410	.418	.296	.302	.184	.027	.014
26	—	—	—	—	.295	.428	.348	.327	.251	.186	.008	.013
27	—	—	—	—	.350	.430	.347	.206	.265	.095	.126	.012
28	—	—	—	—	.121	.401	.244	.281	.271	.084	.036	.013
29	—	—	—	—	.207	.417	.109	.402	.279	.143	.022	.014
30	—	—	—	—	.356	.411	.259	.295	.268	.169	.103	.015
31	—	—	—	—	.456	—	.314	.303	—	.194	—	.012
Monthly total	*	*	*	*	*	10.227	10.760	8.910	7.504	5.288	2.440	.604
Daily average	*	*	*	*	*	.341	.347	.287	.250	.171	.081	.019
Daily maximum	*	*	*	*	*	.446	.474	.431	.363	.229	.161	.110
Daily minimum	*	*	*	*	*	.053	.109	.053	.085	.052	.008	.001

Appendix 1. Daily evapotranspiration at the open-water site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada—Continued

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						2000						
1	0.012	0.053	0.054	0.326	0.339	0.305	0.303	0.198	0.276	0.286	0.135	—
2	.038	.043	.046	.159	.307	.249	.439	.224	.244	.331	.116	—
3	.003	.026	.049	.232	.314	.241	.331	.193	.269	.322	.186	—
4	.009	.074	.044	.303	.210	.265	.351	.246	.352	.330	.185	—
5	.052	.035	.015	.207	.043	.104	.464	.219	.369	.288	.132	—
6	.030	.088	.067	.285	.225	.300	.348	.239	.377	.351	.110	—
7	.008	.073	.045	.309	.254	.152	.424	.286	.346	.322	.163	—
8	.015	.095	.052	.311	.259	.165	.390	.390	.234	.290	.048	—
9	.008	.119	.032	.275	.287	.122	.412	.357	.286	.160	.011	—
10	.007	.040	.264	.285	.275	.212	.306	.367	.366	.066	.028	—
11	.004	.063	.037	.358	.239	.208	.352	.300	.334	.076	.034	—
12	.084	.042	.205	.304	.312	.071	.406	.382	.277	.062	.039	—
13	.020	.033	.133	.094	.203	.295	.373	.322	.196	.063	.002	—
14	.003	.092	.027	.069	.117	.328	.264	.333	.339	.208	—	—
15	.005	.142	.290	.290	.142	.223	.232	.221	.357	.233	—	—
16	.033	.022	.218	.218	.095	.221	.167	.254	.261	.223	—	—
17	.023	.030	.331	.272	.088	.318	.337	.201	.313	.264	—	—
18	.018	.126	.390	.138	.066	.065	.299	.229	.279	.152	—	—
19	.050	.104	.032	.178	.274	.226	.440	.295	.239	.281	—	—
20	.034	.023	.307	.249	.261	.400	.352	.308	.365	.179	—	—
21	.019	.008	.336	.161	.285	.351	.335	.344	.106	.175	—	—
22	.012	.074	.215	.140	.134	.191	.370	.314	.220	.081	—	—
23	.023	.016	.045	.324	.184	.206	.416	.043	.167	.098	—	—
24	.017	.166	.023	.419	.054	.218	.409	.158	.304	.020	—	—
25	.037	.107	.185	.356	.115	.125	.297	.159	.277	.035	—	—
26	.037	.037	.187	.372	.229	.201	.326	.054	.236	.026	—	—
27	.125	.030	.022	.310	.243	.252	.380	.243	.122	.065	—	—
28	.107	.064	.269	.117	.227	.362	.407	.186	.223	.032	—	—
29	.087	.010	.312	.382	.201	.260	.317	.131	.269	.016	—	—
30	.019	—	.316	.406	.272	.235	.294	.058	.253	.016	—	—
31	.046	—	.293	—	.274	—	.244	.098	—	.109	—	—
Monthly total	.987	1.838	4.841	7.850	6.527	6.870	1.785	7.354	8.259	5.159	*	*
Daily average	.032	.063	.156	.262	.211	.229	.348	.237	.275	.166	*	*
Daily maximum	.125	.166	.390	.419	.339	.400	.464	.390	.377	.351	*	*
Daily minimum	.003	.008	.015	.069	.043	.065	.167	.043	.106	.016	*	*

