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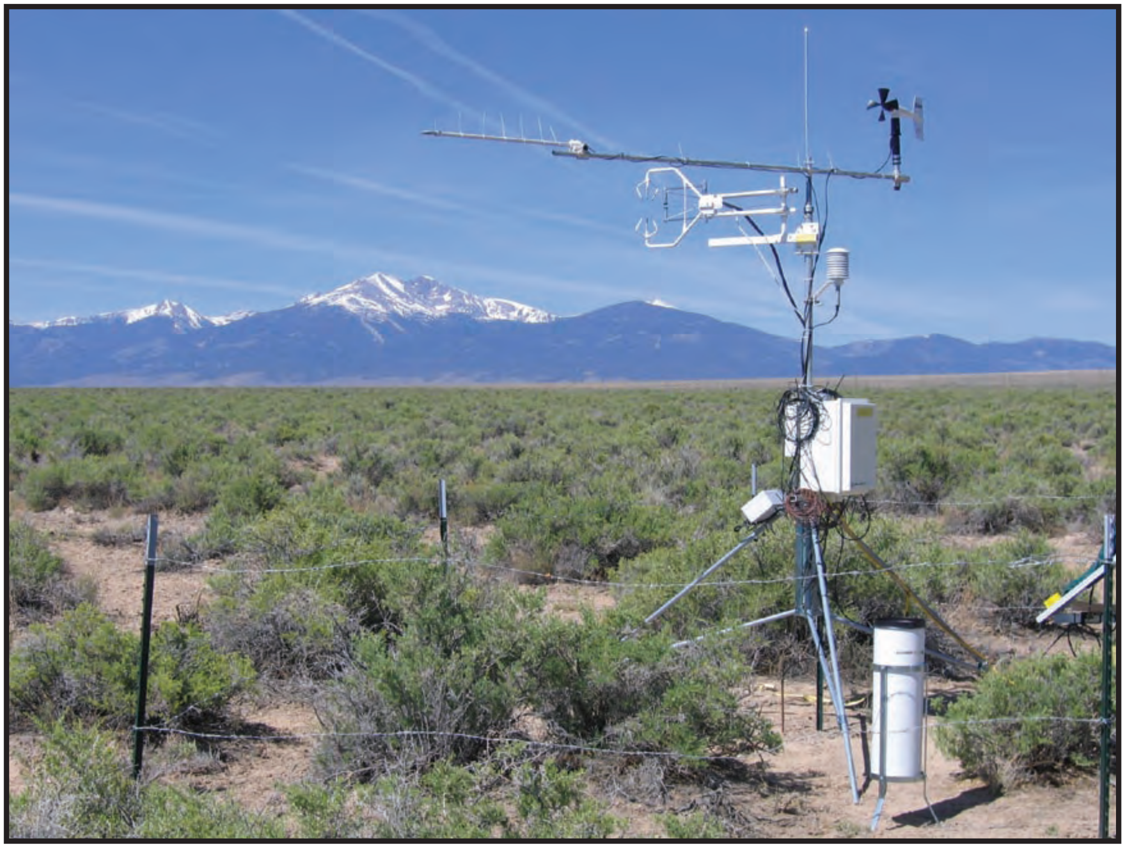

Scientific Investigations Report 2007–5078

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

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

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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.

