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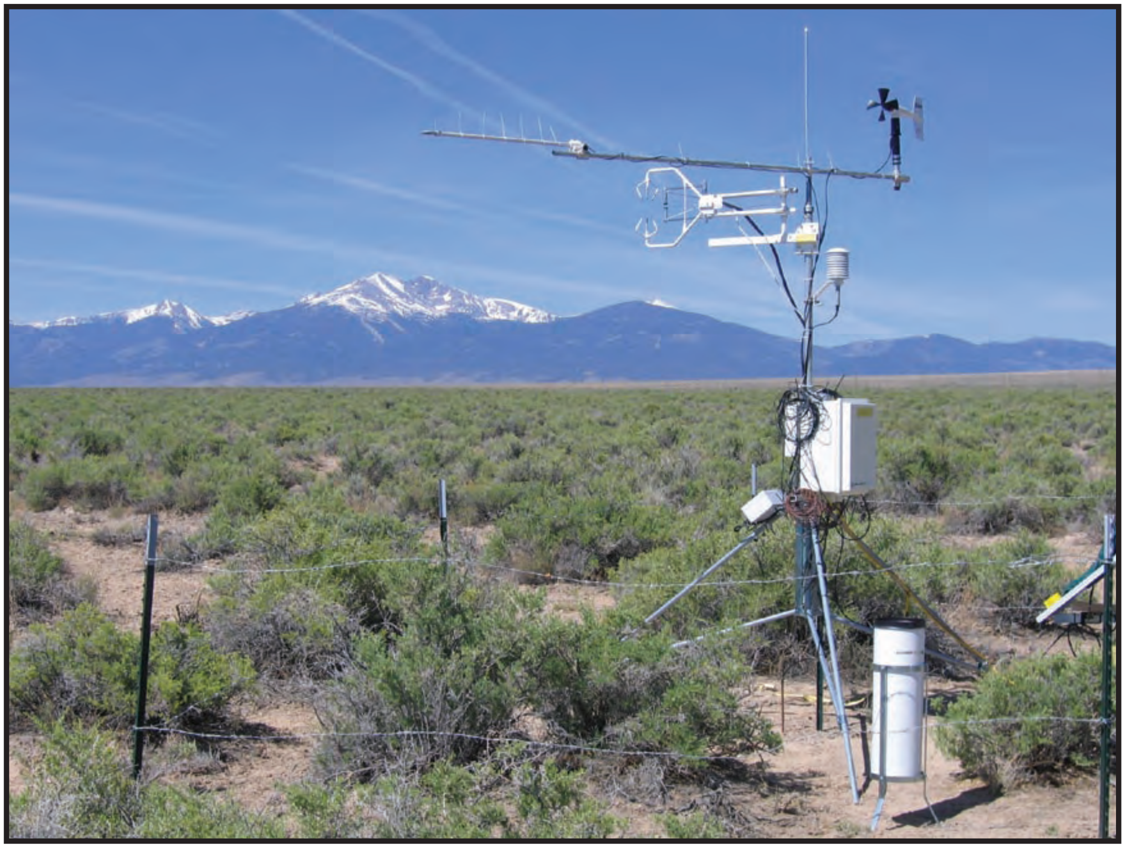

Scientific Investigations Report 2007–5078

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

Cover: Photograph showing evapotranspiration site in Snake Valley (SNV-1), Basin and Range carbonate-rock aquifer system study area, Nevada and Utah. (Photograph taken by Michael Moreo, U.S. Geological Survey, June 2006.)

Evapotranspiration Rate Measurements of Vegetation Typical of Ground-Water Discharge Areas in the Basin and Range Carbonate-Rock Aquifer System, Nevada and Utah, September 2005–August 2006

By Michael T. Moreo, Randell J. Laczniak, and David I. Stannard

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Foreword

Water demands from the lower Colorado River system are increasing with the rapidly growing population of the southwestern United States. To decrease dependence on this over-allocated surface-water resource and to help provide for the projected increase in population and associated water supply in the Las Vegas area, water purveyors in southern Nevada have proposed to utilize the ground-water resources of rural basins in eastern and central Nevada. Municipal, land management, and regulatory agencies have expressed concerns about potential impacts from increased ground-water pumping on local and regional water quantity and quality, with particular concern on water-rights issues and on the future availability of water to support natural spring flow and native vegetation. Before concerns on potential impacts of pumping can be addressed, municipal and regulatory agencies have recognized the need for additional information and improved understanding of geologic features and hydrologic processes that control the rate and direction of ground-water flow in eastern and central Nevada.

In response to concerns about water availability and limited geohydrologic information, Federal legislation (Section 131 of the Lincoln County Conservation, Recreation, and Development Act of 2004; PL 108-424) was enacted in December 2004 that directs the Secretary of the Interior, through the U.S. Geological Survey (USGS), the Desert Research Institute (DRI), and a designee from the State of Utah, to complete a water-resources study of the basin-fill and carbonate-rock aquifers in White Pine County, Nevada, and smaller areas of adjacent counties in Nevada and Utah. The primary objectives of the Basin and Range carbonate-rock aquifer system (BARCAS) study are to evaluate: (1) the extent, thickness, and hydrologic properties of aquifers, (2) the volume and quality of water stored in aquifers, (3) subsurface geologic structures controlling ground-water flow, (4) ground-water flow direction and gradients, and (5) the distribution and rates of recharge and ground-water discharge. Geologic, hydrologic, and supplemental geochemical information will be integrated to determine basin and regional ground-water budgets.

Results of the study will be summarized in a USGS Scientific Investigations Report (SIR), to be prepared in cooperation with DRI and the State of Utah, and submitted to Congress by December 2007. The BARCAS study SIR is supported by USGS and DRI reports that document, in greater detail than the summary SIR, important components of this study. These reports are varied in scope and include documentation of basic data, such as spring location and irrigated acreage, and interpretive studies of ground-water flow, geochemistry, recharge, evapotranspiration, and geology.

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Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
acre	4046.856	square meter (m^2)
acre	0.4047	hectare (ha)
calorie	4.184	joule (J)
calorie per second per square foot	45.04	watt per square meter (W/m^2)
foot (ft)	0.3048	meter (m)
foot per second ($ft/^s$)	0.3048	meter per second (m/s)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
mile per hour (mph)	0.44704	meter per second (m/s)
square mile (mi^2)	2.58999	square kilometer (km^2)
ounce, avoirdupois (oz)	28.35	gram (g)

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 National Geodetic Vertical Datum of 1929 (NVGD of 1929).

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.

Evapotranspiration Rate Measurements of Vegetation Typical of Ground-Water Discharge Areas in the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah, September 2005–August 2006

By Michael T. Moreo, Randell J. Laczniak, and David I. Stannard

Abstract

Evapotranspiration was measured at six eddy-correlation sites for a 1-year period between September 1, 2005, and August 31, 2006. Five sites were in phreatophytic shrubland dominated by greasewood, and one site was in a grassland meadow. The measured annual evapotranspiration ranged from 10.02 to 12.77 inches at the shrubland sites and 26.94 inches at the grassland site. Evapotranspiration rates correlated to measured vegetation densities and to satellite-derived vegetation indexes. Evapotranspiration rates were greater at sites with denser vegetation. The primary water source supporting evapotranspiration was water derived from local precipitation at the shrubland sites, and ground water at the grassland site. Measured precipitation, ranging from 6.21 to 11.41 inches, was within 20 percent of the computed long-term annual mean. The amount of ground water consumed by phreatophytes depends primarily on local precipitation and vegetation density. The ground-water contribution to local evapotranspiration ranged from 6 to 38 percent of total evapotranspiration at the shrubland sites, and 70 percent of total evapotranspiration at the grassland site. Average depth to water ranged from 7.2 to 32.4 feet below land surface at the shrubland sites, and 3.9 feet at the grassland site. Water levels declined throughout the growing season and recovered during the non-growing season. Diurnal water-level fluctuations associated with evapotranspiration were evident at some sites but not at others.

Introduction

The Basin and Range carbonate-rock aquifer system (BARCAS) study area encompasses about 13,500 mi^2 and covers about 80 percent of White Pine County, and parts of Elko, Eureka, Nye, and Lincoln Counties in Nevada, as well as parts of Tooele, Millard, Beaver, Juab, and Iron Counties in Utah (fig. 1). White Pine County is within the carbonate-rock province, a relatively large area extending from western Utah to eastern California where ground-water flow is predominantly or strongly influenced by carbonate-rock aquifers. Much of the carbonate-rock aquifer is fractured and, where continuous, forms a regional ground-water flow system that receives recharge from high-altitude areas where fractured carbonate rocks are exposed. Most areas in White Pine County, Nevada, are within four regional ground-water flow systems (fig. 2)—the larger Colorado and Great Salt Lake Desert flow systems, and the smaller Goshute Valley and Newark Valley flow systems (Harrill and others, 1988). Water moving through the carbonate-rock aquifer provides some recharge to overlying basin-fill aquifers, sustains many of the large, perennial low-altitude springs, and hydraulically connects similar carbonate-rock aquifers in adjacent basins. The regional carbonate-rock aquifer typically is overlain by a basin-fill aquifer in the intermountain basins. The basin-fill aquifer is composed of gravel, sand, silt, and clay and often reaches thicknesses of several thousand feet (Harrill and Prudic, 1998). The gravel and sand deposits typically yield water readily to wells and this aquifer is the primary water supply in the area for agricultural, domestic, or municipal use.

The carbonate-rock aquifer extends beneath numerous surface-water drainage basins, or hydrographic areas[1]. Past studies have combined hydrographic areas to delineate basin-fill or regional ground-water flow systems, based primarily on the direction of interconnected ground-water flow in the underlying carbonate-rock aquifer and the location of terminal discharge areas (Harrill and Prudic, 1998). Although the boundary lines between hydrographic areas generally coincide with actual topographic basin divides, some boundaries

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

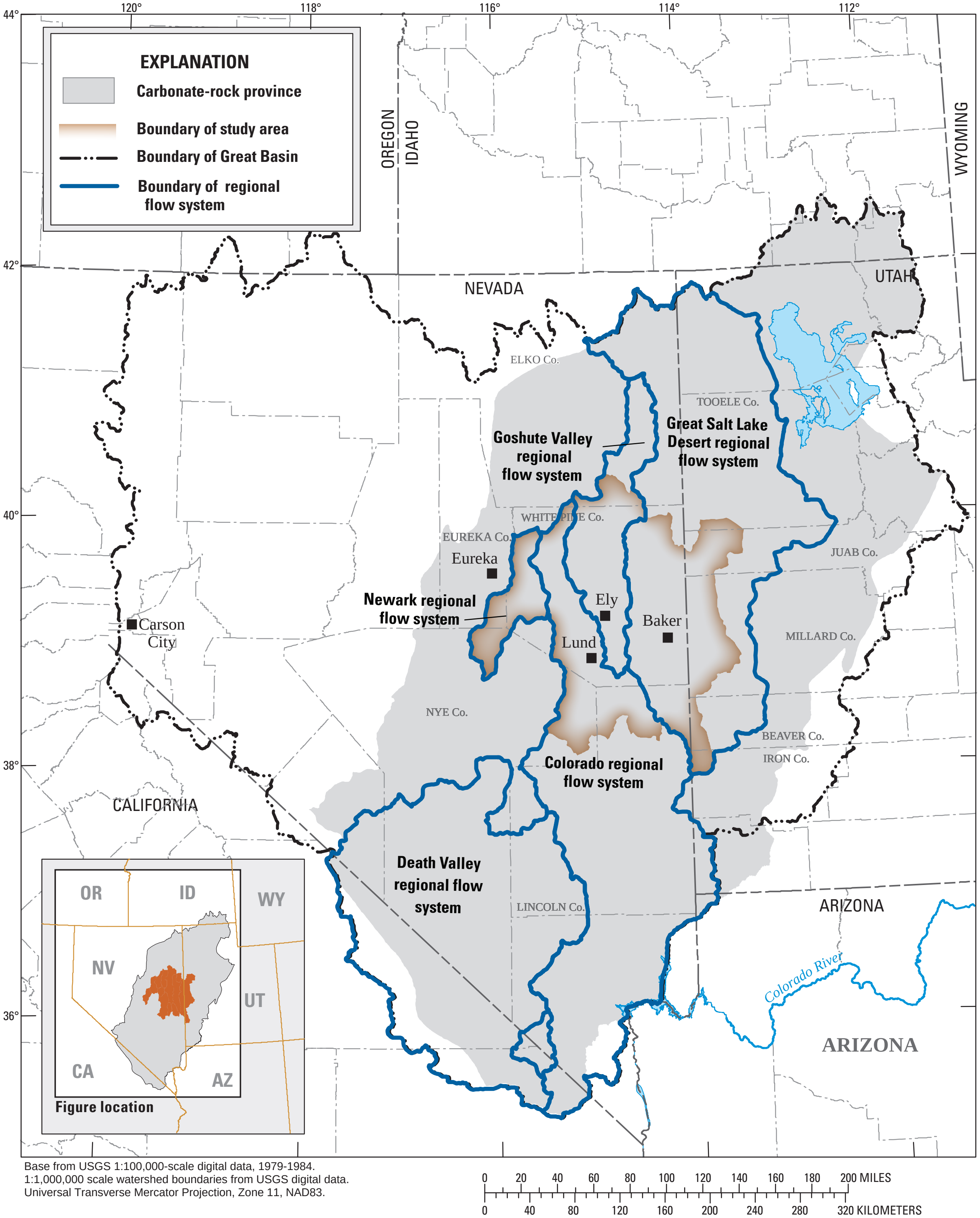


Figure 1. Carbonate-rock province, Basin and Range carbonate-rock aquifer system study area, and associated regional ground-water flow systems, Nevada and Utah.

are arbitrary or represent hydrologic divisions that have no topographic basis. Hydrographic areas were further divided into subbasins that are separated by areas where pre-Cenozoic rocks are at or near the land surface (Welch and Bright, 2007). Hydrographic area names in this report generally refer to formal hydrographic areas of Harrill and others (1988) with two exceptions: (1) ‘Little Smoky Valley’ refers to hydrographic areas 155A and 155B, which are the northern and central parts of Harrill and others (1988) description of Little Smoky Valley, respectively, and (2) ‘Butte Valley’ refers only to hydrographic area 178B, which is the southern part of Harrill and others (1988) description of Butte Valley. For most figures and tables in this report, water-budget components were estimated for the northern and central parts of Little Smoky Valley, but were combined and reported as one value.

Ground-water discharge occurs naturally in topographically low areas of basins where ground water is at or near land surface by three primary processes: (1) spring flow and seepage, (2) transpiration by local phreatophytic vegetation, and (3) evaporation from soil and open water. As ground water emerges from springs, it forms ponds or flows into free-flowing drainages or local reservoirs. Once at land surface, spring water evaporates or infiltrates downward into soils and possibly into an underlying aquifer. In addition to recycled spring flow, the shallow aquifer receives recharge as lateral and upward flow originating from more distant sources. Shallow ground water is available for use by plants or is accessible to the atmospheric processes that drive evaporation.

Historically, quantifying ground-water discharge consistently from the regionally extensive ground-water flow systems of the arid southwestern United States has proven difficult. Spring flow often is difficult to measure because of access or channeling issues. Because most spring flow from ground-water discharge areas evaporates or recharges shallow aquifers, where ultimately, it is evaporated or transpired by local vegetation, many investigators have chosen to estimate ground-water discharge solely on the basis of the evaporation and transpiration that occurs in areas where the water table is near land surface. An important part of this method is to develop sound estimates of evapotranspiration (ET) that occurs from areas of ground-water discharge. ET, the combined processes of evaporation and transpiration, is measured in areas dominated by phreatophytic vegetation.

Purpose and Scope

The purpose of this study was to measure ET rates in environments representative of the different vegetation conditions typical of ground-water discharge areas in the study area. Developing a range of annual ET rates for different vegetation and soil conditions based solely on measurements made in the study area would require multiple years of data collection and many more ET sites than allowed for by project funding and scheduling. Instead, ET rates reported in recent literature (Nichols, 2000; Berger and others, 2001; Reiner and others, 2002; Cooper and others, 2006) were used to develop ranges describing annual ET rates for the different vegetation and soil conditions identified in the BARCAS study. These ranges, documented by the BARCAS study summary report, were assessed and modified based on ET rates computed from field data collected at six ET sites established specifically for this study.