Appendix 2. Daily evapotranspiration at the bulrush-marsh site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Symbol: —, no data; *, no monthly total or daily average, maximum, and minimum given for partial month]

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1999						
1	—	—	—	—	—	0.168	0.315	0.329	0.193	0.081	0.050	0.031
2	—	—	—	—	—	.074	.342	.209	.204	.095	.050	.021
3	—	—	—	—	—	.150	.398	.269	.218	.144	.056	.035
4	—	—	—	—	—	.189	.427	.228	.213	.138	.073	.032
5	—	—	—	—	—	.074	.352	.262	.264	.125	.065	.018
6	—	—	—	—	—	.149	.359	.317	.234	.020	.059	.028
7	—	—	—	—	—	.247	.294	.276	.181	.111	.054	.027
8	—	—	—	—	—	.222	.260	.359	.197	.085	.032	.016
9	—	—	—	—	—	.237	.380	.340	.208	.079	.039	.019
10	—	—	—	—	—	.212	.258	.097	.177	.089	.055	.027
11	—	—	—	—	—	.261	.351	.220	.223	.181	.032	.022
12	—	—	—	—	—	.277	.320	.292	.221	.183	.046	.020
13	—	—	—	—	—	.193	.258	.273	.175	.056	.047	.022
14	—	—	—	—	—	.265	.136	.264	.190	.073	.043	.015
15	—	—	—	—	—	.295	.415	.294	.236	.092	.049	.015
16	—	—	—	—	—	.220	.333	.314	.151	.083	.042	.017
17	—	—	—	—	—	.279	.280	.261	.155	.111	.026	.017
18	—	—	—	—	—	.259	.349	.218	.142	.091	.031	.036
19	—	—	—	—	—	.207	.359	.270	.136	.071	.043	.036
20	—	—	—	—	—	.289	.368	.154	.099	.068	.033	.040
21	—	—	—	—	—	.189	.361	.161	.209	.078	.019	.026
22	—	—	—	—	0.250	.291	.379	.278	.130	.071	.026	.021
23	—	—	—	—	.104	.291	.362	.286	.140	.073	.034	.027
24	—	—	—	—	.231	.203	.287	.151	.164	.065	.031	.030
25	—	—	—	—	.209	.331	.315	.271	.209	.065	.017	.031
26	—	—	—	—	.191	.299	.390	.269	.141	.073	.036	.023
27	—	—	—	—	.234	.068	.275	.173	.185	.057	.028	.019
28	—	—	—	—	.110	.043	.169	.256	.154	.036	.021	.041
29	—	—	—	—	.105	.307	.146	.320	.164	.020	.026	.028
30	—	—	—	—	.198	.318	.222	.250	.114	.065	.050	.024
31	—	—	—	—	.251	—	.295	.206	—	.071	—	.022
Monthly total	*	*	*	*	*	6.607	9.758	7.865	5.426	2.649	1.214	.785
Daily average	*	*	*	*	*	.220	.315	.254	.181	.085	.040	.025
Daily maximum	*	*	*	*	*	.331	.427	.359	.264	.183	.073	.041
Daily minimum	*	*	*	*	*	.043	.136	.097	.099	.020	.017	.015

Appendix 2. Daily evapotranspiration at the bulrush-marsh site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada—Continued

