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Quantifying Ground-Water and Surface-Water Discharge from Evapotranspiration Processes in 12 Hydrographic Areas of the Colorado Regional Ground-Water Flow System, Nevada, Utah, and Arizona

Scientific Investigations Report 2008-5116

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^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)

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

$$°F=(1.8×°C)+32.$$

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

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum 1983 (NAVD 83).

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 Symbols

Abbreviation or Symbol	Meaning
AGU	Agricultural unit
BLM	Bureau of Land Management
CH_{sw}	Channelized surface water component to ET_t along washes and rivers from sources outside the study area
CRFS	Colorado Regional Ground-Water Flow System
DMV	Dense meadowland vegetation
DSV	Dense shrubland vegetation
DWV	Dense woodland vegetation
E	Rate of water evaporation
E_n	Available energy
ET	Evapotranspiration
ET_{gs}	Ground- and surface-water discharge from ET
ET_t	Estimated total evapotranspiration
G	Subsurface heat flux
GW	Ground-water component of ET_{gs}
GW_t	Ground-water component of ET_t
H	Sensible-heat flux
H_b	Sensible heat calculated using the Bowen-variant method
H_e	Sensible heat calculated using the eddy covariance method
MWV	Moderate woodland vegetation
MSAVI	Modified soil-adjusted vegetation index
MSV	Moderate shrubland vegetation
NAIP	National Agriculture Imaging Mapping Program
NPS	National Park Service
NPU	Non-phreatophytic unit
OWU	Open water unit
PL	Annual local precipitation
PL_{GW}	Ground-water components of local precipitation
PL_{SW}	Surface-water components of local precipitation
R_n	Net radiation
SP_{SW}	Channelized surface water component of SWt from springs and seeps
SP_{GW}	Recycled ground water component of GWt from springs and seeps
SW_t	Surface-water component of ETt
SWReGAP	Southwest Regional Gap Analysis Program
UF_{GW}	Ground-water underflow component to ETt
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
λ	Latent heat of vaporization for water
λE	Latent-heat flux (or evaporative flux)
λE_b	Latent-heat calculated using the Bowen-variant method
λE_e	Latent-heat calculated using the eddy covariance method

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By Guy A. DeMeo, J. LaRue Smith, Nancy A. Damar, and Jon Darnell

Abstract

Rapid population growth in southern Nevada has increased the demand for additional water supplies from rural areas of northern Clark and southern Lincoln counties to meet projected water-supply needs. Springs and rivers in these undeveloped areas sustain fragile riparian habitat and may be susceptible to ground-water withdrawals. Most natural ground-water and surface-water discharge from these basins occurs by evapotranspiration (ET) along narrow riparian corridors that encompassed about 45,000 acres or about 1 percent of the study area.

This report presents estimates of ground- and surface-water discharge from ET across 3.5 million acres in 12 hydrographic areas of the Colorado Regional Ground-Water Flow System. Ground-and surface-water discharge from ET were determined by identifying areas of ground- and surface-water ET, delineating areas of similar vegetation and soil conditions (ET units), and computing ET rates for each of these ET units. Eight ET units were identified using spectral-reflectance characteristics determined from 2003 satellite imagery, high-resolution aerial photography, and land classification cover. These ET units are dense meadowland vegetation (200 acres), dense woodland vegetation (7,200 acres), moderate woodland vegetation (6,100 acres), dense shrubland vegetation (5,800 acres), moderate shrubland vegetation (22,600 acres), agricultural fields (3,100 acres), non-phreatophytic areas (3,400,000 acres), and open water (300 acres).

ET from diffuse ground-water and channelized surface-water is expressed as ET_{gs} and is equal to the difference between total annual ET and precipitation. Total annual ET rates were calculated by the Bowen ratio and eddy covariance methods using micrometeorological data collected from four sites and estimated at 3.9 ft at a dense woodland site (February 2003 to March 2005), 3.6 ft at a moderate woodland site (July 2003 to October 2006), 2.8 ft at a dense shrubland site (June 2005 to October 2006), and 1.5 ft at a moderate shrubland site (April 2006 to October 2006). Annual ET_{gs} rates were 3.4 ft for dense woodland vegetation, 3.2 ft for moderate woodland vegetation, 2.2 ft for dense shrubland vegetation, and 1.0 ft for moderate shrubland vegetation. Published annual rates of ET_{gs} were used for the other ET units found in the study area. These rates were 3.4 ft for dense meadowland vegetation, 5.2 ft for agricultural fields, and 4.9 ft for open water. For the non-phreatophytic ET unit, ET_{gs} was assumed to be zero.

Estimated ground- and surface-water discharge from ET was calculated by multiplying the ET_{gs} by the ET-unit acreage and equaled 24,480 acre-ft for dense woodland vegetation, 19,520 acre-ft for moderate woodland vegetation, 12,760 acre-ft for dense shrubland vegetation, 22,600 acre-ft for moderate shrubland vegetation, 680 acre-ft for dense meadowland vegetation, 16,120 acre-ft for agricultural fields, 1,440 acre-ft for open water, and 0 acre-ft for the non-phreatophytic ET unit. Estimated ground-water and surface-water discharge from ET from each hydrographic area was calculated by summing the total annual ET_{gs} rate for ET units found within each hydrographic area and equaled 1,952 acre-ft for the Black Mountains Area, 6,080 acre-ft for California Wash, 4,090 acre-ft for the Muddy River Springs Area, 11,510 acre-ft for Lower Moapa Valley, 51,960 acre-ft for the Virgin River Valley, 16,168 acre-ft for Lower Meadow Valley Wash, 5,840 acre-ft for Clover Valley, and 0 acre-ft for Coyote Spring Valley, Kane Springs Valley, Tule Desert, Hidden Valley (North), and Garnet Valley. The annual discharge from ET_{gs} for the study area totals about 98,000 acre-ft.

Introduction

Rapid population growth and development in southern Nevada has increased demand for additional water supplies. Numerous applications have been submitted to the Nevada State Engineer requesting water rights in rural areas to meet the projected water supply needs for Nevada. Water from springs and rivers in these undeveloped areas sustain riparian habitat that supports numerous species of plants and animals. Some species, such as the Moapa dace, are federally listed as a threatened and endangered species (U.S. Fish and Wildlife Service, 1996). Water is naturally discharged from these areas by surface-water outflow, subsurface outflow, and evapotranspiration (ET).

The U.S. Geological Survey, in cooperation with the National Park Service, Bureau of Land Management, and U.S. Fish and Wildlife Service, conducted a study during 2003–06 to quantify discharge through ET processes for 12 hydrographic areas in the southern part of the Colorado Regional Ground-Water Flow System (fig. 1). The Colorado Regional Ground-Water Flow System (CRFS) is part of a major ground-water flow system within the Great Basin Regional Aquifer System that encompasses much of eastern and southern Nevada, parts of southeastern California, northwestern Arizona, and western Utah (Harrill and Prudic, 1998). Discharge from this regional flow system is by phreatophytic ET from numerous valleys (discharge areas), spring discharge, and surface-water flow into Lake Mead. A large unknown component of the CRFS water budget is the amount of discharge that occurs as ET.

Purpose and Scope

This report documents the methodology and presents estimates of ground-water and surface-water discharge by ET from 12 hydrographic areas in the CRFS (referred to as the study area). Descriptions of the approach include remote-sensing techniques used to determine acreage and density of vegetation, selection of study sites, instrumentation, and methods used to estimate discharge by ET processes.

Description of the Study Area

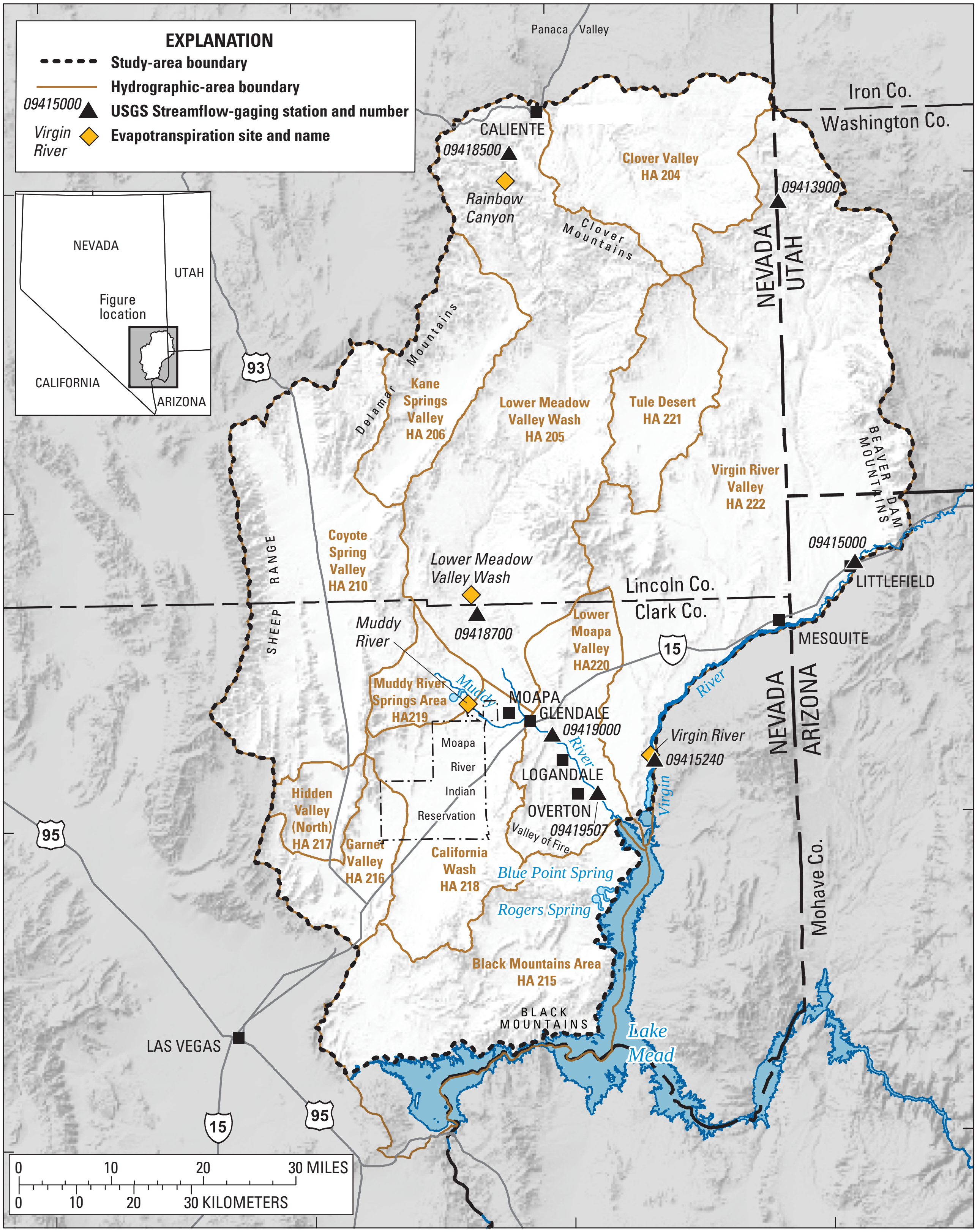
The study area encompasses more than 3.5 million acres in southern Nevada, southwest Utah, and northwest Arizona and includes 12 hydrographic areas[1]: Clover Valley (HA 204), Kane Springs Valley (HA 206), Lower Meadow Valley Wash (HA 205), Tule Desert (HA 221), Coyote Spring Valley (HA 210), Virgin River Valley (HA 222), Muddy River Springs Area (HA 219), Hidden Valley (North) (HA 217), Garnet Valley (HA 216), California Wash (HA 218), Lower Moapa Valley (HA 220), and the part of the Black Mountains Area (HA 215) north of the Las Vegas Valley and Lake Mead shear zones (fig. 1). The study area has numerous valleys and mountains, many of them north–south trending, that range between 5 to 15 mi wide and 10 to more than 20 mi long. The valley floors range in altitude from less than 1,500 ft in the south to more than 4,000 ft in the north with the highest mountain peaks exceeding 7,000 ft.