This report documents ET rates, precipitation, and ground-water levels measured from September 1, 2005, to August 31, 2006. Daily and annual ET rates are estimated and associated assumptions and uncertainties are documented in this report. The report compares measured ET rates, ground-water levels, soil moisture, and precipitation measured at each of the ET sites. Daily and annual ET rates, associated energy budget components, pertinent micrometeorological data, precipitation totals, and continuous ground-water-level records are distributed with this report electronically in a spreadsheet.

Evapotranspiration

ET is the process that transfers water from land surface to the atmosphere and occurs as evaporation (or sublimation when below freezing) from open water, soil, and plant canopies and as transpiration by plants. ET is the primary natural process by which ground water is removed from the soil and shallow water table in areas of phreatophytic vegetation. A change in the depth of the water table or in the moisture content of the soil generally results in a change of ET rates. The volume of water lost to the atmosphere through ET is computed as the product of the ET rate and the acreage of vegetation, open water, and moist soil from which ET occurs. Thus, reliable estimates of ET require accurate estimates of local ET rates and of the acreage associated with a particular ET rate. Acreage associated with different ET rates in the study area is reported by Smith and others (2007) and Welborn and Moreo (2007).

The rate at which water is transferred from land and plant surfaces to the atmosphere defines the ET rate and is driven by radiative energy originating from the sun. This energy, often referred to as net radiation (Rn), is the difference between incoming and outgoing long-wave and short-wave radiation. Net radiation is absorbed at the Earth’s surface, and then is partitioned into energy that is transferred by heat conducted downward into the subsurface, by heat conduction or convection upward into the atmosphere, or is used to convert water from the solid or liquid phase to the vapor phase (Brutsaert, 1982). This partitioning process, which is based on the conservation of energy principle and the first law of thermodynamics, can be expressed as:

$$Rn - G = \lambda E + H, \quad (1)$$

where

- Rn is net radiation, in calories per second per square foot;
- G is soil heat flux, in calories per second per square foot;
- λE is latent heat flux in calories per second per square foot;
- H is sensible heat flux, in calories per second per square foot;
- λ is the heat of vaporization of water in calories per ounce, and
- E is the rate of evaporation in ounces per second per square foot.

The left side of equation 1 represents available energy, and the right side represents turbulent energy flux. Energy used for photosynthesis, and energy stored as heat in short and sparse canopies, are considered negligible and are not accounted for in the energy budget equation as used for this study (Brutsaert, 1982; Wilson and others, 2002). During typical daytime conditions, net radiation, latent-heat flux, sensible-heat flux, and soil-heat flux are positive (fig. 2). Net radiation is positive when incoming long- and short-wave radiation exceeds outgoing long- and short-wave radiation. Sensible- and latent-heat fluxes moving upward from the surface to the atmosphere are positive. Soil heat flux is positive when heat moves from the surface to the subsurface.

The latent heat component (λE) of the energy budget is the energy consumed during the ET process. Accordingly, ET can be calculated by subtracting the sensible heat (H) and soil heat (G) components of the energy budget from the net radiation (Rn). Although seemingly straightforward, this approach has been hampered historically by difficulties in measuring sensible heat. A common solution to this dilemma

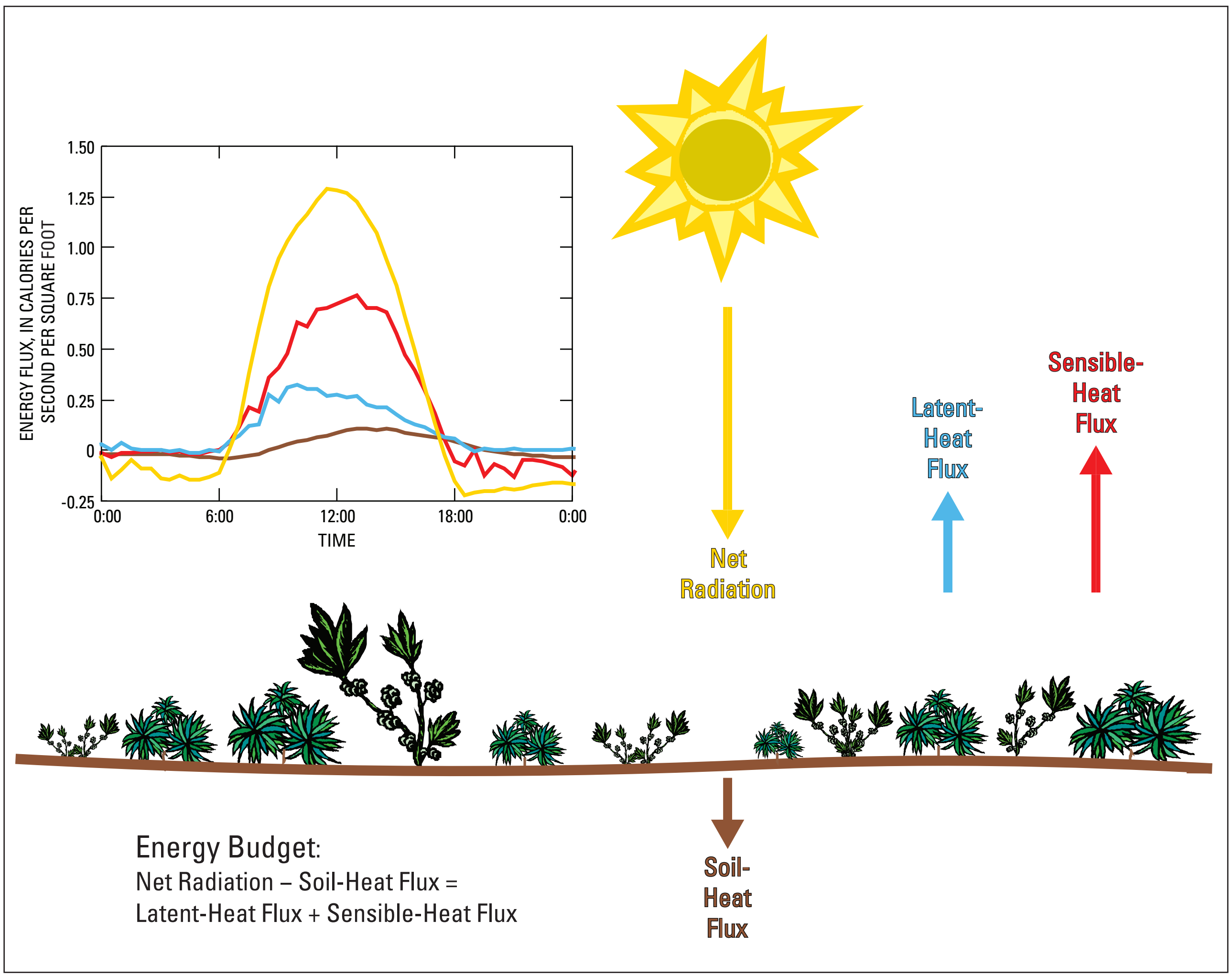


Figure 2. Surface energy processes and plot of typical daily energy budget for shrubs in Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

has been the use of the Bowen ratio method (Bowen, 1926). In simple terms, the proportionality between sensible and latent heat is assumed to be defined by the ratio between the temperature and vapor-pressure gradient. Because temperature and vapor pressure can be measured directly, the Bowen ratio can be substituted into the energy budget to solve for latent heat from measurable parameters. Another more recent method used to estimate ET is the eddy-correlation method. The advantage of this method, also referred to as eddy covariance, is the ability to calculate latent-heat flux (or evaporation) directly from measurements of water-vapor density and vertical wind speed. This capability has led to the recent widespread usage of the method by the scientific community and in this study.

Eddy-Correlation Method

Eddy correlation is a method used to measure atmospheric fluxes transferred by eddies from the Earth's surface to the atmosphere. Eddies are turbulent airflow caused by wind, the roughness of the Earth's surface, and convective heat flow at the boundary between the Earth and the atmosphere (Swinbank, 1951; Brutsaert, 1982; Kaimal and Finnigan, 1994; Campbell and Norman, 1998; Sumner, 2001). ET occurs when water vapor in upward moving eddies is greater than in downward moving eddies. Likewise, sensible heat is positive when upward moving eddies are warmer than downward moving eddies. Water vapor, heat, and other scalars like carbon dioxide transferred by eddies can be measured directly using the eddy-correlation method.

Latent-heat flux is the product of the latent heat of vaporization of water and water vapor-flux density (eqs. 1 and 2). The latent heat of vaporization, although slightly temperature dependent is nearly a constant. Water-vapor flux density is calculated as the covariance of instantaneous deviations from the time-averaged product of water-vapor density and vertical wind speed. Latent-heat flux can be expressed mathematically as:

$$\lambda E = \lambda \overline{w'\rho_v'}\,, \qquad (2)$$

where

w is vertical wind speed, in feet per second; and

ρ_v is water vapor density, in ounces per cubic foot, where the overbar is the mean and the prime is the deviation from the mean over an averaging period.

Sensible heat flux is the movement of heat energy that results from a temperature gradient between the Earth's surface and the atmosphere. The EC method computes sensible heat from temperature and vertical wind speed as:

$$H = \rho C_p \overline{w'T_a'}\,, \qquad (3)$$

where

ρ is air density, in ounces per cubic foot;

C_p is specific heat capacity of air, in calories per ounce per degree Fahrenheit; and

T_a is air temperature, in degrees Fahrenheit, where the overbar is the mean and the prime is the deviation from the mean over an averaging period.

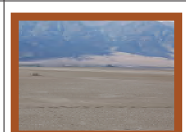
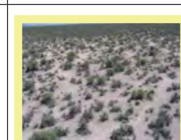
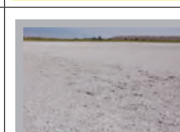
Site Selection

Numerous studies have shown that the amount of water being lost to the atmosphere from areas of ground-water discharge by evaporation and transpiration varies with vegetation type and density and soil characteristics (Laczniak and others, 1999, 2001, 2006; Nichols, 2000; Berger and others, 2001; Reiner and others 2002; DeMeo and others, 2003). The ET rate generally is greater where vegetation is denser and healthier and the soil is wetter. Many of these studies have used multi-spectral satellite imagery to identify and group areas of similar vegetation and soil conditions in major areas of ground-water discharge. Delineations of these groupings commonly are referred to as ET units because they differentiate areas of differing ET.

Ten ET units have been mapped from Thematic Mapper (TM) imagery in the study area (Smith and others, 2007). These 10 ET units were identified as being representative of the different vegetation and soil conditions in the study area from which ground water is lost to the atmosphere through ET (table 1). The characteristics of each ET unit differs—ranging from areas of no vegetation, such as open water, moist bare soil, and dry playa, to areas of vegetation including phreatophytic shrubs, grasses, rushes, and reeds. Each ET unit is assigned a unique ET rate. Three of the ten ET units represent shrub dominated environments. Shrubland, defined as the combined acreage of sparse, moderately dense, and dense desert shrubland ET units, accounts for more than 80 percent of the acreage (908,400 acres) delineated as contributing to ground-water discharge. Riparian vegetation—marshland, meadowland, and grassland—accounts for only about 6 percent of the ET-unit acreage (63,300 acres); and open water accounts for less than 1 percent (1,600 acres) (fig. 3).

Six ET sites were established in August 2006 (table 2, fig. 4). Five were located in shrubland ET units dominated by greasewood (*Sarcobatus vermiculatus*) and to a lesser extent rabbitbrush (*Chrysothamnus nauseous*) (fig. 5). The presence of greasewood and rabbitbrush is indicative of a shallow water table where ground-water discharge is likely (Robinson, 1958; Nichols, 2000; Smith and others, 2007).

Table 1. Evapotranspiration (ET) units identified, delineated, and mapped for different vegetation and soil conditions in potential areas of ground-water discharge in the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 2005–August 2006.

ET-unit name	ET-unit description	Photograph
Xerophytic	Area of no substantial ground-water evaporation. Area dominated by bare dry soil and/or sparse, non-phreatophytic vegetation.	
Open Water	Area of open water including reservoirs, ponds. and spring pools.	
Marshland	Area dominated by dense wetland vegetation, primarily tall reeds and rushes, and some grasses. Vegetation cover typically is greater than 50 percent. Open water is present but typically less than 25 percent. Perennially flooded. Water at or very near surface. Depth to water typically is less than 1 foot.	
Meadowland	Area dominated by short, dense perennial grasses, primarily marsh and meadow grasses. Unit includes occasional desert shrubs and trees, primarily Rocky Mountain junipers and cottonwoods. Vegetation cover typically is greater than 50 percent. Soil typically is moist except in later summer and autumn. Depth to water table typically is less than 5 feet.	
Grassland	Area dominated by short, sparse, perennial grasses, including salt grass, and sod and pasture grasses typically a mix of vegetation types. Unit includes sparse desert shrubs and occasional trees, primarily Rocky Mountain junipers or cottonwoods. Vegetation cover is between 10 and 100 percent. Soil typically is damp to dry. Depth to water table typically is less than 8 feet.	
Moist Bare Soil	Area dominated by moist playa. Near surface soil is damp throughout much of the year. Water table is near or below land surface. Depth to water typically is less than 10 feet.	
Dense Desert Shrubland	Area dominated by sparse desert shrubs, including greasewood, rabbitbrush, shadscale, big sagebrush, and saltbush. Shrubs typically are mixed. Vegetation cover typically is greater than 25 percent. Depth to water can range from about 3 to 50 feet.	
Moderately Dense Desert Shrubland	Area dominated by sparse desert shrubs, including greasewood, rabbitbrush, shadscale, big sagebrush, and saltbush. Shrubs typically are mixed. Vegetation cover typically ranges from 10 to 30 percent. Depth to water can range from about 3 to 50 feet.	
Sparse Desert Shrubland	Area dominated by sparse desert shrubs, including greasewood, rabbitbrush, shadscale, big sagebrush, and saltbush. Shrubs typically are mixed. Vegetation cover typically ranges from 5 to 15 percent. Depth to water can range from about 3 to 50 feet.	
Dry Playa	Area dominated by dry playa. Soil typically dry year round. Water table below land surface. Depth to water typically is greater than 10 feet. This unit may not contribute to ground-water discharge.	
Recently Irrigated Cropland—Historically Mixed Phreatophyte	Area dominated by irrigated cropland. Soil moisture varies with irrigation practice. Water table is below land surface. Depth to water table typically is greater than 5 feet. Prior to irrigation, the unit likely was dominated by sparse desert shrubs to grassland.	

