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Evapotranspiration of mixed shrub communities in phreatophytic zones of the Great Basin region of Nevada (USA)

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ABSTRACT

In this study, evapotranspiration (ET) was estimated for three valleys (White River, Spring Valley and Snake Valley) in the Great Basin region of Nevada (USA) during a 3-year period. ET estimates were based on an energy balance approach using the eddy covariance (EC) method and were scaled to the basin level by developing empirical relationships between ET and remotely sensed spectral data (Landsat). Annual EC–ET values for the three basins and previously published values attained for the same valleys during the same time period were correlated to average normalized difference vegetation index (NDVI) values for the growing period. Resulting empirical relationships accounted for 97% ($p < 0{\cdot}001$) of the variation in the EC–ET estimate for the 10 May–5 September growing period, and 93% ($p < 0{\cdot}001$) of the variation in the EC–ET estimates based on measured or projected yearly ET totals.

Variations in yearly ET estimates at the different shrubland sites ranged from 20 to 50 cm during the two dry years (2006 and 2007, not including the irrigated site). Winter precipitation was shown to be a significant driving force in the physiological response of the plants and the yearly ET totals. In the case of White River Valley, the ratio of winter precipitation to reference evapotranspiration (ET_{ref}) declined from 79 to 11% over the 3-year monitoring period. Overall, ET rates in 2007 (May–Sept.) were highly correlated with the percentage cover of greasewood at the monitoring sites ($R^2 = 0{\cdot}96^{***}$), regardless of the depth to groundwater. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS remote sensing; precipitation; groundwater; plant water status

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INTRODUCTION

Population growth and an extended drought have placed increasing pressures on available water resources in the arid west of the USA. Communities like Las Vegas, Nevada (USA) have looked to groundwater in remote basins of central Nevada to supplement existing resources. Nevada is situated in the Basin and Range physiographic province, where the majority of Nevada's landscape is covered by a series of basins separated by mountain ranges. These basins vary in size. Spring Valley, White River Valley and Snake Valley are all considered large basins, each estimated at more than 400 000 ha in size (similar to the Las Vegas Valley), located in east-central Nevada (USA).

Water withdrawals approved by the Nevada State Engineer must be linked to accurate water balances. In arid and semi-arid environments, evapotranspiration (ET) typically dominates the discharge component of the water balance (Nichols, 1994; Flerchinger *et al.*, 1996; Kurc and Small, 2004). In basins with limited water resources, vegetation will often reveal a close link between precipitation and ET (i.e. water loss through ET approaches precipitation rates). However, in basins that have a shallow and reliable groundwater source, ET and plant growth will not be constrained by limitations associated with low precipitation; here, ET rates may exceed precipitation rates because plants (facultative and obligate phreatophytes) are able to access the groundwater (Meinzer, 1927; Sorenson *et al.*, 1991; Scott *et al.*, 2004; Elmore *et al.*, 2006; Butler *et al.*, 2007).

Basins generally are unique with regard to soil type, groundwater depth, water availability, climate and plant communities. Generalizations often cannot be made, so detailed field studies are needed to better understand basin-specific water relationships (Glenn *et al.*, 2007). Plant density and ET rates in arid basins of western USA vary with growing conditions, typically leading to unique ET processes that occur in both space and time (Malek *et al.*, 1997; Loik *et al.*, 2004; Scott *et al.*, 2004; El Maayar and Chen, 2006; Steinwand *et al.*, 2006; Glenn *et al.*, 2007; Moreo *et al.*, 2007). Although several plant species found in the basins of Spring Valley, White River Valley and Snake Valley are known to be phreatophytes, the extent to which these species meet plant water requirements from groundwater sources is unknown. Nonetheless, the extent to which plants

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Table I. Spring Valley, White River Valley and Snake Valley site locations in east-central Nevada, USA.

Site	Vegetation classification	GPS Location		Basin	Elevation (m)	Data collection
		Northing (Y)	Easting (X)			
SV1	Low-density mixed shrubland	4 294 918.624	719 919.557	Spring Valley	1 761·64	2005, 2006, 2007
SV2a	High-density shrubland	4 351 204.381	720 176.620	Spring Valley	1 679·00	2005
SV2b	Irrigated pasture/grassland	4 360 828.725	716 742.825	Spring Valley	1 705·47	2007
SV3	Moderate-density mixed shrubland	4 375 911.750	715 856.657	Spring Valley	1 711·36	2005, 2007
WRV1	High-density mixed shrubland	4 253 556.677	670 229.512	White River Valley	1 576·30	2005
WRV2	Moderate-density mixed shrubland	4 277 444.669	665 016.698	White River Valley	1 617·84	2005, 2006, 2007
WRV3	Moderate-density mixed shrubland	4 301 044.414	668 299.941	White River Valley	1 661·35	2005
SNK1	High-density stand of greasewood	4 287 266.191	753 181.613	Snake Valley	1 684·87	2007
SNK2	Low-density stand of greasewood	4 325 089.731	754 600.619	Snake Valley	1 564·32	2007

either remain closely coupled to, or become decoupled from groundwater sources is typically revealed during peak environmental demand periods (Horton *et al*., 2001; Cooper *et al*., 2006).

The goal of this research was to assess basin level ET in multiple basins over multiple years, a critical component for basin level water balance closure. ET estimated at the canopy level using an energy balance approach was scaled up using remote sensing technology which was supported by canopy area measurements, reference evapotranspiration (ET_{ref}) and groundwater depth assessments.

MATERIAL AND METHODS

ET measurements

In July 2004, we initiated a long-term assessment of ET at multiple sites in east-central Nevada (Table I). Three sites each were selected in White River and Spring Valley, in which ET measurements (described in the following text) were acquired for 3- to 4-week periods in 2005, rotating from site to site simultaneously in each basin. In 2006, we selected the central site in White River Valley (WRV2) and the southern site in Spring Valley (SV1) for continuous monitoring over a 12-month period. We continued monitoring these two sites in 2007 and added four additional sites (two in Spring Valley, SV2b and SV3, and two in Snake Valley, SNK1 and SNK2). The 2007 data collection started in early May and ended in early September. All sites were selected based on (1) location on valley floors within designated phreatophytic zones with extensive fetch, measured in km; (2) representation of shrub plant communities in the basin (Table II), with the exception of an irrigated pasture grassland site in 2007 in Spring Valley (SV2b) and (3) achievement of a range in total vegetative cover and in particular a range in percentage cover of greasewood (*Sarcobatus vermiculatus*), a known deep rooted phreatophyte (Robinson, 1958). The phreatophytic zone was defined based on field surveys that included information on the presence of phreatophytes, elevational change and known depths to groundwater. The final area was designated based on converging field assessments with Landsat imagery during active growing periods.

Species composition, average canopy height and percentage cover at each site were evaluated by identifying species and estimating canopy cover of each plant (using the equation for an ellipsoid) in a 25 × 25 m plot (Table II). Site descriptions also included soil textural classification for surface soils (Table I).

Depth to ground water was periodically monitored in 2005 using a Solinst water level probe lowered in a non-pumping irrigation well at WRV3 and at a 5-m monitoring well at SV2a (first location). In May 2006, two monitoring wells were installed to a depth of 24·4 m, one each at WRV2 and SV1. In early spring of 2007, three additional wells were installed to a depth of 12·2 m, one each at SV3, SNK1 and SNK2. Monitoring wells were constructed using plastic pipe (5 cm inside diameter), with a screened section (0·5 mm openings) of 3 m length that was positioned to straddle the existing water table. Wells were backfilled with a sand pack from the base of the screen to approximately 60 cm above the top of the screen. Bentonite and neat cement were used to seal the well to ground surface.

All monitoring wells installed in 2006 and 2007 were equipped with HOBO ground water level sensor/data loggers (Onset, Pocasset, MA). The first monitoring wells were installed deeper because of concern over the impact proposed groundwater pumping might have on water table decline. As the later wells were installed

Table II. Species present at each site, percentage greasewood cover, total percentage vegetative cover and soil texture classification for Spring Valley, White River Valley and Snake Valley sites (25 × 25 m).