The study area is characterized by hot summers and mild winters; however, precipitation and temperature do vary according to altitude. Based on four weather observation sites located in the study area with 30-years of record, the average maximum and minimum annual air temperature was 109°F at Overton, Nevada and about 20°F at Caliente, Nevada, respectively. Data from the same weather stations and periods of record indicate that the average annual precipitation ranges from slightly more than 5 in. at Overton and Logandale, Nevada, to just less than 10 in. at Caliente, Nevada (fig. 2).

Upland and high-altitude terrain primarily receive water from local precipitation (as rain or snow) that will evaporate, sublimate, runoff as channelized surface water into washes and rivers, be transpired by upland vegetation, or infiltrate the soil and may eventually recharge the ground-water system. Lowland terrain receives water from multiple ground- and surface-water sources. Ground water in these lower lying areas is supplied by local precipitation, diffuse ground-water underflow, or as recycled water from springs and seeps. Surface water is supplied by local precipitation, channelized surface water from springs and seeps, and channelized surface water along washes and rivers that originate outside the study area. Ground water is evaporated from bare soils or is transpired by phreatophytes and riparian vegetation. Surface water is evaporated from washes, rivers, and reservoirs, or transpired from riparian vegetation along the banks of washes and rivers. Only a few acres are classified as agricultural fields. These fields are dispersed throughout the study area and located within the riparian areas along washes and rivers.

The study area contains two main washes and two rivers: Meadow Valley Wash, Beaver Dam Wash, the Virgin River, and the Muddy River. All these drainages are long and narrow, sustain various plants and fauna, and provide habitat for local wildlife. Meadow Valley Wash receives runoff from higher terrain as well as discharge from several seeps and springs before joining with the Muddy River east of Moapa, Nevada. Beaver Dam Wash receives runoff from the Clover Mountains in the northeast part of the study area and also receives spring discharge just above Littlefield, Arizona (pl. 1). Beaver Dam Wash flows into the Virgin River about 0.5 mi above Littlefield, Arizona (Beck and Wilson, 2006; pl. 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 (Cardinalli and others, 1968; Rush, 1968) for scientific and administrative purposes. 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.



Base from U.S. Geological Survey digital data, 1:100,000, 1988.
Universal Transverse Mercator projection, Zone 11. Shaded-relief from 30-meter Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon.

Figure 1. Hydrographic areas in the study area, southern Nevada and adjacent areas in Utah and Arizona.

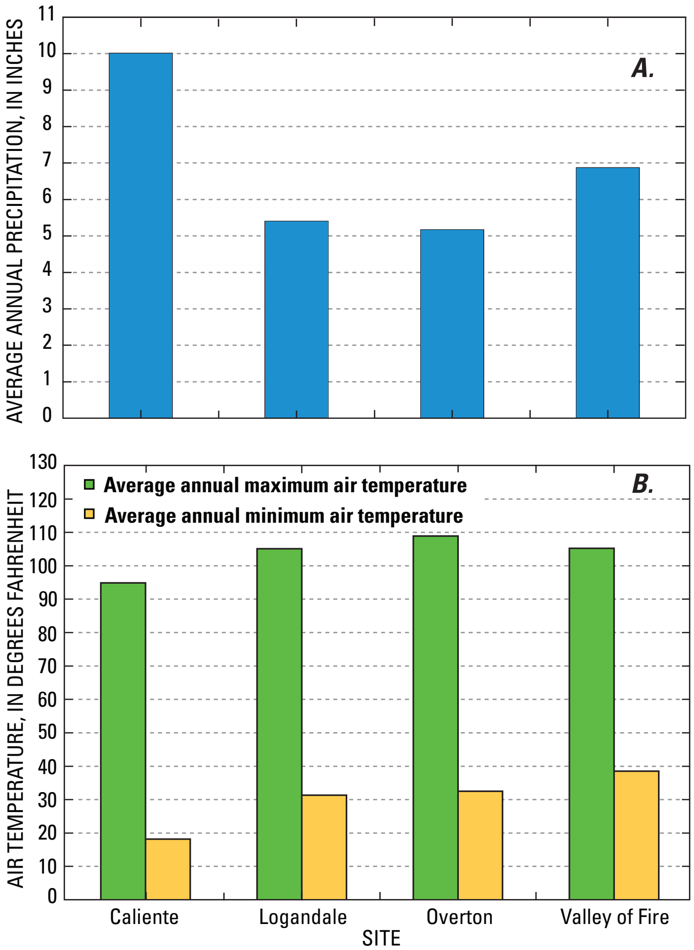


Figure 2. Thirty-year average annual precipitation and 30-year average annual maximum and minimum air temperature in and around the study area, southern Nevada and adjacent areas in Utah and Arizona. (Data from Western Regional Climate Center, 2006).

The Virgin River originates from rain and melted snow in Zion National Park, Utah, and flows southeasterly across southwest Utah. Flow in the river is augmented by springs in Beaver Dam Wash just above Littlefield in northwest Arizona, and continues flowing into southern Nevada before discharging into Lake Mead (pl. 1). The Virgin River supplies water to the Virgin River floodplain which supports a large riparian vegetation community.

The Muddy River originates from a system of regional springs and tributaries (Eakin, 1964) in the Muddy River Springs area (fig. 1; pl. 1). The Muddy River supports a large riparian vegetation community along the reach of the river before discharging into Lake Mead. Ground water also is discharged into Lake Mead from Rogers and Blue Point springs (fig. 1; pl. 1).

Dominant vegetation in the lower altitudes of the study area includes xerophytes such as creosote, yucca, Joshua trees, and saltbrush and at higher altitudes, Pinyon pine and juniper trees. Xerophytes have a shallow root zone and obtain water primarily from local precipitation.

A variety of phreatophytes and riparian vegetation such as mesquite (*Prosopis*), saltcedar (*Tamarix Ramosa*), meadowgrasses, rabbitbrush (*Chrysothamnus viscidiflorus)*, big sage, arrowweed (*Pluchea sericea*), cottonwood (*Populus fremontii*) and willow trees (*Chilopsis)* grow along washes and rivers where the depth to water is within about 40 ft of the surface. About 3,000 acres of agricultural fields, primarily alfalfa, are located along the Virgin River, Meadow Valley Wash, Beaver Dam Wash, and the Muddy River. These fields are irrigated by surface-water diversions, where some water is consumed by ET, and the remainder is either re-diverted back to the source or returned by ground-water infiltration.

Evapotranspiration

Total ET is defined in this study as the annual volume of water lost from an area to the atmosphere. Components that contribute to total ET are surface water, ground water, and local precipitation. The surface-water ET component includes transpiration from riparian vegetation along the banks of washes and rivers and evaporation from open-water surfaces. The ground-water ET component includes transpiration of diffuse underflow from phreatophytes where the water table is 40 ft or less, transpiration from recycled spring water from riparian vegetation near springs and seeps, and evaporation of water from bare soil surfaces where the water table is at or near land surface. This process can be expressed as:

$$ET_t = SW_t + GW_t \quad , \tag{1}$$

where

ET_t is total ET,

SW_t is the surface-water component to ET_t, and

GW_t is the ground-water component to ET_t.

The surface- and ground-water components can be expanded to include their various subcomponents:

$$SW_t = P_{LSW} + SP_{SW} + CH_{SW} \tag{2}$$

$$GW_t = P_{LGW} + SP_{GW} + UF_{GW} \quad , \tag{3}$$

where

P_{LSW} is the surface-water component of local precipitation,

SP_{SW} is channelized surface water from springs and seeps,

CH_{SW} is channelized surface water along washes and rivers from sources outside the study area, and

P_{LGW} is the ground-water component of local precipitation.

SP_{GW} is recycled ground water from springs and seeps, and

UF_{GW} is the ground-water underflow component.

If local precipitation is expressed as the sum of local surface- and ground-water precipitation subcomponents, then:

$$P_L = P_{LSW} + P_{LGW} \quad , \tag{4}$$

where

P_L is local precipitation,

then total ET (ET_t) can be expressed as:

$$\begin{aligned} ET_t &= P_L + (SP_{SW} + CH_{SW}) + (SP_{GW} + UF_{GW}) \\ &= P_L + SW + GW \quad , \end{aligned} \tag{5}$$

where

SW and GW are the total surface- and ground-water components minus their components of local precipitation.

ET_t and P_L can be measured or calculated from micrometeorological data collected in the field. The sum of SW and GW is equal to the difference of ET_t and P_L, and herein referred to as ET_{gs}. ET_{gs} can be expressed as

$$ET_{gs} = ET_t - P_L = SW + GW. \tag{6}$$

The location at which ET_{gs} occurs is not necessarily the same location as the source of the water. For example, ground water can be discharged from a regional spring as spring flow, and then channeled some distance away before infiltrating down into the shallow water table where it is later transpired by the local phreatophytes.

The annual volume of discharge by ET_{gs} was estimated by mapping areas of similar surface and vegetation cover and multiplying the area of the mapped cover by a representative annual ET_{gs} rate. This method is similar to those described by Walker and Eakin (1963) and Laczniak and others (1999). Values of ET_{gs} were either estimated from data collected at field sites or compiled from the literature.

Evapotranspiration Units

Areas of similar land cover are defined as unique ET units. ET units are areas of similar plant type, density, and vigor. ET rates are correlated well with these vegetation characteristics (Ustin, 1992; Laczniak and others, 1999; Nichols, 2000; and Reiner and others, 2002). Eight ET units were identified in this study (table 1, pl. 1): dense meadowland vegetation (DMV; 200 acres), dense woodland vegetation (DWV; 7,200 acres), moderate woodland vegetation (MWV; 6,100 acres), dense shrubland vegetation (DSV; 5,800 acres), moderate shrubland vegetation (MSV; 22,600 acres), agricultural unit (AGU; 3,100 acres), non-phreatophytic unit (NPU; 3,400,000 acres), and open water unit (OWU; 300 acres). More than 99 percent of the study area is occupied by xerophytes, identified as NPU, that subsist on soil moisture from local precipitation and do not contribute to ground-water or surface-water discharge.

Prior to delineating ET units, the extent of discharge areas were delineated using the National Agriculture Imaging Program (NAIP) database, Southwest Regional Gap Analysis Program (SWReGAP) data (Kepner and others, 2005), and field reconnaissance. These areas encompass the spatial extent of phreatophytic and riparian vegetation, and open-water areas where the potential ET_{gs} is greater than zero. Discharge areas typically are mapped in early to mid-summer because color contrasts in the vegetation are highest due to maximum water availability to plants.

ET units were delineated using the modified soil-adjusted vegetation index (MSAVI; Qi and others, 1994). The MSAVI uses selected reflectance bands of Landsat Thematic Mapper satellite data (100 by100 ft pixel resolution; obtained June 21, 2003) that respond to the photosynthetic activity of the vegetation. The MSAVI has an advantage over other vegetation indexes in areas of sparse vegetation because it removes soil influences from the vegetation index at sparse plant cover. MSAVI values are dimensionless and range from -1 to 1. For this study, values were scaled from 0 to 1. Values less than 0 were set equal to 0. MSAVI reflectance values between 0.01 and 0.07 represent areas of non-phreatophytic vegetation or bare soils which have the lowest potential for ET. Values of MSAVI reflectance that were greater than 0.55 correspond to vegetation with the highest potential for ET (such as meadow grasses; table 1). MSAVI reflectance values less than zero represent areas of open water because of the absence of photosynthetic activity (table 1). Open-water areas contributing to evaporation were determined from satellite data and were at least 100 by 100 ft in size. All other open-water areas either did not contribute to total ET or were accounted for in other ET components such as rivers and washes. ET units representing areas of agricultural vegetation (AGU) were identified and delineated manually using the NAIP data.