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						2000						
1	0.023	0.021	0.065	0.157	0.162	0.319	0.385	0.257	0.224	0.093	0.042	—
2	.083	.031	.064	.174	.134	.349	.363	.240	.174	.072	.041	—
3	.019	.043	.075	.092	.122	.213	.283	.215	.195	.069	.059	—
4	.030	.041	.058	.120	.157	.313	.336	.286	.213	.097	.052	—
5	.023	.026	.039	.088	.038	.318	.378	.308	.177	.091	.026	—
6	.020	.031	.047	.138	.205	.349	.317	.280	.201	.094	.027	—
7	.014	.038	.050	.175	.088	.394	.362	.307	.230	.089	.050	—
8	.018	.034	.071	.161	.166	.292	.363	.326	.182	.054	.037	—
9	.029	.031	.071	.107	.113	.207	.345	.318	.140	.067	.022	—
10	.038	.020	.067	.152	.194	.306	.260	.294	.199	.029	.028	—
11	.047	.039	.031	.148	.163	.304	.367	.293	.179	.046	.033	—
12	.038	.034	.077	.127	.220	.203	.396	.351	.161	.060	.028	—
13	.045	.034	.080	.051	.132	.316	.364	.345	.168	.019	.010	—
14	.017	.040	.050	.059	.148	.344	.248	.300	.171	.055	—	—
15	.018	.044	.071	.183	.113	.334	.245	.214	.177	.063	—	—
16	.025	.009	.097	.150	.063	.300	.245	.240	.209	.054	—	—
17	.012	.028	.108	.136	.140	.339	.345	.218	.173	.050	—	—
18	.026	.045	.117	.107	.173	.240	.361	.253	.177	.052	—	—
19	.020	.035	.050	.128	.194	.277	.353	.306	.183	.044	—	—
20	.014	.020	.078	.144	.162	.336	.369	.313	.132	.053	—	—
21	.041	.008	.211	.075	.158	.355	.332	.302	.087	.041	—	—
22	.026	.058	.102	.060	.153	.335	.355	.280	.108	.045	—	—
23	.008	.025	.039	.130	.200	.261	.352	.154	.105	.068	—	—
24	.019	.099	.071	.193	.100	.269	.386	.219	.145	.015	—	—
25	.030	.043	.103	.169	.205	.245	.365	.160	.120	.026	—	—
26	.048	.028	.086	.139	.224	.287	.297	.107	.071	.017	—	—
27	.030	.009	.019	.147	.290	.291	.309	.235	.058	5.045	—	—
28	.022	.090	.076	.035	.290	.357	.351	.224	.058	.065	—	—
29	.035	.032	.123	.264	.322	.340	.334	.132	.076	.025	—	—
30	.026	—	.154	.286	.287	.259	.302	.061	.076	.013	—	—
31	.017	—	.196	—	.283	—	.257	.173	—	.078	—	—
Monthly total	.862	1.035	2.544	4.094	5.398	9.052	1.323	7.712	4.575	1.692	*	*
Daily average	.028	.036	.082	.136	.174	.302	.333	.249	.153	.055	*	*
Daily maximum	.083	.099	.211	.286	.322	.394	.396	.351	.230	.097	*	*
Daily minimum	.008	.008	.019	.035	.038	.203	.245	.061	.058	.013	*	*

Appendix 3. Daily evapotranspiration at the phreatophyte-1 site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Symbol: —, no data; *, no monthly total or daily average, maximum, and minimum given for partial month]