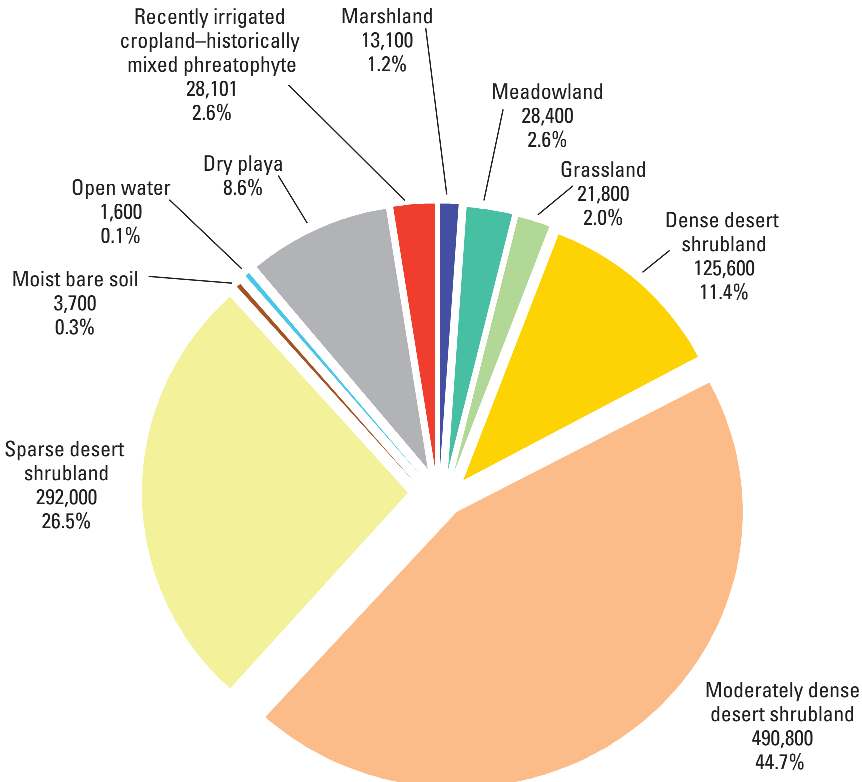


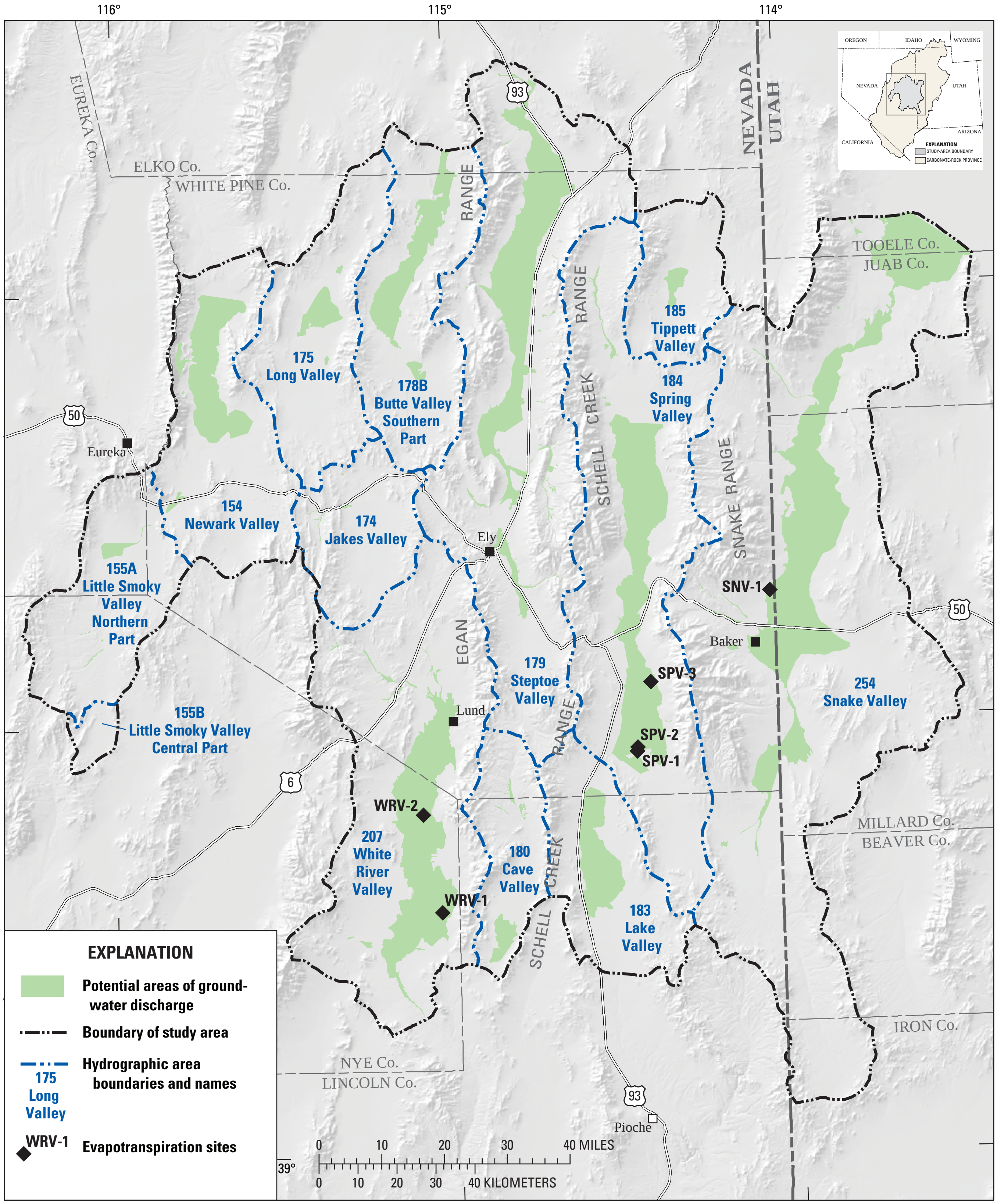
Figure 3. ET-unit acreage, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah. Upper number is acres. Lower number is percentage of total BARCAS study area acreage (Smith and others, 2007).

The typical rooting depth for greasewood is from 5 to 35 ft but has been reported to be as deep as 60 ft (Nichols, 2000). The typical rooting depth for rabbitbrush is less than 25 ft, but has been known to be as deep as 35 ft (Nichols, 2000). A proportionally greater number of ET sites were located in shrubland to evaluate the effect of vegetation density on ET rates, and to better understand the relation between ET and ground-water discharge by the dominant vegetation type of the study area (fig. 6). Only one site, established in the grassland/meadowland ET unit, was located in a mixed grass riparian area to represent an environment indicative of greater ET (fig. 6*D*).

Table 2. Location of evapotranspiration (ET) sites in the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 2005–August 2006.

[**ET site**: SNV is Snake Valley; SPV is Spring Valley, WRV is White River Valley. Location of ET sites is shown in figure 4. **USGS site identification No.:** Unique identification number for site as stored in files and data bases of the USGS. USGS, U.S. Geological Survey. Altitude of land surface is in feet above NGVD 29]

Hydrographic area name and number	ET site	USGS site identification No.	Latitude (decimal degrees)	Latitude (decimal degrees)	Altitude of land surface (feet)	Installation date
Snake Valley (254)	SNV-1	390825114034301	39.140	-114.062	5,110	08-17-05
Spring Valley (184)	SPV-1	384639114280401	38.778	-114.468	5,785	08-12-05
Spring Valley (184)	SPV-2	384709114275601	38.786	-114.466	5,780	08-12-05
Spring Valley (184)	SPV-3	385612114251601	38.937	-114.421	5,785	08-12-05
White River Valley (207)	WRV-1	382449115030301	38.414	-115.051	5,250	08-18-05
White River Valley (207)	WRV-2	383826115061001	38.641	-115.103	5,320	08-18-05



Base from U.S. Geological Survey 1:100,000-scale digital data, 1979–84
1:1,000,000 scale watershed boundaries from U.S. Geological Survey digital data
Universal Transverse Mercator Projection, Zone 11, NAD83

Figure 4. Potential areas of ground-water discharge and location of evapotranspiration (ET) sites in the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

A. Greasewood

B. Rabbitbrush

C. Meadowgrass

Figure 5. Typical phreatophyte vegetation in the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah. Photographs taken by Michael Moreo, U.S. Geological Survey, May 2005.

A. Site SNV-1 is located in the moderately dense shrubland ET unit.

B. Site SPV-1 is located in the sparse desert shrubland ET unit.

Figure 6. South facing view of fetch area from each ET site in the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah. Photographs were taken 10 feet south of each ET site from a height of 17 feet above land surface. Photographs taken by Michael Moreo, U.S. Geological Survey, June and July 2006.

C. Site SPV-2 is located in the moderately dense desert shrubland ET unit.

D. Site SPV-3 is located in the grassland/meadowland ET unit.

Figure 6.—Continued.

E. Site WRV-1 is located in the dense desert shrubland ET unit.

F. Site WRV-2 is located in the moderately dense desert shrubland ET unit.

Figure 6.—Continued.

The modified soil-adjusted vegetation index (MSAVI) developed by Qi and others (1994) was used to delineate ET units, describe source areas for turbulent-flux measurements in terms of vegetation density, and help apportion ET rates to equivalent ET units across the entire study area (Smith and others, 2007). The MSAVI was chosen because it is one of only a few vegetation indexes that attempt to reduce the influence of bare soil. As is typical of most vegetation indexes, the MSAVI is calculated from the reflectance of the red and near-infrared wavelengths (bands 3 and 4 for TM imagery). The index performs favorably for vegetation conditions typical of desert environments, and has been applied successfully by Nichols (2000) and Berger and others (2001) in ET studies of central Nevada. Scaled MSAVI values, computed from TM imagery acquired for the study area, ranged from 16 to 43 for shrubland ET units and from 44 to 92 for grassland and meadowland ET units (table 3).

Instrumentation

High frequency water-vapor density measurements were obtained using a krypton hygrometer. A 3-dimensional (3-D) sonic anemometer was used to collect high frequency wind-speed vectors and temperature measurements. These data allow calculation of latent- and sensible-heat fluxes by the eddy-correlation method. An electronic datalogger received sensor readings ten times per second and computed means, variances, and covariances every 30 minutes. The hygrometer was programmed to convert electronic signals using the "windows scaled, dry vapor range" calibration provided by the manufacturer. The hygrometer and sonic anemometer were oriented vertically about 4 in. apart, facing the prevailing wind direction (south) at a height about 6 ft above the average vegetation height. The proper positioning of the hygrometer and sonic anemometer is important for measuring the water vapor, temperature, and wind speed of the same eddy; and so the adverse effects of local wind distortion caused by vegetation, support structures, and the datalogger enclosure are minimized (table 4, fig. 7).

Net radiation (*Rn*) was measured with a net radiometer positioned about 10 ft above land surface at each site. Shrub distribution at the shrubland sites was patchy and heterogeneous on a local scale. An attempt was made to adjust the net radiometer at each site visually such that measurements would approximate the average ratio of shrub to open ground. Placement of the net radiometer also was adjusted to minimize possible airflow disruption to the south-facing hygrometer and sonic anemometer. A correction to measured net radiation is applied during post-processing when wind speeds exceed 11 mi/h to correct for wind-induced cooling of the net radiometer (Brotzge and Duchon, 2000, eq. 5).

Soil-heat flux was measured with two soil-heat flux plates, four soil-temperature thermocouples, and one soil-moisture probe. An attempt was made to locate these instruments such that a set of one heat-flux plate and two thermocouples is located in partial shade, and the other set in full sun. The soil-heat flux plates are placed at depths of 0.25 ft below land surface. The change in soil and soil-water temperature measured above each plate was converted to heat flux and added to the mean soil-heat flux measured across the plate (Laczniak and others, 1999; table 4, fig. 7).

Table 3. Phreatophyte characteristics of source area of evapotranspiration (ET) sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 2005–August 2006.

[**ET site**: SNV is Snake Valley; SPV is Spring Valley, WRV is White River Valley. Location of ET sites is shown in figure 4. MSAVI, modified soil-adjusted vegetation index]

ET site	ET unit	MSAVI (dimensionless)		Primary phreatophyte	Percent cover	Average vegetation height (feet)
		ET-unit range	Fetch-weighted average			
SNV-1	Moderately dense desert shrubland	21–28	23	Greasewood	10 to 20	3
SPV-1	Sparse desert shrubland	16–20	19	Greasewood, rabittbrush	10 to 15	2
SPV-2	Moderately dense desert shrubland	21–28	22	Greasewood, rabittbrush	15 to 20	3
SPV-3	Grassland/Meadowland	44–92	66	Mixed grasses	90 to 100	0.5
WRV-1	Dense desert shrubland	29–43	30	Greasewood	30 to 40	4
WRV-2	Moderately dense desert shrubland	21–28	26	Greasewood	15 to 25	3

Table 4. Instruments used to measure evapotranspiration (ET), energy balance components, precipitation, and continuous ground-water level at ET and well sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

[**Placement:** Values given are approximate. **Abbreviations:** ft, foot]

Type of measurement	Instrument and model number	Company	Placement
Evapotranspiration	CSAT3 3D sonic anemometer KH20 krypton hygrometer	Campbell Scientific, Inc.	6 ft above vegetation (from 6 to 12 ft above land surface)
Air temperature and humidity	HMP45C TRH probe	Vaisala	6 ft above land surface
Wind speed and direction	5106-5A wind monitor	R.M. Young, Inc.	10 ft above land surface
Net radiation	NR Lite net radiometer	Kipp & Zonen	10 ft above land surface
Soil temperature	TCAV soil thermocouple probe	Campbell Scientific, Inc.	0.1 and 0.2 ft below land surface
Soil heat flux	HFT-3.1 heat flux plate	Radiation and Energy Balance Systems, Inc.	0.25 ft below land surface
Soil moisture	CS616 water content reflectometer	Campbell Scientific, Inc.	From land surface to 0.5 ft below land surface
Precipitation	260-2510 rain and snow gage	Novalynx, Inc.	3 ft above land surface
Ground-water level	miniTROLL pressure transducer	In-Situ, Inc.	From 3 to 10 ft below water table
Datalogger	CR5000 datalogger	Campbell Scientific, Inc.	5 ft above land surface

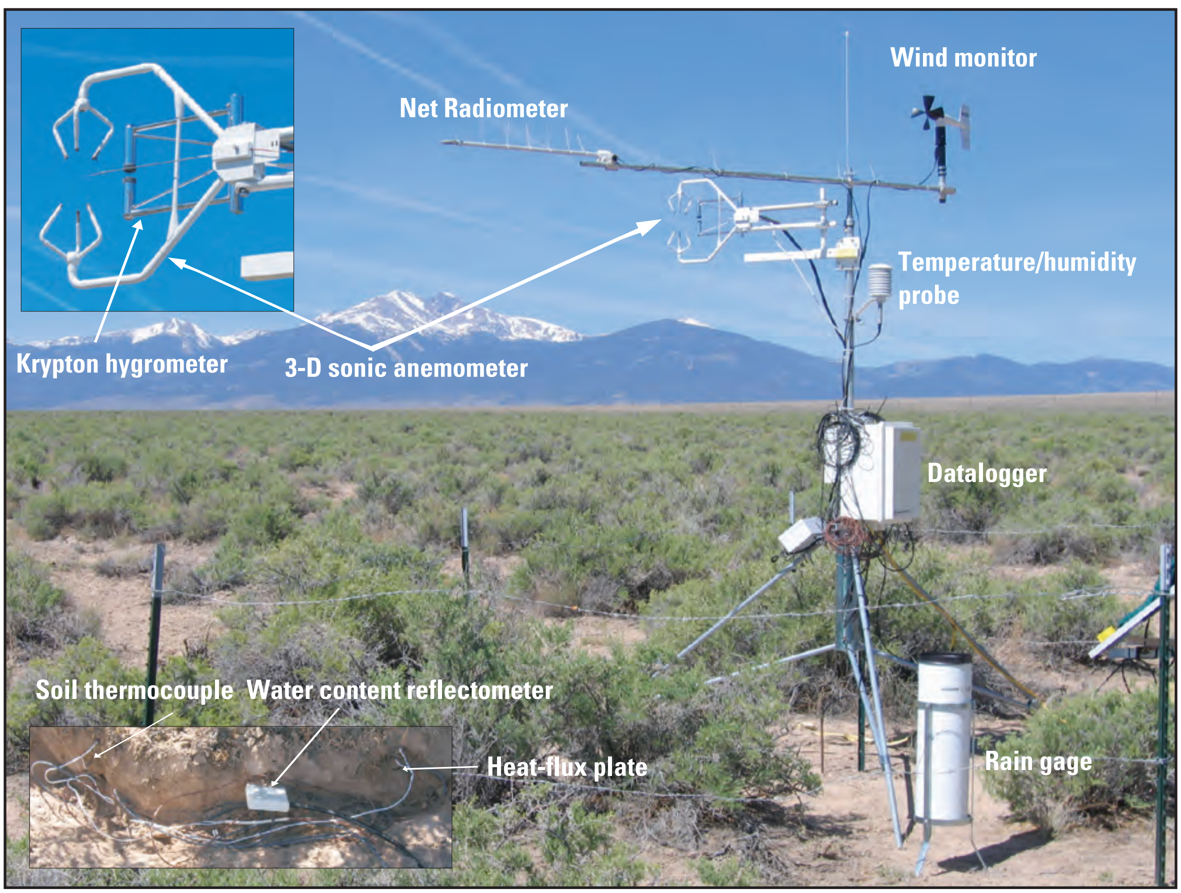


Figure 7. Typical eddy-correlation, ET site (SNV-1) used to measure evapotranspiration, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah. Photograph taken by Michael Moreo, U.S. Geological Survey, June 2006.