Table 1. Evapotranspiration units determined from the modified soil-adjusted vegetation index in the study area, southern Nevada and adjacent areas in Utah and Arizona.

[ET, evapotranspiration. MSAVI, modified soil-adjusted vegetation index. N/A, not applicable]

ET-unit identifier	ET unit	MSAVI value (dimensionless)	ET-unit area (acres)	General description of ET unit
DMV	Dense meadowland vegetation	0.55 and greater	200	Primarily meadow grasses with some tall reedy and rushy marsh plants; perennially flooded; water table at or just below surface.
DWV	Dense woodland vegetation	0.28–0.55	7,200	Primarily dominated by trees, including mixed trees, grasses and shrubs; water table greater than 10 feet below land surface; soil typically dry.
MWV	Moderate woodland vegetation	0.20–0.28	6,100	Primarily mixed trees, with grasses and shrubs; water table greater than 15 feet below land surface; soil typically dry.
DSV	Dense shrubland vegetation	0.15–0.20	5,800	Primarily shrubs, sparse grasses, sparse trees; water table greater than 15 feet below land surface; soil dry.
MSV	Moderate shrubland vegetation	0.07–0.15	22,600	Sparse shrubs and grasses: water table greater than15 feet below land surface; soil dry.
AGU	Agricultural fields	N/A	3,100	Primarily alfalfa; depth to water table unknown.
NPU	Non-phreatophytic vegetation that do not use ground water	0.01–0.07	3,400,000	Primarily dry bare soils and xerophytes; water table typically greater than 20 feet below land surface.
OWU	Open water areas	0	300	Washes, rivers, and springs.

Site Selection and Instrumentation

Micrometeorological stations were instrumented at four sites representative of dense and moderate woodland, and dense and moderate scrubland ET units. Sites were located on the Virgin River floodplain (dense woodland), along the Muddy River (moderate woodland), in Rainbow Canyon (moderate shrubland), and in Lower Meadow Valley Wash (dense shrubland) (fig. 1, pl. 1, and table 2**)**. Site selection was based on field reconnaissance, preliminary ET-unit characteristics, and upwind fetch. Generally, fetch refers to the distance that air travels from the boundary of the surface of interest to the instruments and implies a homogeneous mix of vegetation, soils, surface water, or some combination thereof. The acceptable minimum fetch allowed in this study was 1:100 (1 m in instrument height above measuring surface to 100 m to the boundary of the environment of interest; Weeks and others, 1987).

Data collection for the study began in February 2003 and ceased in September 2006. Equipment was installed at each site for a minimum of 1 year, except for the Lower Meadow Valley Wash site, which was in operation for only 6 months because of technical difficulties. Sites were not installed at the same time but there were periods when data collection did overlap. Missing data resulted from various technical or weather related problems.

The Virgin River floodplain ET site is typified by a dense population of 20 to 30-ft tall saltcedar trees with lesser amounts of mesquite, pickleweed, and arrowweed. This site was located about 8 mi northeast of Overton, Nevada, at an altitude of about 1,200 ft (fig. 1; pl. 1). The floodplain at the site is about 0.62 mi wide and extends several miles north/south, and is comprised of fine-grained sand. The height of the data collection platform was about 30 ft above land surface, raising the instrumentation above the tree tops. Depth to ground water varied from 13 to 15 ft during the site's operation (February 2003–March 2005; table 2). This site was instrumented to collect data for the Bowen-ratio method of calculating ET (fig. 3*A*).

The Muddy River riparian ET site was located about 100 ft from the river surrounded by a dense grove of 10 to 15-ft tall mesquite trees growing in soil composed mostly of silty clays. The Muddy River site is in lower Moapa Valley about 7 mi from the town of Glendale, Nevada at an altitude of about 1,650 ft. Flow in the Muddy River originates from Muddy River Springs, which are about 2.5 mi northwest of the site (fig.1; pl. 1). The Muddy River riparian area is about 980 to 1,300 ft wide and extends from just north of the Muddy River Springs southward to the Moapa River Indian Reservation. The riparian area primarily consists of groves of dense mesquite trees mixed with cottonwood trees, palm trees, and various species of vines. Depth to ground water at this site varied from 14 to 23 ft during the site's operation (July 2003–October 2006; table 2). This site was instrumented to collect data for the Bowen-ratio method of calculating ET (fig. 3*B*).

The Rainbow Canyon site was located about 10 mi south of Caliente, Nevada, and about 200 ft east of Meadow Valley Wash at an altitude of about 4,100 ft. The canyon is north-south trending and very narrow, with a width of less than 0.25 mi. The site is dominated by rabbitbrush and sage that stand about 3 ft tall in gravelly soil. The gravelly soils made it difficult install a well at this site and as a result the depth to ground water is unknown. This site was instrumented to

Table 2. Characteristics of evapotranspiration sites in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; MSV, moderate shrubland vegetation; DSV, dense shrubland vegetation]

Site name	ET-unit identifier	Latitude	Longitude	Altitude (feet)	Depth of water table below land surface (feet)	Period of data collection [total days]	Number of days of ET data
Virgin River	DWV	N36° 35' 15.01"	W114° 19' 42.21"	1,200	13 – 15	02-02-03 – 03-09-05 [766]	521
Muddy River	MWV	N36° 41' 27.50"	W114° 41' 16.30"	1,650	14 – 23	07-30-03 – 10-19-06 [1,177]	917
Rainbow Canyon	MSV	N37° 31' 13.38"	W114° 34' 59.52"	4,100	[1]15 – 20	06-18-05 – 10-19-06 [488]	487
Lower Meadow Valley Wash	DSV	N36° 51' 00.17"	W114° 39' 57.20"	1,900	[2]16	04-11-06 – 10-19-06 [191]	191

[1] Estimate.

[2] Less than 1 foot change in water level.

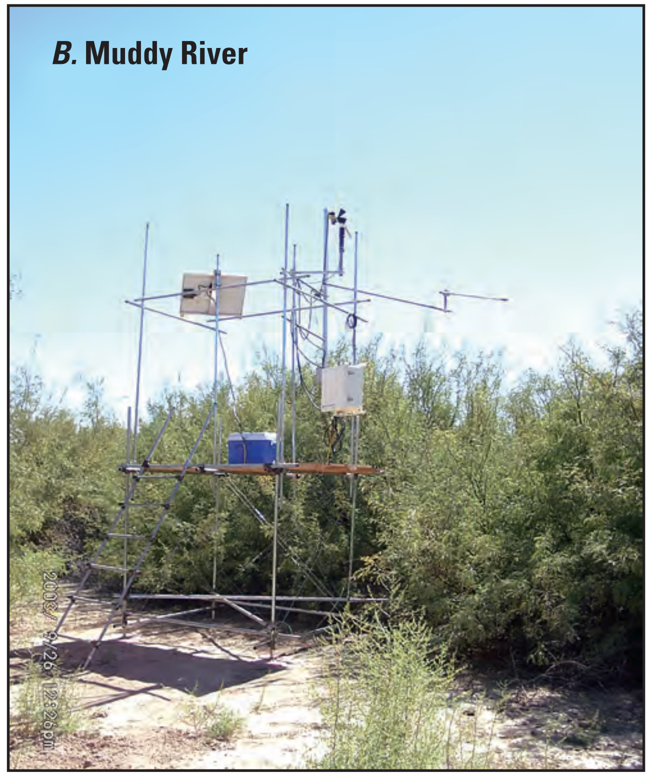
collect data for the eddy-covariance method for calculating ET (fig. 3*C*) and was in operation from June 2005 to October 2006.

The Lower Meadow Valley Wash site was located about 15 mi north of Moapa, Nevada, at an altitude of about 1,900 ft. The site was in a narrow canyon, less than one-half mile across, in a riparian meadow with soils composed of fine-grained sand with some clay. Depth to ground water varied from 16 and 16.5 ft below land surface during the data collection period. The sites vegetation community was diverse and complex with an assortment of saltcedar, mesquite, and cottonwood trees lining the wash on the eastern and far southern edges of the area, xerophytes, mainly creosote and saltbrush, dominating the west edge, and a homogeneous community of arrowweed plants in an irregularly shaped patch (980-ft north-south by 229-ft east-west) in the center of the area. Obtaining an adequate fetch was a challenge at this site due to the mixed vegetation and limited area. This site was instrumented to collect data for the eddy-covariance method of calculating ET (fig. 3*D*). The ET sensors were placed as close to the center of the arrowweed community as possible. At the time of installation in March 2006, the arrowweed plants were about 3.5 ft tall and the ET sensors were placed about 3.5 ft above average vegetation height. This installation allowed for adequate fetch from the south (direction of prevailing wind); however, it was thought that fetch from the east-west direction might be insufficient. As data were collected ET rates were higher than expected and on August 7, 2006, adjustments were made to sensor height by lowering them to 1.5 ft above average vegetation height in an attempt to better account for the fetch from all directions. This adjustment resulted in an even higher ET rate.

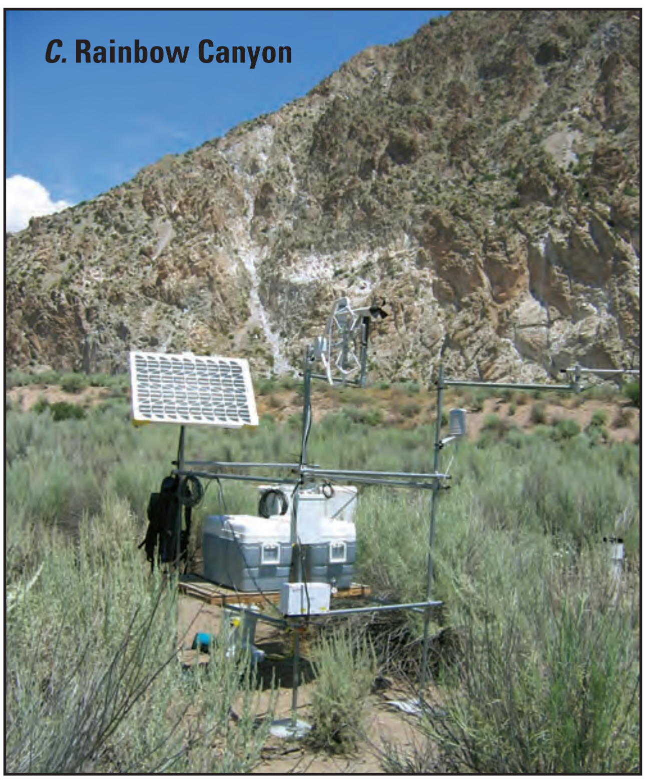
The micrometeorological station at the Lower Meadow Valley Wash site was only in operation from April 11 to October 19, 2006, due to technical difficulties. This time period spans the annual growing season when the majority of the ground- and surface-water discharge from ET occurs. Daily ET rates from the Muddy River site were used as surrogates for missing data from the Lower Meadow Valley Wash site for the periods January 1 to April 11, 2006, and October 20 to December 31, 2006. This substitution was assumed reasonable because the micrometeorological stations were in close proximity and during these periods transpiration is at or near annual minimums.

