Journal of Hydrology (2006) **329**, 595–605

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Water balance for Great Basin phreatophytes derived from eddy covariance, soil water, and water table measurements

A.L. Steinwand [a,*], **R.F. Harrington** [a,1], **D. Or** [b,2]

[a] *Inyo County, Water Department, 163 May St., Bishop, CA. 93514, United States*
[b] *Laboratory of Soil and Environmental Physics (LASEP), School of Architectural, Civil and Environmental Engineering (ENAC/ISTE), Ecole Polytechnique Federale de Lausanne (EPFL), Bâtiment GR 2 (room 399), CH-1015 Lausanne, Switzerland*

Received 6 July 2005; received in revised form 10 March 2006; accepted 13 March 2006

KEYWORDS
Evapotranspiration;
Vadose zone;
Plant water uptake;
Specific yield

Summary This study was conducted in the Owens Valley, California to determine the relative contribution of groundwater and soil water to evapotranspiration (ET) from phreatophytic meadow and scrub plant communities. Groundwater uptake during the growing season was estimated from the difference between ET measured using eddy covariance, and the sum of soil water depletion, precipitation, and evaporation from the water table. Total ET during the growing season (March 26 to October 15) ranged from 53 to 646 mm among all sites and years. ET during winter was small, averaging approximately 40 mm. Estimates of evaporation from the water table based on soil properties and ET measurements at night both suggested this flux was a small component of the water balance. For alkali meadows with water table depths of 1–3 m, groundwater uptake accounted for 60–81% of ET. Shrub-dominated sites had lower cover and transpiration, and relied less on groundwater than meadows. Groundwater uptake was correlated with water table depth and leaf area index ($r^2 = 0.62$ and 0.70, respectively) even though water table depth and vegetation cover were less correlated ($r^2 = 0.44$). A slightly higher correlation was observed between groundwater uptake per unit leaf area and water table depth ($r^2 = 0.73$). Annual ET results from this study could assist the management of groundwater pumping in areas of phreatophytic vegetation by improved accounting of the sources of ET as vegetation leaf area and water table depths vary.

---

[*] Corresponding author. Tel.: +1 760 872 1168; fax: +1 760 873 5695.
E-mail addresses: asteinwand@inyowater.org (A.L. Steinwand), bharrington@inyowater.org (R.F. Harrington), dani.or@epfl.ch (D. Or).
[1] Tel.: +1 760 872 1168; fax: +1 760 873 5695.
[2] Tel.: +41 21 693 8024; fax: +41 21 693 5670.

0022-1694/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2006.03.013

Introduction

Groundwater discharge in the arid western United States supports stream flow, springs, riparian areas, and phreatophytic meadow and scrub plant communities that provide important habitat, agricultural, and recreational uses. Managing groundwater resources to protect these uses requires understanding the relationship between water table fluctuations, soil water, and plant water uptake. Studies of the plant–water relations of Great Basin phreatophytes have investigated the edaphic or physiologic factors controlling their ecology (Branson et al., 1976; Donovan et al., 1996; Trent et al., 1997; Sperry et al., 2002), water acquisition strategies (Donovan and Ehleringer, 1994; Devitt et al., 1997), or response to environmental stresses (Sorenson et al., 1991). Additionally, several studies have quantified evapotranspiration (ET) for shallow groundwater environments to determine estimates of groundwater discharge for riparian areas and phreatophytic scrub and meadow communities that occur widely in the western US (Goodrich et al., 2000; Scott et al., 2004). These studies employed various methods to measure ET including observations of water table fluctuations in lysimeters or wells (Lee, 1912; Robinson, 1970; reviewed by Nichols, 1993), stomatal conductance measurements (Steinwand et al., 2001), and micrometeorological measurements (Duell, 1990; Malek et al., 1990; Nichols, 1994; Laczniak et al., 1999; Berger et al., 2001). A common objective of these studies was to develop groundwater budgets for closed basins and riparian corridors.

Groundwater pumping in the Owens Valley, California is managed to provide a reliable supply for Los Angeles while avoiding adverse impacts to phreatophytic vegetation. Pumping decisions are based on a comparison of soil water and ET estimates derived from an extensive soil water and vegetation monitoring program. The management plan allows groundwater pumping if stored soil water is sufficient to supply vegetation transpiration, but a key shortcoming is inadequate accounting of plant uptake from soil or groundwater sources as water table depths vary due to pumping and climatic conditions. Though several studies have attempted to determine groundwater contribution to ET of irrigated crops based on the soil water balance (e.g., Stuff and Dale, 1978; Wallender et al., 1979), few studies have examined soil water availability and source of uptake for desert phreatophytes. In environments such as the Owens Valley where the water table fluctuates due to groundwater pumping, the relative contribution of groundwater uptake to ET would be expected to vary as the vegetation is forced to rely more heavily on retained soil water than on recharge from the water table (Sorenson et al., 1991). Or and Groeneveld (1994) developed the only soil water model specifically for Great Basin phreatophytes over a fluctuating water table, but that study and others (Scott et al., 2000; Snyder and Williams, 2000) suggested partitioning transpiration between soil water and groundwater for native phreatophytes was still poorly understood. The objective of this study was to quantify partitioning of plant water uptake between soil water and groundwater during the growing season for different water table depths and phreatophyte assemblages. Additionally, we estimated the annual amount of ET from groundwater for phreatophytic meadow and shrub communities.

Study area and methods

The Owens Valley is a closed basin on the eastern slope of the Sierra Nevada in California and at the western edge of the Great Basin physiographic province (Fig. 1). Although the climate of the valley floor is arid (mean precipitation of 10–15 cm) and summer rain infrequent, snowmelt runoff from the Sierra Nevada creates a shallow water table that supports approximately 28,000 ha of native phreatophytic shrublands, meadows, and riparian areas. Since the early 1900s, water resources of the Owens Valley have been managed by the Los Angeles Department of Water and Power as the primary water supply for the City of Los Angeles.

