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Research paper

Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community

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Abstract

Evapotranspiration rates and the ground water component of evapotranspiration at a site in Colorado's San Luis Valley that is dominated by shrubby phreatophytes (greasewood and rabbitbrush) were compared before and after a water table drawdown. Evapotranspiration (ET) rates at the site were first measured in 1985–1987 (pre-drawdown) when the mean water table depth was 0.92 m. Regional ground water pumping has since lowered the water table by 1.58 m, to a mean of 2.50 m. We measured ET at the same site in 1999–2003 (post-drawdown), and assessed physical and biological factors affecting the response of ET to water table drawdown. Vegetation changed markedly from the pre-drawdown to the post-drawdown period as phreatophytic shrubs invaded former wetland areas, and wetland grasses and grass-like species decreased. Lowering the water table reduced estimated total annual ET from a mean of 409.0 to 278.0 mm, a decrease of 32%, and the ground water component of ET (ET_g), from a mean of 226.6 to 86.5 mm, a decrease of 62%. Two water table depth/ET models that have been used in the San Luis Valley overestimated the reduction in ET_g due to lowering the water table by as much as 253%. While our results corroborate the generally observed negative correlation between ET rates and water table depth, they demonstrate that specific models to estimate ET as a function of water table depth, if not verified, may be prone to large errors. Both the water table drawdown and the vegetation change are continuing 20 years after the drawdown began, and it is unclear how site ET rates and processes will differ after the water table has stabilized and vegetation has adjusted to the new site hydrologic conditions.

Keywords: Ground water; Evapotranspiration; Water table decline; Phreatophytes; San Luis valley

1. Introduction

The increasing human population of the intermountain West has increased demand for water, making the proper management of water resources critical. Ground water models are being developed in many regions of the West to guide water management, and they must account for evapotranspiration (ET), which can be a major depletion of ground water (Emery et al., 1973; Nichols, 1994; Laczniak et al., 1999), particularly in areas dominated by

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phreatophytes, plants that obtain at least some water from shallow ground water. In arid regions, the area of non-riparian phreatophytes may be very large. For example, the native phreatophytic shrub greasewood (*Sarcobatus vermiculatus* (Hooker) Torrey) occupies an area of at least 4.8 million hectares in western North America (Shreve, 1942).

Short- and long-term water table declines can be produced by ground water pumping, the diversion of streams that recharge ground water, as well as climate variation and change. Water table depth is often cited as a principal factor controlling ET rates in phreatophyte communities (Robinson, 1958; Emery, 1970; Sala et al., 1996; Devitt et al., 2002; Nichols, 2000); however, little is known about this response. Thus, it is hard to predict changes in ET rates for any site that could result from a change in the position of the water table. Higher ET rates commonly occur in sites with the shallowest water tables, and lower ET rates in sites with deeper water tables (Robinson, 1958; Duell, 1990; Nichols, 1994). This apparently straightforward relationship has led to the use of single water table depth/ET functions (Emery, 1970), or suites of functions (Nichols, 1994; Nichols, 2000) to estimate site ET from ground water. Such functions are attractive because they make intuitive sense, are simple to apply, and they allow the estimation of annual ground water ET for any site using a simple measurement of water table depth. In addition, these functions can be applied at the landscape scale using maps of water table depth, calculated with models such as Modflow (Harbaugh et al., 2000; McDonald and Harbaugh, 2003).

The hypothetical water table depth/ET relationship has been used to quantify water that could be ‘salvaged’ from phreatophytes by pumping the water table to depths below plant root zones (Emery, 1970; US Bureau of Reclamation, 1987). However, this relationship does not consider other factors that can influence or control site ET rates, such as plant canopy cover (Nichols, 2000), leaf area (Sala et al., 1996), and community composition (DeMeo et al., 2003), all of which are affected by soil salinity, soil water holding capacity, and nutrient availability. In addition, most studies of water table depth/ET relationships have measured ET at multiple sites with different water table depths, and different soil and vegetation characteristics as well (Eakin, 1960; Everett and Rush, 1964; Eakin et al., 1967; Nichols, 1994; Nichols, 2000). The short-term and long-term ecological responses of phreatophyte communities to water table change have rarely been investigated.