Between September 2004 and August 2005, about twice the average annual amount of rain (12.74 in.) was recorded in Moapa, Nevada. Precipitation data for Moapa (gauge ID 3264) are available from the Clark County Regional Flood Control District, Nevada, at http://acequia.ccrfcd.org/rainfallhistory/loadrainfall.aspx?Year=2004 for 2004 and at http://acequia.ccrfcd.org/rainfallhistory/loadrainfall.aspx?Year=2005 for 2005. Severe flooding occurred in Meadow Valley Wash, Beaver Dam Wash, and the Virgin River Valley from November 2004 to January 2005. During this period, only the Virgin River and Muddy River sites were in operation; sensors at the Rainbow Canyon and Lower Meadow Valley Wash sites had not yet been installed. The Virgin River site was inaccessible due to the flooding which resulted in a permanent loss of data after March 9, 2005. The Muddy River site also received substantial amounts of rain during that period—more than 11 in. at Muddy River Springs—and although flooding was relatively minor, access to the site was difficult. As a result, data were lost at the Muddy River site from May to September 2005. All other periods of missing data were the result of equipment problems.

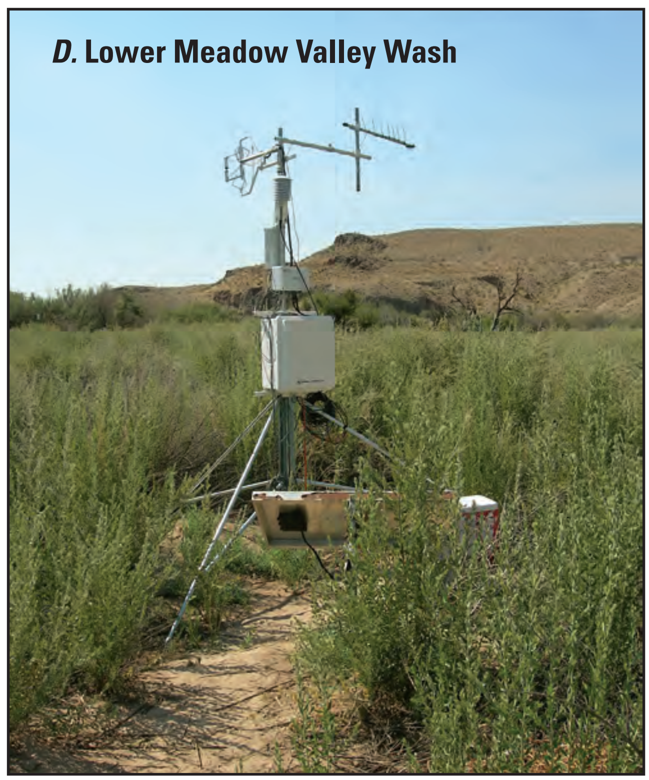
Photograph taken by Guy De Meo, U.S. Geological Survey, 2003.



Photograph taken by Guy De Meo, U.S. Geological Survey, 2003.



Photograph taken by Timothy Olsen, U.S. Geological Survey, 2005.



Photograph taken by Jon Darnell, U.S. Geological Survey, 2006.

Figure 3. Evapotranspiration sites at (*A*) Virgin River, (*B*) Muddy River, (*C*) Rainbow Canyon, and (*D*) Lower Meadow Valley Wash in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Evapotranspiration Calculations

ET is a process by which water from the Earth's surface is transferred to the atmosphere. The transfer requires energy to change water from a liquid to a vapor state. This relation between water loss and energy consumption is the basis for many of the energy-budget methods used to estimate ET. ET, as used in this report, includes evaporation from open water and soil and transpiration from plants. Micrometeorological instruments were used at field sites to collect the necessary parameters to derive energy fluxes used in the determination of ET.

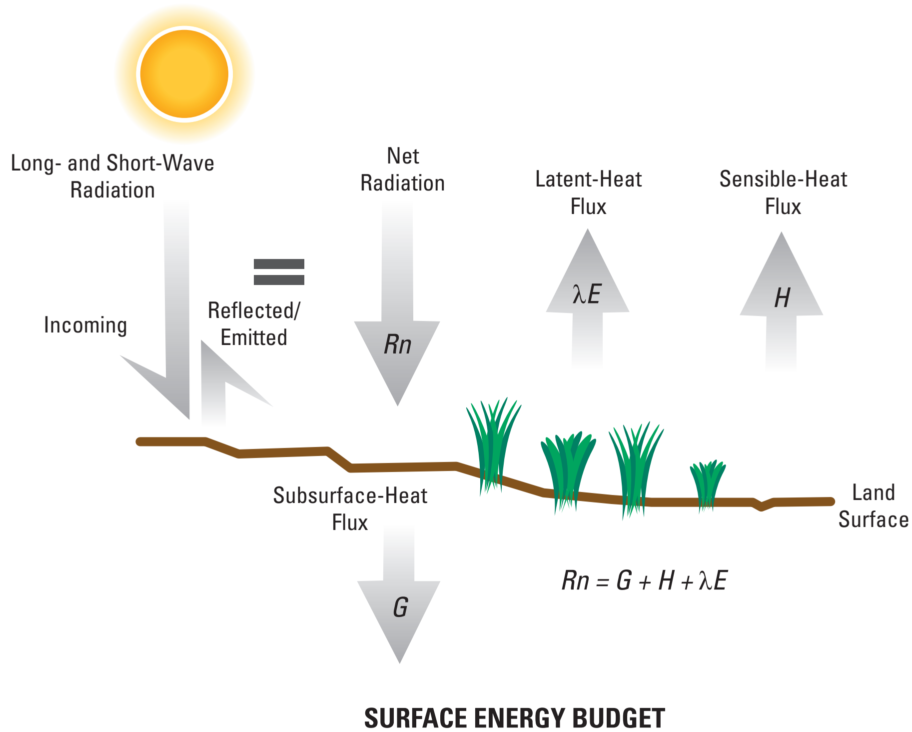


Figure 4. Energy budget of the surface of the Earth.

Energy Budget and Methods

Energy at the surface of the Earth can be described by an energy budget that balances the incoming and outgoing energy fluxes (fig. 4). Assuming that energy use by biological processes and storage of heat by the vegetation are negligible, the energy budget for conditions typical of the study area can be expressed as

$$R_n = G + H + \lambda E \quad , \qquad (7)$$

where

R_n is net radiation (energy per area per time),

G is subsurface-heat flux (energy per area per time),

H is sensible-heat flux (energy per area per time), and

λE is latent-heat flux (energy per area per time)

where

λ is the latent heat of vaporization for water (energy per mass), and

E is the rate of water evaporation (mass per area time).

Net radiation (R_n) is the primary term in the energy budget and is the algebraic sum of incoming and outgoing long- and short-wave radiation. Subsurface-heat flux (G) represents how much energy the soil or water column gains or loses during a given period. Net radiation (R_n) and subsurface-heat flux (G) can be measured or computed in the field. The difference between R_n and G is the energy available at the surface of the Earth. Sensible-heat flux (H) is the energy exchanged between the atmosphere and the surface. When H is positive, the surface of the Earth is heating the atmosphere; when negative, the atmosphere is heating the surface. Latent-heat flux (λE) is the energy used to evaporate or transpire water from soil, open water, and plants. In this study, the Bowen-ratio (Bowen, 1926) and eddy-covariance (Dyer, 1961) methods were used to determine the energy-budget fluxes and calculate ET. Although both methods determine R_n and G using the same instrumentation, H and λE are calculated differently.

Energy-Budget Closure

According to the principal of conservation of energy, the sum of all components of the energy budget is zero and is referred to as energy-budget closure. The achievement of closure is used to assess the measurement accuracy of the individual components of the energy budget. The better the closure, the better the confidence is in the field measurements. To measure relative balance of closure, Duell (1985), calculated the ratio of sensible-heat flux (H) and latent-heat flux (λE) to the available energy ($E_n = R_n - G$) times 100. When this ratio is 100 percent then all of the E_n is accounted for in H and λE and the energy budget is closed. When closure is less than 100 percent, E_n is greater than H and λE indicating that either latent- and (or) sensible-heat flux are being underestimated by the equipment. When the closure is greater than 100 percent, then H and λE are greater than E_n and are being overestimated by the equipment.

Bowen-Ratio Method

Sensible-heat flux (H) and latent-heat flux (λE) involve turbulent transfer coefficients of heat and vapor that are difficult to determine, and as a result, neither H nor λE can be solved directly. In 1926, Bowen developed the Bowen-ratio method to solve the energy budget by taking the ratio of sensible-to latent-heat flux ($H/\lambda E$). This approach solves for H and λE by using all components of the energy budget, resulting in a complete balance or closure of the budget (Laczniak and others, 1999). By using this method, ET can be calculated from measurable micrometeorological data.

Eddy-Covariance Method

The eddy-covariance method is based on the principal that turbulent eddies can vertically transport sensible and latent heat (Brutsaert, 1982). Estimates of sensible-heat flux (H) and latent-heat flux (λE) are determined by using instrumentation that makes rapid measurements of fluctuations in vertical wind speed, water vapor, and air temperature over short intervals of time. Unlike the Bowen ratio, all energy-budget components are calculated independently. This computational independence of H and λE frequently results in difficulties achieving energy-budget closure; however, this approach to measuring energy fluxes can provide a more accurate representation of H and λE because they are not forced to balance. In this study, corrections for temperature-induced fluctuations in air density (Webb and others, 1980) and for the sensitivity of oxygen (Tanner and Greene, 1989) were used in the calculations of latent-heat flux.

Bowen-Variant Method

Sometimes energy-budget closure is not achievable with the eddy-covariance method due to unavoidable placement of instrumentation in the environment. Poor closure is a consequence of either over- or under-estimating the sensible- and latent-heat fluxes. The eddy-covariance method assumes that sensible- and latent-heat fluxes are over- or under-estimated equally (Moore, 1976). To compensate for this assumption, German (2000) took the ratio of H to λE estimated with eddy-covariance sensors and calculated the same fluxes using a variant of the Bowen ratio (Sumner, 2001). The sensible- and latent-heat flux can be expressed as

$$\lambda E_b = \frac{R_n - G}{1 + \frac{H_e}{\lambda E_e}} \quad . \tag{8}$$

$$H_b = \lambda E_b \frac{H_e}{\lambda E_e} \tag{9}$$

where

λE_e is the latent heat calculated using the eddy-covariance method,

R_n is net radiation,

G is subsurface-heat flux,

H_b is the sensible heat calculated using the Bowen-variant method,

H_e is the sensible heat calculated using the eddy-covariance method, and

λE_b is the latent heat calculated using the Bowen-variant method.

Micrometeorological Data

Micrometeorological data collected at all sites included net radiation, subsurface-heat flux, subsurface soil temperature, and soil-water content. Additionally, at sites instrumented for applying the Bowen-ratio method, air temperature and relative humidity were measured at 1.6 and 4.9 ft above the average canopy height of the vegetated surface of interest (fig. 5*A*). Sites used for the eddy-covariance method required a sonic anemometer to measure three-dimensional wind speeds and a krypton hygrometer (mounted about 5 ft above the average canopy height) to determine water vapor density used to calculate sensible- and latent-heat flux (fig. 5*B*). The following instrumentation was installed and supporting data were collected at each site: a two-dimensional anemometer to measure wind speed and direction, a shallow well with a submersible pressure transducer to measure fluctuations in ground-water level, and a volumetric precipitation gage to collect bulk rainfall. At the Rainbow Canyon site, gravelly soils prevented the installation of the shallow well so the ground-water level was unknown. Data to determine Bowen-ratio values were measured at 10- or 30-second intervals and averaged over 20 minutes. Data to determine the eddy-covariance values were measured at 0.1-second intervals and also averaged over 20 minutes. For all instrumented sites, the 20-minute data were stored and retrieved for processing every month.