Evapotranspiration, soil water, and water table measurements were collected to provide an accounting of the sources of water uptake by plants. Field sites were selected based on plant species composition, fetch, and depth to the water table sufficient to subirrigate the vegetation but deep enough to minimize surface evaporation. Vegetation at the sites ranged from high cover alkali meadow to low cover phreatophytic scrub (Table 1). Depth to water criteria were relaxed to include one site with deep water table (RBS) where subirrigation may have been absent, and one site with a shallow water table (AM2) where appreciable bare soil evaporation may have occurred to expand the range of conditions studied. Leaf area index (LAI) was measured approximately monthly along four 50 m transects aligned north, south, east, and west of the ET station using the point quadrat method (Goodall, 1952) and extinction coefficients from Groeneveld (1997). Vegetation cover was measured simultaneously using the point-intercept method (Bonham, 1989) to allow comparison with previous studies. Depth to water table (Z_{wt}) was measured approximately biweekly during the growing season and monthly during the winter in piezometers on site except for RBS, SBS, and DSS. Z_{wt} at sites without piezometers was observed when access tubes were installed in the spring and fluctuations estimated from piezometers located nearby. Regional water levels and soil water monitoring indicated Z_{wt} at DSS was similar in 2002 and 2003. Water level loggers vented for barometric compensation were installed in piezometers at AM1 and SBM in summer 2003 to replace manual measurements. Soil water content was determined approximately biweekly during the growing season using a combination of neutron, gravimetric, and time domain reflectometry (TDR) methods. Soil water measurements were collected approximately monthly during the winter. Measurements were collected at three or four locations adjacent to the vegetation transects. Neutron access tubes extended to the water table in spring (except at RBS) when the annual minimum Z_{wt} typically occurs. Soil depths from 0 to 12 cm were measured with gravimetric or TDR methods. Precipitation was recorded manually after each event at nearby rain gauges. Precipitation preceding the 2000, 2001, and 2002 growing seasons consisted of small events, and annual precipitation was below average (approximately 130 mm) each year. Precipitation preceding the 2003 growing season, however, was 3–5 times that of previous years (Table 1).

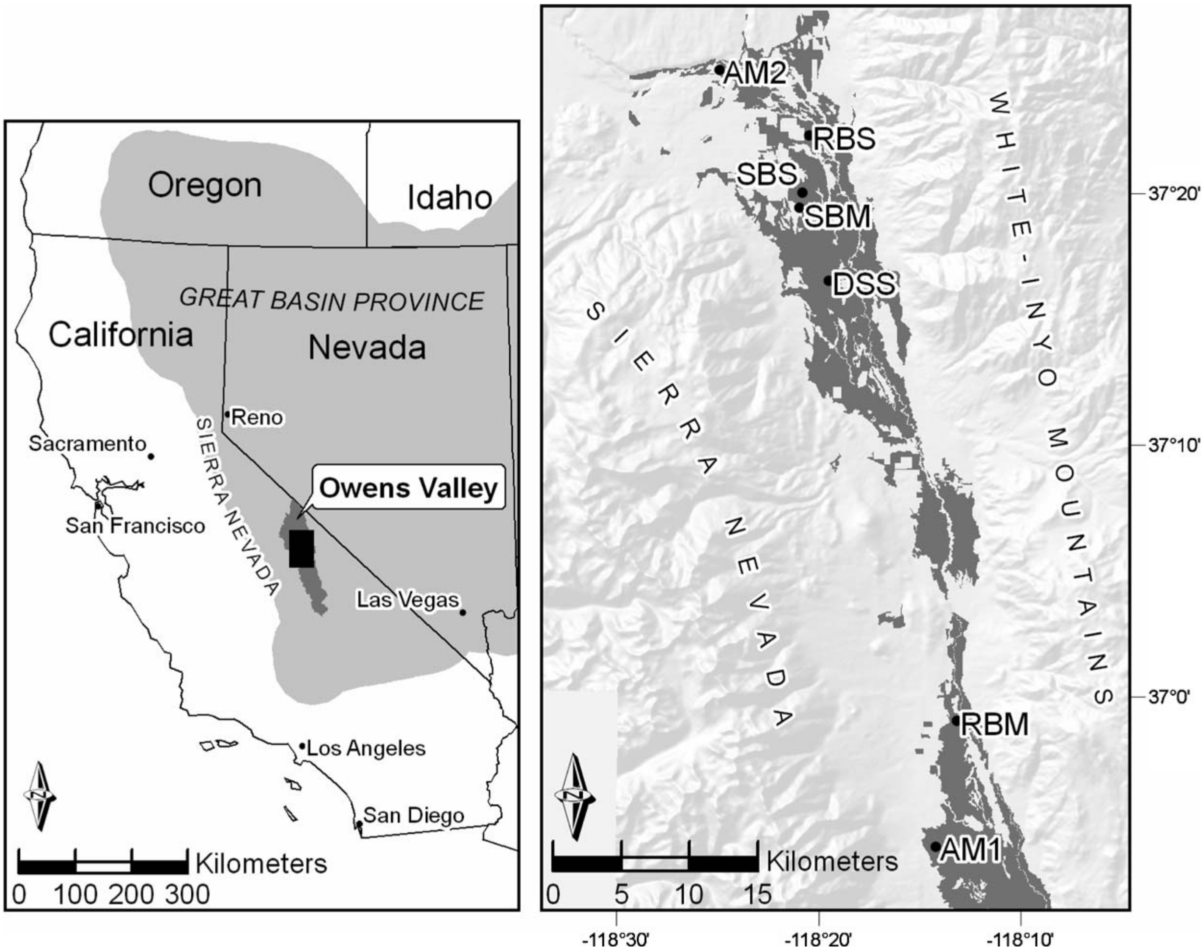

Figure 1 Great Basin physiographic province and location of study sites in the Owens Valley. Shaded area represents the approximate extent of phreatophytic plant communities on the Owens Valley floor.

Table 1 Site characteristics

Year	Site	Vegetation type[a]	Depth to water (m)	Winter precipitation (mm)	Maximum LAI
2000	AM1	Alkali meadow	2.2–2.5	25	1.64
2001	AM1	Alkali meadow	2.2–3.0	59	1.49
2001	RBM	Rabbitbrush meadow	2.6–3.2	59	1.46
2001	SBS	Nv. saltbush scrub	3.9–4.1	83	0.94
2002	AM1	Alkali meadow	2.3–3.1	31	1.16
2002	AM2	Alkali meadow	1.3–2.1	20	1.30
2002	RBS	Rabbitbrush scrub	>5.0	32	0.34
2002	SBM	Nv. saltbush meadow	2.1–2.4	26	0.39
2002	DSS	Desert sink scrub	4.0	26	0.27
2003	AM1	Alkali meadow	2.1–3.3	225	1.16
2003	SBM	Nv. saltbush meadow	2.1–2.4	92	0.85
2003	DSS	Desert sink scrub	4.0	151	0.55

Depth to water is the minimum and maximum depths experienced during the growing season. Precipitation values are winter totals beginning October 1 the previous year.

[a] Meadows dominated by grasses: alkali sacaton (*Sporobolus airoides*) and/or saltgrass (*Distichlis spicata*); scrub sites dominated by shrubs rabbitbrush (*Chysothamnus nauseosus*), Nevada saltbush (*Atriplex lentiformis* ssp. *torreyi*), or greasewood (*Sarcobatus vermiculatus*). RBS may be mixture of non-phreatophytic rabbitbrush subspecies *holeocus* and phreatophytic subspecies *consimilis*. Shrub meadows are mixture of shrubs and grasses.