Phreatophytes respond in a variety of ways to water table decline, but both the magnitude and rate of water table decline can affect vegetation, and thus ET response. Rapid declines of even 1 m under riparian phreatophytes, such as cottonwood (*Populus deltoides* Marshall), or mesquite (*Prosopsis* spp.), can cause significant short-term (Cooper et al., 2003) or long-term (Scott et al., 1999) changes in leaf area, branch density, or whole plant density. Lowered water tables have been found to reduce plant xylem pressure potential, and cause subsequent canopy dieback and mortality when a threshold water depth was reached (Horton et al., 2001), and root system dieback triggered branch dieback and leaf reduction (Williams and Cooper, 2005). Reductions in leaf area and plant density would likely reduce stand ET rates (Sala et al., 1996). Water table changes may not, however, affect plant density or leaf area of all species. For example salt cedar, *Tamarix ramosissima* Ledeb., may not be completely dependant upon ground water availability and is considered a facultative phreatophyte (Busch et al., 1992). Thus, depending upon the initial vegetation and depth to water table, a permanent water table decline may result in vegetation changing from obligate phreatophytes, to facultative phreatophytes, to non-phreatophytic upland species (Stromberg et al., 1996).

Less is known about the potential responses of non-riparian phreatophytes to changing water table depth. The growth and leaf area of the widespread phreatophytes greasewood and rabbitbrush (*Ericameria nauseosa* (Pallas ex Pursh) Nesom and Baird) is controlled by soil water recharged by precipitation as well as capillary water rising from the water table (Sorenson et al., 1989). However, an experiment to lower the water table in an area with shallow ground water in the Owens valley, California, found that plant cover was reduced at some sites but not for all species (Sorenson et al., 1989). In addition, Charles (1987) found that greasewood was affected by a water table decline, but rabbitbrush was not in the San Luis valley, Colorado. The response of some, but not all species, may occur because phreatophytes, such as greasewood, may use largely precipitation-recharged soil water in certain seasons (Chimner and Cooper, 2004), and rabbitbrush may be able to grow without using ground water. In addition, greasewood roots can reach to at least 18 m depth (Robinson, 1958), and it may respond to a water table decline by growing deeper roots.

In 1985, the US Geological Survey (USGS) initiated a study to investigate the coupling of ET rates with water table depth in the San Luis Valley (SLV) in southern Colorado (Stannard and Weaver, 1995). Extensive areas in the SLV are dominated by greasewood and rabbitbrush in sites with shallow (1–5 m depth) water tables. Their study sites were within the US Bureau of Reclamation closed basin project area, where large scale ground water pumping was to be initiated in 1986 with an expected water table decline of 1.2–2.4 m (US Bureau of Reclamation, 1987). ET rates were measured at USGS site 1 for several days each month during the 1985–1987 growing seasons (the pre-drawdown period).

The closed basin project has now been pumping for more than a decade and significant water table decline has occurred. We occupied Stannard and Weaver's USGS site 1 to measure ET rates from 1999–2003 (the post-drawdown period) to determine the effects of water table drawdown on site physical and ecological characteristics. The goals of our study were to: (1) characterize ground water levels over the past 25 years at USGS site 1, (2) quantify site ET rates, (3) compare daily ET rates and seasonal and annual ET totals of the pre-drawdown and post-drawdown periods, (4) determine whether vegetation changes have occurred, (5) evaluate ET/water table depth functions that have been used in SLV, and (6) use our analyses to evaluate the use of ET curves for estimating ground water 'salvage' that results from lowering water tables under phreatophytic communities.

2. Study area

The SLV is a high elevation (2300 m) basin located between two 4000-m elevation mountain ranges: the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west (Fig. 1). The valley floor, which is nearly flat, extends 160 km north to south and 70 km east to west. The northern 7600 km^2 of the SLV is a closed basin. It receives inflow from the adjacent mountains, but there are no natural surface or