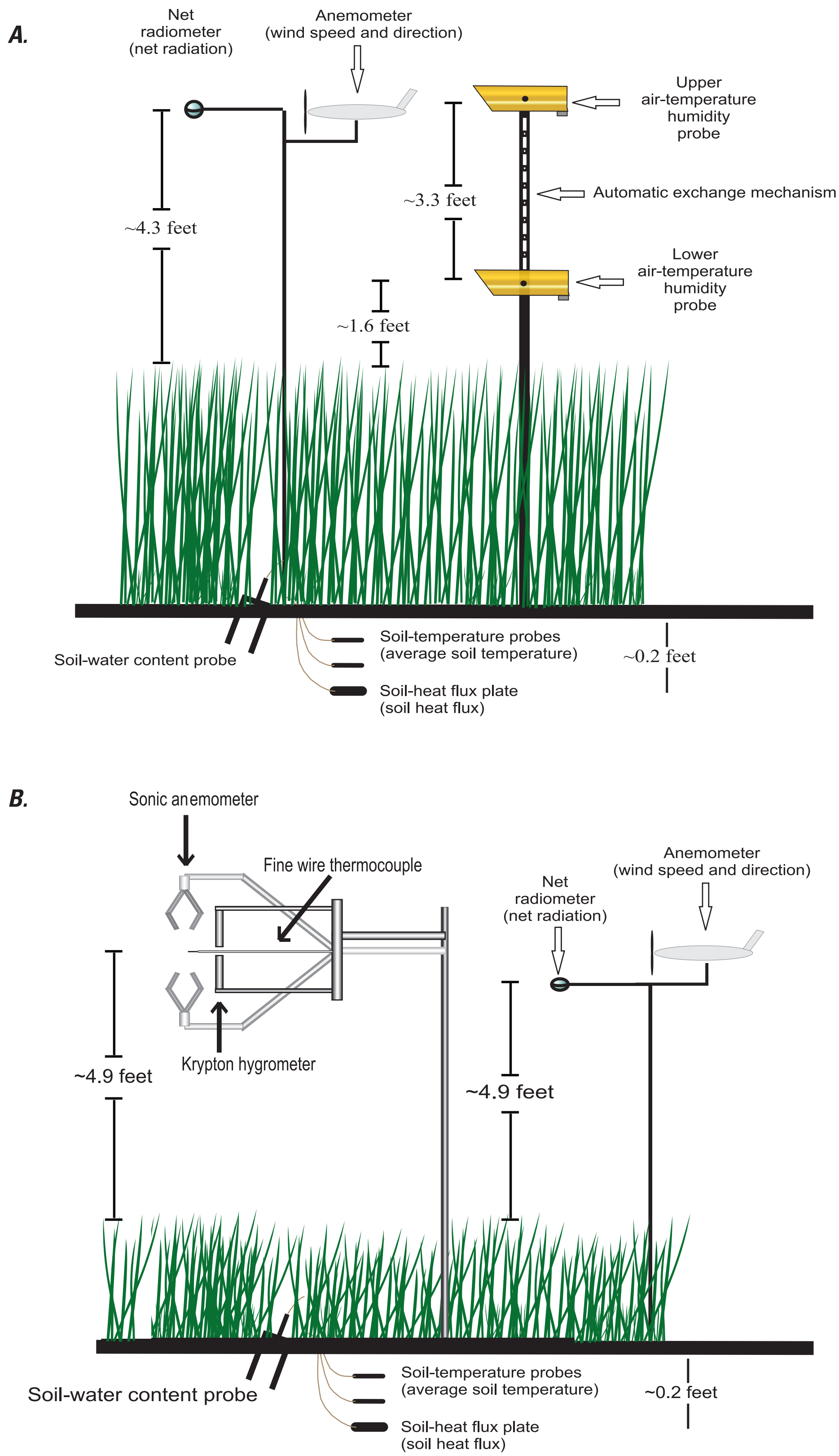
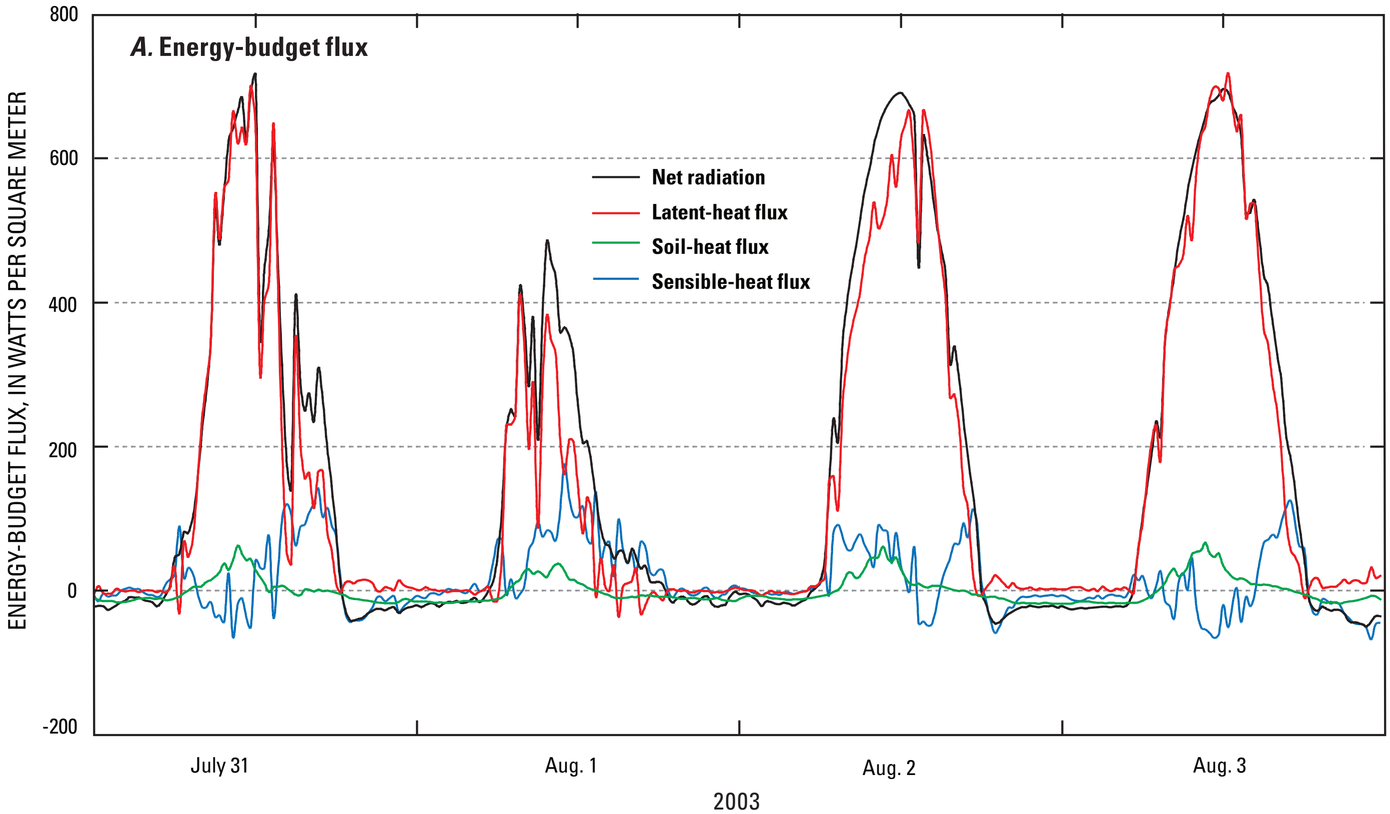


Figure 5. Instrumentation used to measure micrometeorological data for the (*A*) Bowen-ratio and (*B*) eddy-covariance methods.

Daily and Annual Total Evapotranspiration

The stored micrometeorological data were used to calculate the energy budget, 20-minute ET, daily ET, and annual ET. The data-reduction process included (1) determining the 20-minute averaged individual components of the energy budget (net radiation, subsurface-heat flux, latent-heat flux, and sensible-heat flux; fig. 6*A*), (2) calculating 20-minute ET values from the latent-heat flux, (3) summing the 20-minute ET values over a 24-hour period to obtain daily ET rates (fig. 6*B*), and (4) whenever possible, calculating average daily ET values using two or more years of data (fig. 6*C*).



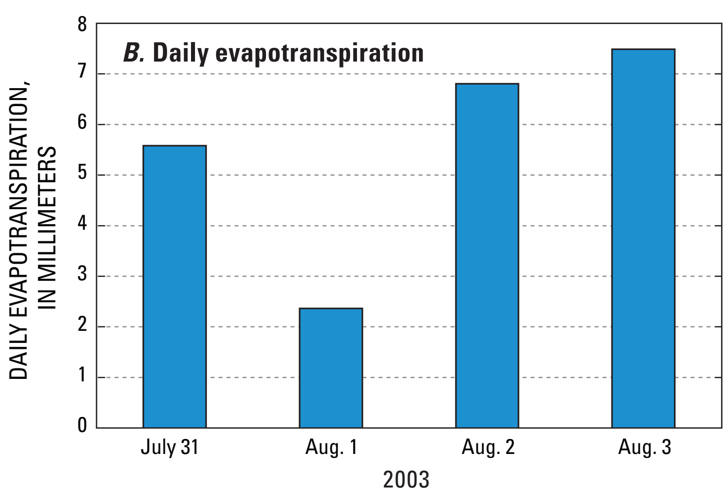


Figure 6. Example of (*A*) 5-day energy-budget flux at Muddy River site, July 31–August 3, 2003, (*B*) daily evapotranspiration for the Muddy River site July 31–August 3, 2003, and (*C*) daily evapotranspiration collected at the four sites, southern Nevada, and adjacent areas in Utah and Arizona, July 31–August 3, 2003.

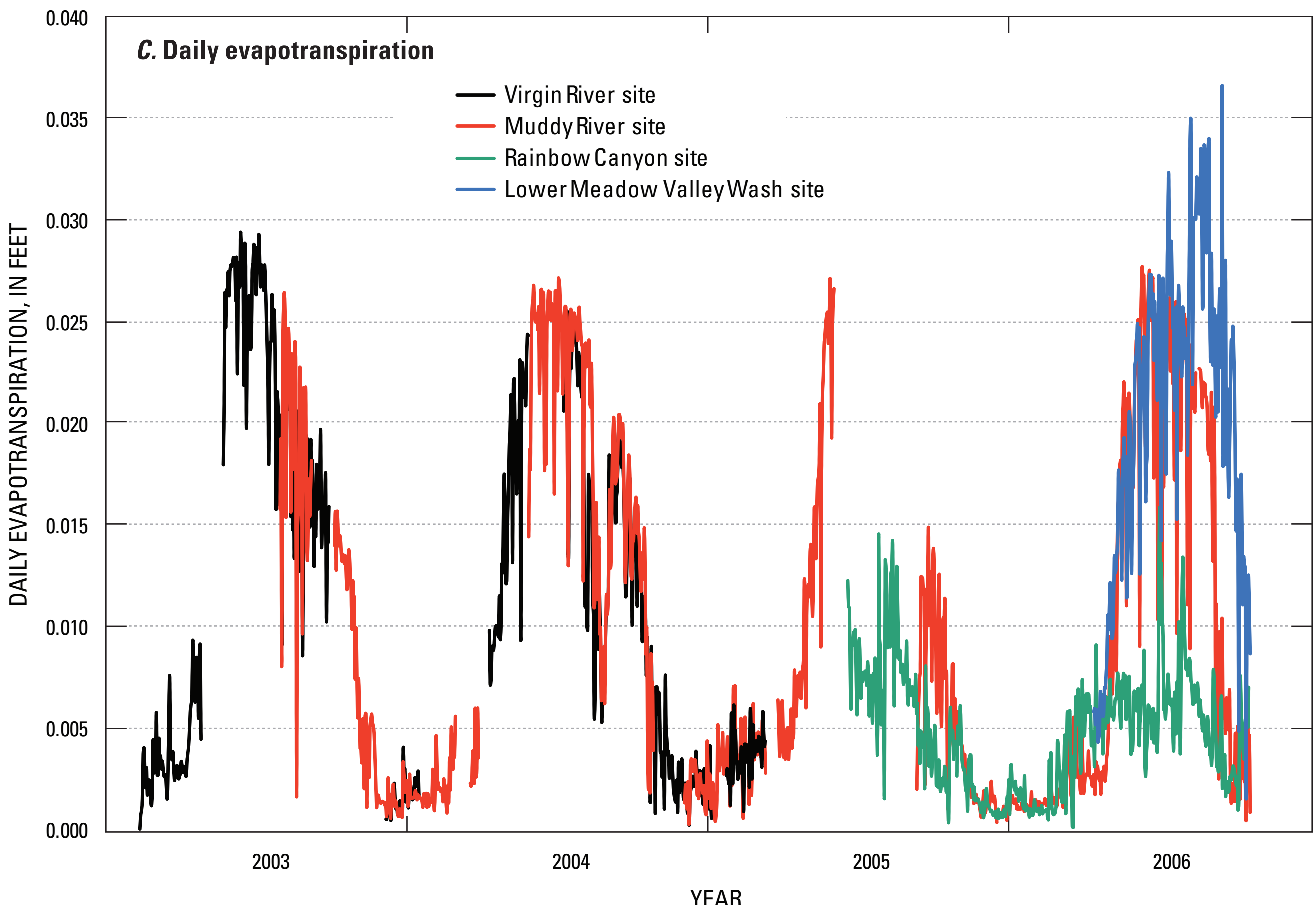


Figure 6.—Continued.