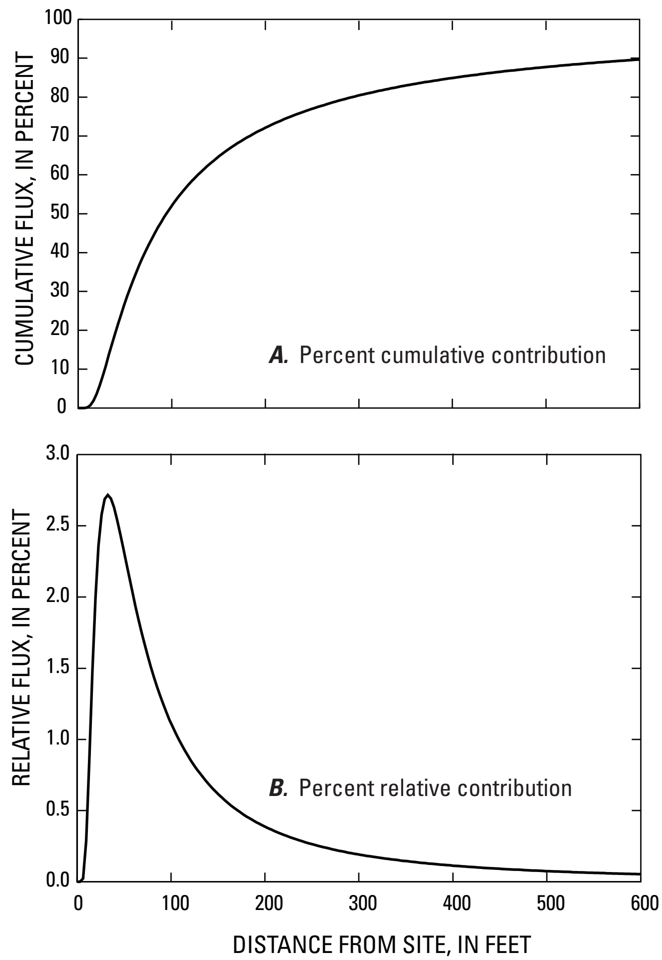

Figure 8. Contribution to measured turbulent flux from source area at distance away from ET site WRV-1, Basin and Range carbonate-rock aquifer system study area, Nevada and Utah.

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.

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).