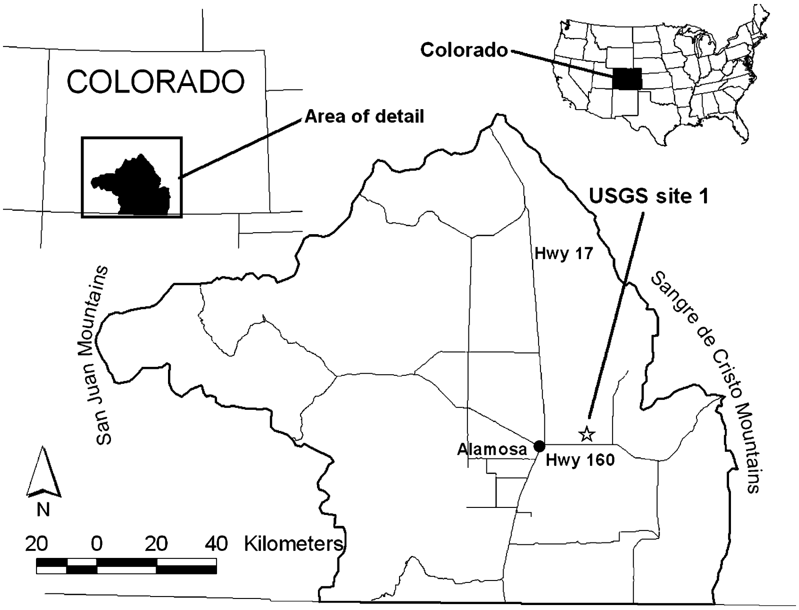

Fig. 1. Location of the San Luis valley in southern Colorado.

ground water outflows. Prominent land uses include intensive irrigated agriculture on arable land and livestock grazing in wet meadows and shrublands.

The SLV has warm summers, cold winters, and abundant sunshine. Average annual precipitation on the valley floor ranges from 180 to 250 mm, with approximately 2/3 of the precipitation falling as monsoon rains in July through September (Doesken et al., 1984). The surrounding mountains receive mean annual precipitation of 800–1500 mm, falling largely as snow, and snowmelt runoff supports numerous streams that are perennial in their mountain reaches. However, once these streams reach mountain front alluvial fans they recharge ground water and only intermittently flow onto the valley floor. Historically, streams that emerged onto the valley floor supported extensive wetland complexes, although these streams have been diverted over the past 130 years to provide irrigation water for hay production. Ground water recharge from these streams supports shallow (1–5 m deep) water table depths across much of the San Luis Valley floor (Crouch, 1985).

USGS site 1 is located 15.7 km east-northeast of Alamosa, Colorado (NW 1/4 SE 1/4 of Section 30, T38N, R12E; UTM Zone 13, N438664 m, E4151379 m, NAD27 datum; Fig. 1). The site supports a complex of small playas (shallow seasonal ponds) and low sand dunes vegetated by greasewood and rabbitbrush shrubs up to 1.5 m tall. Playas support herbaceous vegetation dominated by saltgrass (*Distichlis spicata* (L.) Greene) and rush (*Juncus arcticus* Willd.) up to 30 cm tall. This assemblage of shrub phreatophytes is widespread across western North America, dominating the vegetation of valley floors from the SLV westward across the basin and range province to the Owens Valley of California.

3. Methods

3.1. Data collection and calculation of evapotranspiration

Evapotranspiration during the post-drawdown period was measured continuously for several days per month during each study year, and calculated using the Bowen ratio energy balance (BREB) method (Tanner, 1960; Fritschen and Simpson, 1989; Moncrieff et al., 2000), using a micrometeorological system from Radiation Energy Balance Systems Inc. (REBS Inc., Bellevue, WA, see Fritschen and Simpson, 1989). Platinum resistance elements were used to measure temperature in the atmosphere and the cavity where humidity was measured. Humidity was measured with a hydroscopic polymer capacitance chip. Net radiation (R_n) was measured with a REBS, Inc. Q*7.1 Net radiometer, which is sensitive to wavelengths from 0.25 to 60 μm. It was deployed and leveled ~2.5 m above the ground surface and oriented due south. Soil heat flux (G) was measured using two heat flow transducers buried 5 cm below the ground surface, and two 10 cm-long soil temperature probes buried at a 45° angle that measured heat storage in the top 5 cm of soil. Humidity and temperature sensor pairs were vertically separated by 1 m. Measurements were made every 15 s and averaged over 15 min intervals. To remove bias between sensors, their positions were exchanged every 15 min using an automated system. ET was calculated for 30 min intervals and summed over each 24-h period.