ET rates can vary from year to year and from one day to the next in response to rapidly changing weather conditions. Annual ET rates sometimes have to be estimated due to periods of missing or inaccurate data, or varied weather conditions. To correct for data gaps and to obtain an annual average ET rate, the entire record of available ET from the Virgin River site, Muddy River site, and Rainbow Canyon site were used to determine the average daily ET rate, which then can be summed to determine the annual ET rate (fig. 7). Average daily ET values were calculated for each calendar day from each year that data were available for that day. Some days had available data from only 1 year while others days had available data for as many as 4 years at the Muddy River site. This approach could not be used at the Lower Meadow Valley Wash site because data were only collected from April 12, 2006 to October 19, 2006.

At the Rainbow Canyon and Lower Meadow Valley Wash sites, the riparian areas were very narrow limiting the available fetch needed to determine the energy-budget and estimate ET. The accuracy of ET estimates was assessed by comparing the averaged 20-minute closure values at these two sites on July 2 and on August 20, 1996, spanning the hours from 0700 to 1600 PST. These dates were selected for comparison because vegetation were very productive and ET likely was at or near annual maximum. Additionally at the LMVW site, July 2 is representative of the lower sensor height while August 20 is representative of the raised sensor height. Average closure at the Rainbow Canyon site was about 100 and 90 percent on July 2 and on August 20, respectively. Average closure at the Lower Meadow Valley Wash site was about 128 and 168 percent on July 2 and on August 20, respectively. The Rainbow Canyon site achieved good closure indicating that all the sensors were sampling air from the same environment and that fetch was not much of an issue during these periods. At the Lower Meadow Valley Wash site, however, closure was poorer indicating that the measured sensible-heat and latent-heat flux were greater than the measured available energy suggesting that fetch was an issue before and after the adjustments were made to the instruments.

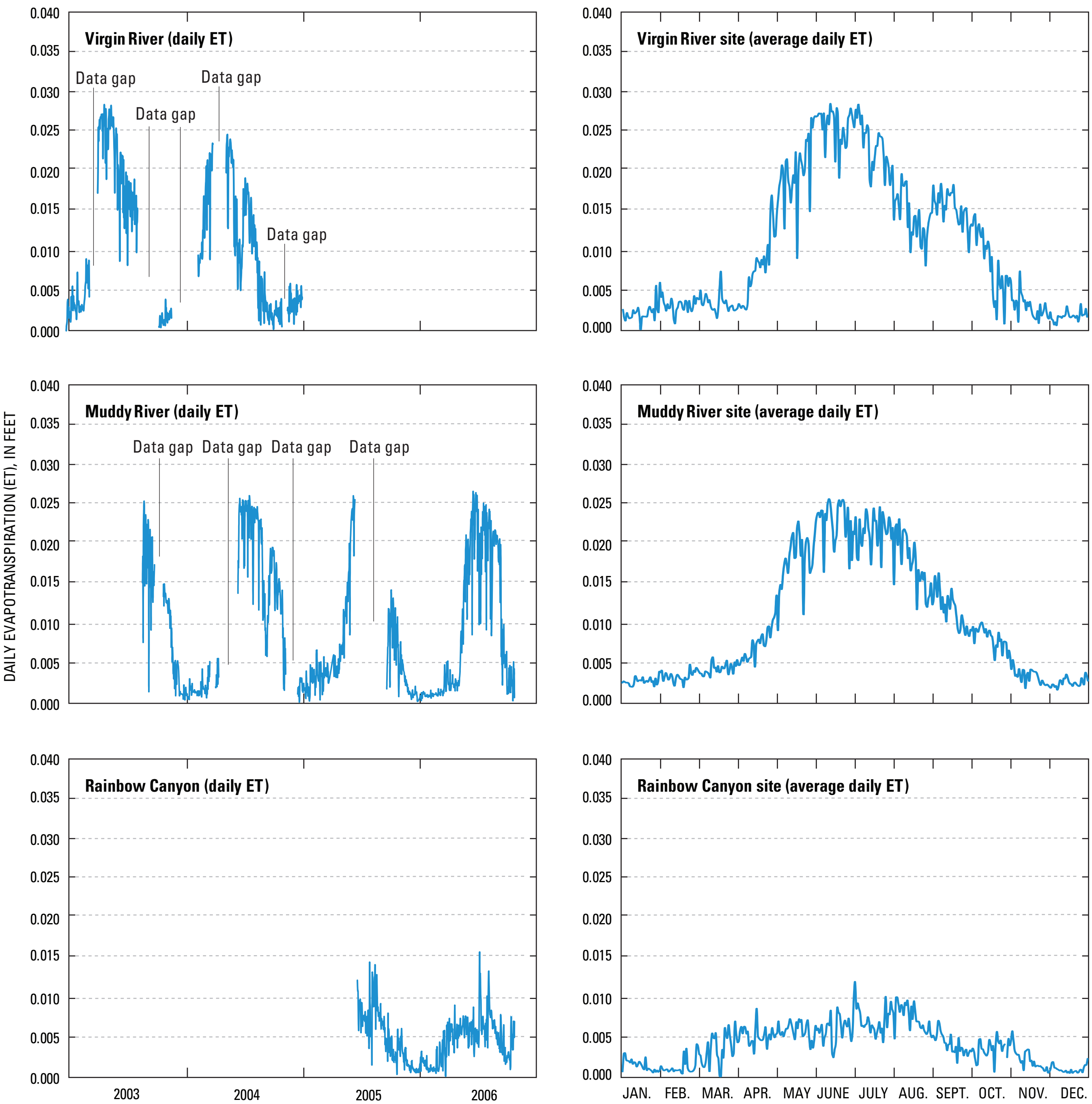


Figure 7. Collected daily evapotranspiration for the Virgin River site from February 2003 to March 2005, the Muddy River site from July 2003 to October 2006, and from the Rainbow Canyon site from June 2005 to October 2006 and the corresponding average daily evapotranspiration for each site calculated from the collected daily evapotranspiration in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Bowen-variant approach (eq. 8 and 9) was applied to provide additional estimates of ET rates for comparison against the eddy-covariance results. Figure 8 displays the Bowen-variant ET rates (Y-axis) plotted against the eddy-covariance ET rates (X-axis) for both the Rainbow Canyon and Lower Meadow Valley Wash sites. The closer the slope of the ET trend line and the Y=X line the better agreement between the Bowen-variant and eddy covariance ET rates. The slope of the trend line at the Rainbow Canyon site is closer to the Y=X line than at the Lower Meadow Valley Wash site (fig. 8).

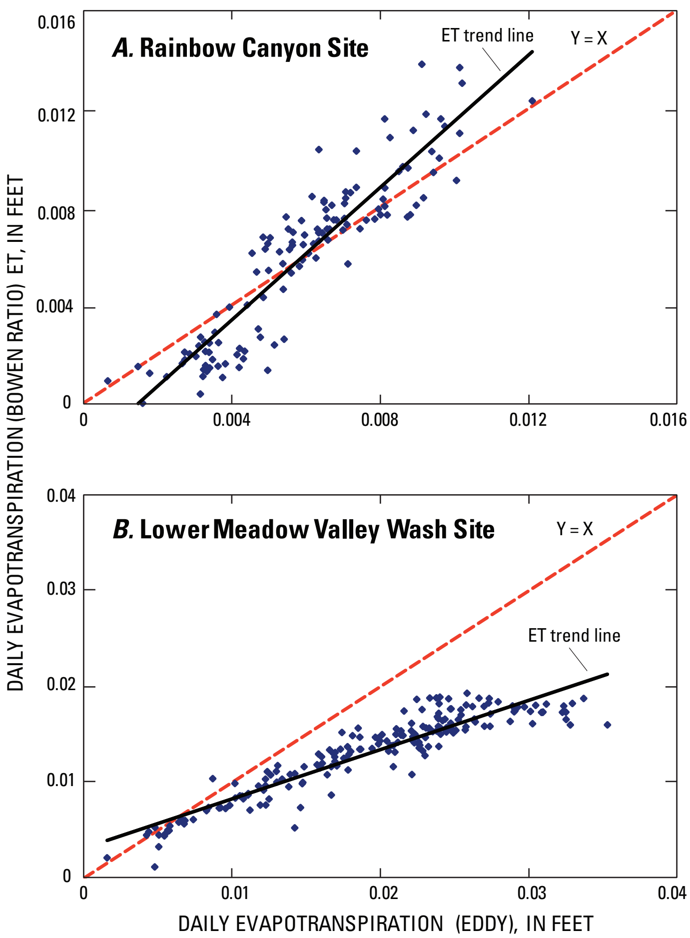


Figure 8. Regression of daily evapotranspiration calculated with the Bowen-variant and eddy-covariance methods using sensible- and latent-heat fluxes from the eddy-covariance equipment at the Rainbow Canyon site from June 19, 2005, to October 19, 2006, and the Lower Meadow Valley Wash site, from April 12 to October 18, 2006, southern Nevada.

This suggests that there is better agreement between the eddy covariance and the Bowen-variant ET rates at the Rainbow Canyon site than at the Lower meadow Valley Wash site. The estimated total annual ET rates at Lower Meadow Valley Wash site were 4.1 and 2.8 ft from the eddy-covariance and the Bowen-variant methods, respectively. At the Rainbow Canyon site, the estimated total annual ET rate was 1.5 ft for both methods (table 3). These results also suggest that fetch may have been a problem at the Lower Meadow Valley Wash site along with rapid growth of vegetation during the time of data collection. The Bowen-variant ET rate of 2.8 ft was the rate used to determine the total annual ET for Lower Meadow Valley Wash.

From January 1 to April 11, 2006 and October 20 to December 31, 2006, data were not collected at the Lower Meadow Valley Wash site. Daily ET rates from the Muddy River site were used as proxy data. During the first period of missing data (January 1–April 11, 2006) daily ET from the Muddy River site for the same period were used. However, during the second period of missing data (October 20–December 31, 2006) daily ET from October 20 to December 31, 2005 were used because data were not being collected at either site. These daily ET substitutions were assumed reasonable because the sites were in close proximity to one another and substitutions were made during the time of year when transpiration of ground- and surface- water discharge from vegetation are at or near annual minimums (fig. 9).