Site	Species	Scientific name	Percentage greasewood cover	Total percentage vegetative cover	Soil texture classification (0–20 cm)
SV1	Greasewood	*Sarcobatus vermiculatus*	3·2	27	Loamy sand
SV1	Sagebrush	*Artemisia tridentata*			
SV1	Rabbitbrush	*Chrysothamnus nauseosus*			
SV1	Shadscale	*Atriplex confertifolia*			
SV1	Annuals				
SV2a	Greasewood	*Sarcobatus vermiculatus*	13	62·1	Silty clay loam
SV2a	Rabbitbrush	*Chrysothamnus nauseosus*			
SV2a	Mixed grass	*Distichlis spicata, Spartina gracilis, Juncus balticus*			
SV2b	Pasture/Grassland	*Phleum pratense, Festuca pratensis, Juncus balticus, Plantago major*		100	Loam
SV3	Greasewood	*Sarcobatus vermiculatus*	21·8	32	Silty clay
SV3	Rabbitbrush	*Chrysothamnus nauseosus*			
SV3	Shadscale	*Atriplex confertifolia*			
SV3	Pickleweed	*Salicornia europeae*			
WRV1	Greasewood	*Sarcobatus vermiculatus*	50·1	62	Clay loam
WRV1	Sagebrush	*Artemisia tridentata*			
WRV1	Annuals				
WRV2	Greasewood	*Sarcobatus vermiculatus*	20·3	55	Loam
WRV2	Sagebrush	*Artemisia tridentata*			
WRV2	Rabbitbrush	*Chrysothamnus nauseosus*			
WRV2	Shadscale	*Atriplex confertifolia*			
WRV3	Greasewood	*Sarcobatus vermiculatus*	28·1	42	Loam
WRV3	Sagebrush	*Artemisia tridentata*			
WRV3	Rabbitbrush	*Chrysothamnus nauseosus*			
WRV3	Shadscale	*Atriplex confertifolia*			
WRV3	Cactus				
SNK1	Greasewood	*Sarcobatus vermiculatus*	52·5	62·4	Loam
SNK1	Sagebrush	*Artemisia tridentata*			
SNK1	Shadscale	*Atriplex confertifolia*			
SNK1	Annuals				
SNK2	Greasewood	*Sarcobatus vermiculatus*	13	13	Clay
SNK2	Sagebrush	*Artemisia tridentata*			
SNK2	Rabbitbrush	*Chrysothamnus nauseosus*			
SNK2	Shadscale	*Atriplex confertifolia*			
SNK2	Saltlover	*Halogeton glomeratus*			
SNK2	Annuals	—	—	—	—

at far greater distances from the proposed pumping area, the decision was made to place them at a shallower depth. Automated transducer measurements were converted to water depth measurements using HOBO software (HOBOware Pro VS 2·3·1, 2007). Absolute pressure was compensated for changes in weather and altitude using barometric pressure readings, obtained from barometric pressure sensors mounted on nearby weather stations.

An automated weather station was initially located at SV2a and WRV2 in 2004. The weather stations (Campbell Scientific, Logan UT) were equipped with sensors to measure wind speed, temperature, relative humidity, solar radiation and barometric pressure. Precipitation was measured with a tipping bucket (152·4 mm orifice, 1·5 m height) and a standard bulk rain and snow gage (200 mm orifice, 1·0 m height) installed adjacent to all weather stations. Sensors were installed at a 2 m height. Hourly data were incorporated into the Penman–Monteith equation to predict ET_{ref}—grass. In November 2005, we relocated the weather station in Spring Valley to SV1, whereas in White River Valley, the weather station remained at WRV2. In 2007, we added four additional weather stations, such that all locations had automated weather stations.

Extensive plant measurements were taken at each site over the 3-year period. However, in this manuscript we report only on the mid-day leaf xylem water potential data, assessed with a Scholander pressure chamber (Soil Moisture Corp., Santa Barbara, CA). The sites were approximately 483 km from the University, making predawn measurements a logistical problem; thus we focused on mid-day measurements confined to a period between 1130 and 1330 h.

To assess ET at the canopy level, we used an energy balance approach. Eddy covariance (EC) flux systems (Campbell Scientific, Logan UT) were set up on towers in selected areas that met fetch requirements, and had minimal obstructions such as hills, stream beds or depressions in all directions as delineated by field surveys and satellite observations. The systems were initially set up at SV2a and WRV2 (the central locations in Spring and White River Valleys), but during early spring 2005, we began to rotate the systems from one site to another approximately every 3–4weeks, leaving all soil-based sensors in place at each site (soil heat flux plates, soil temperature probes and soil water content reflectometers). Energy and H_2O fluxes were measured with the EC systems as described by Goulden *et al.* (1996). Briefly, fluxes of H_2O were measured using a 3-D sonic anemometer (CSAT-3, Campbell Scientific Inc., Logan, UT, USA) and an open-path infrared gas analyser (IRGA, Li-Cor 7500, Li-Cor Inc, Lincoln NE, USA). Sensors on the EC tower were placed 1 m above the plant canopy, except for the irrigated pasture/grassland site, where sensors were placed 1·55 m above the canopy. The total horizontal sensor separation between the sonic anemometer and Li-Cor 7500 for the 2004 through 2006 data series was set at 0·18 m (0·10 m longitudinal and 0·15 m lateral) with no vertical sensor separation. Horizontal sensor separation beginning in 2007 was kept as close to zero as possible by placing the IRGA sensor head directly below the sonic anemometer sensor path (Kristensen *et al.*, 1997; Lee *et al.*, 2004; Ivans S. 2007, personal communication.). This configuration had the added effect of reducing flux loss and reliance on sensor separation correction routines (Kristensen *et al.*, 1997). Vertical sensor separation was set at 0·26 m (±2 cm) for all sites with the exception of 0·19 m for the irrigated pasture/grassland site. Raw 10 Hz binary data and online 30-min computed fluxes with a correction for density effects (Webb *et al.*, 1980), were collected from CR5000 data loggers (Campbell Scientific, Logan, UT, USA) for every 3 weeks, and were later post-processed using the EdiRe Programme (Version 1·4·3·1184; Clement and Moncreif, 2007) (Table III).

To achieve a zero mean vertical velocity from the sonic anemometer, coordinate rotations were applied following the planar fit method (Wilczak *et al.*, 2001). New coordinate rotations were applied whenever the sonic anemometer was moved, which occurred twice per year to adjust for the change in prevailing wind patterns (early spring—south facing and early fall—north facing). Coordinate coefficients b_0, b_1 and b_2 were calculated from at least 2 weeks of sonic data (Clement R. 2007, personal communication) using the MATLAB software (Math Works, 2007) source code from Lee *et al.* (2004).

Additional quality assurance/quality control (QA/QC) procedures were applied following the methods of Foken and Wichura (1996). Sensor performance, stationarity of covariances and turbulence quality flags were used to identify data for manual graphical inspection (Table III). These QA/QC tests removed between 2·3 and 10·3%, 4·2 and 6·4% and 1·7 and 4·4% of the 2005, 2006 and 2007 flux data, respectively.

Table III. Post-processing corrections of 10 Hz data series implemented in the EdiRe programme and quality control and assurance tests for EdiRe 30-min flux output data series.

EdiRe post-processing method	Method implementation details
Despiking (Højstrup, 1993)	Spike detection of six standard deviations, window of four and a consistency of 30% (Xu, 2004; Clement R. 2007, personal communication).
Density corrections for H_2O flux	Webb *et al.* (1980) and Leuning (2007)
Frequency response corrections	Massman (2000, 2001)
A perfect first-order scalar sensor timing adjustment.	Time adjustment of 0·032 s for Li-Cor 7500, (Wohlfahrt G. 2007, personal communication).
Iteration of interdependent variables	Two-step iterations to compensate for interdependence between momentum and frequency response, (Wohlfahrt G. 2007, personal communication).
Buoyance flux conversion to sensible heat flux	Schotanus *et al.* (1983)
Cross wind correction	Lui *et al.* (2001)
EdiRe QA/QC method	QA/QC implementation
The integral turbulence test—ITT	Kaimal and Finnigan (1994); Lee *et al.* (2004), and Arya (2001)
The stationarity test (ST)	Foken and Wichura (1996); Lee *et al.* (2004)
Despiker 1%, kurtosis and skewness tests	Vickers and Mahrt (1997)
The automatic gain control test (AGC, percentage blockage of viewing window >70)	(Wohlfahrt G. 2007, personal communication)

Missing data associated with loss of power, sensor malfunction or inclement weather were gap filled. The method of substitution for flux data was based on the number of missing values. When the number of missing values was small (<4 h), a linear fit was used to estimate values through interpolation. For longer gaps (>4 h), daily averages for the time period preceding and following the gap were used. This protocol was consistent with that identified by AMERIFLUX (2008) as a standard data filling scheme (Falge *et al.* 2001a,b; Huxman T. 2005, personal communication).

EC fluxes were calculated as $F = \rho < w'C' >$, where F represents the flux of sensible heat or latent heat, w is the vertical wind velocity, C is the temperature or water vapor mixing ratio, <>represents Reynolds averaging, the primes represent deviations from the Reynolds average and ρ is air density. Energy balance closure was estimated during the growing period by dividing latent heat (LE) plus sensible heat (H) by the available energy [net radiation (R_n) minus soil heat flux (G)]; thus $(LE + H)/(R_n - G) = 1{\cdot}00$ (100%) for perfect energy balance closure. Energy closures ranged from a low of 84% to a high of 104%, with 11 of the 14 site by year closures in the range of 84–99%. These closures were similar to those reported by Moreo *et al.* (2007) for the same three valleys.

Remote sensing measurements

Terrain-corrected, Landsat 5 Thematic Mapper (TM) images were acquired for the 2005–2007 growing seasons (EROS, 2006). While all images listed below were examined for developing an empirical relationship between ET and normalized difference vegetation index (NDVI), a few images were excluded from the calculation of basin-wide ET because of significant cloud cover.