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1999						
1	—	—	—	—	—	0.074	0.145	0.087	0.039	0.026	0.012	0.019
2	—	—	—	—	—	.068	.143	.083	.037	.020	.015	.013
3	—	—	—	—	—	.128	.137	.083	.043	.020	.013	.017
4	—	—	—	—	—	.118	.118	.071	.038	.020	.013	.017
5	—	—	—	—	—	.048	.106	.030	.047	.021	.011	.013
6	—	—	—	—	—	.128	.124	.084	.049	.009	.011	.021
7	—	—	—	—	—	.121	.122	.074	.047	.023	.009	.018
8	—	—	—	—	—	.105	.114	.087	.046	.021	.009	.014
9	—	—	—	—	—	.084	.123	.089	.043	.023	.015	.019
10	—	—	—	—	—	.091	.101	.065	.037	.022	.011	.019
11	—	—	—	—	—	.094	.127	.100	.041	.021	.010	.015
12	—	—	—	—	—	.104	.112	.082	.041	.020	.011	.017
13	—	—	—	—	—	.101	.098	.095	.027	.020	.009	.020
14	—	—	—	—	—	.118	.075	.084	.034	.017	.009	.013
15	—	—	—	—	—	.132	.115	.078	.039	.016	.008	.016
16	—	—	—	—	—	.138	.096	.086	.026	.012	.010	.017
17	—	—	—	—	—	.124	.095	.083	.029	.012	.007	.019
18	—	—	—	—	—	.133	.109	.059	.031	.012	.014	.020
19	—	—	—	—	—	.114	.112	.061	.032	.015	.009	.018
20	—	—	—	—	—	.147	.116	.052	.045	.016	.016	.020
21	—	—	—	—	—	.111	.110	.096	.040	.014	.021	.013
22	—	—	—	—	—	.117	.114	.096	.021	.014	.021	.016
23	—	—	—	—	—	.119	.115	.098	.029	.014	.019	.015
24	—	—	—	—	—	.122	.102	.091	.034	.014	.017	.015
25	—	—	—	—	—	.124	.093	.086	.036	.012	.014	.016
26	—	—	—	—	—	.108	.104	.075	.026	.013	.014	.015
27	—	—	—	—	—	.110	.098	.064	.022	.013	.014	.014
28	—	—	—	—	0.054	.117	.085	.025	.019	.024	.011	.012
29	—	—	—	—	.067	.120	.052	.075	.023	.014	.011	.012
30	—	—	—	—	.096	.130	.068	.070	.022	.014	.010	.011
31	—	—	—	—	.076	—	.085	.048	—	.014	—	.009
Monthly total	*	*	*	*	*	3.346	3.314	2.356	1.043	.525	.375	.490
Daily average	*	*	*	*	*	.112	.107	.076	.035	.017	.013	.016
Daily maximum	*	*	*	*	*	.147	.145	.100	.049	.026	.021	.021
Daily minimum	*	*	*	*	*	.048	.052	.025	.019	.009	.007	.009

Appendix 3. Daily evapotranspiration at the phreatophyte-1 site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada—Continued

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						2000						
1	0.009	0.026	0.051	0.043	0.042	0.085	0.041	0.064	0.087	0.026	—	—
2	.013	.038	.046	.052	.048	.089	.084	.053	.053	.020	—	—
3	.017	.040	.041	.042	.052	.102	.053	.058	.048	.020	—	—
4	.011	.039	.039	.048	.047	.095	.067	.098	.057	.020	—	—
5	.020	.030	.022	.046	.037	.086	.086	.070	.044	.021	—	—
6	.017	.038	.040	.040	.090	.092	.074	.071	.040	.009	—	—
7	.020	.037	.025	.041	.055	.078	.094	.082	.032	.023	—	—
8	.028	.028	.044	.041	.109	.060	.091	.076	.031	.021	—	—
9	.018	.029	.054	.036	.078	.113	.078	.068	.025	.023	—	—
10	.040	.018	.082	.037	.067	.092	.047	.075	.027	.009	—	—
11	.031	.037	.027	.038	.048	.096	.089	.063	.023	—	—	—
12	.033	.038	.079	.036	.052	.063	.096	.067	.023	—	—	—
13	.024	.009	.079	.023	.045	.092	.096	.069	.025	—	—	—
14	.012	.044	.052	.049	.057	.079	.077	.060	.026	—	—	—
15	.019	.041	.087	.070	.049	.102	.066	.048	.025	—	—	—
16	.025	.010	.065	.040	.014	.086	.060	.058	.026	—	—	—
17	.010	.024	.067	.039	.067	.092	.076	.057	.021	—	—	—
18	.011	.051	.071	.058	.086	.061	.084	.063	.017	—	—	—
19	.032	.049	.052	.041	.101	.091	.084	.059	.026	—	—	—
20	.019	.025	.061	.051	.083	.086	.083	.051	.032	—	—	—
21	.039	.010	.070	.039	.081	.103	.087	.051	.006	—	—	—
22	.031	.065	.060	.037	.078	.097	.090	.053	.019	—	—	—
23	.012	.014	.038	.040	.111	.090	.084	.028	.116	—	—	—
24	.020	.019	.065	.040	.083	.092	.085	.050	.030	—	—	—
25	.025	.024	.059	.041	.146	.080	.077	.047	.008	—	—	—
26	.056	.018	.064	.041	.061	.063	.063	.039	.019	—	—	—
27	.033	.014	.033	.052	.100	.078	.075	.046	.022	—	—	—
28	.034	.043	.055	.026	.080	.079	.078	.039	.019	—	—	—
29	.039	.017	.050	.042	.068	.085	.078	.028	.023	—	—	—
30	.029	—	.048	.042	.074	.048	.081	.019	.022	—	—	—
31	.018	—	.051	—	.080	—	.068	.114	—	—	—	—
Monthly total	.746	.876	1.677	1.270	2.190	2.554	2.393	1.822	.972	*	*	*
Daily average	.024	.030	.054	.042	.071	.085	.077	.059	.032	*	*	*
Daily maximum	.056	.065	.087	.070	.146	.113	.096	.114	.116	*	*	*
Daily minimum	.009	.009	.022	.023	.014	.048	.041	.019	.006	*	*	*