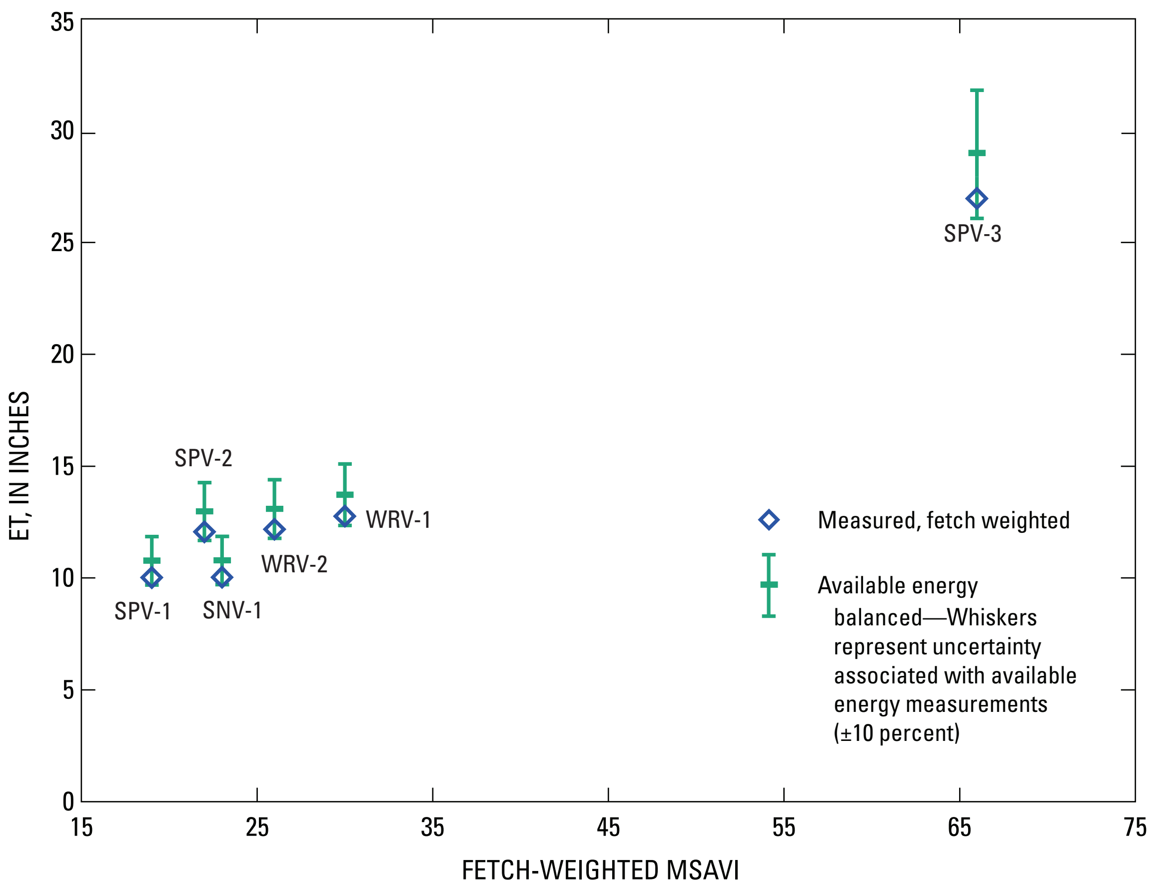

Figure 10. Evapotranspiration (ET) rates measured at ET sites, ET rates if turbulent flux were forced to balance with average available energy, and the fetch-weighted modified soil-adjusted vegetation index (MSAVI), Basin and Range carbonate-rock aquifer system study area, Nevada and Utah, September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

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.

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

Summary of annual parameters measured at ET site in BARCAS study area, September 1, 2005 to August 31, 2006

[ET is evapotranspiration, GW is ground water, SNV is Snake Valle, SPV is Spring Valley, WRV is White River Valley, Rn is net radiation, G is soil heat flux, LE is latent-heat flux, H is sensible-heat flux, EBR is energy balance ratio, BLSD is below land surface datum]

Measured Parameter	ET Site					
	SNV-1	SPV-1	SPV-2	WRV-1	WRV-2	SPV-3
ET, in inches	10.03	10.02	12.07	12.77	12.18	26.94
Precipitation, in inches	6.03	8.33	8.90	8.62	11.08	7.74
GW ET, in inches	4.00	1.69	3.17	4.15	1.10	19.20
Rn, in Watts per square meter	71.51	69.43	66.57	78.38	81.63	79.63
G, in Watts per square meter	0.53	-0.44	1.38	-1.09	-1.21	-0.23
LE, in Watts per square meter	19.85	19.87	23.90	25.25	24.12	53.25
H, in Watts per square meter	43.32	37.57	44.99	54.46	45.52	22.39
EBR, dimensionless	0.89	0.82	1.06	1.00	0.84	0.95
Average GW Level, in feet BLSD	17.16	9.78	7.24	32.39	23.58	3.89

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

Measured Monthly Precipitation (inches), September 1, 2005 to August 31, 2006

[ET is evapotranspiration, SNV is Snake Valley, SPV is Spring Valley, WRV is White River Valley]

Month		ET site					
		SNV-1	SPV-1	SPV-2	SPV-3	WRV-1	WRV-2
September	2005	0.31	1.13	1.13	1.13	0.81	0.79
October	2005	1.16	0.80	0.67	0.56	1.26	0.82
November	2005	0.04	0.44	0.38	0.52	0.25	0.33
December	2005	0.14	0.58	0.63	0.77	1.05	1.09
January	2006	0.14	0.08	0.09	0.13	0.09	0.14
February	2006	0.39	0.52	0.56	0.33	0.40	1.26
March	2006	1.26	1.41	1.64	1.49	2.15	2.13
April	2006	0.32	0.92	0.91	0.88	0.99	1.40
May	2006	0.25	0.09	0.18	0.23	0.01	0.17
June	2006	0.55	0.47	0.48	0.52	1.07	1.61
July	2006	1.30	1.87	2.20	1.16	0.51	1.33
August	2006	0.17	0.02	0.03	0.02	0.03	0.01
Total		**6.03**	**8.33**	**8.90**	**7.74**	**8.62**	**11.08**