Several assumptions are implicit in using the energy balance approach (Duell, 1990; Stannard and Weaver, 1995; Fritschen and Simpson, 1989). These assumptions appear to be met when the vegetation is relatively short and uniform, as it is at the study site.

Ohmura (1982) discusses conditions under which the BREB method produces counter-gradient or extremely inaccurate latent heat fluxes. These errors typically occur near sunrise and sunset, and occasionally during the night, when the true values of H and λET are small (Ohmura, 1982). If these errors occurred at night, when λET in the SLV is typically expected to be zero, λET was set to zero. If these errors occurred during sunrise or sunset, λET was modeled by linear interpolation from temporally proximate values.

During the pre-drawdown period, ET was measured continuously for several days per month using both the BREB method and the eddy correlation (EC) method (Stannard and Weaver, 1995). For the BREB method, two wet-bulb and dry-bulb psychrometers separated by 1 m were sampled every 2 s, and 5-min averages were recorded. Psychrometers were physically exchanged every 5 min to remove instrument bias. ET was calculated for 10-min intervals and summed for each 24-h period. When ET was measured using both methods on a given day, the energy balance value was used in this study. If an energy balance value was not available, a value calculated using eddy correlation was used. Using data calculated using different ET methods was considered acceptable because Stannard and Weaver (1995) found high correlation and minimal bias between the methods.

A shallow ground water monitoring well was installed at the study site in the early 1980's and water levels were measured regularly from 1985 through 1987, and again during 1999 through 2001 and in 2003. Monthly water table depths measured from 1975 through 2001 at Rio Grande Water Conservation District (RGWCD) monitoring well 59a, located approximately 1 km SW of the study site, were used to identify trends in regional water table depth.

In the pre-drawdown period, rainfall was measured using an unshielded Sierra Misco model 2501 tipping-bucket rain gage with a sensitivity of 1 mm, and rainfalls of less than 1 mm were estimated (Stannard and Weaver, 1995). In the post-drawdown period, rainfall was measured using an unshielded Texas instruments 8″ tipping-bucket rain gage with a sensitivity of 0.254 mm. Because ET measurements were made primarily during the growing season during both periods, snowfall was not measured. Precipitation on days lacking on-site measurements were assumed equal to amounts reported at the national weather service station in Alamosa, Colorado, 15.7 km SE of the site.

Soil moisture was measured in the pre-drawdown period using the neutron scattering method (Bowman and King, 1965) at 15-cm intervals down the soil profile and calibrated using soil samples collected near access tubes (Stannard, 1993). During the post-drawdown period, soil moisture was measured by time domain reflectometery using Campbell scientific 615 probes, with one probe installed at 0–30 cm and 30–60 cm soil depths.

3.2. Statistical analyses of ET

Analysis of covariance (ANCOVA) was used to compare mean daily ET rates during the growing season (May 1 through September 30) of the pre-drawdown period (1985–1988) to the post-drawdown period (1999–2003). Daily ET values from all years within each period were used to calculate the mean daily rate for that period. Because at least several days were sampled in every month of both periods, as well as during both rainy and dry intervals, we assumed that overall sampling was representative of mean conditions. During an interval of 3 weeks in the post-drawdown period, equipment failure precluded ET calculation. However, ET variation in June is typically very similar to late May and early July, so we believe this gap does not pose problems with respect to sample adequacy.

For the ANCOVA, years were treated as replicates to avoid issues associated with serial correlation within a year. To account for the unbalanced design, we used the Satterthwaite adjustment for degrees of freedom and variances were calculated separately for each period. The ANCOVA was performed using the Proc mixed routine in SAS (SAS Institute, 2003) and the restricted maximum likelihood method of estimating covariance parameters.

ANCOVA allows the removal of variance from a dependent variable (in this case, ET) that cannot be predicted from the independent variable of interest (in this case, period: pre-drawdown or post-drawdown). In our study, in addition to period, three other variables contribute significantly to the variability in daily ET ($p < 0.001$ from the ANCOVA output): (1) recent precipitation, (2) seasonal leaf area changes as represented by the average of the functions presented by Stannard (1993), and (3) daily available energy. These additional variables may confound the relationship between ET and period. By accounting for them we were better able to characterize the change in ET that can be accounted for by water table decline.