Appendix 4. Daily evapotranspiration at the desert-shrub upland site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

Symbol: —, no data; *, no monthly total or daily average, maximum, and minimum given for partial month]

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
							1999					
1	—	—	—	—	—	—	0.095	0.034	0.019	0.010	0.010	0.030
2	—	—	—	—	—	—	.090	.023	.016	.010	.012	.018
3	—	—	—	—	—	—	.084	.026	.018	.012	.008	.020
4	—	—	—	—	—	—	.070	.062	.018	.010	.007	.019
5	—	—	—	—	—	—	.072	.064	.019	.009	.006	.014
6	—	—	—	—	—	—	.069	.030	.014	.022	.006	.028
7	—	—	—	—	—	—	.064	.023	.017	.024	.006	.022
8	—	—	—	—	—	—	.067	.027	.017	.016	.031	.014
9	—	—	—	—	—	—	.069	.023	.015	.014	.021	.016
10	—	—	—	—	—	—	.055	.063	.014	.011	.009	.016
11	—	—	—	—	—	—	.065	.089	.018	.011	.008	.017
12	—	—	—	—	—	—	.054	.047	.016	.009	.009	.021
13	—	—	—	—	—	—	.061	.043	.010	.010	.007	.020
14	—	—	—	—	—	—	.042	.030	.020	.008	.007	.012
15	—	—	—	—	—	—	.055	.026	.017	.010	.007	.020
16	—	—	—	—	—	—	.045	.028	.015	.010	.008	.021
17	—	—	—	—	—	—	.041	.024	.014	.009	.027	.022
18	—	—	—	—	—	—	.047	.020	.019	.008	.027	.055
19	—	—	—	—	—	—	.041	.038	.018	.011	.017	.031
20	—	—	—	—	—	0.094	.043	.017	.030	.009	.028	.025
21	—	—	—	—	—	.094	.039	.028	.021	.009	.025	.027
22	—	—	—	—	—	.094	.042	.064	.014	.008	.019	.022
23	—	—	—	—	—	.094	.037	.032	.016	.007	.020	.020
24	—	—	—	—	—	.093	.032	.025	.015	.007	.031	.017
25	—	—	—	—	—	.093	.037	.025	.014	.007	.021	.018
26	—	—	—	—	—	.092	.035	.024	.013	.006	.019	.019
27	—	—	—	—	—	.091	.031	.070	.012	.008	.015	.016
28	—	—	—	—	—	.089	.027	.044	.013	.016	.011	.013
29	—	—	—	—	—	.090	.020	.025	.012	.010	.009	.012
30	—	—	—	—	—	.091	.024	.024	.011	.010	.012	.011
31	—	—	—	—	—	—	.095	.034	.019	.010	.010	.030
Monthly total	*	*	*	*	*	*	1.582	1.118	.487	.329	.444	.626
Daily average	*	*	*	*	*	*	.051	.036	.016	.011	.015	.020
Daily maximum	*	*	*	*	*	*	.095	.089	.030	.024	.031	.055
Daily minimum	*	*	*	*	*	*	.020	.017	.006	.006	.006	.011