Latent and sensible heat fluxes were measured using eddy covariance (EC) methods (Arya, 2001). Towers were instrumented to measure all components of the energy balance (EB) to allow an independent check of the latent (λE) and sensible (H) heat fluxes measured by EC. Soil heat flux (G) was corrected for thermal storage in the soil above the flux plates, and λE was corrected for krypton hygrometer beam absorption by oxygen (Campbell Scientific Inc., 1998) and fluctuating air density (Webb et al., 1980). Fluxes were averaged over 30-min intervals. Post-processing of the EC data included inspection of the record for anomalies in all data streams, and inspection of the turbulent flux data for sonic anemometer spikes or signal losses. If more than 5% of the 10 Hz signal from the eddy covariance sensors was lost over a 30-min sampling interval, that interval was discarded. Sites were visited approximately biweekly to clean the sensors, download the data logger, and measure soil water content. Instruments were removed from the field and recalibrated by the manufacturer each winter.

The sum of the turbulent fluxes measured at each site was less than available energy, similar to observations in numerous other studies using EC methods (Twine et al., 2000). Comparison of latent and sensible heat fluxes and the Bowen ratio measured by adjacent Bowen ratio and EC systems operated simultaneously for two weeks at an alkali meadow site (AM1) showed that the Bowen ratio system measured greater latent and sensible heat fluxes, but similar Bowen ratios. Daily energy balance discrepancies ranged from near 0 to 150 W m^{-2}, averaging 44 W m^{-2} over the course of the two-week comparison. Mean available energy ($R_n - G$) during this period was 124 W m^{-2}, thus the turbulent fluxes accounted for only about two-thirds of the available energy. Energy balance discrepancies were present at all sites, regardless of the magnitude of the turbulent fluxes or whether sensible or latent heat was the dominant flux at a site. The energy balance discrepancy tended to increase over the course of the growing season at most sites, however no instrument calibration drift or other systematic error in the eddy covariance systems was identified.

Eddy covariance measurements were corrected for energy imbalance to determine ET using the Bowen ratio, β:

$$\mathrm{ET} = \frac{R_n - G}{\lambda(\beta + 1)}, \tag{1}$$

where R_n is net radiation, β is the Bowen ratio ($H/\lambda E$), and all others as defined above. This method of correcting the energy balance discrepancy was used because it closes the energy balance without favoring either sensible or latent heat in the apportionment of turbulent fluxes. Using Eq. (1) to correct the EC measurements increased ET estimates from a few tenths of mm day^{-1} up to 1 mm day^{-1} depending on the site. One disadvantage of adopting this correction was the shorter record of ET because there were fewer days when all instruments were functioning. To bridge data gaps and allow for consistent limits of integration for the seasonal ET totals, daily ET was fit to a two-term Fourier series (Salas et al., 1980). This model was chosen because of its demonstrated ability to model reference ET in the Owens Valley (Or and Groeneveld, 1994). Occasionally, the fitted model was poorly constrained and gave negative values during winter when EC data were lacking. When this occurred, daily ET was assumed to be 0.01 mm day^{-1} and the model revised. The effect on the water balance calculations was negligible because only daily ET values during the growing season were summed. Examples of daily eddy covariance results and fitted models are shown in Fig. 2.

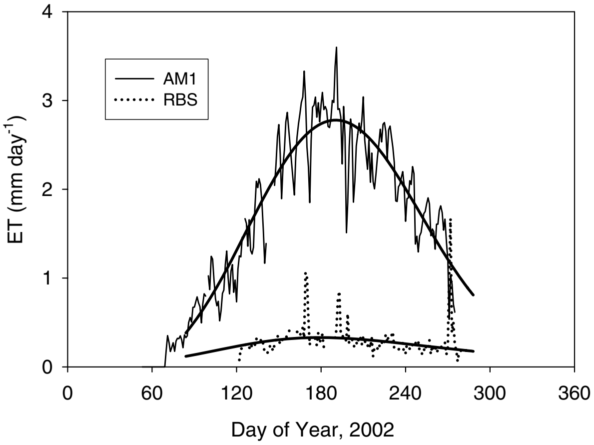

Figure 2 AM1 and RBS daily ET measured in 2002 and fitted Fourier models. ET has been corrected for energy imbalance. Except for SBM, the Fourier models were acceptable for integration with r^2 between 0.57 (RBS) and 0.98 (AM1). The Fourier models were truncated at the beginning and end of growing season.

Results and discussion

Site characteristics

The sites spanned a range of non-riparian phreatophytic vegetation communities, groundwater depths, and soil water conditions (Table 1). Groundwater levels typically were shallowest in the spring and declined to maximum depth in October at the end of the growing season. Water tables rose during the winter when vegetation was senescent. At sites monitored multiple years, the water levels were similar each spring.

Total ET and the portion derived from groundwater was expected to vary depending on Z_{wt} and water content of the unsaturated zone. The sites included an array of conditions ranging from meadow sites with shallow water table and wet soils to scrub sites with deep water table and dry soils. Mixed grass and shrub assemblages had intermediate soil and water table characteristics. Soils at meadow sites AM1 and AM2 were moist throughout the entire profile in the spring, and water content decreased at all depths during the growing season due to water table decline and plant uptake (Fig. 3). SBM had relatively shallow water table (2.1 m) similar to the meadow sites, but the upper 1 m of soil was dry in 2002 following the dry winter. Recharge at SBM from capillary rise above the water table in the loamy sand soil was restricted to depths below 1.1 m; however, in 2003, the soil profile was moist throughout after the wetter winter. At two sites (RBM, DSS) with deeper water tables, uptake occurred predominately from shallow depths affected by infiltrating precipitation (approximately 1 m) and lower depths recharged by capillarity above the water table (Fig. 3b). Intermediate depths at the deep water table sites had nearly static water contents. The unsaturated zone at two scrub sites, RBS and SBS, was dry loamy sand or sand three or more meters thick above the water table suggesting the vegetation was weakly coupled with the water table.

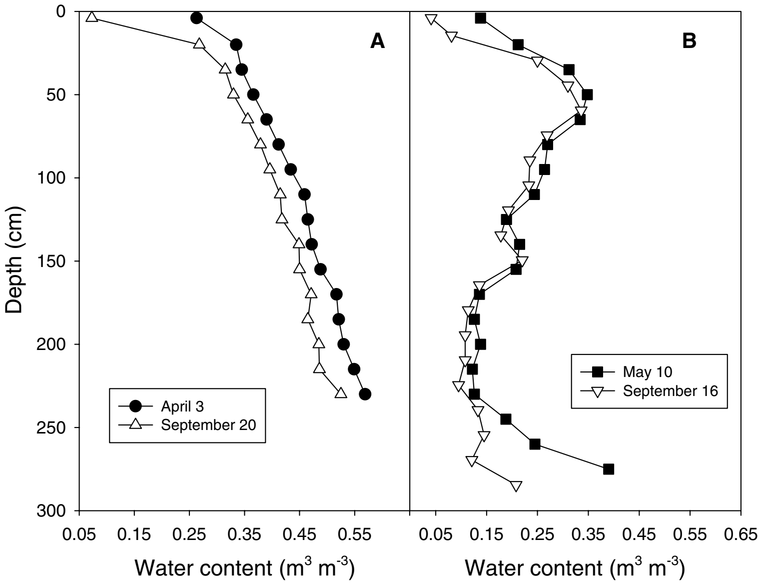

Figure 3 Soil water profiles near the beginning and end of the 2001 growing season. A, AM1; B, RBM.