In the SLV, a precipitation event can more than double daily ET, thus differences in precipitation can dramatically shift mean daily ET rates. However, the effect of a recent rain on ET in arid regions decreases rapidly and exponentially (Kurc and Small, 2004), and after several days its effect on daily ET can no longer be measured. We accounted for this pattern by representing precipitation in the ANCOVA as the sum of weighted daily precipitation for the previous 7 days. More recent precipitation was weighted more heavily, with the weight given to each daily precipitation value decreasing exponentially so that after a week the effect of precipitation was negligible. The seasonality of plant leaf area (LAI) was represented using functions developed by Stannard

(1993) from LAI measures made on site. Stannard presented separate functions for each year, but because the functions were similar and maximum LAI was within 5% between years, an average value for any given day was calculated as the mean of 1985–87 values. We used these mean values for both the pre-drawdown and post-drawdown periods to represent the seasonality of LAI change rather than the absolute value of LAI. Available energy was the measured difference between net radiation (R_n) and soil heat flux (G).

We estimated mean growing season ET by multiplying the mean growing season ET rate for the period by 153, the approximate number of days between significant leaf emergence (May 1) and senescence (September 30) for the dominant shrubby phreatophytes. Our method of comparing periods required assuming a fixed-length growing season, even though the interannual timing of leaf emergence and senescence may vary by up to 10 days. We believe the error introduced by this assumption is small because ET rates are low before May 1 and after September 30.

We estimated total mean annual ET for each period by summing the growing season estimate and an estimate of non-growing season ET (Oct 1–Apr 30), when cold temperatures and leafless plants produce low ET rates. Because transpiration is insignificant when plants are leafless and frozen soils inhibit both capillary movement of ground water to the surface and snowmelt to recharge soils, we assumed that Oct 1–Apr 30 ET was equal to winter precipitation, which, like summer precipitation, typically evaporates or sublimates shortly after falling. Annual ground water ET (ET_g) was estimated by subtracting annual precipitation from total annual ET (Malek et al., 1990; Reiner et al., 2002; DeMeo et al., 2003).

To complement the ANCOVA we compared mean daily ET rates for portions of each study period when little or no precipitation fell. We did not control for available energy, and due to the small sample size, a statistical analysis could not be performed. We identified intervals of at least three consecutive days in the pre-drawdown period where the sum of weighted daily precipitation for the previous 7 days was no more than 0.3 mm (‘rainless intervals’). We found three such intervals, one each occurring in May, June and August. In the post-drawdown period, we analyzed all ET measurement days for rainless intervals that occurred within ±2 weeks of the three pre-drawdown rainless intervals. For each data set, mean daily ET, 7-day precipitation, and available energy were calculated. We then calculated the percent difference in mean daily ET and available energy.

4. Results

4.1. Water table change

During the pre-drawdown period, the study site water table ranged from 0.42 to 1.25 m below the soil surface, with a mean of 0.92 m (Fig. 2). The post-drawdown water table ranged from 2.24 to 2.61 m depth during 1999–2003, with a mean of 2.50 m, which was 1.58 m lower than the pre-drawdown mean. From 1985 to 2003 the regional water table measured at RGWCD well 59a declined by ~2.0 m, from ~1.5 to 3.5 m below the ground surface (Fig. 3). During this period, annual variation of the water table also decreased from ~0.75 to ~0.40 m. On-site water table depths are highly correlated with RGWCD well 59a ($r^2=0.966$), suggesting that well 59a represented the magnitude of long-term water table decline and annual water table variation at the study site.

4.2. Evapotranspiration rates

ET rates at the study site during both study periods followed a seasonal pattern with a gradual rise in daily

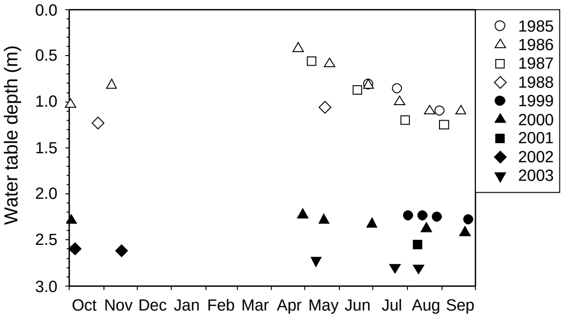

Fig. 2. Water table depth measurements at the study site during the pre-drawdown period 1985–1988 (mean water table depth = 0.92 m) and the post-drawdown period 1999–2003 (mean water table = 2.50 m). Years are ‘water years’, October 1—September 30.