Precipitation data were collected at each ET site using a National Weather Service approved standard 8-in. diameter volumetric rain gage (fig. 7). The 8-in. rain gage is considered the most accurate means of collecting precipitation data and is the standard by which other rain gage designs are evaluated (Gordon, 2002). The water accumulated in the rain-gage measuring tubes were measured and recorded during monthly site visits. Once measured, the fluid was discarded, and each tube was refilled with a thin layer of mineral oil to prevent evaporative losses of the collected precipitation between site visits. Because less than 2 in. of snow was observed on the ground during the reporting period, no data loss is estimated as a result of snow overtopping the collection funnel. Monthly precipitation data collected at each ET site are presented in appendix A.

A well was installed near each ET site to measure local shallow ground-water level variations and to evaluate the influence of water-table depth on ET. A comparison of ET rates and concurrent water-level decline can be used to help determine the source of water contributing to ET. Well location and construction information are given in table 5. Locations ranged from 5 to 525 ft distant from the ET sites depending on site accessibility. Four of six wells were drilled with a portable trailer-mounted auger and two with a hand auger. All wells were cased with schedule 40 flush-threaded 2-in. poly-vinyl chloride pipe, and the lower 5 to 15 ft were slotted with 0.02 in. openings to allow for water entry from the aquifer. Number 3 aquarium grade washed Monterey sand was used to fill the well annulus around the slotted section of casing and bentonite filled the annulus from above the sand to near the surface. Each well was developed with an inertial pump to ensure proper contact with the monitored aquifer. Water-level fluctuations were monitored with a vented-cable water-level transducer that recorded water pressure. Data were downloaded and depth-to-water measurements taken with a calibrated steel tape during monthly site visits. Regression analysis was used to relate depth-to-water measurements to 30-minute pressure readings made by the transducer. Water-level data are given in appendix A.

Data from other instruments listed in table 4 but not discussed in the text are used in calculation processes. All instruments were calibrated by the manufacturer shortly before installation. Each site was visited monthly, typically during the first week of each month, for routine site maintenance and data acquisition. Instruments were checked and evaluated routinely, and repaired or replaced as necessary. The net radiometer and 3-D sonic anemometer were checked for proper horizontal level, and adjusted if necessary, and both the net radiometer and krypton hygrometer were cleaned with distilled water as necessary. The solar panels were cleaned of dust and debris and batteries routinely were refilled with distilled water. Notes were taken documenting soil moisture and vegetation conditions at the time of the visit.

Source Area of Measurements

The source area for measurements of turbulent flux, net radiation, and soil heat flux is the area from which the measured parameters originate. The size of the source area varies according to instrument design and placement, and the variable being measured. An estimate of the source area is necessary to characterize the vegetation that contributes to measured fluxes.

Turbulent-flux measurements are weighted averages of the flux originating from an assemblage of elemental surfaces upwind of the sensors. The major axes of the elliptical isopleths (lines of equal value) defining the weighting function pass through the sensors and are aligned with the primary wind direction. In this study, the source area for turbulent-flux measurements is defined as the area enclosed within the 90-percent isopleth. The measured flux is equal to 0.9 times the flux originating within the source area, plus 0.1 times the flux originating outside the source area.

Table 5. Location, construction, and average ground-water level depth for wells installed and measured at or near evapotranspiration (ET) sites in Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

[**Well site**: SNV is Snake Valley; SPV is Spring Valley, WRV is White River Valley. **USGS site identification No.:** Unique identification number for site as stored in files and data bases of the USGS. Altitude of land surface is in feet above NGVD29. Well depth, depth to open interval, and average depth to water in well are in feet below land surface. **Abbreviations:** USGS, U.S. Geological Survey]

Well site	USGS site identification No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Well depth (feet)	Depth to open interval, in feet		Aquifer type	Well installation date	Transducer installation date	Average depth to water in well (feet)
						Top	Bottom				
SNV-1W	390825114034302	39.140	-114.062	5,110	22	17	22	Unconfined	01-04-06	01-04-06	17.16
SPV-1W	384640114280101	38.778	-114.467	5,790	25	15	25	Unconfined	08-23-05	10-06-05	9.78
SPV-2W	384709114280101	38.786	-114.467	5,795	20	9	19	Unconfined	08-23-05	10-06-05	7.24
SPV-3W	385612114251602	38.937	-114.421	5,785	15	10	15	Unconfined	10-04-05	10-04-05	3.89
WRV-1W	382454115030201	38.415	-115.051	5,230	53	43	53	Confined	08-24-05	10-05-05	32.39
WRV-2W	383826115060501	38.641	-115.101	5,320	45	30	45	Confined	08-25-05	10-05-05	23.58

The size of the turbulent flux (λE and H) source area depends on atmospheric stability, surface roughness, and sensor height above the zero plane displacement. The zero plane displacement (d) is some height between the land surface and vegetation tops where semi-logarithmic wind-speed profiles above the vegetation would extrapolate to near zero wind speed and is a function of vegetation height and density (Campbell and Norman, 1998). The zero-plane displacement (d) for the six ET sites established for this study ranged from 4 in. at the grassland/meadowland site to about 2 ft at the densest desert shrubland site (WRV-1). The roughness length (z_o), a measure of the friction effect of wind created by the surface roughness, ranged from 0.07 ft at the grassland/meadowland site to 0.33 ft at ET site WRV-1 (Garratt, 1992). Source area calculations assumed mildly unstable atmospheric stability (Schuepp and others, 1990). The cumulative contribution to turbulent flux measured from the source area increases with distance from the sensors. The relative contribution of turbulent flux measured from the source area is zero at the sensor location, increases rapidly to a maximum a short distance upwind of the sensors, then decreases asymptotically with increasing distance from the site. For example, 90 percent of turbulent flux measured at ET site WRV-1 is contributed by the area within about 600 ft of the sensors, but the source for one-half of the turbulent flux measured is from an area within about 80 ft of the sensors (fig. 8). The major axis length of the source area commonly is referred to as the fetch. Fetch ranged from about 530 ft at shrubland ET sites SPV-2 and SNV-1 to 650 ft at shrubland ET site SPV-1 and grassland/meadowland ET site SPV-3.

The source area of available energy (Rn and G) instrumentation is much smaller than that of the turbulent-flux instrumentation. The source area for net-radiometer measurements is a cosine-weighted average circular area with a radius of 10 times the sensor height. The sensor height above the vegetation at a distance from the sensor is assumed to be the average vegetation height. The calculated source area for the net radiometer ranged from an average radius of 70 ft at the shrubland ET sites to 92 ft at the grassland/meadowland ET site. The source area for the heat-flux plates is very small and limited to an area not more than a few square feet directly above the instruments.

The average MSAVI was computed for the turbulent-flux source area of each ET site from TM data imaged in July 2005 to help refine delineated ET units throughout the study area. The average MSAVI value for a turbulent-flux source area was computed as the fetch-weighted average of the pixels within the source area (table 3, fig. 9). For example, MSAVI values for pixels in the source area of ET site SPV-2 range from 15 to 28 with a fetch-weighted average MSAVI value of 22 (fig. 9). Only pixels with their center point within the source area were considered part of the source area.

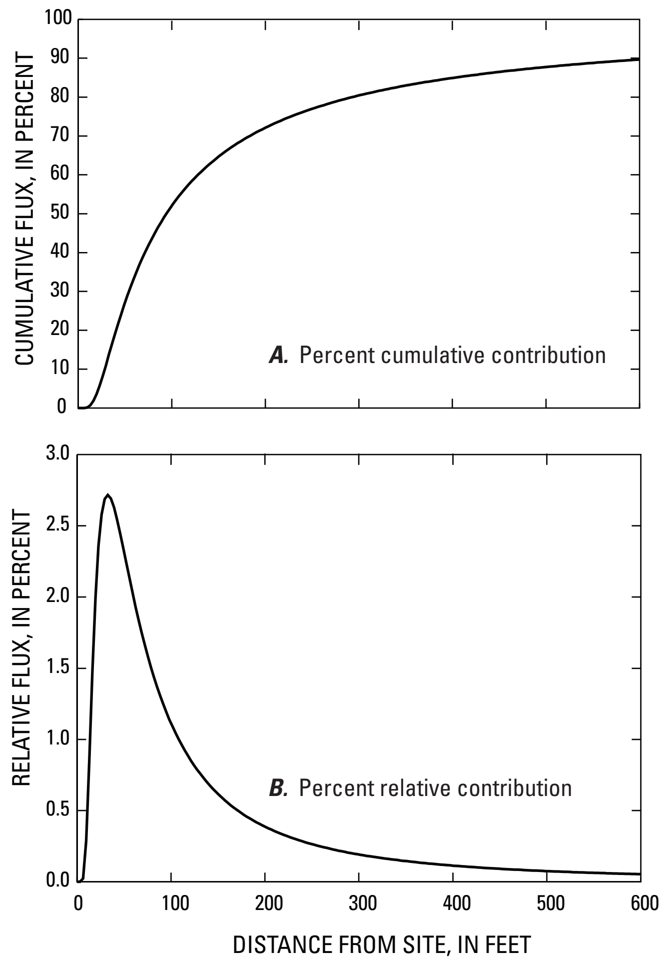


Figure 8. Contribution to measured turbulent flux from source area at distance away from ET site WRV-1, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

Data-Reduction Procedures

An accurate quantification of ET is necessary to evaluate the effect differing vegetation densities may have on local ET rates. Corrections must be applied to raw covariance measurements to compensate for limitations both in the eddy-correlation theory and equipment design. Filtering, or the removal, identification, and replacement of poor quality data also are necessary. Procedures were developed to collect and process data in a consistent, logical, and timely manner for all six ET sites. All collected data were maintained, stored, and processed in digital spreadsheets archived at the USGS Nevada Water Science Center in Henderson, Nev.

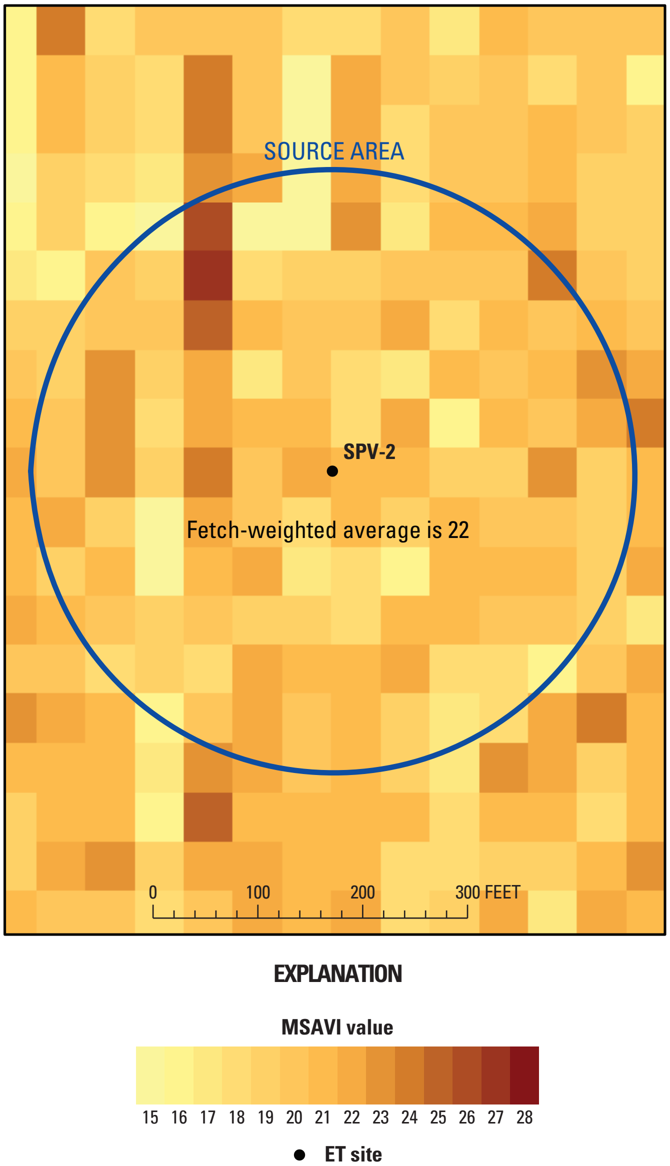


Figure 9. Source area for evapotranspiration (ET) site SPV-2 and distribution of imagery-derived MSAVI values by pixel, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

Numerous corrections and filters applied to latent- and sensible-heat-flux data were necessary, in addition to proper site construction and maintenance, to estimate ET as accurately as possible. During post-processing, raw covariances of sensible- and latent-heat are two-dimensionally rotated to the natural wind coordinates to correct for errors associated with a slightly sloping (less than 2 percent) rather than completely flat land surface and small sonic anemometer misalignment effects (Kaimal and Finnigan, 1994). Corrections are then applied to account for krypton hygrometer oxygen sensitivity (Tanner and Greene, 1989), variations in air density (Webb and others, 1980), sensor geometry, sampling interval, and averaging time (Moore, 1986). In addition, sensible-heat-flux estimates were corrected for air density and sound path deflection of sonic derived temperatures (Schotanus and others, 1983).

The susceptibility of latent-heat-flux data based on hygrometer and sonic anemometer measurements to spurious data were attributed primarily to the design of the hygrometer. When the windows of the hygrometer get wet, typically because of precipitation or dew and frost formation, data were considered poor quality and rejected. Evaluation of questionable data included time-series analysis of latent-heat-flux data and other environmental factors. Water accumulation on the hygrometer caused a rapid decrease in millivolt output, which results in easily identified spikes in latent-heat-flux data. Decreased net radiation and increased humidity often accompany adverse weather conditions and help to identify weather conditions indicative of suspect data. Analysis of daily time series data led to the identification and removal of about 4 percent of daytime (which corresponds to periods of positive net radiation) latent-heat-flux values and about 5 percent of nighttime measurements. Most equipment operated problem free for the reporting period; however, long periods of missing or poor quality data did occur in a few instances because of equipment malfunction (table 6). Notably, the source lamp on the krypton hygrometer at site WRV-2 failed resulting in the need to estimate an additional 18 percent of latent-heat-flux data at the site.

The sonic anemometer is much less susceptible to interference from moisture than the hygrometer. The transducer heads are smaller than the hygrometer windows, and thus water accumulation is less problematic. In addition, the transducers are covered with a mesh material that effectively wicks moisture away from the transducer heads. The datalogger records the number of acceptable measurements made by the sonic anemometer in each 30-minute period. If 10 percent or more of the 18,000 measurements made during a 30-minute period are flagged as poor, then the 30-minute average is discarded. Less than 0.5 percent of sonic anemometer data were identified as spurious and removed.

Once questionable data were identified and removed, the resulting gaps were filled using estimated values. The estimation method depended on the time of day and the gap length. Any gaps in latent-heat-flux data occurring between 8 p.m. and 4 a.m., a period when energy is negligible, were estimated as zero because latent-heat-flux values typically average near zero during this period. Gaps of less than 2 hours between 4 a.m. and 8 p.m. were filled by simple linear

Table 6. Extensive periods of missing or poor-quality data at evapotranspiration (ET) and well sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

[**ET site:** SNV is Snake Valley; SPV is Spring Valley, WRV is White River Valley. Location of ET sites is shown in figure 4]

Site	Period of missing or poor-quality data	Parameter	Cause for gap
ET			
SNV-1	May 7 to June 1, 2006	Soil-heat flux	Wires chewed
SPV-3	September 1, 2005, to October 5, 2006	Soil-heat flux	Wires chewed
WRV-2	March 1 to May 15, 2006	Latent-heat flux	Krypton hygrometer failure
Well			
SPV-1W	April 1 to August 1, 2006	Ground-water level	Transducer failure
WRV-1W	November 30, 2005, to January 3, 2006	Ground-water level	Operator error

interpolation. For gaps spanning more than 2 hours, an energy-balance approach was used. This approach used an energy balance ratio (*EBR*), defined as the turbulent flux divided by available energy, which can be expressed mathematically as:

$$EBR = \frac{\lambda E + H}{Rn - G}, \tag{4}$$

where

EBR is energy balance ratio, dimensionless.