Appendix 4. Daily evapotranspiration at the desert-shrub upland site, May 1999–November 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada—Continued

Day of month	Evapotranspiration (inches)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						2000						
1	0.010	0.028	0.050	0.027	0.053	0.074	0.034	0.020	0.063	0.011	0.055	—
2	.015	.038	.073	.031	.056	.081	.026	.016	.034	.011	.048	—
3	.021	.036	.072	.035	.063	.073	.022	.021	.036	.014	.059	—
4	.019	.035	.069	.037	.050	.074	.025	.029	.027	.012	.043	—
5	.025	.026	.042	.036	.038	.065	.024	.019	.024	.011	.027	—
6	.018	.025	.056	.030	.106	.069	.028	.033	.022	.009	.023	—
7	.022	.024	.036	.036	.160	.061	.024	.018	.020	.009	.030	—
8	.032	.018	.058	.036	.128	.042	.022	.011	.018	.009	.026	—
9	.025	.017	.068	.034	.097	.088	.020	.011	.015	.008	.035	—
10	.026	.019	.074	.038	.066	.058	.058	.015	.015	.055	.039	—
11	.031	.047	.064	.042	.058	.048	.029	.013	.013	.051	.027	—
12	.032	.054	.077	.041	.054	.040	.022	.014	.015	.052	.035	—
13	.021	.003	.068	.037	.048	.047	.018	.010	.013	.049	—	—
14	.014	.053	.049	.055	.052	.050	.017	.010	.012	.036	—	—
15	.010	.064	.044	.110	.048	.046	.019	.011	.013	.027	—	—
16	.021	.012	.034	.058	.059	.040	.020	.016	.015	.021	—	—
17	.011	.034	.066	.053	.053	.042	.021	.017	.009	.019	—	—
18	.024	.051	.038	.084	.094	.047	.019	.014	.015	.013	—	—
19	.029	.055	.041	.046	.098	.044	.017	.010	.012	.012	—	—
20	.018	.033	.037	.056	.087	.036	.018	.009	.017	.012	—	—
21	.046	.011	.031	.049	.084	.038	.017	.014	.020	.023	—	—
22	.033	.073	.029	.052	.072	.031	.014	.011	.022	.014	—	—
23	.015	.019	.060	.049	.057	.031	.012	.010	.031	.016	—	—
24	.020	.059	.033	.050	.040	.036	.015	.019	.018	.016	—	—
25	.034	.037	.029	.050	.105	.032	.014	.014	.015	.021	—	—
26	.049	.047	.031	.061	.158	.029	.015	.020	.014	.027	—	—
27	.037	.037	.020	.060	.130	.034	.016	.017	.008	.037	—	—
28	.037	.088	.037	.041	.117	.031	.014	.015	.012	.058	—	—
29	.036	.035	.033	.047	.106	.041	.015	.013	.012	.028	—	—
30	.029	—	.029	.051	.083	.035	.015	.044	.011	.013	—	—
31	.029	—	.030	—	.067	—	.018	.125	—	.055	—	—
Monthly total	.788	1.078	1.477	1.431	2.485	1.462	.646	.620	.569	.749	*	*
Daily average	.025	.037	.048	.048	.080	.049	.021	.020	.019	.024	*	*
Daily maximum	.049	.088	.077	.110	.160	.088	.058	.125	.063	.058	*	*
Daily minimum	.010	.003	.020	.027	.038	.029	.012	.009	.008	.008	*	*