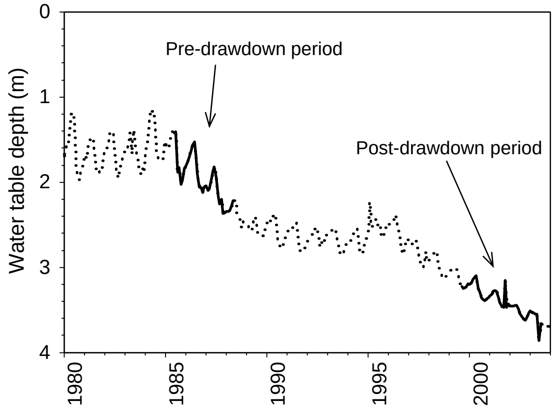

Fig. 3. Water table depth for the period 1980–2004 at RGWCD Well 59a located ~1 km SW of the study site. The pre- and post-drawdown ET measurement periods are indicated with bold lines.

ET rates through May, and highly variable daily rates from late May through August as the typically dry weather is interrupted by discrete rain events. The frequency of rain events increases from mid July through August when monsoonal flow increases the frequency and intensity of thunderstorms, creating higher daily ET rates. A steady decline in ET occurs through September (Fig. 4).

Results of the ANCOVA indicated that mean daily ET during the growing-season decreased significantly ($p<0.006$) from 2.0 mm/d for the pre-drawdown period ($n=27$) to 1.4 mm/d for the post-drawdown period ($n=157$), a decrease of 30%. The highest measured daily ET rate was 5.5 mm/d, while on several other days ET rates reached 3.0–4.0 mm/d. These high values invariably occurred following summer rains. In general, differences in daily ET rates between the pre- and post-drawdown periods were most pronounced during the annual low precipitation period of May through mid-July (see Fig. 4). The August and September similarity in ET rates between the two study periods is likely due to monsoon rains increasing ET rates in all years. The mean annual total ET was 409 mm during 1985–1987, and 278 mm for 1998–2003.

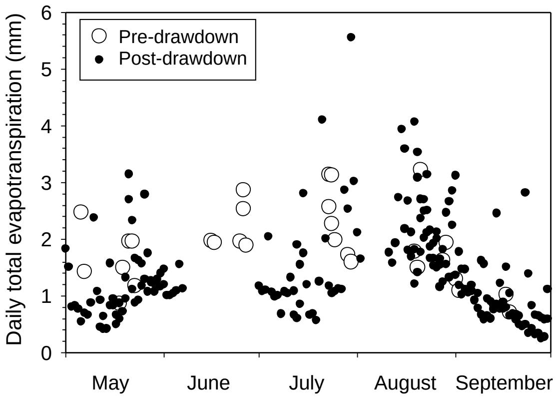

Fig. 4. Measured daily pre- and post-drawdown period evapotranspiration rates.

Table 1
Comparison of mean daily ET (mm) and available energy (MJ/m^2) during early, middle, and late summer rainless periods

Period 1:	n	ET	Energy	Precip
May 7–Jun 5				
Pre-decline	3	1.7	10.1	0.1
Post-decline	18	0.9	12.2	0.0
Difference		−0.8	2.1	
Change		−46.9%	21.3%	
Period 2: Jun 2–Jul 9				
Pre-decline	3	2.2	11.2	0.2
Post-decline	6	1.0	11.9	0.1
Difference		−1.2	0.7	
Change		−54.0%	5.9%	
Period 3: Aug 11–Sep 12				
Pre-decline	3	1.7	9.1	0.1
Post-decline	12	1.0	11.2	0.0
Difference		−0.7	2.1	
Change		−44.0%	23.2%	

Number of days ET was measured is shown as 'n'. A rainless period was defined as a period of ≤0.3 mm precipitation during the previous 7 days.

During rainless intervals, mean daily ET rates were 0.8, 1.2, and 0.7 mm/d higher during the early, middle, and late summer in the pre-drawdown than the post-drawdown periods (Table 1). The lower post-drawdown daily ET rates occurred despite available energy being 21.3, 5.9 and 23.2% higher than during the comparable pre-drawdown periods.