The *EBR* equals unity when turbulent flux is equal to available energy. The *EBR* was calculated at each ET site over the entire period of operation (long-term *EBR*) and for periods when net radiation was positive (daytime *EBR*). Gaps in the latent-heat flux of 2 hours or longer occurring between 4 a.m. and 8 p.m. when the sonic anemometer was functioning were filled by rearranging equation 4 to solve for λE using the daytime *EBR* as:

$$\lambda E = EBR\left(Rn - G\right) - H. \tag{5}$$

Estimates of latent-heat flux using the daytime *EBR* components and equation 5 ensure latent-heat-flux estimates maintain the long-term *EBR*.

During less than 0.4 percent of the collection period, both the krypton hygrometer and sonic anemometer were inoperable. This situation occurs when wet conditions prevail for 2 or more hours. For such occasions, the Priestley-Taylor potential evapotranspiration (PET) equation was used to estimate latent heat, and sensible heat was approximated by rearranging and solving equation 5 (Priestley and Taylor, 1972; Flint and Childs, 1991). A PET estimator is assumed reasonable because when both instruments are wet for more than 2 hours at a time, the ground is sufficiently moist such that evaporation would no longer be limited by water availability, and therefore evaporation should be nearly equal to PET (Stannard, 1993).

Thirty-minute averaged data were summed into daily estimates. Gaps created by missing soil-heat-flux measurements (table 6) were filled using daily estimates computed as averages of good-quality data for periods before and after the gap. Finally, daily estimates for the entire 1-year period (September 1, 2005–August 31, 2006) were summed to estimate annual ET. Graphs and tables of daily and annual estimates of ET, energy balance components, and other pertinent micrometeorological data for each ET site are presented in appendix A.

Airflow measured by the sonic anemometer can be disrupted when the wind direction originates from behind the support structure. To minimize airflow disruption, care was taken during sensor deployment to place equipment, particularly the datalogger enclosure, away from the streamline of the sonic anemometer. All sonic anemometers were positioned to face due south (180 degrees). Turbulent flux measured when wind originated from 300 to 360 degrees and 0 to 15 degrees were considered questionable and further evaluated. The northwest sector angle is greater because the krypton hygrometer is mounted in that sector. Energy balance closure is the difference between net radiation and other energy flux components of the energy budget and can be expressed mathematically as:

$$EBC = Rn - (\lambda E - H - G), \tag{6}$$

where

EBC is energy balance closure, in calories per second per square foot.

No clear trend was evident that showed the daytime energy balance closure had decreased as a function of daytime wind direction; therefore, latent-heat-flux values were not filtered on the basis of wind direction.

Friction velocity, often referred to as *u**, is a measure of atmospheric turbulence (Campbell and Norman, 1998). High *u** values indicate increased turbulent mixing, which typically results in a better energy balance closure (Wilson and others, 2002). Turbulent-flux data measured during periods when *u** is less than some threshold value often are filtered and have been replaced in other studies. Wilson and others (2002) question the validity of eliminating turbulent-flux data based solely on a threshold *u** value. Values of *u** were compared with values of *EBC* to evaluate whether a site specific threshold could be established at any of the ET sites, and none were evident. Gu and others (2005) report that threshold *u** values vary between sites and exhibit seasonal trends. This approach was not used because of limited data.

Measured ET rates have a potential error of about 10 percent. The *EBR* is often used to evaluate the performance of an eddy-correlation system; notwithstanding good energy balance closure can result from offsetting erroneous measurements. Wilson and others (2002) studied the results of other investigators and report *EBR* values ranging from 0.39 to 1.69 for 50 site-years of data at 22 eddy-correlation ET sites with an average value of 0.8, thus implying that on average 80 percent of available energy is accounted for by their turbulent-flux measurements. The potential error was assessed for this study by calculating the *EBR* for all sites combined to reduce uncertainties related to random instrument bias. For example, a 5-percent difference between net radiometers could occur based on the calibration factors alone (Brotzge and Duchon, 2000). The *EBR* for ET sites in this study ranges from 0.82 to 1.06, and the average is 0.925 or 92.5 percent (appendix A); considerably better than the average value reported by Wilson and others (2002). If available energy measurements were considered to be error-free, then forcing turbulent-flux closure with average available energy would be recommended, and would result in an increase in ET by about 8 percent. However, whether the measurement of available energy is more accurate then turbulent flux is unknown (Wilson and others, 2002). The accuracy of available energy measurements generally is considered to be about ±10 percent (fig. 10).

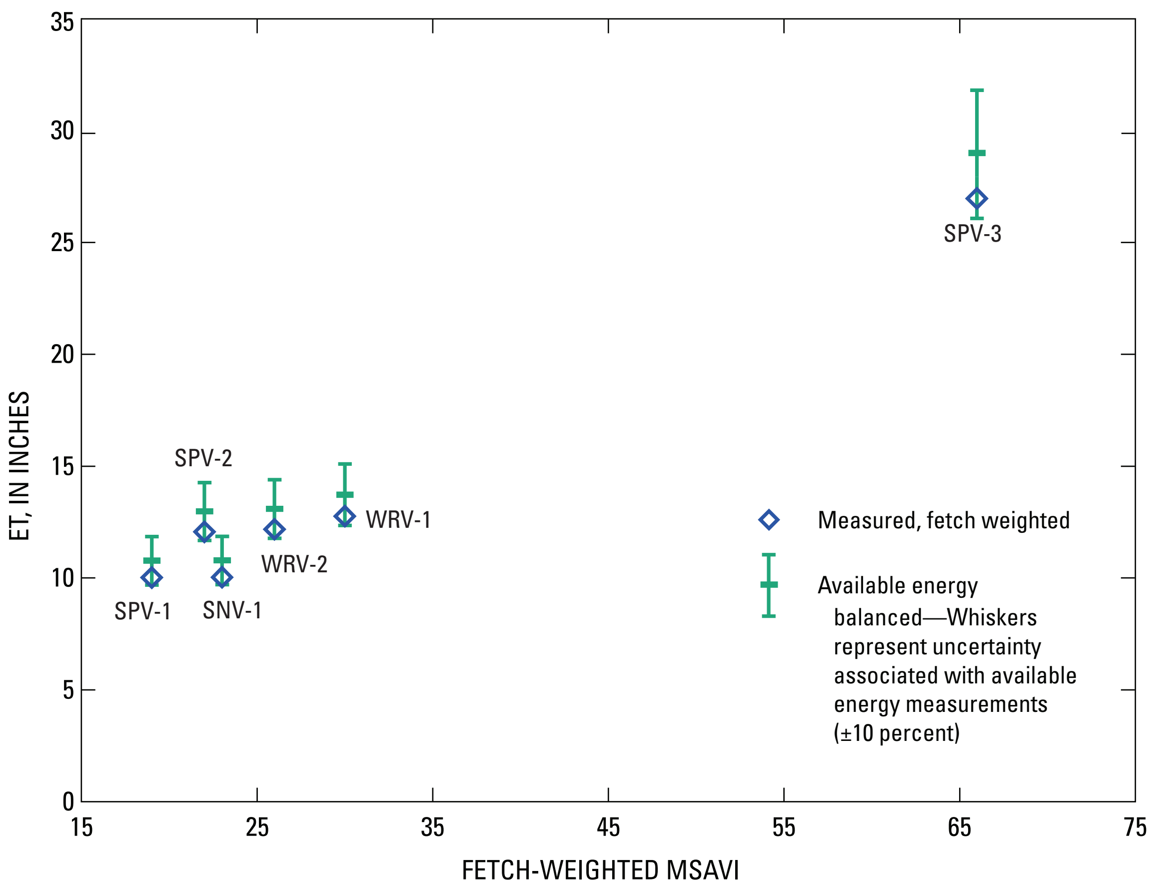


Figure 10. Evapotranspiration (ET) rates measured at ET sites, ET rates if turbulent flux were forced to balance with average available energy, and the fetch-weighted modified soil-adjusted vegetation index (MSAVI), Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

Measurement Results

Total ET includes water originating from precipitation, ground water, and surface water. Ground-water ET (ET*g*) is the water lost to the atmosphere through ET of ground water. ET*g* was calculated by subtracting precipitation measured from mesured ET at each ET site. Local surface-water run-on, defined as surface water occurring within the source area for turbulent-flux measurements, may increase total ET. Local surface-water run-on was not observed, nor were there any nearby major surface-water drainages; therefore, the contribution of local surface-water run-on to the total ET computed during the reporting period is considered negligible. As computed, total ET does include mountain-front surface-water runoff outside the source area for turbulent-flux measurements that infiltrates and contributes to regional ground-water recharge estimated for the BARCAS study (Flint and Flint, 2007).

Precipitation

Measured precipitation ranged from 6.03 to 11.08 in. at ET sites SNV-1 and WRV-2, respectively (table 7). Measured precipitation at each ET site was compared to the 30-year mean (1970–2000) as generated by the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) computer program (Daly and others, 1994). PRISM interpolates the 30-year mean from precipitation measured at maintained climate stations. The spatial resolution was enhanced by downscaling the model grid size from 4,000 to 270 m (Flint and Flint, 2007). Annual precipitation measured at each ET site was within 20 percent of the PRISM computed long-term mean. Above-mean precipitation was measured only at the ET site WRV-2, which received about 29 percent more precipitation than the ET site WRV-1 located about 15 mi south-southeast.

Measured precipitation corrected for under catch ranged from 6.21 to 11.41 (table 7). All rain gages underestimate precipitation catch. The primary cause for underestimation in the volumetric rain gages used in this study is wind. Wind-induced catch deficiencies are high when wind speeds are high. Extrapolating the average wind speed (about 5 mi/h) following a semi-logarithmic wind profile from the wind monitor to the rain gage, the wind speed at the collection funnel is estimated as 3 mi/h (Campbell and Norman, 1998). Based on an average wind speed of 3 mi/h, underestimation of measured precipitation due to wind is estimated as 3 percent (Larsen and Peck, 1974).

Table 7. Measured evapotranspiration and precipitation at evapotranspiration (ET) sites and average annual precipitation computed by PRISM, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

[**ET site:** SNV is Snake Valley; SPV is Spring Valley, WRV is White River Valley. Location of ET sites is shown in figure 4. PRISM, Parameter-Elevation Regressions on Independent Slopes Model]

ET site	Evapotranspiration, in inches		Precipitation, in inches		
	Measured	Computed ground water	Measured	Corrected	Mean annual computed by PRISM
SNV-1	10.03	3.82	6.03	6.21	6.37
SPV-1	10.02	1.44	8.33	8.58	9.56
SPV-2	12.07	2.90	8.90	9.17	9.45
SPV-3	26.94	18.97	7.74	7.97	9.34
WRV-1	12.77	3.89	8.62	8.88	8.94
WRV-2	12.18	.77	11.08	11.41	9.51

Evapotranspiration

Typically, ET is highest from mid-spring through mid-summer when net radiation is high and lowest during winter when net radiation is low. Net radiation is the energy that drives the ET process; however, in addition to energy, there also must be an available water source for any ET to take place.

Daily ET at the shrubland sites peaks significantly at two different times during the collection period (fig. 11). The first peaking period begins in early March and extends through about mid-April or mid-May, depending on spring precipitation and local soil moisture (fig. 12). Following the early spring rainy period, soil moisture begins to decrease and ET abruptly decreases. ET does not decrease as abruptly at ET site WRV-2 most likely because this site received more precipitation (monthly precipitation totals in appendix A), or less likely because values for latent-heat flux were estimated during this period (table 6). The second peaking period, from about mid-June to mid-August, coincides with increased net radiation, depleted soil moisture, and declining water levels. Ground-water levels declined at a nearly constant rate through most of the growing season (fig. 13). Greasewood leaves were bright green and the plant vigorous during the first peaking period when the source of water was primarily soil moisture elevated by spring precipitation. Greasewood leaves progressively wilted and turned dull green to yellow during the second peaking period when soil moisture was limited.

Potential evapotranspiration (PET) is a measure of the evaporative power of the atmosphere and defines the amount of ET that would occur assuming an unlimited water supply. To help better understand the source of evaporated and transpired water, PET was calculated using the Priestley-Taylor (1972) method and 30-minute data collected at the grassland/meadowland ET site SPV-3 (fig. 14). The annual PET for the grassland ET site is assumed to represent the typical PET response for the study area. ET computed at the grassland ET site also is shown in figure 14. The Gaussian pattern of PET in figure 14 was closely matched by measured ET at the grassland ET site. The grassland ET site represents a higher ET environment where annual ET far exceeds annual precipitation, ET and PET are closely coupled through most of the growing season, and where ground water rather than precipitation serves as the primary water source for local ET (table 7).

The ET site SPV-1 represents a typical shrubland environment. ET at site SPV-1 begins to deviate from PET in early spring (fig. 14). During the winter and early spring, local soil moisture was sufficient to meet the evaporative demand imposed by the atmosphere. Starting in mid-spring, soil moisture in the upper soil zone began decreasing and ET and PET began to diverge. This separation indicates that evaporative demand could no longer be met with locally available water. The divergence of ET and PET continues throughout the remainder of the growing season indicating continued water-limited conditions. Measured ET at site SPV-1 barely exceeds precipitation, indicating that precipitation rather than ground water is the primary source of water consumed by ET (table 7). Measured ET at the other shrubland ET sites has a similar relation to PET.

ET computed at each ET site for the 1-year measurement period is plotted against the fetch-weighted MSAVI value computed for each ET site's source area (fig. 10). ET at the two shrubland ET sites (SPV-1 and SPV-2) in Spring Valley was higher with respect to the MSAVI value than at the shrubland ET sites in Snake Valley (SNV-1) and White River Valley (WRV-1 and WRV-2). The depth to water was shallower, the soil sandier, and the presence of rabbitbrush is greater at the Spring Valley ET sites (tables 3 and 7); additionally, ET increases as fetch-weighted MSAVI increases, and the depth to water decreases.

ET at sites SNV-1, WRV-1, and WRV-2 also increases as fetch-weighted MSAVI increases, but in contrast to the Spring Valley ET sites, ET increases as the depth to ground water increases. Moreover, the ratio of measured ET to fetch-weighted MSAVI is lower than the Spring Valley sites (fig. 10). Differences between these shrubland ET sites and those in Spring Valley are: the depth to water is deeper, the soil texture is finer, and local precipitation varies more between the White River Valley and Snake Valley ET sites; and the water beneath the two White River ET sites is confined and overlain by a thick clay sequence.

The relation between measured ET and fetch-weighted MSAVI for the shrubland ET sites was relatively weak (R^2 = 0.59). Many of the factors that may influence the relation between ET rates and vegetation are listed in the preceding paragraphs. Because spatial and temporal data are limited, assessing the significance of each individual factor rates was not possible.

Ground-Water Evapotranspiration

The ground-water ET rate (ET*g*), also referred to as the ground-water discharge rate, was calculated by subtracting the local precipitation from ET measured over the 1-year reporting period. The amount of ground water contributing to local ET during the reporting period depended primarily on local precipitation and vegetation density. ET measured for the reporting period exceeds the measured precipitation at all ET sites indicating that another source(s) of water contributed to ET (fig. 15, table 7). Possible water sources are soil moisture retained from the period prior to the study period or shallow ground water.

The contribution of antecedent soil moisture to ET is considered negligible, and the difference between total ET and measured precipitation is assumed to be supplied primarily by ground water. Harrington and others (2004) report that in a similar phreatophyte shrubland environment the uptake of water by roots occurs primarily within the upper meter of unsaturated soil (upper-root zone), and in the capillary fringe above the saturated zone (lower-root zone). These authors concluded that the source of soil moisture to the upper-root zone was local precipitation, and the source to the lower-root zone was ground water. Harrington and others (2004) state that soil-water retention in the intermediate-root zone depends primarily on soil texture, and did not change significantly from year to year. In this study, the soil-water content in the upper-root zone (about 6 in.) was nearly equal at the start and end of the reporting period indicating only a small change in upper-root zone soil moisture (fig. 16).