- 2005: 4/14, 5/25, 6/01, 6/26, 7/19, 8/29, 9/5 and 9/14
- 2006: 5/12, 5/19, 6/4, 6/20, 6/29, 7/15, 8/7, 8/16, 9/1 and 9/17
- 2007: 4/13, 4/29, 5/15, 5/31, 6/16, 7/2, 7/18, 8/19 and 9/20

The images were atmospherically corrected, normalized and converted to ground reflectance values using the empirical line method (Farrand *et al.*, 1994; Smith and Milton, 1999) and field spectral measurements (FieldSpec Pro, Analytical Spectral Devices, Inc., Boulder, CO) acquired on 20 June 2006 (during a Landsat overpass) for four light to dark soil areas with minimum vegetation. All images were atmospherically corrected with the single-date field spectra to provide simultaneous image normalization with a minimum number of processing steps.

While a suite of vegetation indices were initially examined, e.g. simple ratio, NDVI, soil adjusted vegetation index (SAVI), modified SAVI, green NDVI and enhanced vegetation index (EVI), results of regression analyses (higher R^2 values) and historical use in the area led us to select NDVI.

$\text{NDVI} = (R_{\text{NIR}} - R_{\text{RED}})/(R_{\text{NIR}} + R_{\text{RED}})$ (Rouse *et al.*, 1974), where R_{NIR} is the amount of electromagnetic energy reflected from the near infrared portion of the spectrum and R_{RED} is the amount of red reflectance.

A survey grade Global Positioning System (GPS) was used to acquire the coordinates for each EC tower location. These coordinates were then used to extract three sets of NDVI values for each tower site from the Landsat image data. The three sets of NDVI values included the single pixel value for the EC tower location, the average for a 5 × 5 pixel square centred on the EC tower and the average for a 5 × 5 pixel square with the EC tower location centred along the northern perimeter of the square. These three sets of numbers were regressed against the EC-measured ET data to develop an empirical relationship that would enable estimates of total ET within each basin's phreatophytic zone. The single pixel correlations had R^2 values equal to or greater than the multi-pixel approach at all sites during the entire monitoring period. As such only the single pixel approach is reported.

To calculate the total annual ET for each valley's phreatophytic zone, areas within the Landsat images that corresponded to clouds/cloud shadows, open water and any negative ET pixels were first defined by thresholding various image bands including the blue band (TM 1), the NDVI band and the ET band. Negative ET pixels result from application of the regression equation to NDVI pixels with a value <0. The negative ET (and NDVI) pixels were found to correspond primarily to moist soil and water.

Only images with cloud cover <30% were used for basin ET calculations. To provide an ET estimate for areas covered by clouds and shadows, cloud-free images were used to estimate ET for off-scene and cloud areas. For the single-date ET images, cloud areas were superimposed on cloud-free images to calculate an average percentage of ET for the cloud areas versus the rest of the basin. This percentage was then applied to estimate a total basin ET value for images with clouds or portions of the basin that were not within the image scene. For the growing season, average NDVI calculation for the cloud and off-scene (missing) areas actually had to be backfilled. To do this, the cloud or missing areas were superimposed on all cloud-free and complete basin image dates. Averages for these areas were calculated and then used to backfill the cloud and missing areas to allow calculation of an average growing season NDVI image, which in turn was used to calculate a total annual ET image. ET values of all pixels within the phreatophyte zone of each valley were then summed excluding open water and any negative ET pixels for the individual date images. Only the open water areas had to be excluded from the annual ET image generated from the average growing season NDVI image. (Note: A large dry lake bed located in the northern most part of Spring Valley, called the Yelland Playa, was excluded from all Spring Valley ET image summations.)

The ENvironment for Visualizing Images (ENVI) software package (ITT™ Visual Information Solutions, Boulder, CO) was used for all image and data analyses.

Based on the data obtained during different time periods at different sites over a 3-year period, we developed empirical relationships between ET (LE converted to mm evaporation) and NDVI obtained from Landsat data to estimate total ET, as was demonstrated by Nagler *et al.* (2005). ET–NDVI correlations were assessed based on daily paired data from years 2005–2007 and on total annual ET estimates from years 2006–2007, and average growing period NDVI values from years 2006–2007.

Data analysis

Data were analysed using descriptive analyses, analysis of variance (ANOVA) and/or linear and multiple regression analyses. Multiple regressions were performed in a backward stepwise manner, with deletion of terms occurring when p values for the t-test exceeded 0·05. To eliminate the possibility of co-correlation, parameters were

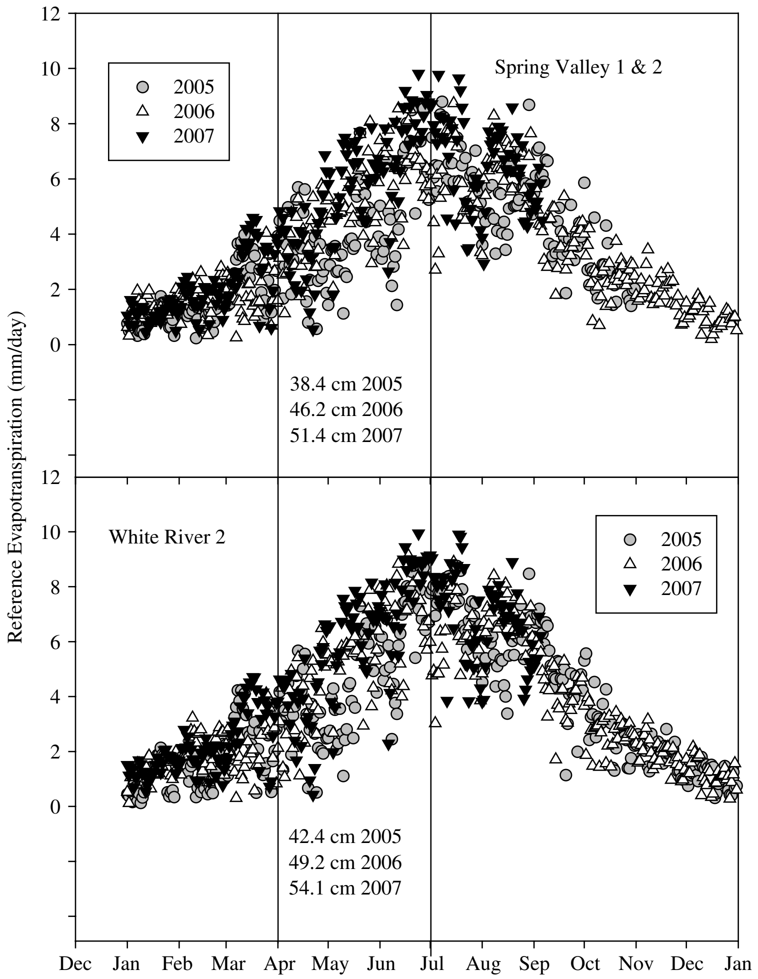

Figure 1. ET$_{\text{ref}}$ for SV2/SV1 and WRV2 in 2005, 2006 and 2007. ET$_{\text{ref}}$ totals are included for the April, May and June period in each year.

Table IV. ET$_{\text{ref}}$, ET/ET$_{\text{ref}}$, ET actual, precipitation and ET minus precipitation by year for the two long-term monitoring sites.

	2005		2006					2007 (1 January–5 September)	
	ET$_{\text{ref}}$ (cm)	Precipitation (cm)	ET$_{\text{ref}}$ (cm)	ET (cm)	ET/ET$_{\text{ref}}$	Precipitation (cm)	ET−Precipitation (cm)	ET$_{\text{ref}}$ (cm)	Precipitation (cm)
SV1	118·92[a]	30·65[a]	127·11[b]	24·04[b]	0·19	15·55[b]	8·49[b]	112·00[b]	8·71[b]
WRV2	131·05	26·62	136·16	42·43	0·31	26·54	15·89	118·89	10·51

[a] SV2 and SV1 sites combined (10 months SV2, 2 months SV1).
[b] SV1 only

included only if variance inflation factors (VIF) were <2 and the sum total was <10. If the accepted VIF were exceeded, parameters were eliminated and regression analyses were rerun. All statistical analyses were performed using SigmaStat Software (Systat Software Inc., Point Richmond, CA).

RESULTS

Reference evapotranspiration

ET$_{\text{ref}}$ followed a sinusoidal pattern in all basins, peaking during the month of July (Figure 1). In Spring Valley and White River Valley, ET$_{\text{ref}}$ ranged from values >9 mm to values $<0{\cdot}10$ mm/day, whereas the highest ET$_{\text{ref}}$ estimated during the entire study was 10·5 mm occurring in Snake Valley during 2007. Table IV reports the annual ET$_{\text{ref}}$ totals for the long-term monitoring site located in Spring Valley and White River Valley. Results show that ET$_{\text{ref}}$ totals were higher in White River Valley than in Spring Valley, and that both valleys revealed an increasing trend of ET$_{\text{ref}}$ when the data were compared between 2005, 2006 and 2007 (Figure 1). The environmental demand increased each year during the most active growing period (April–June) in both Spring Valley and White River Valley (Figure 1). One-way repeated measures ANOVA indicated a significant difference ($p < 0{\cdot}001$) in the mean ET$_{\text{ref}}$ values during

Table V. ET_{ref}, ET actual, precipitation, ET minus precipitation and groundwater depth (average ± standard deviation) for the period 10 May–5 September 2006 and 2007 along with the projected yearly ET totals in 2007.