The water table at RBS was deeper than 5 m and water content of the entire unsaturated zone was near the plant limiting water content (0.02—0.05 $m^3\,m^{-3}$). ET at this site following a dry winter was negligible. At SBS, the water table in spring was shallower (3.9 m), but ET declined during late May and June corresponding with the exhaustion of winter precipitation stored in the upper soil profile. This observation suggested that the uptake rate of groundwater alone was insufficient to support early season leaf area. Leaf area and ET at this site increased following approximately 35 mm of rain in early July suggesting shallow roots of *Atriplex lentiformis* were able to exploit midsummer rain. The Fourier model cannot accommodate the dual seasonal maxima observed at this site, and the daily modeled values exceeded the measured values during May through June by a total of 24 mm. The growing season ET estimate for SBS derived from the model integration was reduced by this amount to account for this site's deviation from the Fourier model.

Soil water balance partitioning

Partitioning of the soil water balance to determine the amount of groundwater transpired during the growing season is shown in Fig. 4 and Eqs. (2a)—(2d):

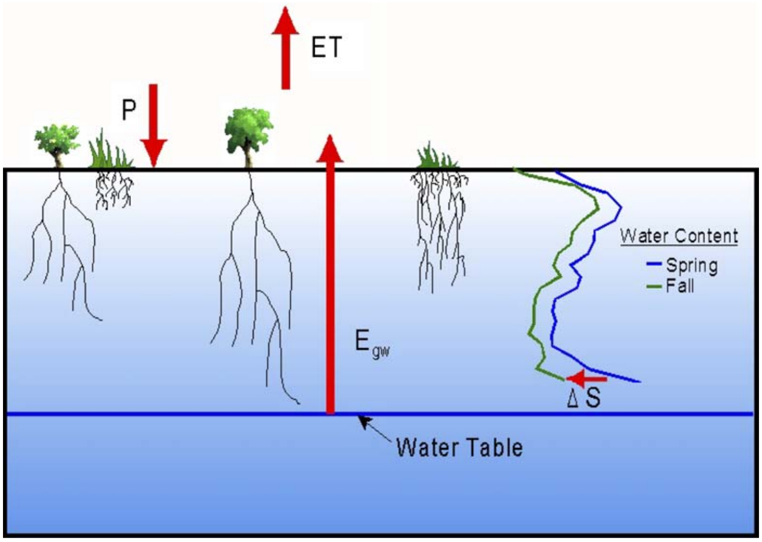

Figure 4 Partitioning of growing season ET into soil and groundwater (gw subscript) components. *E* is evaporation, *T* is transpiration, *P* is precipitation, and Δ*S* is change of stored soil water from the start to the end of the growing season. Bold arrows are water balance components measured or estimated in this study.

$$\mathrm{ET} = \mathrm{ET}_{\mathrm{soil}} + \mathrm{ET}_{\mathrm{gw}}, \quad (2a)$$

$$\mathrm{ET}_{\mathrm{soil}} = P + \Delta S, \quad (2b)$$

$$\mathrm{ET}_{\mathrm{gw}} = E_{\mathrm{gw}} + T_{\mathrm{gw}}, \quad (2c)$$

$$T_{\mathrm{gw}} = \mathrm{ET} - E_{\mathrm{gw}} - P - \Delta S, \quad (2d)$$

where ET is evapotranspiration, ΔS is change in soil water storage over the growing season, P is precipitation during the growing season, $\mathrm{ET}_{\mathrm{soil}}$ is ET derived from the vadose zone, and $\mathrm{ET}_{\mathrm{gw}}$, T_{gw}, and E_{gw} are evapotranspiration, transpiration, and evaporation derived from groundwater. Runon, runoff, and deep percolation of precipitation during the growing season were negligible. The growing season was defined as March 25 to October 15, approximately concordant with vegetation phenology at these sites. The control depth for the water balance calculation was Z_{wt} at the beginning of the growing season. Water made available by a declining water table (thickening vadose zone) and water flux upward from the water table into the vadose zone via capillarity were counted as groundwater. Eqs. (2a)–(2d) assume that all summer P is used by vegetation or evaporates, which was a reasonable assumption given the low summer precipitation. Double counting of P that infiltrated into the soil was avoided by defining ΔS as the maximum difference between measurements early and late in the growing season and ignoring small precipitation driven increases in ΔS during the summer.

Hydraulic redistribution of water in the vadose zone through plant roots has been demonstrated for many species (Jackson et al., 2000) and can affect the ecosystem water balance (Horton and Hart, 1998). Although hydraulic redistribution was not explicitly accounted for in this study, the water balance (Eq. 2) included changes in soil water storage and ET produced by this process. Hydraulic redistribution at night can increase the quantity of soil water transpired the following day (Richards and Caldwell, 1987; Wan et al., 1993). For phreatophytes, however, the contribution to overall plant water use is likely insignificant if plants have access to groundwater (Hultine et al., 2003). If ET was enhanced during this study by nocturnal recharge, it was measured by the eddy covariance systems. Soil water recharge through plant roots during the winter was included in the spring soil water measurement used to calculate ΔS. Water transfers within the vadose zone such as downward translocations of precipitation (Hultine et al., 2004) would not affect the water balance. Upward flux of water through roots tapping the water table was counted as groundwater similar to capillarity because the source of the water is the same.

Eddy covariance ET measurements

Eddy covariance measurements were collected through most of the growing season at seven sites over four years (12 site-year combinations). The sum of latent and sensible fluxes overall accounted for 57–77% of the available energy throughout the growing season. Sites with high and low ET rates exhibited similar energy balance closure suggesting that both turbulent fluxes were underestimated. ET rates usually peaked in late June or early July corresponding with the measured trends in evaporative demand inferred from reference ET (Or and Groeneveld, 1994) and LAI.