If soil moisture was elevated in the intermediate-root zone from the previous winter, that water likely either percolated to the lower-root zone or was lost to ET prior to the beginning of data collection in September 2005.

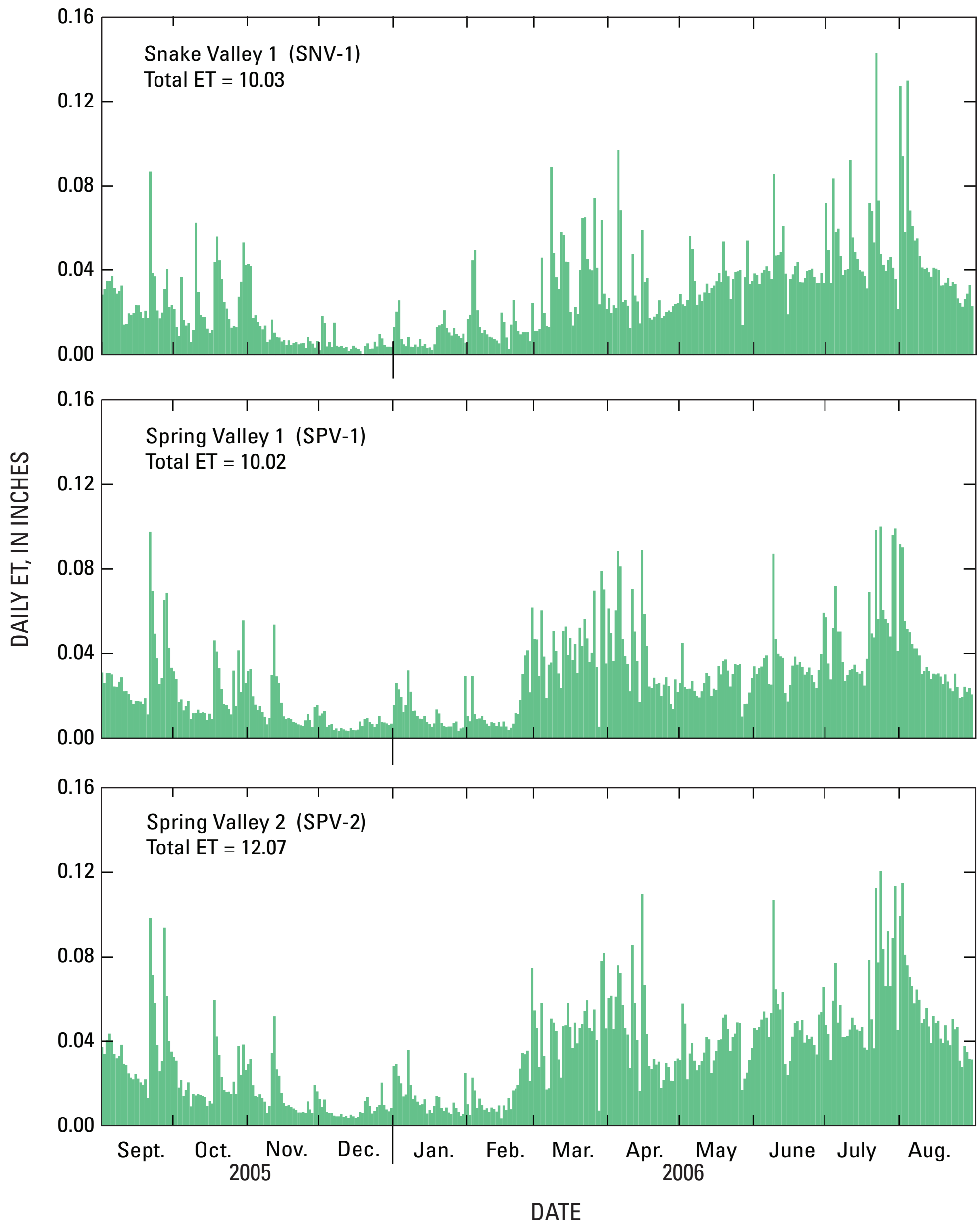


Figure 11. Daily evapotranspiration (ET) measured at ET sites in Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

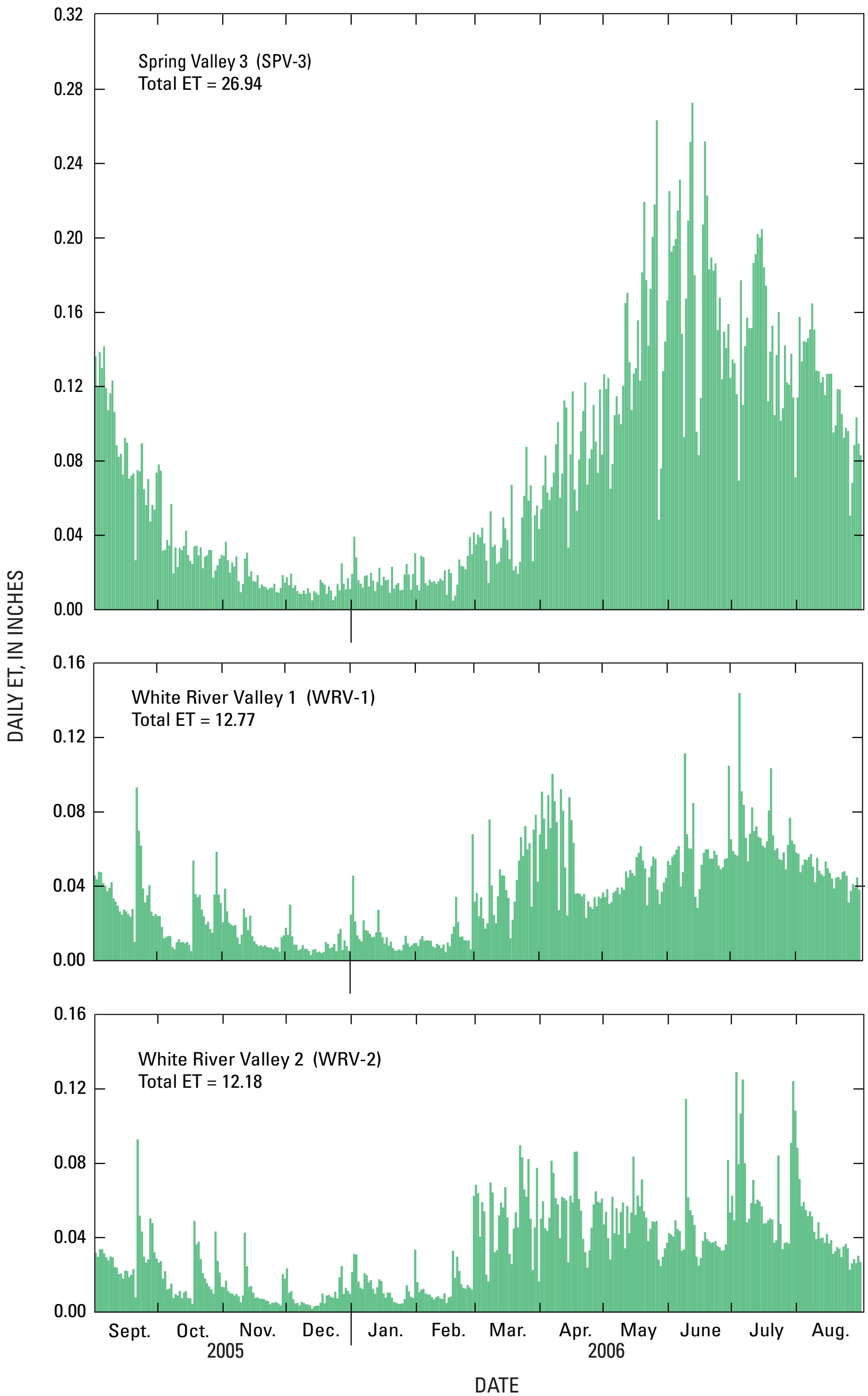


Figure 11.—Continued.

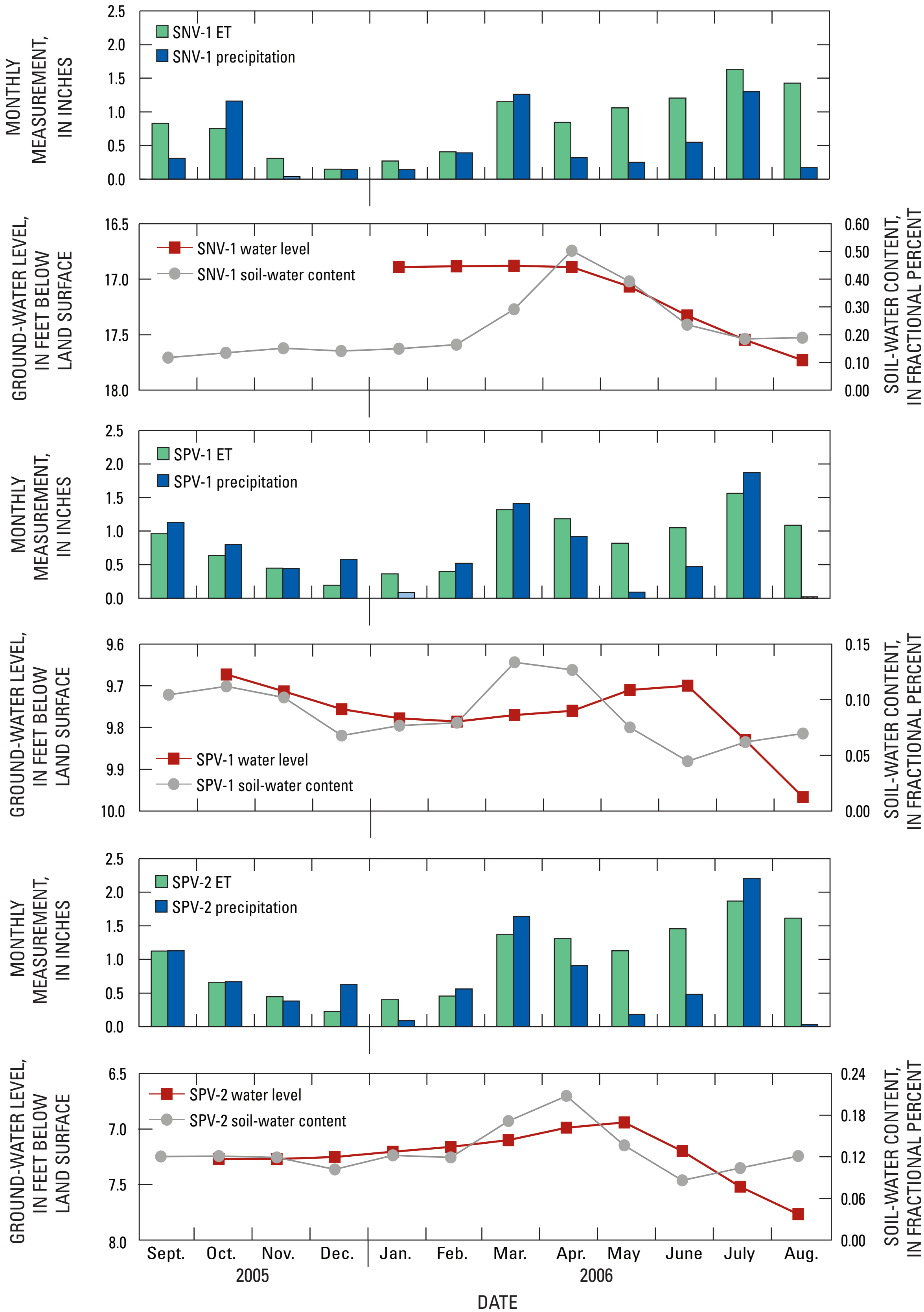


Figure 12. Monthly evapotranspiration (ET) and precipitation, and monthly average ground-water levels measured in wells near ET sites and soil moisture measured at ET sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