	ET_{ref} (cm)	ET (cm)	ET/ET_{ref}	Precipitation (cm)	ET minus precipitation (cm)	ET year (cm)	Groundwater depth (m^b
SV1-2006	71·43	11·18	0·16	4·85	6·33	24·04^a	4·64 ± 0·01
WRV2-2006	76·60	18·60	0·24	7·39	11·21	42·43^a	5·82 ± 0·03
SV1-2007	79·53	9·04	0·11	3·48	5·56	20·24	4·66 ± 0·05
SV2b-2007	73·60	71·56	0·97	3·79	67·77	124·97	—
SV3-2007	77·85	14·52	0·19	3·10	11·42	27·24	5·28 ± 0·04
WRV2-2007	83·53	10·60	0·13	6·13	4·49	27·48	5·78 ± 0·04
SNK1-2007	84·82	30·57	0·36	3·66	26·91	49·88	5·00 ± 0·04
SNK2-2007	85·62	9·94	0·12	1·19	8·75	21·37	9·31 ± 0·04

[a] Actual yearly ET totals - not projected.

[b] September–December 2006, January–September 2007

the growing period in Spring Valley when all 3 years were contrasted. However, in White River Valley ET_{ref} during the growing period was different when 2005 and 2006 were contrasted with 2007 but 2005 and 2006 were not significantly different. ET_{ref} increased by 11·7 cm (28%) between 2005 and 2007 in White River Valley, while it increased 13·0 cm (34%) during the same time interval in Spring Valley.

Precipitation

Precipitation totals for each year are reported in Table IV, which indicated similar values for 2005 and 2006 in White River Valley (26·6 vs 26·5 cm) but a lower value in Spring Valley in 2006 (30·7 vs 15·6 cm). Although 2007 data were incomplete (Table V), precipitation totals from 1 January to 5 September (SV1 and WRV2) were significantly lower ($p < 0{\cdot}05$) in 2007 when compared to the other years. No significant differences ($p > 0{\cdot}05$) in rainfall were revealed at the six sites during the 10 May–5 September monitoring period in 2007. Total winter precipitation (i.e. from 1 November to 31 March) revealed a decreasing trend over the 3-year period. In White River Valley (WRV2), the winter precipitation total decreased from 17·45 cm in 2005 to 10·26 cm in 2006 to 2·99 cm in 2007 (83% decline). In Spring Valley (SV1 and SV2a), precipitation decreased from 14·2 cm in 2005 to 6·6 cm in 2006 to 4·2 cm in 2007 (70% decline). However, it should be noted that the total precipitation values in Spring Valley are somewhat complicated by the fact that the station was moved to a new location in 2006 (SV1 approximately 56 km due south of SV2a).

The impact of precipitation was assessed by evaluating the ratio of precipitation to ET_{ref} for both the growing and non-growing periods (Figure 2), with the assumption that higher precipitation associated with lower ET_{ref} would have a higher probability of recharging the active root zones. We also chose this ratio as it reflects a simple relationship between supply and demand that can be generated at most weather station locations throughout western USA. In the case of the long-term monitoring site in White River Valley (WRV2), the ratio declined from 79% to 40% to 11% when the 2005, 2006 and 2007 data sets were compared. In Spring Valley (SV2/SV1) the ratio declined from 68% to 28% to 16% during this same 3-year period. A simple t-test comparing the changes in the ratio of precipitation of ET_{ref} over the 3-year period indicated no significant differences between the two valleys. The results indicated that 2005 had higher winter precipitation, which was ideal for initiating new spring growth and supporting higher ET rates.

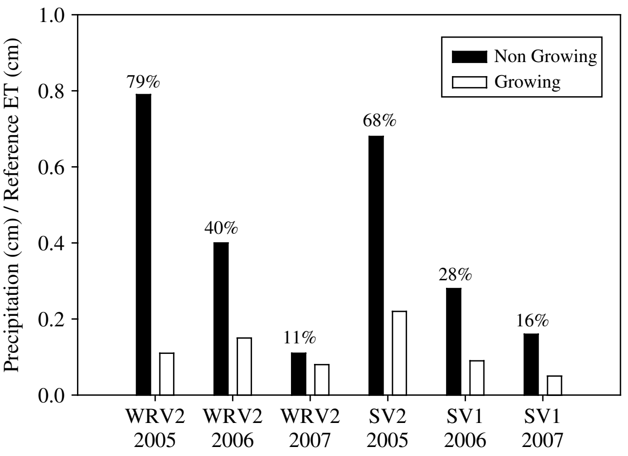

Figure 2. Ratio of precipitaion to ET_{ref} during the growing and non-growing periods at WRV2, and SV2/SV1 during 2005, 2006 and 2007, where the growing period is defined as 1 April–31 October and the non-growing period as 1 November–31March.

Depth to groundwater

Depth to groundwater for all sites is reported in Table V. Groundwater depth for the two sites with the longest monitoring period is plotted with time in Figure 3. In both cases, water table depths rose during the winter–spring recharge period but declined by late May and continued to decline throughout the remaining summer and early fall period. Although this response was most likely influenced by regional groundwater fluctuations, the groundwater decline at both locations was also associated with increasing environmental demand and full canopy development. We speculate that during this drier summer period, soil moisture depletion occurred, which led to increased reliance on groundwater by early summer. All of the 2007 ET monitoring sites which possessed monitoring wells (i.e. all except SV2b) revealed water table depths between

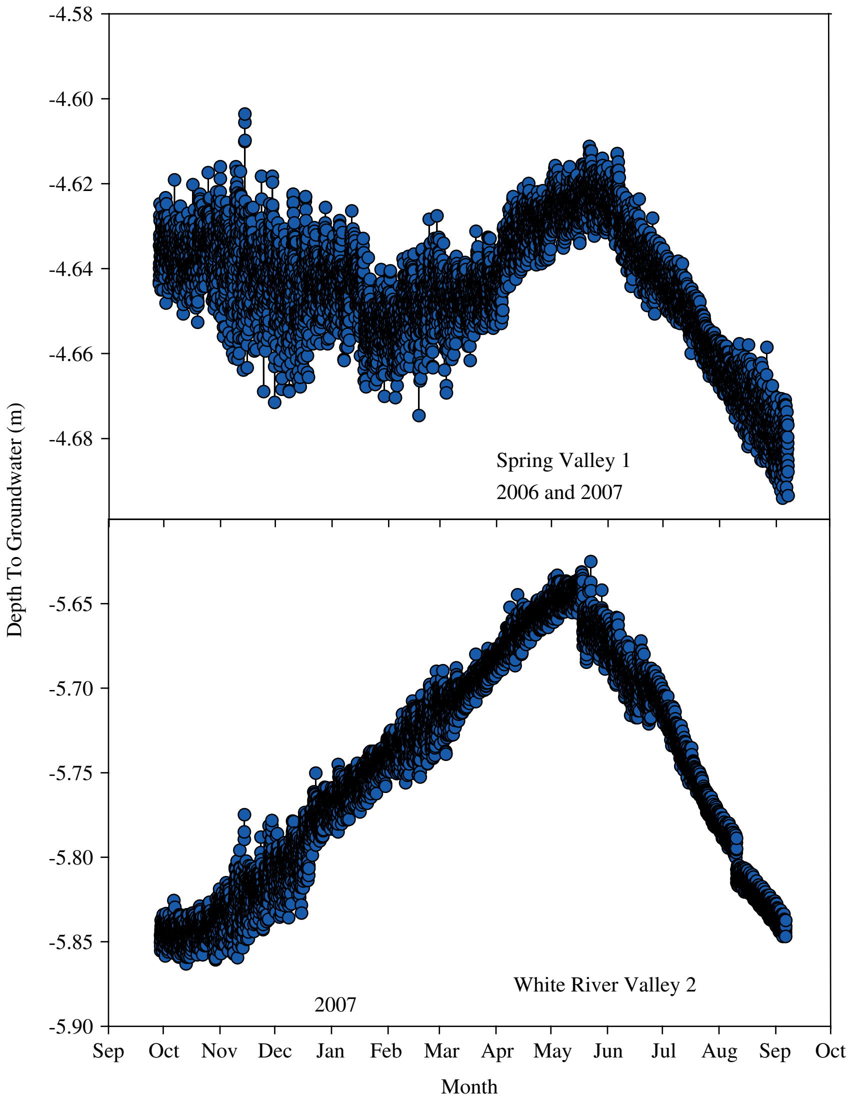

Figure 3. Depth to groundwater monitored over a 12-month period at Spring Valley 1 and White River Valley 2.

4·5 and 5·8 m. The one exception occurred at the SNK2 site, where the average groundwater depth was 9·3 m. Continuous depth readings for the five sites monitored in 2007 revealed a gentle linear decline over time (depth as a function of time, $R^2 = 0{\cdot}93^{***}$–$0{\cdot}98^{***}$). One-way ANOVA (repeated measures) revealed that the median groundwater depth values for all sites during 2007 were significantly different at the $p < 0{\cdot}001$ level. Although depth to groundwater appeared to change very little during 2007, daily oscillations were observed at all sites. For example, when individual weeks were evaluated more closely over the summer period at the SNK1 site, a decline of about 6 cm occurred each month with daily oscillations of about ±3 cm occurring by late August. At SV1, the groundwater depth also declined, but only on the order of 3 cm/month, with minor daily oscillations.