Groundwater evaporation

The only term in Eq. (2d) that was not measured directly was E_{gw}, which was estimated by summing nighttime ET when transpiration was negligible and extrapolating the nighttime rate to 24 h. Because summer precipitation is infrequent and the upper soil layers are dry most of the growing season, we hypothesized the groundwater evaporation rate would be governed by the transport rate through the unsaturated zone and minimally influenced by diurnal fluctuations in atmospheric demand. Nighttime ET should overestimate E_{gw} because it includes soil evaporation and leakage through plant stomata (Snyder et al., 2003). To test whether this procedure gave realistic estimates of E_{gw}, we compared nighttime ET with theoretical predictions of evaporation from the water table based on soil water retention measurements on soil cores collected at the sites (Gardner, 1958). The seasonal totals of E_{gw} resulting from the theoretical predictions exceeded nighttime ET by only

Table 2 Soil water balance components and calculation of T_{gw} for EC sites

Year	Site	T_{gw} (mm)	ET (mm)	P (mm)	ΔS (mm)	E_{gw} (mm)	T_{gw}/ET	ET_{r} (mm)
2002	AM2	520	646	2	97	27	0.81	1225
2002	AM1	300	377	1	68	8	0.80	1225
2000	AM1	339	460	11	99	11	0.74	1172
2001	AM1	315	446	15	104	12	0.71	1211
2001	RBM	316	471	15	131	9	0.67	1211
2003	AM1	318	527	38	163	8	0.60	1160
2002	SBM	100	177	3	72	2	0.57	1225
2001	SBS	69	141	35	34	3	0.49	1211
2003	SBM	98	282	5	177	2	0.35	1160
2002	DSS	36	108	3	69[a]	0	0.33	1225
2003	DSS	51	205	17	134	3	0.25	1160
2002	RBS	11	53	3	37[a]	2	0.21	1225

The values represent growing season totals (March 25 to October 15) and are ranked by T_{gw}/ET. Reference ET (ET_{r}) was estimated using a modified Penman method (Pruitt and Doorenbos, 1977) at a meteorological station maintained in an irrigated grass pasture the Owens Valley (CIMIS, 2003).

[a] Initial soil water measurement was 1 month into growing season and soil was near limiting water content suggesting ΔS was underestimated. ΔS estimated by adding winter precipitation (35 mm) depleted before first the soil water measurement.

18 to 28 mm for sites with shallow water table and fine-textured soils where E_{gw} would be expected to be greatest (AM1 and AM2). E_{gw} estimated using either the Gardner prediction or nighttime ET was negligible for the other sites (Table 2). The Gardner model exceeded nighttime ET in April when the water table was shallowest a small amount (0.25–0.30 mm day^{-1}), but the two were of similar magnitude for the remainder of the season. Overestimation early in the season was expected because the Gardner model only considers soil factors controlling evaporation rate and ignores that evaporative demand early in the growing season is less than during midsummer. The similarity of the two estimates when summed over the growing season and the small magnitudes of estimates suggested that summing nighttime ET provided an acceptable value for E_{gw} and did not result in significant water balance errors.

Seasonal water balance

Components of the seasonal soil water balance are presented in Table 2. Total growing season ET ranged between 53 and 646 mm. The daily ET rate exceeded the rate of soil water depletion all season suggesting plants were relying on groundwater and soil water simultaneously as opposed to preferentially depleting soil water in the early summer and accessing groundwater later in the growing season. Also, nearly static water contents for intermediate depths at some sites (Fig. 3) suggested roots bypassed available soil water in some profiles in favor of uptake from deeper in the profile or directly from the water table. Nighttime ET never exceeded 0.5 mm day^{-1} except immediately following rain showers, and the portion of E derived from the water table was a negligible fraction of the soil water balance for all sites (Table 2). Summer precipitation was slightly greater in 2003 than in previous years but was still a small component of the water balance, less than 38 mm. Direct uptake from the water table, T_{gw}, accounted for 60–81% of ET at sites with high cover and shallow water table. At scrub sites with low ET, the fraction of T derived from groundwater was less than meadow and scrub meadow sites (Table 2). RBS, with water table below 5 m and low ET (Fig. 2), probably was not coupled to groundwater suggesting the uncertainty of the water balance estimate of T_{gw} is greater than 11 mm. At sites monitored multiple years (AM1, SBM, DSS), the amount of groundwater uptake was relatively constant between years reflecting the similar water table conditions each year even though total ET varied annually depending on LAI and winter precipitation.

Plant water uptake and water table fluctuations

Determination of T_{gw} as the residual in the soil water balance lumps error for each component into the estimate. Because of this uncertainty, it was important to compare the results with an independent estimate of T_{gw}. Seasonal and diurnal water table fluctuations often coincide with plant activity providing observational evidence of groundwater uptake by plants (Robinson, 1958; Meyboom, 1966; Reiner et al., 2002). We examined the relationship between evapotranspiration and water table fluctuations measured at half-hourly intervals at two sites, AM1 and SBM, to differentiate between behavior during the daytime when plants transpire and during the night when T is substantially reduced. These sites were selected because they had similar Z_{wt}, but dissimilar vegetation and soil characteristics.

The influence of plant uptake on diurnal water table fluctuations was apparent in the hydrographs (Fig. 5). To establish independent support for the values of T_{gw} derived from Eq. (2), values of readily available specific yield from Loheide et al. (2005), Table 1, were combined with the diurnal fluctuations to estimate daily ET$_{gw}$. AM1 had predominately clay loam/loam textures at depths near the water table (27–28% clay, 28–32% sand). Soils at SBM had 1% clay and greater than 90% sand content. The close agreement between ET$_{gw}$ estimated from the water balance and diurnal water table changes for SBM were encouraging, but the results for the two methods at AM1 were substantially different (Table 3).

The largest source of error in estimating ET$_{gw}$ from diurnal water table fluctuations is the estimation of specific yield (Loheide et al., 2005). Specific yield was determined for days with practically no change in water table depth at night (this condition was strictly for convenience of completing the calculation) according to

$$S_y = \frac{\mathrm{ET}}{\Delta Z_{wt}}, \qquad (3)$$

where S_y is specific yield, ET is daily evapotranspiration, and ΔZ_{wt} is change in water table depth. Small changes in water levels during the night affected the daily S_y values negligibly, approximately ±0.02. ET measured by the EC systems included contributions from both groundwater and the vadose zone, and ET$_{gw}$ could not be determined on a daily basis for the calculation of S_y because of the infrequency of soil water measurements. The average of daily S_y was adjusted by multiplying by the seasonal ratio of ET$_{gw}$ to ET (Table 2), resulting in estimated S_y of 0.18 for the sandy site SBM and 0.28 for the clay loam site, AM1. Values for AM1 in particular differ from the value for clay loam of 0.021 given in Loheide et al. (2005).

The definition for ET$_{gw}$ in this study included plant uptake from the increment between the shallow water table at the start of the growing season and deeper water table later in the growing season. For the purpose of constructing

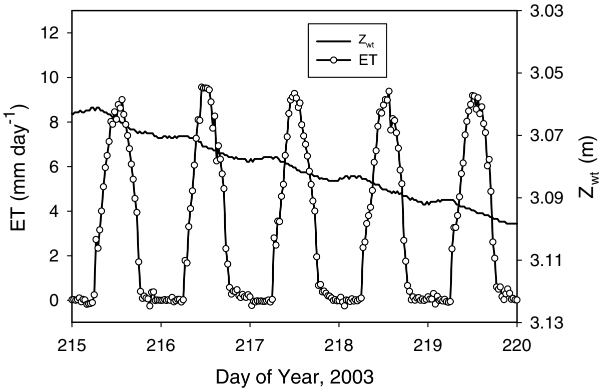

Figure 5 Example of ET and Z_{wt} for five days measured at AM1 in 2003.