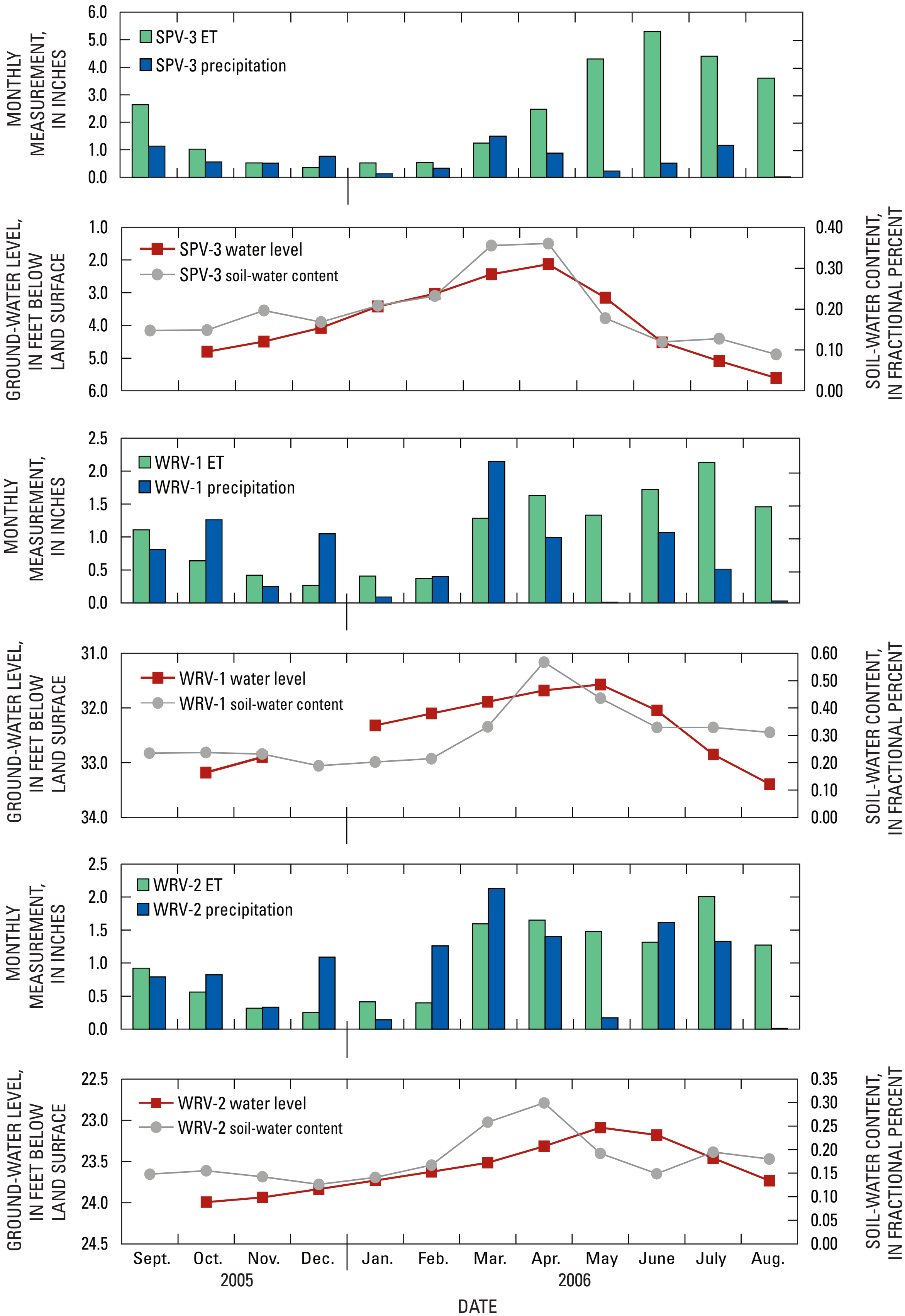


Figure 12.—Continued

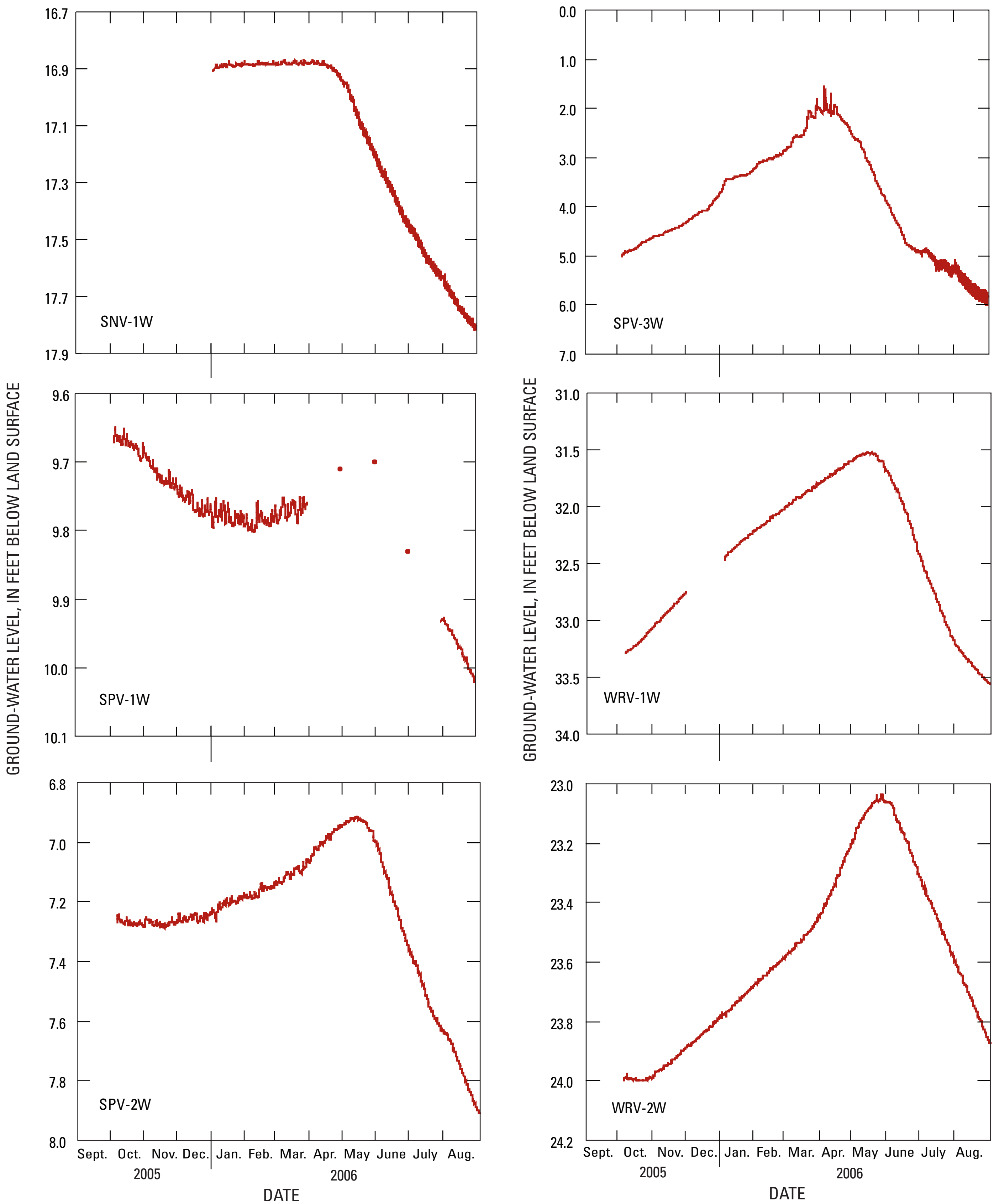


Figure 13. Ground-water levels measured in wells near ET sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

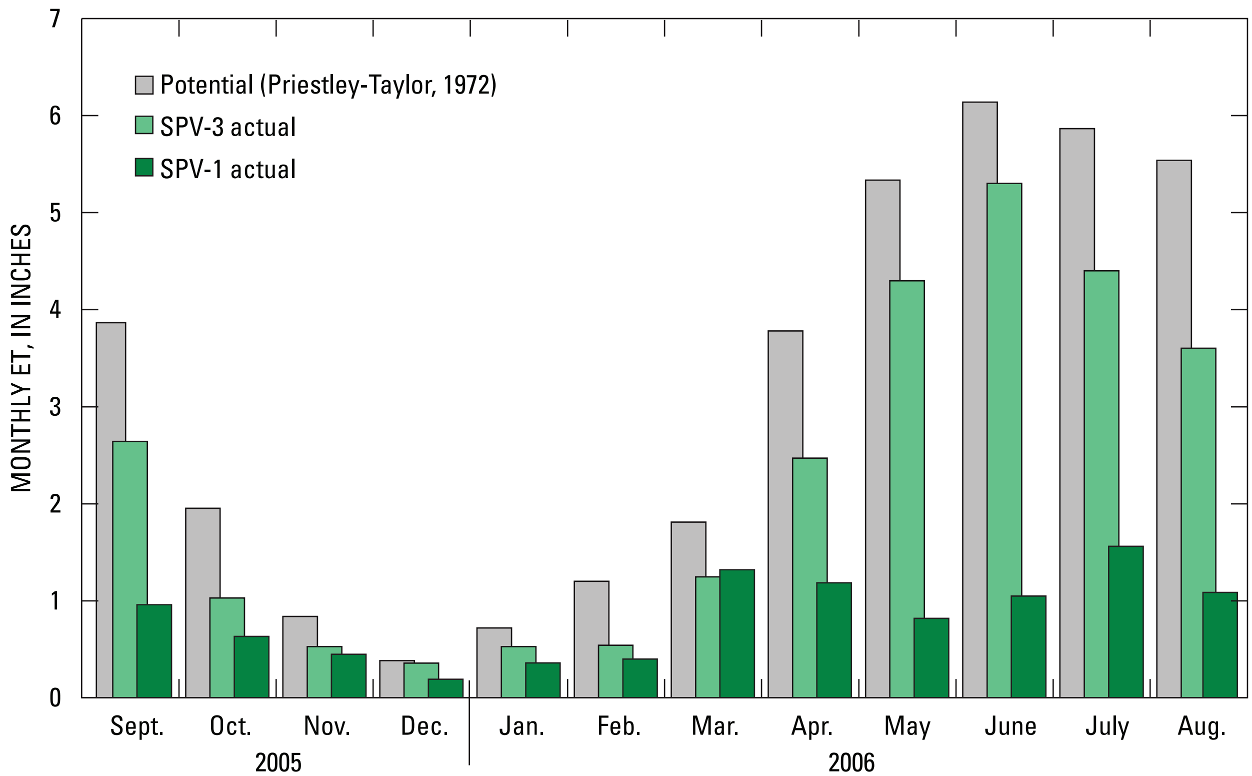


Figure 14. Monthly potential evapotranspiration (PET) and evapotranspiration (ET) measured at grassland/meadowland ET site SPV-3, and measured at sparse desert shrubland ET site SPV-1, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah September 1, 2005, to August 31, 2006.

Relatively sandy soil like that found at the Spring Valley ET sites generally has relatively high permeability and low specific retention (lithologic logs are presented in appendix A). Infiltration of precipitation in discharge areas made up of sandy soil typically moves rapidly through the unsaturated zone to the lower-root zone or is transpired by the local vegetation precluding any extended periods of high soil moisture (fig. 16). Conversely, fine-textured soil like that found near the Snake Valley and White River Valley ET sites generally has low permeability and high specific retention—conditions that impede any infiltration through the unsaturated zone and generally increase soil moisture in the upper-root zone. Precipitation retained in the upper-root zone likely was lost to ET during the summer when PET is high. Continuous monitoring of soil-water content and soil-water potential throughout the entire unsaturated zone would allow for analysis of the direction of water movement which may contribute to a better estimate of ET*g*.

Typically, ground-water levels in discharge areas decline each growing season when phreatophytes withdraw ground water and discharge exceeds recharge, and rise after the growing season when phreatophytes are quiescent and recharge exceeds discharge. Ground-water levels at ET sites SPV-3 and SNV-1 began declining about 1 month earlier than at other ET sites indicating that phreatophytes in these areas began using ground water earlier than at ET sites SPV-1, SPV-2, WRV-1, and WRV-2 (fig. 13, appendix A). ET at site SPV-3 (grassland/meadowland) is typical of a more densely vegetated environment where precipitation accounts for a smaller portion of the water lost to ET, and ground water is the primary water source. ET*g* was proportionally greater at ET site SNV-1 than at the other shrubland ET sites because there was less precipitation. Precipitation in Snake Valley generally is less than in other valleys in the study area. The drier conditions in Snake Valley likely result from rain shadow effects caused by the Snake Range, which separates Snake Valley from Spring Valley. The early reliance on ground water at ET sites SPV-3 and SNV-1 also is apparent in the diurnal water-level fluctuation (fig. 13, appendix A).

Ground-water levels for 7 days of the growing season in August 2006 are plotted in figure 17. Diurnal fluctuations in ground-water levels from wells SPV-3W and SNV-1W near ET sites are clearly evident. Water levels rise in the late evening through early morning when ET decreases, and then

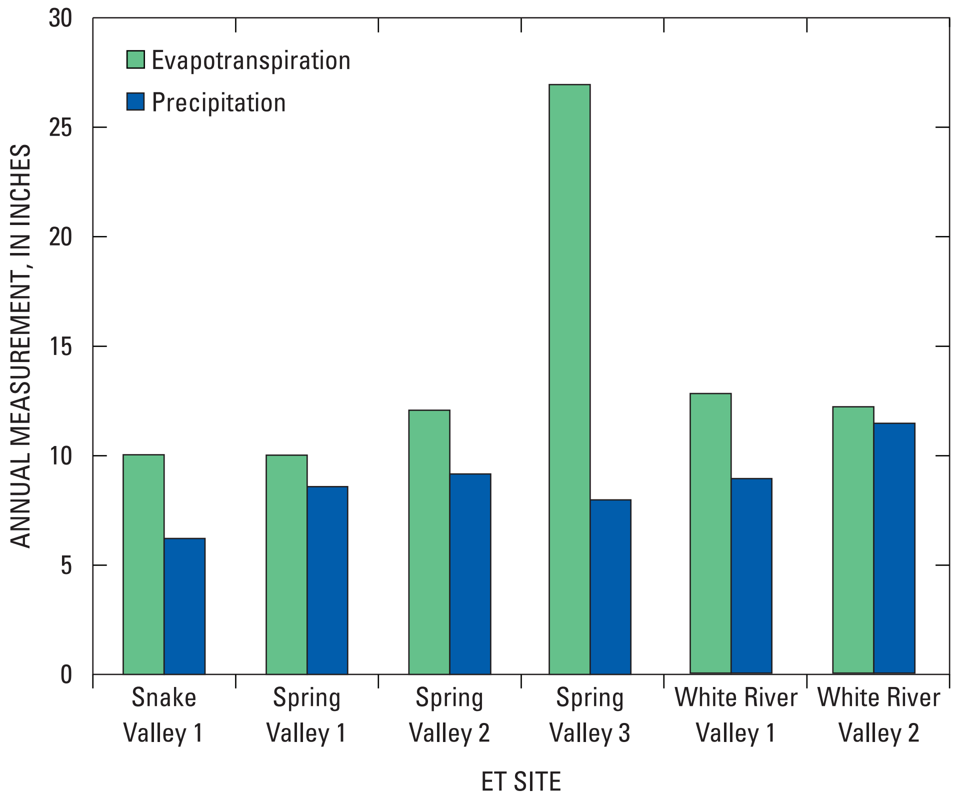


Figure 15. Annual evapotranspiration (ET) and precipitation measured at ET sites in Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

decline throughout the day as local phreatophytes withdraw shallow ground water. This pattern and the correlation with ET are less clear at ET sites in Spring Valley shrubland. White (1932) reported only 15 of 34 wells in pure or mixed stands of greasewood in the Escalante Valley, Utah, displayed diurnal fluctuations. The diurnal fluctuations at ET sites SPV-1 and SPV-2 likely are subdued by the relatively high permeability of the coarse-grained sand making up the shallow water-table aquifer. High permeability allows for rapid replacement by lateral inflow any water removed by ET during the day (White, 1932). Diurnal fluctuations are much less apparent or nonexistent at ET sites WRV-1 and WRV-2. Here, measured water levels exhibit a confined response. Both White River Valley wells are screened at depths greater than 25 ft. The tapped interval is overlain and confined by a thick clay sequence that includes minor sand and gravel stringers that were dry during drilling (see lithologic log in appendix A). Water levels in both wells rose more than 10 feet above the bottom of the confining clay layer. Typically, water levels measured in a confined system represent a pressure response of the potentiometric surface that is spread over a large area, causing the magnitude of any diurnal fluctuations to be small and effectively masked by the declining rate of recharge during the growing season.

Assuming a negligible contribution from antecedent soil moisture at the shrubland ET sites, most of the water being lost to ET during the reporting period originated from local precipitation. ET*g* ranges from 0.77 in. at the moderately dense desert shrubland ET site WRV-2 to 18.97 in. at the grassland/meadowland ET site SPV-3 (table 7, fig. 18*A*). Based on differences between total ET and corrected precipitation measured at the shrubland ET sites, ET*g* ranges from 6 percent of total ET at site WRV-2 to 38 percent at site SNV-1 (fig. 18*B*). These two ET sites also received the most and least precipitation, respectively (fig. 18*C*). Among the three ET sites receiving similar precipitation (WRV-1, SPV-2, and SPV-1), the ET site where vegetation was densest, WRV-1, used 30 percent ground water and the ET site where vegetation was sparsest, SPV-1, used 14 percent ground water (table 3, fig. 18).