In the case of the two Snake Valley sites (SNK1 and SNK2), the water table decline was greater at SNK1 than at SNK2 in May/June, but by early summer the declines were approximately equal (Figure 4). The total decline was approximately 18 cm at both sites; however, the percentage cover at SNK2 was approximately five times lower than that observed at SNK1. Inferring groundwater extraction by plants based on these groundwater changes will require information not only on daily changes in groundwater depth and ET rates but also information on soil water in the vadose zone and the specific yield of the aquifer. It was interesting to note that at SNK1, the greatest daily oscillations occurred late in the summer associated with declining ET rates (although ET spikes were observed associated with rainfall events), suggesting that the response was most likely linked to a greater dependence of the phreatophytes on groundwater versus soil moisture, although this response may also have been magnified because of a slower recharge rate. At SNK2, ET changed little over the monitoring period, yet strong daily oscillations in groundwater depth were observed by late summer, suggesting that greasewood at this site was able to maintain a low but somewhat constant ET by increasing groundwater extraction during this late summer period. Future research will need to further

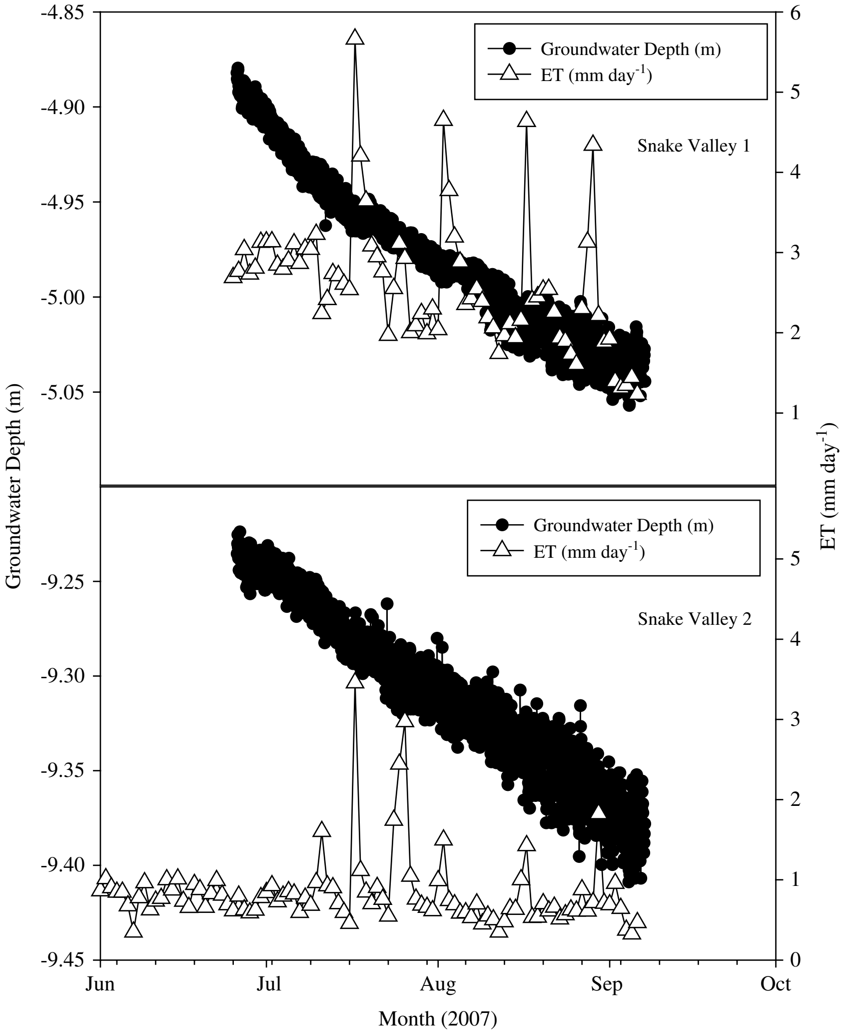

Figure 4. Depth to groundwater and daily ET during summer months in 2007 at SNK 1 and SNK2.

substantiate the link between ET, soil moisture depletion and increased groundwater oscillations.

Plant water status

Mid-day leaf xylem water potential (ψ_L, MPa) was assessed on a monthly basis during the growing season in both Spring Valley and White River Valley during 2005 and 2006, but only in Spring Valley in 2007. Greasewood, big sage and rabbitbrush ψ_L declined during the growing season in each year in both the valleys. One-way ANOVAs (repeated measures) contrasting the wet year (2005) with a dry year (Spring Valley 2006 or 2007, White River Valley 2006) indicated significant differences in the mean values among designated years ($p < 0{\cdot}001$). Mean ψ_L values for greasewood in Spring Valley were −3·27 MPa in 2005 versus −3·95 MPa in 2007, big sage −2·62 MPa in 2005 versus −3·80 MPa in 2007 and rabbitbrush −2·47 MPa in 2005 versus −2·97 MPa in 2007 (Figure 5). In White River Valley, greasewood mean ψ_L values were −3·13 MPa in 2005 versus −4·45 MPa in 2006, big sage −2·68 MPa in 2005 versus −3·44 MPa in 2006 and rabbitbrush −2·06 MPa in 2005 versus −3·01 MPa in 2006. Lower ψ_L values associated with the drier years compared to the wetter year were noted even during the early spring period for all the three species in both valleys (shown only for Spring Valley in Figure 5), coinciding with the significantly lower winter precipitation. When comparing species within the same valley, in Spring Valley, rabbitbrush was found to have a significantly ($p < 0{\cdot}001$) more positive mean ψ_L than big sage or greasewood in both 2005 (−2·47 MPa vs −2·62 and −3·27 MPa, respectively) and 2007 (−2·97 MPa vs −3·8 and −3·95 MPa, respectively) but only more positive than greasewood (−2·99 MPa vs −3·91 MPa) in 2006, whereas in White River Valley, a significant difference in mean ψ_L values was observed only in 2006 between big sage (−3·44 MPa) and greasewwod (−4·45 MPa). Finally, when comparing mean ψ_L for the same species in both valleys in 2005 and 2006, no significant differences were noted.

Daily E T

In 2005, 2006 and 2007, daily ET values in excess of 3 mm/day occurred at all sites during some period of monitoring, with values exceeding 5 mm on certain days

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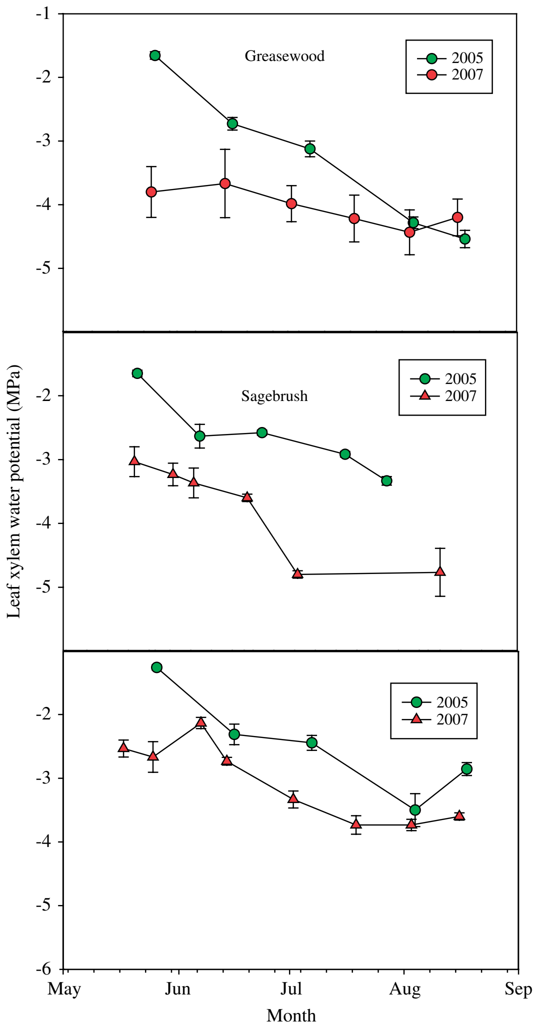

Figure 5. Leaf xylem water potential (MPa, mid day) as a function of time for greasewood, big sage and rabbitbrush in Spring Valley, contrasting the wetter 2005 year with the drier 2007 year.