Table 3 Groundwater uptake estimated from soil water balance and from seasonal change in depth to water table and estimated specific yield

Year	Site	Day of year	Z_{wt} range (m)	ET_{gw}[a] (mm)	SWB ET_{gw} (mm)
2001	AM1	93–263	2.17–3.02	18	302
2002	AM1	95–268	2.25–3.12	18	284
	SBM	112–246	2.15–2.36	67	72
2003	AM1	98–270	2.09–3.31	9	302
	SBM	98–300	2.07–2.44	118	93

The values of ET_{gw} determined from the water balance were adjusted to match the time period corresponding to the minimum and maximum DTW.

[a] Estimated based on readily available S_y from Loheide et al. (2005) and measured water table fluctuations.

a seasonal soil water balance, it is appropriate to consider water below the minimum Z_{wt} as groundwater, but uptake from this zone may not be reflected in diurnal water table changes. The ΔS during the growing season for the 2–2.5 m depth increment at AM1 was approximately 21 mm. If ΔS in the increment between the high and low water table (Table 1) were similar, the small change to the seasonal ET_{gw}/ET ratio used to adjust S_y cannot account for the large difference in S_y and estimated groundwater ET.

The presence of plant uptake at AM1 produced a soil profile far from the quasi-equilibrium state expected for gravity drainage of a hydrostatic profile, yet quasi-equilibrium is a common assumption of Eq. (3) (Nachabe, 2002). Loheide et al. (2005) concluded the effect of plant uptake on S_y estimated from diurnal fluctuations was small, but their uptake rates were half that measured at AM1 suggesting that our S_y may be exaggerated by 11% or more compared to vales derived from translation of the characteristic curve. Uptake by phyreatophytes and concomitant water table decline can be viewed as a propagating drying front induced by plant roots. This hypothesis is consistent with the larger differences in S_y observed at the site with finer-textured soils. In fine textured soils, phreatophyte uptake from soil near the water table can remove an appreciable amount of water in excess of the drainable porosity and S_y would be exaggerated. In coarser soils, however, the quantity of water available for plant uptake is similar to the quantity released by drainage, and values of S_y based on diurnal fluctuations would be similar to estimates based on the characteristic curve.

Groundwater pumping may lower the water table and decouple the water table from the root zone. Under such conditions, vegetation cover and the plant water uptake from the water table would be expected to decrease, and reliance on stored soil water would increase. Thus, modeling the soil water balance (and groundwater budget) requires an expression to vary T_{gw} as a function of vegetation cover or Z_{wt}. This study did not artificially lower the water table during the growing season preventing direct observation of this process. The study sites, however, spanned a range of water table and vegetation conditions including coupled and decoupled sites.

Groundwater uptake, vegetation abundance, and Z_{wt} typically covary (Nichols, 2000). T_{gw} was correlated with LAI and Z_{wt} with coefficients of determination (r^2) of 0.70 ($p < 0.005$) and 0.62 ($p < 0.005$), respectively, and LAI and Z_{wt} were weakly correlated for this set of locations ($r^2 = 0.42$; $p < 0.05$). Taking the ratio of T_{gw} to peak LAI (LAI_{max}) accounted for inherent site differences in plant community and LAI due to edaphic factors or stress-induced reduction in leaf area that affect ET. Over the range of Z_{wt} investigated, this relationship yielded a slightly higher r^2 than the relationships with the variables individually, $r^2 = 0.73$ ($p < 0.005$) (Fig. 6). The single outlier from the well-defined trend also was informative. In 2002, the results from SBM plotted on the same trend as other sites. In 2003 however, this site showed significant increase in LAI_{max} and ET in response to greater availability of water in the upper portion of the soil from higher winter precipitation. It is difficult to generalize from a single point, but the outlier suggests that T_{gw}/LAI_{max} could vary for sites where leaf area and ET show substantial response to presence or absence of soil water in the upper profile under similar water table conditions.

Annual groundwater ET

Winter ET was estimated to permit comparison with previous studies of annual ET in the Great Basin. The eddy covariance instruments were removed from the field over winter for recalibration, but during this study, data were collected

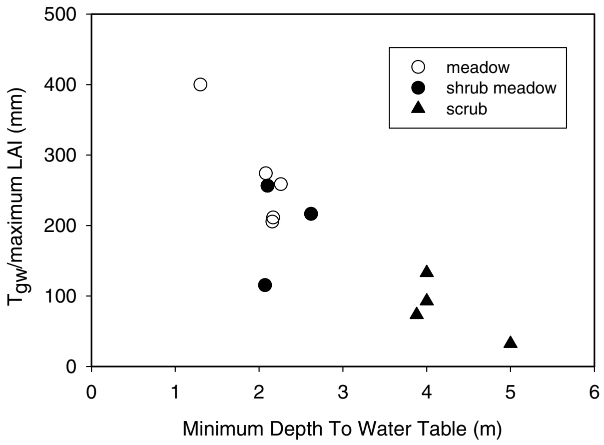

Figure 6 T_{gw} scaled by maximum LAI as a function of Z_{wt} at the beginning of the growing season. Z_{wt} value for RBS is an estimate and could be deeper than 5.0 m.

at one alkali meadow site (AM1) for several weeks in November, December, and January after the growing season when transpiration was negligible. This site had a relatively shallow water table and clay loam soils and should provide an upper bound of the groundwater contribution to ET in winter for these sites. Winter ET measurements for all years were pooled to include days with dry and moist soil surfaces. These data and reference ET measured in the Owens Valley (CIMIS, 2003) were used to develop a transpiration coefficient (K_c) for the winter (October 16 to March 24). Daily ET was the product of average K_c (0.12) and daily reference ET. The average ET for four winters was 40 mm which was added to values in Table 2 to estimate annual totals. This average value included data collected during three winters with very low precipitation and one winter with above average precipitation (Table 1). ET for a particular year would vary depending on the proportion of days with dry and moist soil surfaces, but we expect the ET during the winter to be small due to low atmospheric demand and negligible transpiration.

Estimates of annual ET from groundwater from this study are similar to previous measurements made in the Owens Valley. Duell (1990) measured ET at several sites in the Owens Valley in 1984 and 1985 using Bowen ratio, eddy covariance, and Penman methods. We estimated annual ET from groundwater from Duell's (1990) data by subtracting measured precipitation from the annual ET estimates given in his Table 5. Precipitation data were from stations operated by either the National Oceanic and Atmospheric Administration or the Los Angeles Department of Water and Power. Duell's (1990) estimates of winter ET based on the Penman Combination method were 1.5 to 4 times greater than our estimates of winter ET. Duell's (1990) study assumed that vegetation cover did not change interannually, an assumption arousing skepticism; however, his results and those from this study show a similar relationship between ET from groundwater and vegetation cover (Fig. 7a). Duell's (1990) results and those from this study also show a similar relationship between ET from groundwater and Z_{wt}, except for Duell's (1990) site A, which had relatively high ET from groundwater despite having a relatively deep water table during both years of his study (Fig. 7b). We cannot explain why this site deviates from the otherwise consistent relationship between ET from groundwater and Z_{wt} observed at other sites.