The total annual ET rates for the four ET sites ranged from a minimum of 1.5 ft at Rainbow Canyon which was a moderate shrubland site to 3.9 ft at the Virgin River which was a dense woodland vegetation site (fig. 10; table 4). The total annual ET rate for the Virgin River site determined in this study was in the same range (2.5–4.7 ft) as the ET rate for a similar type site on the Virgin River reported by Devitt and others (1998) and slightly higher than the range of values (2.5–3.5 ft), reported for the same area by Weeks and others (1987).

Table 3. Annual evapotranspiration rate from the eddy-covariance and Bowen-variant methods at Rainbow Canyon (June 2005–October 2006) and Lower Meadow Valley Wash (January–December 2006) sites, southern Nevada.

ET site name	Annual evapotranspiration rate (feet)	
	Eddy covariance	Bowen-variant method
Rainbow Canyon	1.5	1.5
Lower Meadow Valley Wash	4.1	2.8

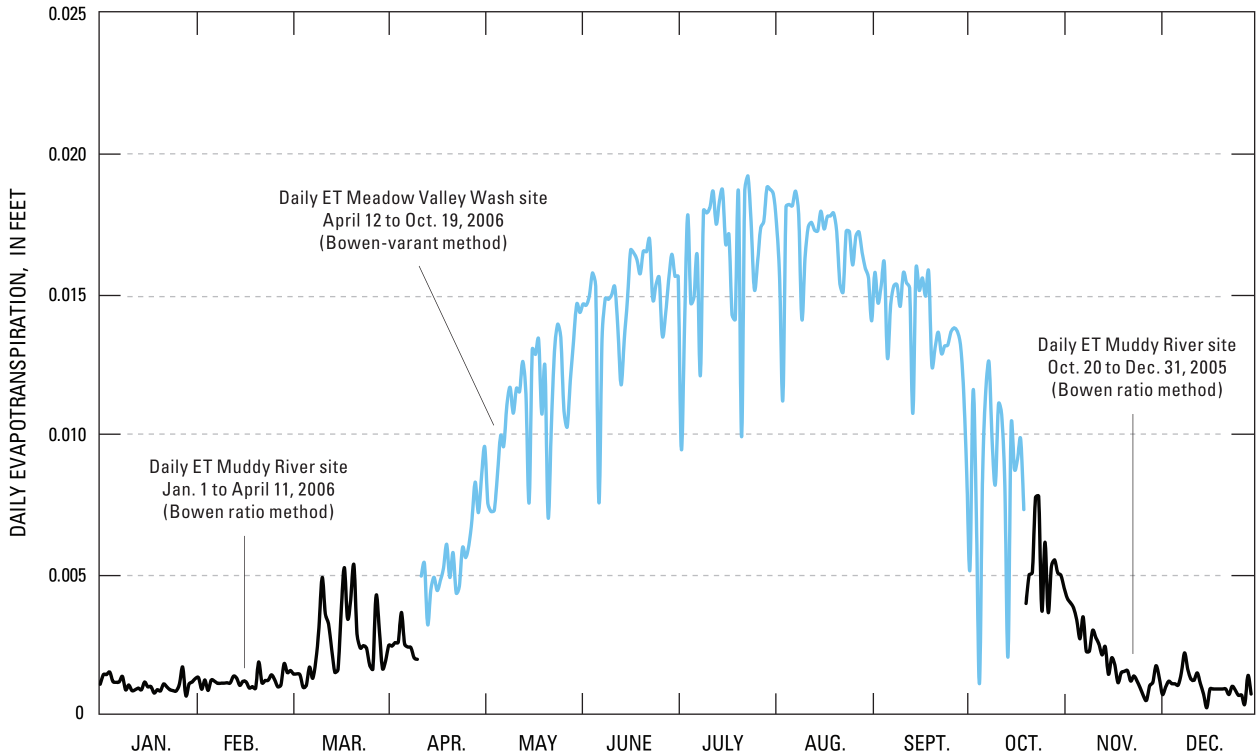


Figure 9. Daily evapotranspiration at the Lower Meadow Valley Wash site with data substituted from the Muddy River site January 1 to April 11, 2006, and October 19 to December 31, 2005, southern Nevada.

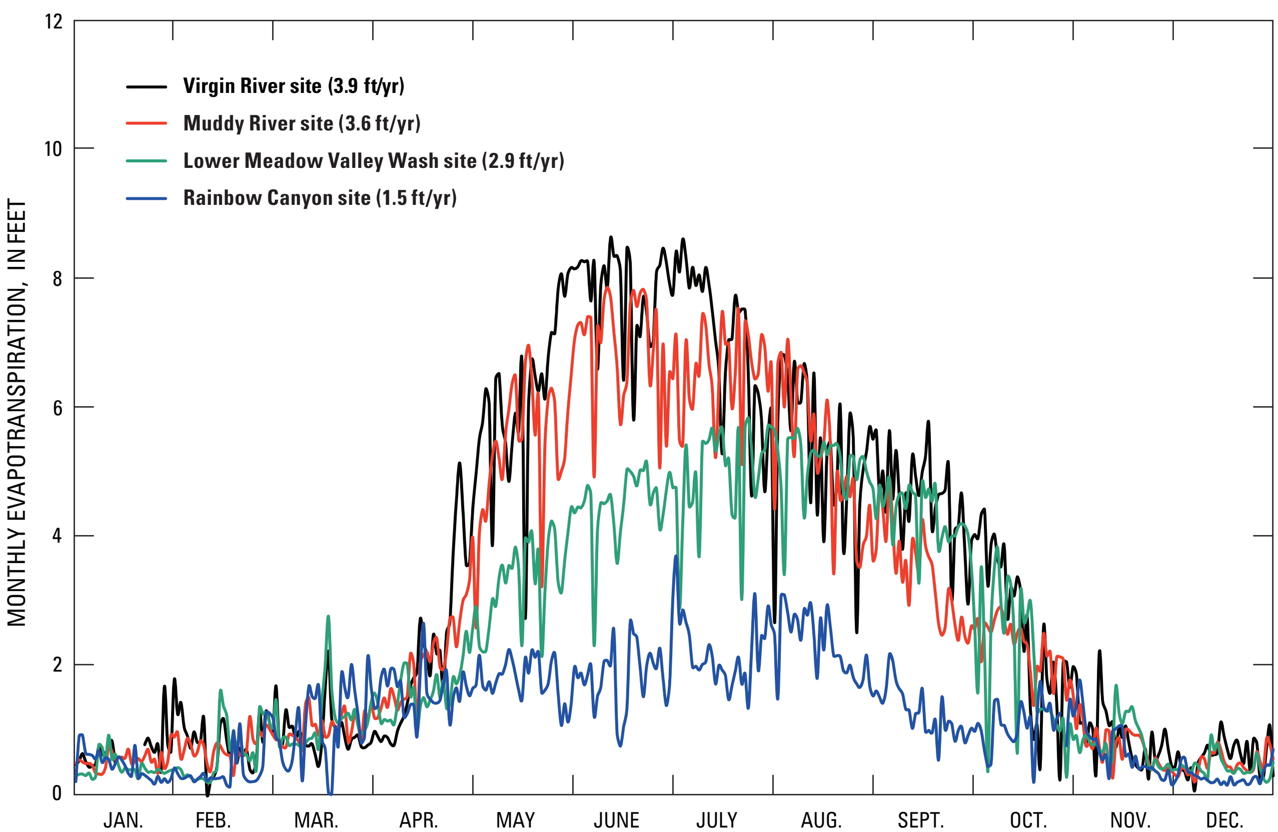


Figure 10. Monthly evapotranspiration for Virgin River, Muddy River, Lower Meadow Valley Wash, and Rainbow Canyon sites in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Table 4. Annual total evapotranspiration rate, measured precipitation, and annual ground- and surface-water ET rate from sites in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. ET_{gs}, ground- and surface-water discharge from ET. ET_t, estimated total evapotranspiration rate. **ET-unit identifier:** DWV, dense woodland vegetation; MWV, moderate woodland vegetation; MSV, moderate shrubland vegetation; DSV, dense shrubland vegetation]

Site name	ET-unit identifier	Annual ET_t rate (feet)	Annual precipitation (feet)	Annual ET_{gs} rate (feet)
Virgin River	DWV	3.9	0.5	3.4
Muddy River	MWV	3.6	.4	3.2
Rainbow Canyon	MSV	1.5	.5	1.0
Lower Meadow Valley Wash	DSV	2.8	.6	2.2

Estimates of Annual Ground- and Surface-Water Discharge from Evapotranspiration

A combined estimate of ground-water and surface-water discharge from ET along narrow riparian areas for 12 selected hydrographic areas of the CRFS was computed from estimates of total annual ET. The approach used in this study assumes that all ground water and surface water discharged across the study area is evaporated or transpired locally from within seven of the eight identified ET units (pl. 1). Although springflow is not directly accounted for in this approach, it is considered part of the ET component on the assumption that it is evaporated or recycled back into the ground-water or surface-water system and is eventually evaporated or transpired. As estimated, total annual ET includes any precipitation falling onto the study area that is evaporated or captured by the ground- or surface-water system to be evaporated or transpired. Total annual ET is adjusted to remove any water contributed by local precipitation prior to computing discharge.

Estimated rates of ET_{gs} were determined from micrometeorological stations located in four of the eight ET units identified in the study area. These four sites were considered to be essential for understanding the magnitude of ground-water and surface-water discharge because they were located in areas that were representative of vegetation with higher ET rates or were representative of the larger ET units found in the study area. Published annual ET discharge rates from similar ET units were used for computation in the other three ET units contributing to discharge in the study area.

Micrometeorological stations were installed in very dense saltcedar trees (DWV unit Virgin River site), in moderately dense mesquite trees (MWV unit Muddy River site), in dense arrowweed (DSV unit Lower Meadow Valley Wash site), and in moderately dense rabbitbrush and sage (MSV unit Rainbow Canyon site). The total annual ET_{gs} rate for these ET units ranged from 3.4 ft for DWV to 1.0 ft for MSV (table 4). Published rates of ET_{gs} used in this study are the DMV unit (3.4 ft) from Laczniak and others (1999), and the OWU (4.9 ft) and the AGU (5.2 ft) from the Bureau of Reclamation (2005) (table 5). The annual ET_{gs} rate for the OWU is an average of open water evaporation values for different reaches of the Lower Colorado River (Davis Dam to Parker Dam and Parker Dam to Imperial). The annual ET_{gs} rate for the AGU is the consumptive use of water by ET from alfalfa.

The amount of surface- and ground-water discharged from each ET unit was calculated by multiplying the annual ET_{gs} rate by the ET unit acreage (table 5). The ET unit with the greatest annual discharge was the DWV unit at 24,480 acre-ft and the ET unit with the least amount was the DMV unit at 680 acre-ft. The difference between the discharge volumes of these ET units was due to the difference in their size because both had the same ET_{gs} rate. The area of the DWV unit is 36 times larger than the DMV unit.

Estimates of annual ET_{gs} discharge were determined for each of the 12 hydrographic areas. This was accomplished by first determining the acreage of each ET unit for each hydrographic area (fig. 1; table 6). The acreages were then multiplied to the ET_{gs} rate that corresponds to that ET unit to determine the discharge for each ET unit within the hydrographic area. The discharge of each ET unit, within the hydrographic area, was summed together giving the total annual discharge for each hydrographic area (table 7). The annual ET_{gs} discharges were 1,952 acre-ft from the Black Mountains Area, 6,080 acre-ft from the California Wash, 4,090 acre-ft from the Muddy River Springs Area, 11,510 acre-ft from the Lower Moapa Valley, 51,960 acre-ft from the Virgin River Valley, 16,168 acre-ft from the Lower Meadow Valley Wash, 5,840 acre-ft from Clover Valley, and 0 acre-ft from Coyote Spring Valley, Kane Springs Valley, Tule Desert, Hidden Valley (North), and Garnet Valley. The total amount of annual discharge from ET_{gs} for the study area is 97,600 acre-ft.