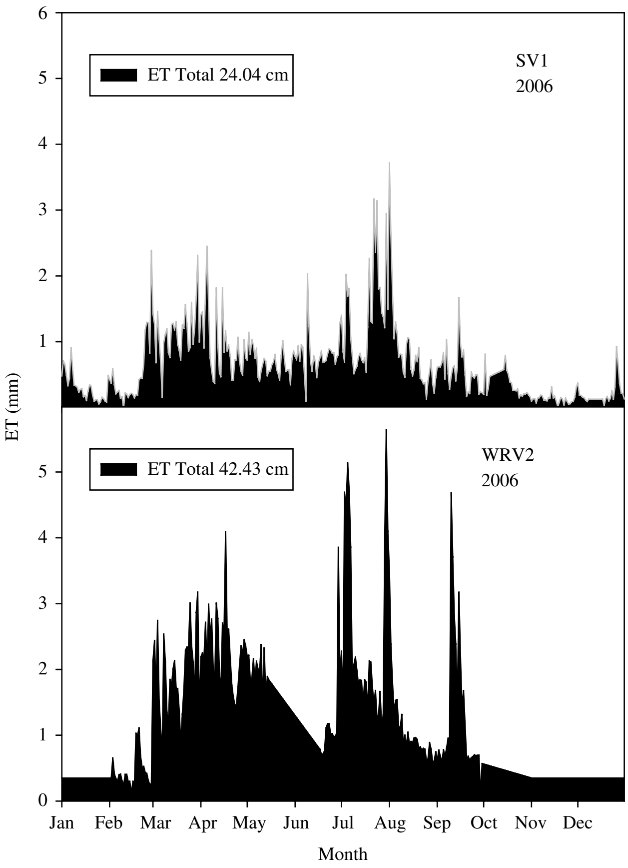

Figure 6. Daily ET for SV1 and WRV2 in 2006, with yearly totals.

at sites WRV1 (2005), WRV2 (2006), SV2 (2005) and SNK1 (2007). At SV2b (irrigated pasture/grassland site) in 2007, daily ET values exceeded 10 mm for a few days in mid June. Daily ET is plotted in Figure 6 as a function of time for SV1 and WRV2 in 2006. The majority of ET occurred during the period March–October, with total annual estimates of 24·0 cm at site SV1 compared to 42·4 cm at site WRV2 (equipment failure occurred during several periods, linear gap filling was selected because no correlations existed with ET_{ref} or other weather-based parameters). Significant spikes in ET at SV1 and WRV2 during the summer and fall period were associated with rainfall events. Although the water table was over 1 m deeper at WRV2 compared to SV1, higher ET totals were associated with higher vegetative cover (55 vs 27%) and especially higher greasewood cover (20 vs 3%)

Cumulative ET, ET_{ref}—Precipitation and ET/ET_{ref}

In arid environments, the difference between cumulative ET and cumulative precipitation can be used to assess possible linkages between plant community ET and groundwater extraction. In Tables IV and V, yearly cumulative ET, ET_{ref}, precipitation and ET minus precipitation are reported for all sites and years where such data were available. ET minus precipitation estimates for site WRV2 in 2006 was 15·9 cm compared to 8·5 cm for site SV1. Although both sites were coupled to groundwater as inferred by the ET minus precipitation estimates and the groundwater response noted in Figure 3, we believe the higher groundwater extraction estimated for WRV2 was directly linked to the significantly higher percentage greasewood in the plant community (Table II). For example, in 2007, ET totals from 10 May to 5 September was found to be highly correlated with greasewood percentage cover estimates [ET (cm) = $5{\cdot}04 + 0{\cdot}47$ (greasewood percentage cover), $R^2 = 0{\cdot}96$, p $<0{\cdot}01$, not including the pasture grassland site], whereas total percentage vegetative cover accounted for 82% of the variation in the ET total, suggesting a stronger linkage with greasewood which is a known phreatophyte. During this same time period, the ET minus precipitation totals ranged from 4 to 27 cm at the mixed shrubland sites (all sites except SV2b). These totals, however, did not include winter precipitation. At SV2b, ET minus precipitation was high (68 cm), reflecting the irrigation applied to the pasture grassland site and not groundwater extraction. However at SNK1, ET minus precipitation was almost 27 cm, or three times the amount measured at SNK2. A dense mono-specific stand of greasewood was found at SNK1, with groundwater at approximately 4·9 m, compared to a very sparsely vegetated greasewood plant community at

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SNK2, where average groundwater depth was measured at 9·3 m.

Ratios of ET to ET_{ref} are reported in Table IV based on 2006 data and in Table V for the 10 May–5 Septemebr growing period in 2006 and 2007. Ratios for the mixed shrubland sites ranged from 0·11 to 0·36, with the highest value associated with the highest greasewood percentage cover site (SNK 1). These ratios were significantly lower than the irrigated pasture grassland site which had a growing period ratio of 0·97. We were also able to compare three 40- to 42-day time periods during late spring to early summer in 2005 and 2007. At all three sites the ratios were significantly higher ($p < 0{\cdot}01$) during the wetter 2005 period compared to the drier 2007 period (WRV2; 0·39/2005 vs 0·14/2007, SV3; 0·33/2005 vs 0·16/2007 and SV1; 0·45/2005 vs 0·16/2007). Such ratios are used in irrigated agriculture but only under non-water stress conditions and only when conditions are reproducible relative to the conditions in which the ratios were originally generated. In the case of the irrigated pasture grassland site, ET tracked ET_{ref} in an almost constant 1 : 1 ratio. When higher amounts of moisture were available to plants, especially during the more active spring early summer period, elevated ET was demonstrated (2005 vs 2007) relative to ET_{ref}. The usefulness of such ratios in mixed shrubland sites will be linked to the site-specific areas and times, especially periods when precipitation and soil moisture are optimum such that plant stress is avoided. Applying such ratios under non-optimum conditions would be problematic, as one would have to apply ratios that had been generated under similar kinds of stress (matric vs osmotic), duration of stress and intensity of stress.

Estimating yearly ET based on growing period ET

In 2007, ET values were calculated from EC data from 10 May to 5 September at most sites. To estimate 12-month totals, we tested the approach of gap filling the November–January period with 0·35 mm/day and linear fitting between 1 February and 10 May and between 6 September and 1 November (transition periods). A value of 0·35 mm/day was selected based on existing winter values and validated with data reported by Moreo *et al.* (2007) collected in 2006 ($0 \cdot 29 \pm 0{\cdot}20$ mm/day). The linear fit was based on anchoring the ET with an average ET value from 10 May to 14 May and from 1 September to 5 September. When we used this approach for the complete 2006 SV1 ET data set, it resulted in an 8% underestimation of the actual ET total. We also used this approach with published data by Moreo *et al.* (2007) for the same valleys in 2006. At their shrubland sites, the 10 May—5 September time period represented, on average, 49% of the total ET estimate, which was the same for this study when the gap filling approach was used. The error associated with estimating ET using this approach with the United States Geologic Survey USGS 2006 shrubland sites was a 6·3% (±3·9) underestimation.

Table VI. ET–NDVI daily regression equations based on basins and year.

Basin	Year	Equation	R^2
SV	2005	$\text{ET} = -0{\cdot}008 + 22{\cdot}90\ \text{NDVI}$	$0{\cdot}79^{**}$
SV	2005 + 2006	$\text{ET} = -0{\cdot}11 + 22{\cdot}67\ \text{NDVI}$	$0{\cdot}79^{***}$
SV	2005 + 2006 + 2007	$\text{ET} = -0{\cdot}15 + 22{\cdot}11\ \text{NDVI}$	$0{\cdot}75^{***}$
WRV	2005	$\text{ET} = 0{\cdot}055 + 21{\cdot}12\ \text{NDVI}$	$0{\cdot}68^{**}$
WRV	2005 + 2006	$\text{ET} = -0{\cdot}99 + 25{\cdot}21\ \text{NDVI}$	$0{\cdot}61^{**}$
WRV	2005 + 2006 + 2007	$\text{ET} = -1{\cdot}26 + 26{\cdot}68\ \text{NDVI}$	$0{\cdot}67^{***}$
SNK	2007	$\text{ET} = -0{\cdot}15 + 14{\cdot}90\ \text{NDVI}$	$0{\cdot}81^{***}$
SV/WRV/SNK	2005 + 2006 + 2007	$\text{ET} = -0{\cdot}09 + 16{\cdot}95\ \text{NDVI}$	$0{\cdot}63^{***}$

*, ** and *** represent $p < 0{\cdot}05$, $p < 0{\cdot}01$ and $p < 0{\cdot}001$ level of significance

Development of the NDVI: ET empirical relationships

In 2005, NDVI–ET relationships were developed based on paired Landsat and daily ET estimates, excluding dates that occurred within a day of major precipitation events. This approach led to correlations in 2005 based on seven Landsat dates in Spring Valley and five Landsat dates in White River Valley. The R^2 value was higher for the Spring Valley data set than for the White River Valley data set (Table VI, $R^2 = 0{\cdot}79^{**}$ vs $0{\cdot}68^{**}$), with a slightly greater slope for Spring Valley (22·9 vs 21·1). Both data sets contained ET that ranged from ~1–5 mm/day. In 2006, we merged the 2005 data with the 2006 data in both valleys, and in 2007 we merged all 3 years of data. However, we also assessed the data for each year separately (Table V). In assessing the equations for the 2005 + 2006 data and the 2005 + 2006 + 2007 data, the correlations were strongly linked to the 2005 data set that anchored the equations. With the larger data sets, the R^2 values were slightly less than those obtained for the regression generated for the 2005 data set. Although the slopes were similar for all regression equations generated for Spring Valley, the slope increased significantly for the 2007 equation compared to the 2005 equation in White River Valley (21·1 vs 26·6). In Snake Valley, the regression equation was based solely on the 2007 data, and the R^2 value was slightly higher than for the other valleys ($R^2 = 0{\cdot}81^{***}$) with a significantly lower slope (14·90) than what was generated for other valleys and years. When all basins and years were merged, a lower R^2 value was obtained (Table VI), supporting the decision