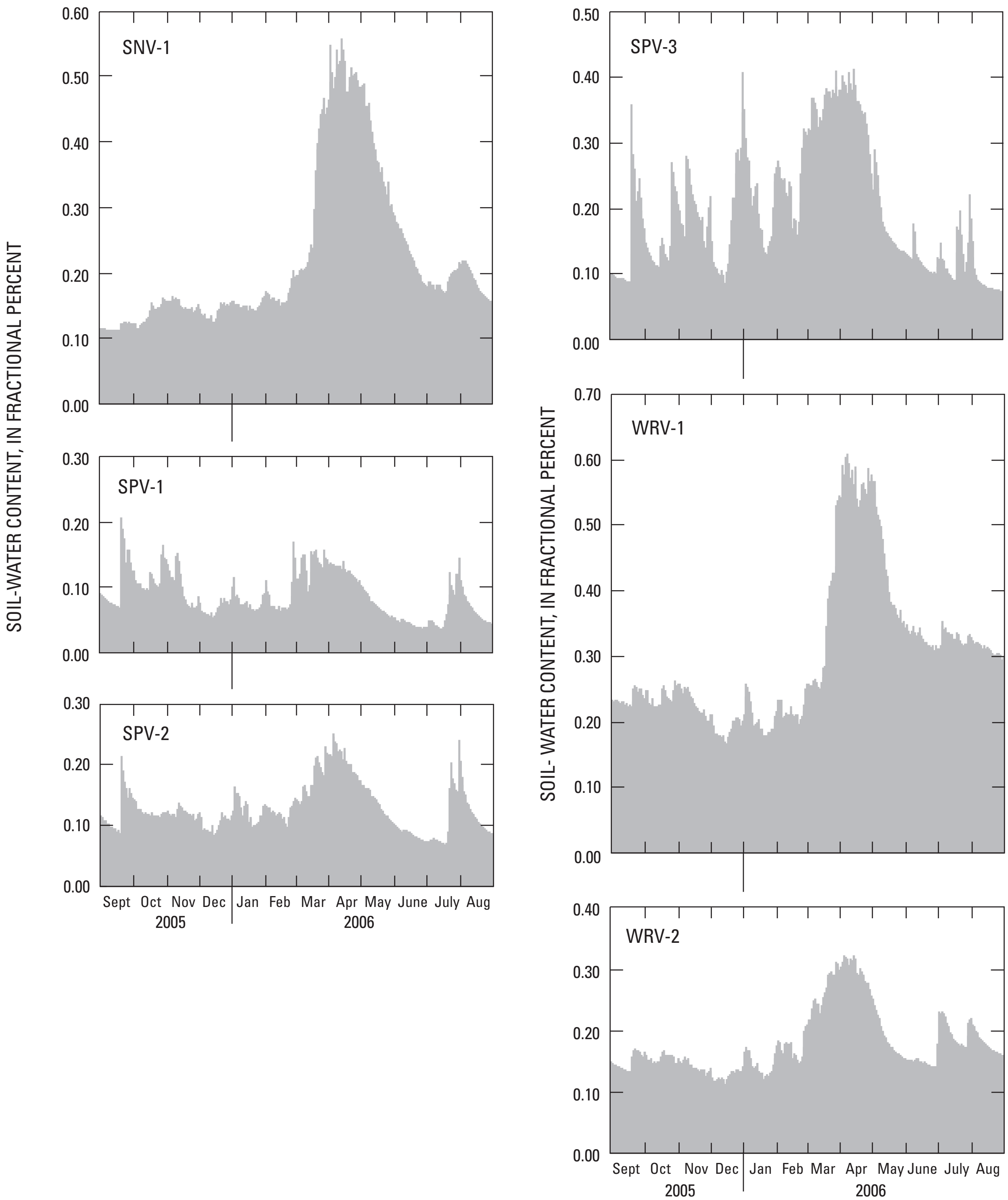


Figure 16. Volumetric soil-water content measured at ET sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

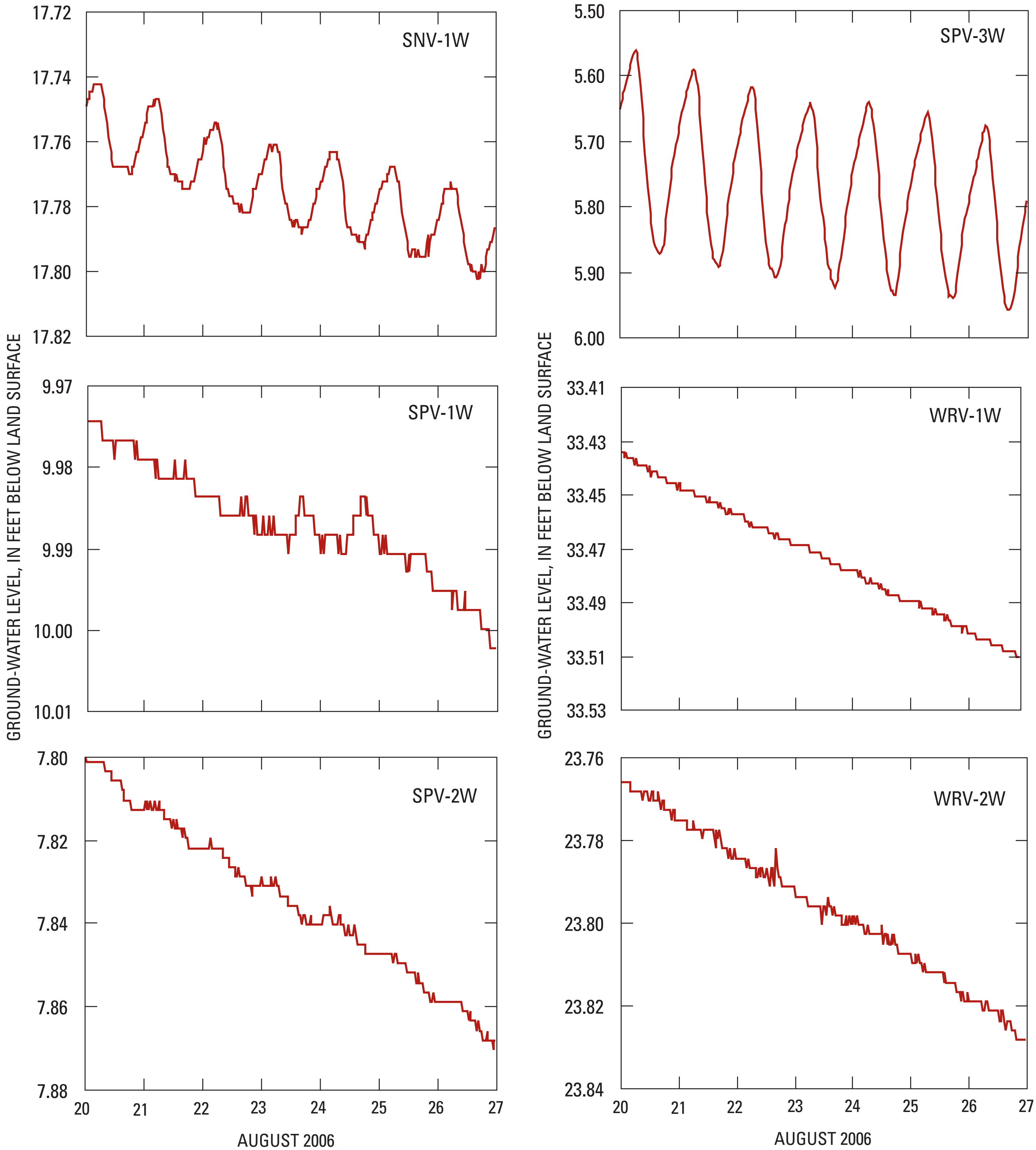
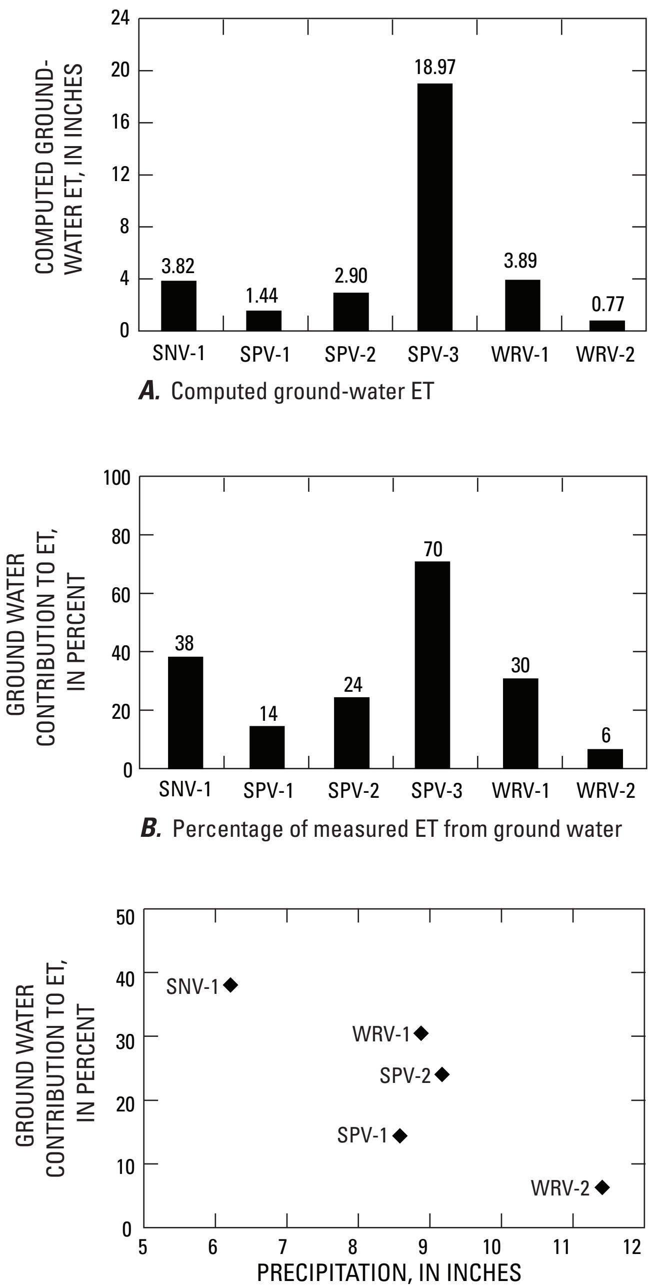


Figure 17. Fluctuations in ground-water levels measured in wells near ET sites, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, August 20–27, 2006.



A. Computed ground-water ET

B. Percentage of measured ET from ground water

C. Percentage of measured ET from ground water and total precipitation at five shrubland sites

Figure 18. Annual ground-water contribution to measured evapotranspiration (ET) in Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 1, 2005, to August 31, 2006.

Limitations of Methodology

The accuracy and use of measured ET rates described by this report are limited by the accuracy of the eddy-correlation method and the limited spatial extent and temporal period of ET data. Briefly, the accuracy of discharge estimates for the BARCAS study is limited by: (1) accuracy of measured ET rates (2) accuracy of previously published ET rates (3) method used to extrapolate ET rates to a regional area, and (4) estimation and subtraction of precipitation over a regional area.

Measured ET rates documented by this report have a potential error of 10 percent. The quality of annual ET estimates is considered very good. The average *EBR* calculated was considerably better than the average for other ET studies. Resulting estimates of annual ET are reasonable compared to published values.

The uncertainty of discharge estimated in the BARCAS study can be reduced on a hydrographic area basis by establishing additional ET sites to help reduce the uncertainty in the relation between ET rates and vegetation for a period sufficient to cover wet and dry years. Discharge estimated for Snake Valley in particular could be refined because the acreage of shrubland is almost double that of any other valley. A small change in discharge rates (ET*g*) for shrubland ET units over a large area, which depend on the local ET and precipitation rate, has a significant impact on discharge estimates. Long-term ET data collection is as important as long-term precipitation data collection because ground-water discharge estimates rely on ET and precipitation estimates. Establishing additional long-term ET sites would: (1) reduce reliance on previous estimates made from data obtained outside the study area, (2) decrease the extent of interpolation, (3) provide greater temporal coverage to help confirm whether phreatophytic shrubs reduce ground water usage during wet periods, (4) reduce uncertainties related to antecedent soil moisture, and (5) improve the characterization of the relation between ET and MSAVI by evaluating the effects of differing precipitation, soil texture, depth to water, and phreatophyte distribution.

Summary

Part of the focus of the Basin and Range carbonate-rock aquifer system (BARCAS) study is to improve the current understanding and conceptualization of the ground-water flow system. An integral part of the improvement process is to develop a refined ground-water budget based on recharge and discharge estimates that are determined consistently across the study area. Historically, quantifying ground-water discharge consistently from the large extensive ground-water flow systems of the arid Southwest has proven difficult. Many investigators have chosen to estimate ground-water discharge solely on the basis of the evapotranspiration (ET) that occurs in areas where ground water is near land surface. An important part of this method is to develop sound estimates of ET that occurs from areas of ground-water discharge.

The purpose of this study was to measure ET rates in environments representative of the different vegetation conditions typical of ground-water discharge areas in the study area. This report documents ET rates, precipitation, and ground-water levels measured from September 1, 2005, through August 31, 2006. Daily and annual ET rates were estimated, and any associated assumptions and uncertainties are documented in this report. Daily and annual ET rates, associated energy budget components, pertinent micrometeorological data, precipitation totals, and continuous water-level records are compiled in an electronic spreadsheet that is distributed as part of this report.

Six ET sites were established in August 2006. Five were located in shrubland ET units dominated by greasewood and to a lesser extent rabbitbrush. ET units are areas grouped by similar vegetation and soil characteristics. Delineations of these groupings commonly are referred to as ET units because they differentiate areas of differing ET. The characteristics of each ET unit differs—ranging from areas of no vegetation, such as open water, moist bare soil, and dry playa, to areas of vegetation including phreatophytic shrubs, grasses, rushes, and reeds. A proportionally large number of sites were located in shrubland ET units specifically to evaluate the effect of vegetation density on ET rates, and to better quantify ET rates for the dominant vegetation type of the study area. Shrubland accounts for more than 80 percent of the acreage delineated as contributing to ground-water discharge. Classic riparian vegetation—marshland, meadowland, and grassland—accounts for only about 6 percent of the ET-unit acreage in the study area. Only one site, established in the grassland/meadowland ET unit, was located in a mixed grass riparian area to represent an environment indicative of greater ET.

The modified soil-adjusted vegetation index (MSAVI) was used to delineate ET units, describe source areas for turbulent-flux measurements in terms of vegetation density, and help apportion ET rates to equivalent ET units across the study area. Normalized MSAVI values, computed from TM imagery acquired for the study area, ranged from 16 to 43 for shrubland ET units and from 44 to 92 for grassland and meadowland ET units. Greater MSAVI values generally indicate denser vegetation.

Numerous corrections and filters applied to latent- and sensible-heat-flux data are necessary, in addition to proper site construction and maintenance, to estimate ET as accurately as possible. Corrections must be applied to raw covariance measurements to compensate for short-comings both in the eddy-correlation theory and equipment design. Analysis of daily time-series data led to the identification, removal, and replacement of about 4 percent of daytime latent-heat-flux measurements and about 5 percent of nighttime measurements.

Measured precipitation corrected for wind-induced under catch ranged from 6.21 inches at ET site SNV-1 to 11.41 inches at ET site WRV-2. Measured precipitation at each ET site was compared to the 30-year average as generated by the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) computer program. Annual precipitation measured at each ET site was within 20 percent of the computed long-term annual mean.

The measured annual ET ranged from 10.02 inches at the sparsest shrubland ET site to 12.77 inches at the densest shrubland ET site. Daily ET at the shrubland sites peaks at two different times during the collection period. The primary source of water supporting the first peaking period is soil moisture elevated by spring precipitation, whereas the second peaking period is supported by decreasing soil moisture and ground water. Water-level records indicate the amount of ground water uptake by roots is nearly constant through most of the growing season once water levels begin to decline. Plant growth and vigor are supplemented by elevated soil moisture when available. Greasewood appears more vigorous when soil moisture is elevated.

ET measured at the grassland ET site (26.94 inches) closely followed potential evapotranspiration (PET) for most of the growing season. The grassland ET site represents a higher ET environment where annual ET far exceeds annual precipitation, and ground water rather than precipitation serves as the primary water source for local ET.

ET measured at the shrubland ET sites began to deviate from PET in early spring, indicating that evaporative demand could no longer be met by local available water. Measured ET at the shrubland ET sites barely exceeded precipitation, indicating that precipitation rather than ground water is the primary source of water lost to ET.

The amount of ground water contributing to local ET during the reporting period depended primarily on local precipitation and vegetation density. Measured ET exceeded measured precipitation at all ET sites for the reporting period. The rate of ground-water discharge from ET (ET*g*, or ground-water ET)—calculated in this report by subtracting corrected precipitation from measured ET for the reporting period—ranged from 0.77 to 3.82 inches at the shrubland ET sites, and was 18.97 inches at the grassland/meadowland ET site. ET*g* for the shrubland sites ranged from 6 percent of total ET at site WRV-2 in White River Valley to 38 percent at site SNV-1 in Snake Valley. These two sites also received the most and least precipitation, respectively. The grassland/meadowland site (SPV-3) in Spring Valley used 70 percent ground water.

Measured ET rates documented by this report have a potential error of 10 percent. The quality of annual ET estimates is considered very good. The relatively weak correlation ($R^2 = 0.59$) between measured ET and fetch-weighted MSAVI for the shrubland ET sites is attributed to precipitation, depth to water, soil texture, and aquifer type differences between ET sites.

Acknowledgments

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The authors also gratefully acknowledge the professionalism and dedication of the following past and present U.S. Geological Survey employees who contributed in many ways to the completion of this study: Walter Nylund (retired), Nyle Pennington, James Wood, J. LaRue Smith, Donald Harper, Ronald Veley, Keith Halford, Alan Flint, Alan Welch, Wayne Belcher, David Susong, Mary Tumbusch, Linda Rogers, Michael Pavelko, Guy DeMeo, Carl Herman, Daniel Bright, and Toby Welborn.

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Appendix A. Evapotranspiration data for the Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September 2005–August 2006.

The spreadsheet distributed as part of this report is in Microsoft® Excel 2003 format. Column headers are described within the spreadsheet. Data are presented in native units. Appendix A data are available for download at URL: http://pubs.water.usgs.gov/sir20075078.

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SIR 2007–5078