Table 5. Evapotranspiration unit acreage, annual ground- and surface-water evapotranspiration rate, and annual ground- and surface-water ET discharge for all evapotranspiration units within the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; AGU, agricultural unit; MSV, moderate shrubland vegetation; OWU, open water unit]

ET-unit identifier	ET-unit area (acres)	Annual ET_{gs} rate (feet)	Annual ET_{gs} discharge (acre-feet)
DMV	200	[1]3.4	680
DWV	7,200	3.4	24,480
MWV	6,100	3.2	19,520
DSV	5,800	2.2	12,760
MSV	22,600	1.0	22,600
AGU	3,100	[2]5.2	16,120
OWU	300	[2]4.9	1,440

[1] Data from Laczniak and others (1999).

[2] Data from Bureau of Reclamation (2005).

Table 6. Area of ET units (in acres) for each of the 12 hydrographic areas in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; MSV, moderate shrubland vegetation; AGU, agricultural unit; OWU, open water unit]

Hydrographic area	ET unit identifier, in acres							
	NPU	MSV	DSV	MWV	DWV	DMV	AGU	OWU
Black Mountains Area	320,000	1,000	200	100	0	0	0	40
California Wash	200,000	1,200	200	200	200	0	600	0
Muddy River Springs Area	60,000	1,450	300	300	300	0	0	0
Lower Moapa Valley	160,000	1,450	600	700	700	0	700	100
Virgin River Valley	1,000,000	8,700	3,300	3,600	4,900	100	1,300	150
Lower Meadow Valley Wash	600,000	6,500	800	900	700	0	500	10
Clover Valley	230,000	2,300	400	300	400	100	0	0
Coyote Spring Valley	420,000	0	0	0	0	0	0	0
Kane Springs Valley	140,000	0	0	0	0	0	0	0
Tule Desert	120,000	0	0	0	0	0	0	0
Hidden Valley (North)	50,000	0	0	0	0	0	0	0
Garnet Valley	100,000	0	0	0	0	0	0	0

Table 7. Estimates of annual discharge from ground- and surface-water evapotranspiration for each ET unit in each hydrographic area in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003-06.

[ET, evapotranspiration; ET_{gs}, ground- and surface-water evapotranspirarion. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; MSV, moderate shrubland vegetation; AGU, agricultural unit; OWU, open water unit]

Hydrographic area	Annual ET_{gs} discharage, in acre-feet								Total annual ET_{gs} discharge (acre-feet)
	NPU	MSV	DSV	MWV	DWV	DMV	AGU	OWU	
Black Mountains Area	0	1,000	440	320	0	0	0	192	1,952
California Wash	0	1,200	440	640	680	0	3,120	0	6,080
Muddy River Springs Area	0	1,450	660	960	1,020	0	0	0	4,090
Lower Moapa Valley	0	1,450	1,320	2,240	2,380	0	3,640	480	11,510
Virgin River Valley	0	8,700	7,260	11,520	16,660	340	6,760	720	51,960
Lower Meadow Valley Wash	0	6,500	1,760	2,880	2,380	0	2,600	48	16,168
Clover Valley	0	2,300	960	960	1,360	340	0	0	5,840
Coyote Spring Valley	0	0	0	0	0	0	0	0	0
Kane Springs Valley	0	0	0	0	0	0	0	0	0
Tule Desert	0	0	0	0	0	0	0	0	0
Hidden Valley (North)	0	0	0	0	0	0	0	0	0
Garnet Valley	0	0	0	0	0	0	0	0	0
Total	0	22,600	12,760	19,520	24,480	680	16,120	1,440	97,600

Environmental Influences on Ground- and Surface-Water Discharge from Evapotranspiration

Hydrographic and atmospheric conditions can affect ET measurements and may influence the total annual discharge rates determined for ET_{gs}. Of particular concern in the study area were potential influences on ET_{gs} discharge from ground- or surface-water inflow to support riparian vegetation along the Virgin River, from agricultural areas that were, at one time, populated with natural vegetation, and from areas of limited fetch.

Influence of Ground- and Surface-Water Flow along the Virgin River

A simple water budget was computed along the Virgin River between the USGS streamflow-gaging stations at Littlefield, Arizona (09415000) and near Overton, Nevada (09415240) to evaluate the general influence of ground- or surface-water flow that supports riparian vegetation contributing to ET_{gs} discharge (table 8; pl. 1). The average annual streamflow was calculated for the Littlefield and Overton gaging stations between January 1, 2003, and December 28, 2004. The 2-year average annual streamflow at the Virgin River at Littlefield, Arizona and Virgin River near Overton, Nevada was 102,000 and 72,000 acre-ft, respectively. The difference (or loss) in streamflow between these two gaging stations was 30,000 acre-ft. The ground- and surface-water discharge was calculated for this specific reach of the river, between the two gages, by determining the acreage of riparian vegetation between the two gages using the ET unit data and multiplying the ET_{gs} rate for the Virgin River site. This computation resulted in an annual ground- and surface-water discharge of about 31,000 acre-ft between the two gages. The ground- and surface-water discharge is about 1,000 acre-ft more than the lost streamflow between the two gages. This result suggests that most, if not all, of the lost streamflow between these two gages can be accounted for by ET.

Table 8. Characteristics of U.S. Geological Survey streamflow-gaging stations for the Virgin River at Littlefield, Arizona, and Virgin River near Overton, Nevada, January 1, 2003, through December 28, 2004.

[**Altitude:** Datum is National Geodetic Vertical Datum of 1929. **Latitude/Longitude:** Datum is North American Datum of 1927 in degrees, minutes, and seconds]

Site No.	Site name	Altitude (feet)	Average channel discharge (acre-feet)	Latitude	Longitude
09415000	Virgin River at Littlefield, Arizona	1,764	102,000	36° 53' 30"	113° 55' 25"
09415240	Virgin River near Overton, Nevada	1,230	72,000	36° 34' 59"	114° 19' 27"

Influence of Agricultural Areas

Across the study area, about 3,000 acres of agricultural fields have replaced natural vegetation. The total annual ET_{gs} rate of 5.2 ft for AGU is significantly higher than the total annual ET_{gs} rate (1.0–3.4 ft) for natural vegetation ET units. To estimate the influence on ET_{gs} discharge from the replacement of natural vegetation by agricultural fields, discharge was recalculated for AGU areas using the rate from a natural vegetation ET unit. Across the study area, most of the agricultural unit replaced vegetation in the DWV unit. Therefore, by using the DWV unit ET_{gs} rate rather than the AGU ET_{gs} rate, the total study area discharge decreased about 6,000 acre-ft, from 98,000 to 92,000 acre-ft. This resulted in a change in total ground- and surface-water discharge by about 1 percent.

Influence of Fetch

ET rates in the study area were possibly affected by limited fetch (Stannard and others, 2004) because much of the 45,300 acres of riparian vegetation occurs in narrow corridors. Analysis of satellite imagery showed that about 33 percent of the vegetation borders the outer 200 ft of the riparian corridors. The effects of limited fetch are uncertain because remote-sensing techniques do not account for environmental influences along the boundary of narrow riparian corridors such as depth to water and weather conditions. For example, ET could decrease because vegetation near the edge of the riparian areas might become stressed due to a combination of lack of water and hot, dry air from the surrounding desert. On the other hand, if ample water were available, the advection of hot dry air could increase ET (this is referred to as an oasis effect).

Sensitivity of ET discharge due to limited fetch was evaluated by reducing the acreage around the outer edge of the riparian areas by removing 1 and then 2 pixels or 0.02 square acres and 0.05 square acres, respectively. The process reduces the total area around the riparian areas by about 18 percent for 1 pixel and 33 percent for 2 pixels. A 33 percent decrease in acreage for the riparian areas decreases the estimated total ET discharge for the study area by about 8 percent—from about 98,000 to 91,000 acre-ft. While fetch effects may have significant impacts at isolated locations, the overall change in ET discharge for the study was not significantly influenced by limited fetch.

Limitations to Estimates of Ground- and Surface-Water Discharge from Evapotranspiration

The estimated discharge by ET_{gs} is limited by the (1) assumptions inherent in the energy budget, (2) small number of sites used to estimate ET and precipitation, (3) short time duration that field sites were in operation, (4) application of published annual ET discharge rates measured prior to this study, (5) instrumentation bias, (6) missing data for at the Virgin River and LMVW sites due to flooding, and (7) accuracy of the delineated ET units.

Summary

The U.S. Geological Survey, in cooperation with the National Park Service, Bureau of Land Management, and U.S. Fish and Wildlife Service conducted a study to quantify the amount of ground- and surface-water discharged by evapotranspiration processes in 12 hydrographic areas in the southern part of the Colorado Regional Ground-Water Flow System.

In various locations in the study area, ground water that is discharged from springs combines with surface water from outside the study area making it difficult to determine the original source of the water. Water from these various sources is transpired by crops, phreatophyte and riparian vegetation, and evaporated from open-water surfaces. This study quantified annual ET discharge from diffuse ground-water and channelized surface-water (expressed as ET_{gs}) by (1) delineating and classifying the study area into eight ET units primarily based on information from multi-spectral satellite imagery and Southwest Regional Gap Analysis Program data, (2) estimating ET rates at four micrometeorological stations located in representative ET units or using published ET rates for similar environments, and (3) estimating the volume of annual ground- and surface-water discharged from ET by summing the products of ET unit acreage and ET rate for each ET unit.

The eight ET units identified in the study area include: dense meadowland vegetation, dense woodland vegetation, moderate woodland vegetation, dense shrubland vegetation, moderate shrubland vegetation, agricultural fields, non-phreatophytic, and open water. Field sites were installed in four ET-unit areas: dense woodland vegetation, moderate woodland vegetation, dense shrubland vegetation, and moderate shrubland vegetation. Two of the sites collected data for use with the Bowen-ratio method of calculating ET and two of the sites collected data for use in the eddy-covariance method of calculating ET.

Sites that collected data for the Bowen-ratio method were installed in a dense grove of saltcedar trees along the Virgin River floodplain and in an area of dense mesquite trees along the Muddy River. Sites that collected data for the eddy-covariance method were installed in Lower Meadow Valley Wash—one in Rainbow Canyon just south of Caliente, Nevada, and one just north of Moapa, Nevada. Local precipitation from each site was subtracted from the total annual ET rate to obtain the ET_{gs} rate for that ET unit. The annual ET_{gs} rate was multiplied by the acreage of the ET units across the study area to estimate the total annual discharge from ET_{gs}.

The energy flux used to estimate ET was calculated using two energy-budget approaches—the Bowen-ratio and the eddy-covariance methods. In addition, a variant of the Bowen-ratio method was applied at two sites using data collected for the eddy-covariance method. Data for these methods were collected at four micrometeorological sites placed in selected vegetated environments (ET units) for varying periods. The annual ET_{gs} rates for individual ET units ranged from 1.0 to 5.2 feet and the annual ET_{gs} discharge for the 12 hydrographic areas in the study area ranged from 0 to about 52,000 acre-feet. The annual discharge from ET_{gs} across the study area was about 98,000 acre-feet.

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Bill Gibbs
Bob Crist
Debra Grillo
Sharon Wahlstrom
Bobbie Jo Richey

For more information concerning the research in this report, contact the
Director, Nevada Water Science Center
U.S. Geological Survey
2730 N. Deer Run Road
Carson City, Nevada 89701
http://nv.water.usgs.gov

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