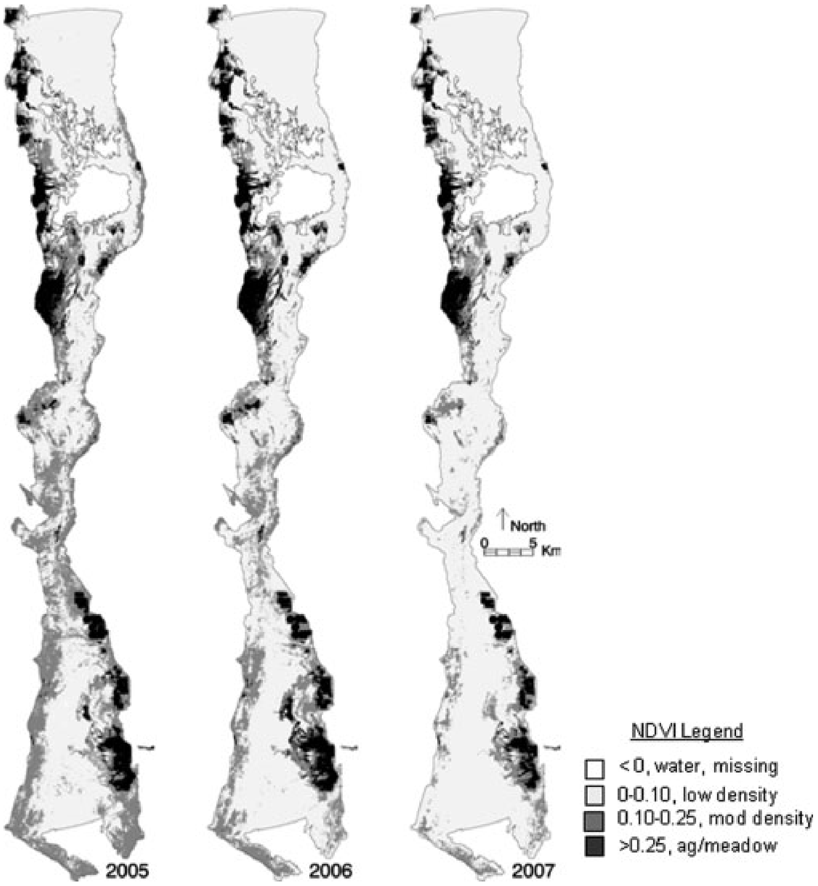

Figure 7. Average NDVI images for Spring Valley during the growing seasons of 2005, 2006 and 2007.

to evaluate the daily ET–NDVI data based on individual valleys and years.

In 2006 and 2007, we also generated equations based not just on single days, but on larger ET periods (10 May—5 September, and 12-month actual or predicted totals). For the ET–NDVI equations generated for the 10 May–5 September period, we included all six sites in 2007 and SV1 and WRV2 for 2006. Regression analysis was performed with the 2006 and 2007 average growing period NDVI values (Figure 7, coefficient of variation for NDVI in 2006; 26 ± 10%, 2007; 27 ± 8%) with corresponding annual and growing season measured ET for each tower location and each year. The data were fit to a curvilinear equation, anchored at the high end with data from site SV2b (irrigated pasture grassland site). However, when we added data for the same time periods from the USGS sites, the regression became linear with a coefficient of determination of $0{\cdot}97^{***}$ (Figure 8).

Regression equations were also developed based on the relationship between average NDVI values for the growing period versus the 12-month ET estimate, which was either measured (e.g. sites SV1 and WRV2 during 2006) or predicted based on the gap filling approach previously described. The correlation was highly significant ($R^2 = 0{\cdot}99^{***}$) and also fit the previously published USGS data (Figure 8, $R^2 = 0{\cdot}93^{***}$).

We recognize that the NDVI–ET relationships were influenced by the irrigated pasture grassland site with the majority of data associated with lower NDVI–ET values. However, even these lower values were structured in a highly linear fashion ($R^2 = 0{\cdot}89^{***}$ 10 May–5 September). We chose to incorporate the irrigated pasture grassland site because (1) it led to an increase in the R^2 value and (2) it allowed for the capture of higher NDVI areas that would otherwise be outside of the working range of the predictive equations generated.

The 2005 year was significantly wetter (Table IV) and less stressful for the plant communities in both Spring Valley and White River Valley compared to 2006 and 2007 (Figure 5). This led to the question: Could the average NDVI–ET approach for larger data sets also work for the 2005 data? To answer this question, ET data were summed at each site in 2005 for the various time periods, and compared to pooled data from the same time periods in 2006 and 2007. The regression equations generated for the 2006/2007 data were always highly correlated ($R^2 > 0{\cdot}90^{***}$). However, when we determined if the 2005 data points were adequately described by the 2006/2007 regression equation, the regression equation underpredicted the actual value at five out of the six sites (by 36, 52, 52, 37 and 43%). Only at site WRV2 for the summer period (19 July–18 August) did the equation overpredict the 2005 data (in this case by 70%). Such results confirmed that basin-wide ET estimates in 2005 based on using empirical relationships from the drier years would need to be increased by at least 25%.

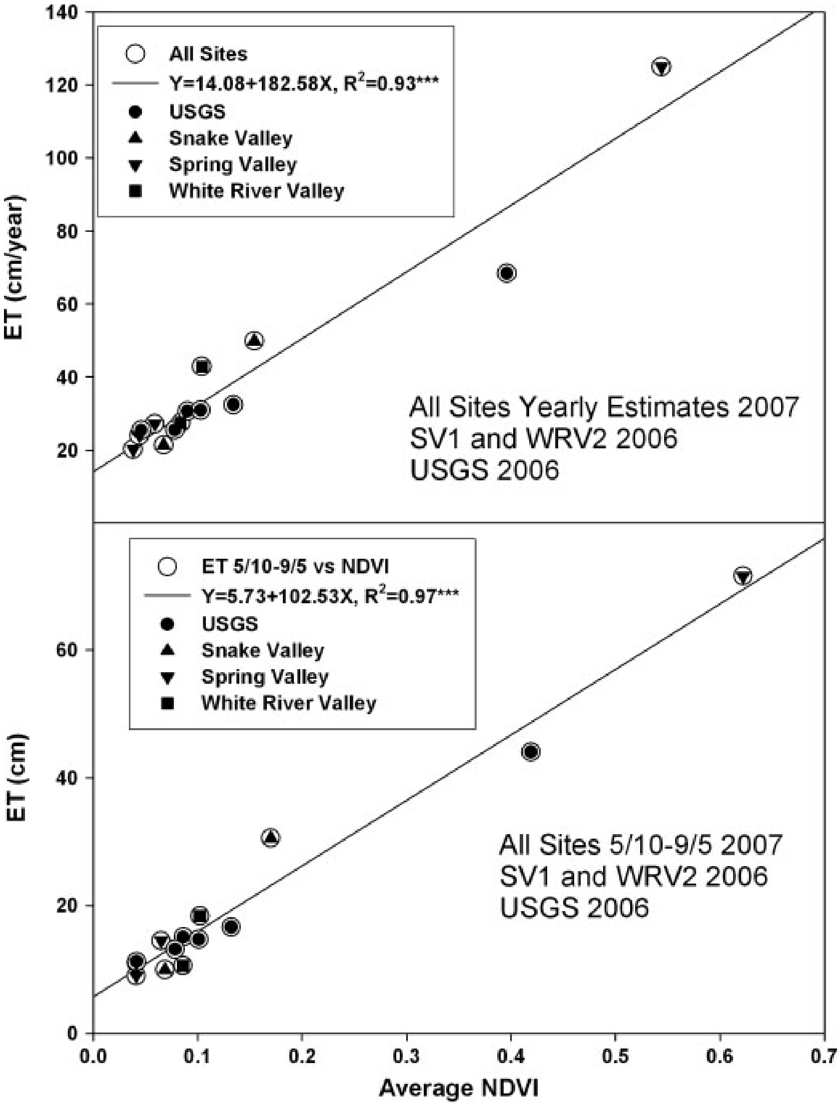

Figure 8. Relationship between ET and average NDVI for all sites for the period 10 May–5 September 2007 and SV1, WRV2 and USGS sites in 2006 (upper graph). Relationship between yearly ET and average NDVI for all sites in 2007 and SV1, WRV2 and USGS sites in 2006 (lower graph). Regression lines based on data from all sites, designated as symbols within circles.

Basin-wide ET estimates

Basin-wide ET was estimated using two different techniques. The first technique estimated ET based on developing an empirical relationship between daily NDVI and ET data, converting all NDVI pixels to ET and summing them for each basin on dates when Landsat images were collected. The daily basin ET estimates were then plotted as a function of time and the area under the response curve was estimated using integration. The second technique was based on developing a relationship between the average growing season NDVI (Figure 7) and the yearly ET estimates at multiple sites. Daily NDVI–ET correlations were limited to individual basins; however, the average NDVI approach was demonstrated to be accurate for all basins in 2006 and 2007 (Figure 8), but not in 2005.