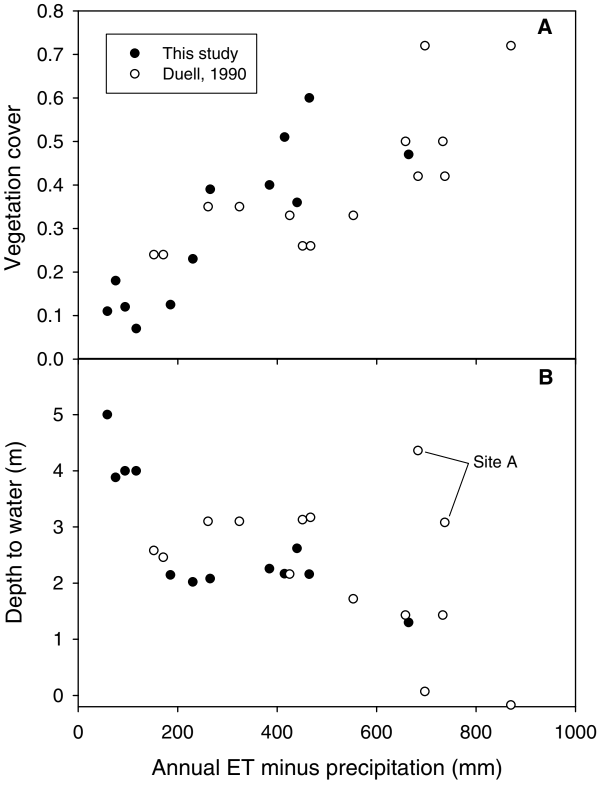

Figure 7 Comparison of annual ET measured in this study and in Duell's (1990) study in the Owens Valley as a function of plant cover (A) and Z_{wt} (B). Data presented are annual ET minus water year precipitation.

Conclusions

The portion of transpiration of desert phreatophytes derived from the water table was estimated from a growing season water balance as the difference between measured ET, soil water depletion, precipitation, and evaporation. Growing season ET ranged from 53 to 646 mm among all sites and years; average non-growing season ET was small, approximately 40 mm. Groundwater uptake by plants during the growing season accounted for 60—81% of ET for high cover meadows with water table depths of 1—3 m (sites AM1 and AM2). Groundwater uptake during the growing season accounted for 35—67% of ET in communities of mixed grasses and shrubs (sites SBM and RBM). At shrub-dominated sites (RBS, SBS, and DSS), groundwater uptake accounted for 21—33% of ET. The differing dependence on groundwater suggests that relative to the shrub-dominated plant communities, meadows may be particularly sensitive to declines in water levels.

Estimates of the amount of groundwater transpired determined from seasonal water table fluctuations one site were comparable to values obtained from closure of the water balance for the site with coarse-textured soil. The agreement between the two methods for a site with finer-textured soil was poor. This was attributed to the relative importance of plant uptake causing S_y to deviate from estimates based on translation of the characteristic curve. The effect would be expected to be larger in fine-textured soils where the volume of water available for uptake following water table decline is greater. Even though quantitative estimates of ET from diurnal fluctuations in water levels may be problematic for some sites, the essential function of groundwater uptake in phreatophytic ecosystems can be readily observed. The disappearance of diurnal fluctuation could provide early warning of plant stress induced by decoupling the water table from plant roots to guide groundwater management.

Groundwater management often attempts to minimize environmental impacts from altered water table conditions. Modeling impacts of groundwater management on phreatophytes depends on accurate relationships defining the groundwater uptake as leaf area and water table depth vary. In this study, the ratio of groundwater transpired to

LAI was correlated to Z_{wt}, but one site with similar water table conditions deviated from the relationship apparently because LAI responded strongly to availability of soil water at shallow depths from higher winter precipitation. Future work should focus on generalization of the plant uptake partitioning results to include a broader range of conditions including varying water levels and derivation of general relationships for water use predictions to aid groundwater management (Or and Groeneveld, 1994). Corroboration of the water balance results from this study could be obtained by pairing water balance measurements with more direct methods to track water uptake using tracers such as naturally occurring isotopes.

Estimates of annual ET_{gw} have potentially important applications for the development of basin scale groundwater models. Groundwater ET is often a large but poorly quantified component of the groundwater budget of basins in the western US. Future work for the Owens Valley could include combining field estimates of ET with remotely sensed images to construct spatial estimates of ET to incorporate into existing groundwater models. Further, groundwater models often rely on a function based on water table depth and presumed rooting depths to vary ET_{gw}. Relationships like that in Fig. 7 could substitute for poorly defined or arbitrary functions in models for regions dominated by these plant communities.

Acknowledgements

Funding for this research was provided by the California Department of Water Resources under Grant Agreement No. 460001827, Inyo County, and the Los Angeles Department of Water and Power. The authors wish to thank two anonymous reviewers for their valuable comments and suggestions on the manuscript.

References

Arya, S.P., 2001. Introduction to Micrometeorology, second ed. Academic Press.

Berger, D.L., Johnson, M.J., Tumbusch, M.L., 2001. Estimates of evapotranspiration from the Ruby Lake National Wildlife Refuge Area, Ruby Valley, Northeastern Nevada, May 1999–October 2000. USGS Water Resources Investigations Report 01-4234.

Bonham, C.D., 1989. Measurements for Terrestrial Vegetation. John Wiley and Sons, New York, NY.

Branson, F.A., Miller, R.F., McQueen, I.S., 1976. Moisture relations in twelve northern desert shrub communities near Grand Junction, Colorado. Ecology 57, 1104–1124.

Campbell Scientific Inc., 1998. Eddy Covariance System Operator's Manual CA27 and KH20, Revision 7/98.

CIMIS, 2003. California Irrigation Management Information System. Agriculture and Water Conservation Section, Department of Water Resources, Sacramento, CA.

Devitt, D.A., Sala, A., Mace, K.A., Smith, S.D., 1997. The effect of applied water on the water use of saltcedar in a desert riparian environment. J. Hydrol. 192, 233–246.

Donovan, L.A., Richards, J.H., Muller, M.W., 1996. Water relations and leaf chemistry of *Chrysothamnus nauseousus* spp. *consimilus* (Asteracea) and *Sarcobatus vermiculatus* (Chenopodiaceae). Am. J. Bot. 83, 1637–1646.