Appendix 5. Daily evapotranspiration computed using the eddy-correlation method, May–September 2000, Ruby Lake National Wildlife Refuge, northeastern Nevada

[Symbols: —, no data; *, no monthly total or daily average, maximum, and minimum given for partial month]

Site	Meadow				Phreatophyte-2		Phreatophyte-3			Phreatophyte-4		Phreatophyte-5	
	Evapotranspiration (inches)												
Day of month	**May**	**June**	**July**	**Aug.**	**Aug.**	**Sept.**	**May**	**June**	**July**	**July**	**Aug.**	**Aug.**	**Sept.**
1	—	0.106	0.154	0.106		0.047	—	0.049	0.068	—	0.067	—	0.073
2	—	.148	.168	.096	—	.027	—	—	.063	—	—	—	.039
3	—	.122	.115	.119	—	.029	—	.058	.043	—	.056	—	.030
4	—	.107	.123	.133	—	.034	—	.062	.050	—	.094	—	.032
5	—	.163	.191	.096	—	.020	—	.057	.056	—	.067	—	.026
6	—	.157	.145	.114	—	.020	—	.060	.052	—	.066	—	.025
7	—	.233	.206	.161	—	.022	—	—	.065	—	.079	—	.023
8	—	.145	.205	.171	—	.020	—	.047	.060	—	.073	—	.022
9	—	.060	.172	.170	—	.016	—	.075	.061	—	.078	—	.019
10	—	.116	.146	.175	—	.023	—	.051	.085	—	.064	—	.019
11	—	.127	.165	.114	—	.017	—	.051	.061	—	.056	—	.017
12	—	.104	.205	.133	—	.016	—	.035	.067	—	.065	—	.017
13	—	.083	.203	.141	—	.022	—	.047	.059	—	.065	—	.018
14	—	.122	.141	.138	—	.021	—	.057	.050	—	.058	—	.019
15	—	.135	.100	.108	—	.016	—	.061	.041	—	.047	—	.018
16	—	.102	.090	.102	—	.022	—	.050	.040	—	.054	—	.019
17	—	.113	.162	.107	—	.015	—	.054	.046	—	.055	—	.015
18	—	.107	.143	.119	—	.014	—	.047	.050	—	.063	—	.012
19	—	.133	.161	.144	—	.013	—	.055	.054	—	.058	—	—
20	—	.108	.093	.101	—	—	—	.053	—	—	.047	—	—
21	—	.122	—	.098	—	—	—	.057	—	0.080	.049	—	—
22	—	.153	—	.118	—	—	—	.055	—	.086	.052	—	—
23	—	.107	—	.046	—	—	—	.051	—	.081	.027	—	—
24	—	.121	—	.081	—	—	—	.057	—	.081	.048	—	—
25	—	.066	—	.067	—	—	—	.054	—	.075	.038	—	—
26	0.092	.073	—	.052	—	—	0.116	.053	—	.071	.048	—	—
27	.189	.090	—	.085	—	—	.104	.056	—	.075	.045	—	—
28	.152	.144	—	.074	—	—	.087	.065	—	.080	.037	—	—
29	.158	.105	—	.047	—	—	—	.060	—	.077	.027	—	—
30	.138	.120	—	—	—	—	—	.051	—	.066	—	—	—
31	.105	—	—	—	0.088	—	.045	—	—	.072	—	0.099	—
Monthly total	*	3.594	*	3.216	*	*	*	1.529	*	*	1.582	*	*
Daily average	*	.120	*	.111	*	*	*	.055	*	*	.056	*	*
Daily maximum	*	.233	*	.175	*	*	*	.075	*	*	.094	*	*
Daily minimum	*	.060	*	.046	*	*	*	.035	*	*	.027	*	*