Basin-wide ET estimates were generated from the daily NDVI–ET correlations for Spring Valley and White River Valley in 2005, 2006 and 2007 and in Snake Valley in 2007. ET estimates in 2005 were similar for both Spring Valley at 288·5 million m^3 versus White River Valley at 297·5 million m^3. However, lower yearly ET was estimated for White River Valley (156·7 million m^3) compared to Spring Valley (241·0 million m^3) in 2007. These estimates included adjustments for high NDVI (>0·25) areas typically associated with agricultural lands and grasslands because they were outside of the range of NDVI–ET data for the mixed shrubland sites (based on the daily NDVI–ET correlations). These adjusted totals are reported in Table VII (i.e. conservative approach of using a high NDVI value of 0·25, Figure 8, addition of 60 cm). The percentage of land within each basin assigned to the high NDVI category ranged from an average of 6·2% in Snake Valley, 8·4% in Spring Valley to 8·9% in White River Valley over the study period.

The average NDVI approach was able to incorporate all NDVI areas because of inclusion of the high NDVI value associated with the irrigated pasture grassland site. However, this approach was demonstrated to underestimate the wetter 2005 data by approximately

Table VII. Basin-wide ET estimates for Spring Valley and White River Valley in 2005, 2006 and 2007 and Snake Valley 2007 based on daily NDVI–ET estimates and average NDVI yearly ET estimates. Area of pheatophytic zone in Spring Valley and White River Valley in 2005, 2006 and 2007 and Snake Valley in 2007.

	Spring Valley		White River Valley		Snake Valley		Spring Valley	White River Valley	Snake Valley
	Daily NDVI	Average NDVI	Daily NDVI	Average NDVI	Daily NDVI	Average NDVI	Area of pheatophytic zone		
	millions m^3						millions m^2[b]		
2005	288·5	287·6[a]	297·5	278·0[a]	—	—	632·2	576·9	—
2006	241·7	228·9	178·9	223·8	—	—	633·0	577·7	—
2007	241·0	202·9	156·7	188·1	217·9	295·4	633·3	573·6	1036·1

[a] Estimate adjusted by 25% based on assessing the underestimate of 2005 data based on 2006 and 2007 regression equation.

[b] Zones assessed based on field surveys and aerial photos

25%. As such, the 2005 yearly estimate is based on a 25% adjustment (Table VII). Future wet years will be needed to further validate this adjustment. Although both techniques yielded different ET estimates, Spring Valley and White River Valley were similar (larger difference noted in Snake Valley), which provided a possible range in ET for each basin on a year-to-year basis (150–300 million m^3, Table VII). However, based on greater limitations associated with the single-day NDVI approach (e.g. inability to adequately incorporate changes in growth, climate and ET with 5–10 measurements over an approximate 150-day response period), the estimates associated with the average NDVI and yearly ET estimates would be recommended for modelling purposes.

Finally, we assessed the impact of the decline in winter precipitation on basin-wide yearly ET estimates in 2005, 2006 and 2007 for Spring Valley and White River Valley; Snake Valley was not included because of lack of winter precipitation data. The winter precipitation/ET$_{\text{ref}}$ was selected from the two long-term monitoring sites (SV1 and WRV2). Although additional precipitation data at multiple sites over multiple years is needed to fine tune such a relationship, a highly linear correlation was obtained [Basin ET(million m^3) $=$ 179 $+$ 138·5(winter rain/ET$_{\text{ref}}$), $R^2 = 0{\cdot}93^{**}$), indicating that based on the data obtained in this study winter precipitation was a major driving force in dictating basin-wide ET on a year-to-year basis, with a significantly higher coefficient of determination associated with the average NDVI–ET approach compared to the daily NDVI–ET approach ($R^2 = 0{\cdot}93^{**}$ vs $0{\cdot}57^{*}$).

DISCUSSION

We assessed ET in three east-central Nevada basins located in western USA by scaling up energy balance ET estimates measured at fixed tower locations using an empirical relationship with Landsat-derived NDVI values. Similar approaches have been reported by Nagler *et al.* (2005) and Glenn *et al.* (2007). We selected NDVI as an index based on preliminary regression analysis results and prior historical use in Nevada and other arid and semi-arid regions (Malo and Nicholson, 1990; Peters and Eve, 1995; Peters *et al.*, 1997; Weiss *et al.*, 2004). After an examination of Landsat images collected in 2005, which originally included fall and winter dates, we found that images restricted to the growing season (April–September) provided the best correlation with ET. This corresponded to research by Ramsey *et al.* (1995) who found a lack of clear phenological separation among different vegetation in Utah during the fall and winter time periods. When the ET correlations were based on average NDVI values established during the growing period and incorporated previously published values obtained for the same valleys during the same time period (Moreo *et al.*, 2007), we could account for 97% of the variation in the ET estimate for the 10 May—5 September growing period and 93% of the variation in the ET estimates based on measured or projected yearly ET totals. A single mid summer NDVI approach was successfully reported by Groeneveld *et al.* (2007) as a first-order approximation for arid and semi-arid shallow groundwater locations. However, in our study (deeper groundwater, mixed phreatophytic and non-phreatophytic vegetation) changes in NDVI were sometimes significant on a month-to-month basis, as either the dependence on soil moisture and/or groundwater changed, or it changed in a different fashion during wet years versus dry years, supporting the average NDVI approach.

Variations in yearly ET estimates at the different sites ranged from 20 to 50 cm during the two dry years (2006 and 2007, excluding SV2b, the irrigated site). By comparison, Steinwand *et al.* (2006) reported a similar range in ET for Great Basin phreatophytes in Owens Valley, California, whereas Malek *et al.* (1997) reported ET of shrubland ecosystems in Goshute Valley, Nevada to be lower and more closely linked to precipitation. Although the daily ET–NDVI approach in our study was basin restricted, the approach of averaging NDVI during the growing period was demonstrated to be applicable in all three basins.

The amount of winter precipitation was shown to be a significant driving force in the physiological response of the plants as well as the yearly ET totals. In the case of White River Valley, the ratio of winter precipitation to

ET_{ref} declined from 79 to 11% over the 3-year monitoring period. We found that such changes (wet vs dry year) led to a direct lowering of leaf xylem water potential values of all three shrub species monitored. During the drier years of 2006 and 2007, all three species had lower ψ_L values during the spring period compared to the wetter 2005 year, reflecting the significant step down in the ratio of winter precipitation to ET_{ref}. However, even in the wet year, ψ_L declined during the growing period, suggesting that whatever groundwater extraction was occurring, it was not adequate to offset stress during the later periods of summer.

ET rates in 2007 were highly correlated with the percentage cover of greasewood ($R^2 = 0{\cdot}96^{***}$), regardless of the depth to groundwater. Although Cooper *et al.* (2006) reported reduced ET as a function of water table depth, they were studying the impact of groundwater pumping and warned that many models that estimate ET as a function of water table depth are prone to large errors, especially if vegetation changes during the water table decline are not considered. Daily groundwater oscillations during the growing period reflected a direct coupling between the vegetation and the groundwater. When cumulative ET_{ref}, ET and rainfall were compared over time in 2007, results suggested a wide range in potential groundwater accessibility by the plant communities. Further research will be needed to discern the extent to which each species is accessing groundwater.

ET totals for a complete 1-year period was shown to exceed precipitation by 55–60% during 2006. At all sites, we found that episodic rainfall events during the summer period led to immediate oscillations in daily ET totals. We did not attempt to partition the evaporation component from the transpiration component in this study, though ancillary stable isotope data reported by Conrad (2009) for greasewood suggested that greasewood was effective in transpiring elevated soil moisture associated with these summer rainfall events. Though these results indicate a linkage between precipitation and physiological response, Loik *et al.* (2004) stressed that ecosystem response to water pulses in dryland ecosystems is complex and requires consideration of multi-scale factors. Because many of these plant communities were highly dependent on precipitation to meet plant water requirements, a greater effort in the future should be made to assess variations in precipitation on both spatial and temporal scales. A similar ET response to interannual variations in precipitation and plant response was reported by Weaver *et al.* (2002) in northern temperate grasslands, and by Scott *et al.* (2004) in riparian mesquite woodlands in semi-arid climates.

Although a certain amount of uncertainty must be attached to the basin level ET estimates, as we recognize that error can be propagated through the various steps in the estimates, results suggested that all the three basins had annual ET totals in the 150–300 million m^3 range, with a significant decline from the wetter (2005) year to the drier (2007) year, where a 29–32% decline was observed (average NDVI approach). Moreover, we noted that our dry year data set poorly described data for the wet year. These differences clearly indicated the need to assess basin estimates over prolonged periods of time. The use of equations generated in this study will need to be further tested over time to capture the intra annual and inter annual variability in ET at these sites and basins before long-term hydrologic balances can be properly assessed. Such small data sets cannot adequately address the concerns of stationarity, and that scientists have truly assessed the natural variability within such systems (Milly *et al.*, 2008).

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