Donovan, L.A., Ehleringer, J.R., 1994. Water stress and use of summer precipitation in a Great Basin shrub community. Funct. Ecol. 8, 289–297.

Duell, L.W.F., 1990. Estimates of evapotranspiration in alkaline scrub and meadow communities of the Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods. USGS Water Supply Paper 2370-E.

Gardner, W.R., 1958. Some steady state solutions of the unsaturated moisture flow equation with applications to evaporation from a water table. Soil Sci. 85, 228–232.

Goodall, D.W., 1952. Some considerations in the use of point quadrats for the analysis of vegetation. Aust. J. Sci. Res. 5, 1–41.

Goodrich, D.C., Scott, R., Qi, J., Goff, B., Unkrich, C.L., Moran, M.S., Williams, D., Schaeffer, S., Snyder, K., MacNish, R., Maddock, T., Pool, D., Chebouni, A., Cooper, D.I., Eichinger, W.E., Shuttleworth, W.J., Kerr, Y., Marsett, R., Ni, W., 2000. Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. Ag. For. Met. 105, 281–309.

Groeneveld, D.P., 1997. Vertical point quadrat sampling and an extinction factor to calculate leaf area index. J. Arid Environ. 36, 475–485.

Horton, J.L., Hart, S.C., 1998. Hydraulic lift: a potentially important ecosystem process. Tree 13, 232–235.

Hultine, K.R., Williams, D.G., Burgess, S.S.O., Keefer, T.O., 2003. Contrasting patterns of hydraulic redistribution in three desert phreatophytes. Oecologia 135, 167–175.

Hultine, K.R., Scott, R.L., Cable, W.L., Goodrich, D.C., Williams, D.G., 2004. Hydraulic redistribution by a dominant, warm-desert phreatophyte: seasonal patterns and response to precipitation pulses. Funct. Ecol. 18, 530–538.

Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci. 5, 482–488.

Laczniak, R.J., DeMeo, G.A., Reiner, S.R., Smith, J.L., Nylund, W.E., 1999. Estimates of ground-water discharge as determined from measurements of evapotranspiration, Ash Meadows area, Nye County, Nevada. US Geological Survey Water-Resources Investigations Report 99-4079, 70pp.

Lee, C.H., 1912. An intensive study of the water resources of a part of the Owens Valley, California. USGS Water Supply Paper 294.

Loheide, S.P., Bulter, J.J., Gorelick, S.M., 2005. Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: a saturated–unsaturated flow assessment. Water Resour. Res. 41, W07030. doi:10.1029/2005WR003942.

Malek, E., Bingham, G.E., McCurdy, G.D., 1990. Evapotranspiration from the margin and moist playa of a closed desert basin. J. Hydrol. 12, 15–34.

Meyboom, P., 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. J. Hydrol. 4, 38–62.

Nachabe, M.N., 2002. Analytical expressions for transient specific yield and shallow water table drainage. Water Resour. Res. 3 (10), 1193. doi:10.1029/2001WR00107.

Nichols, W.D., 1993. Estimating annual ground-water discharge by greasewood in areas of shallow groundwater in the northern Great Basin using an energy-combination model. Water Resour. Res. 29, 2771–2778.

Nichols, W.D., 1994. Groundwater discharge by phreatophyte shrubs in the Great Basin as related to depth to groundwater. Water Resour. Res. 30, 3265–3274.

Nichols, W.D., 2000. Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada. USGS Prof. Paper 1628.

Or, D., Groeneveld, D.P., 1994. Stochastic estimation of plant–available soil water under fluctuating water table depths. J. Hydrol. 163, 43–64.

Pruitt, W.O., Doorenbos, A., 1977. In: Proceedings of the International Round Table Conference on Evapotranspiration, Budapest, Hungary.

Reiner, S.R., Laczniak, R.J., DeMeo, G.A., LaRue Smith, J., Elliot, P.E., Nylund, W.E., Fridrich, C.J., 2002. Ground-water discharge determined by measurements of evapotranspiration, other available hydrologic components, and shallow water-level changes, Oasis Valley, Nevada, US Geological Survey Water Resources Investigations Report 01-4239.

Richards, J.H., Caldwell, M.M., 1987. Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. Oecologia 73, 486–489.

Robinson, T.W., 1958. Phreatophytes. US Geological Survey Water-supply Paper 1423, 83pp.

Robinson, T.W., 1970. Evapotranspiration by woody phreatophytes in the Humboldt River Valley near Winnemucca, Nevada. US Geological Survey Prof. Paper 491-D, 41pp.

Salas, J.D., Delleur, W., Yevjevich, V., Lane, W.L., 1980. Applied Modeling of Hydrologic Time Series. Water Resource Publications, Fort Collins, CO.

Scott, R.L., Edwards, E.A., Shuttleworth, W.J., Huxman, T.E., Watts, C., Goodrich, D.C., 2004. Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. Ag. For. Met. 122, 65–84.

Scott, R.L., Shuttleworth, W.J., Goodrich, D.C., Maddock III, T., 2000. The water use of two dominant vegetation communities in a semiarid riparian ecosystem. Ag. For. Met. 105, 241–256.

Snyder, K.A., Richards, J.H., Donovan, L.A., 2003. Night-time conductance in C_3 and C_4 species: do plants lose water at night? J. Exp. Bot. 54, 861–865.

Snyder, K.A., Williams, D.G., 2000. Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. Ag. For. Met. 105, 227–240.

Sorenson, S.K., Dileanis, P.D., Branson, F.A., 1991. Soil water and vegetation responses to precipitation and changes in depth to ground water in Owens Valley, California. US Geological Survey Water Supply Paper 2370-G.

Sperry, J.S., Hacke, U.G., Oren, R., Comstock, J.P., 2002. Water deficits and hydraulic limits to leaf water supply. Plant Cell Environ. 25, 251–263.

Steinwand, A.L., Harrington, R.F., Groeneveld, D.P., 2001. Transpiration coefficients for three Great Basin shrubs. J. Arid Environ. 49, 555–567.

Stuff, R.G., Dale, R.F., 1978. A soil moisture budget model accounting for shallow water table influences. Soil Sci. Soc. Am. J. 42, 637–643.

Trent, J.D., Blank, R.R., Young, J.A., 1997. Ecophysiology of temperate desert halophytes: *Allenrolfia occidentalis* and *Sarcobatus vermiculatus*. Great Basin Nat. 57, 57–65.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Ag. For. Met. 103, 279–300.

Wallender, W.W., Grimes, D.W., Henderson, D.W., Stromberg, L.K., 1979. Estimating the contribution of a perched water table to the seasonal evapotranspiration of cotton. Agron. J. 71, 1056–1060.

Wan, C.G., Sosebee, R.E., McMichael, B.L., 1993. Does hydraulic lift exist in shallow-rooted species — A quantitative examination with a half-shrub *Gutierrezia sarothrae*. Plant Soil 153, 11–17.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Quart. J. R. Meteorol. Soc. 106, 85–100.