4.3. Ground water evapotranspiration

Our calculations of ET$_g$ are based on the assumption that there is little net change in soil water storage during a year, and our volumetric soil water content measurements support this assumption. In 1986 during the pre-drawdown period, soil water

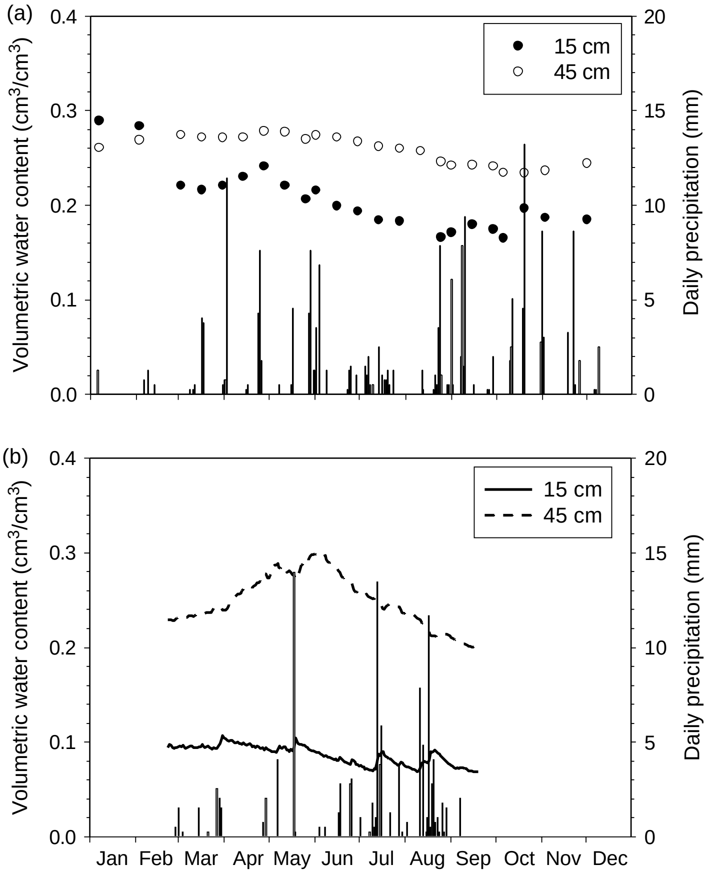

Fig. 5. Soil water content and daily precipitation during (a) the pre-drawdown year 1986, and (b) the post-drawdown year 2000.

content at 45 cm below the ground surface changed by only a few percent over the course of a year, and was essentially unchanged from January to the following December (Fig. 5(a)). In 2000 following the water table decline, soil volumetric water content at 45 cm varied from 20 to 30%, but was little changed over the year (Fig. 5(b)). Even at the shallower depth, soil water content generally stayed within a 5% range (Fig. 5(a) and (b)). At this shallower depth, soil water increased by a few percent after rainfall, but these increases dissipated within a couple of weeks.

Little long-term soil water change resulted from rainfall. This likely occurred because ET rates exceeded precipitation in every month during the study periods. Even during rainy periods, such as late-summer 2001, weekly ET totals matched or exceeded precipitation totals (Table 2), which precluded the possibility of precipitation-induced soil water recharge on this time scale. For a 7-week period that ended in late September 2001, ET was 60% greater than total precipitation.

Table 2
Weekly ET and precipitation totals (mm) for August and September 2001

Week	ET	Precip.
Aug 11–Aug 18	18.6	17.9
Aug 19–Aug 25	12.7	5.0
Aug 26–Sep 1	15.2	14.9
Sep 2–Sep 8	8.7	0.0
Sep 9–Sep 15	7.0	5.3
Sep 16–Sep 22	5.7	1.0
Sep 23–Sep 29	2.5	0.0
Totals:	70.4	44.1

When average annual precipitation (182.4 mm for 1985–1987 and 191.5 mm for 1998–2003) is subtracted from mean total annual ET for each period, the mean total annual ET_g was 226.6 mm for 1985–1987 and 86.5 mm for 1998–2001, a decrease of 62%. The post-drawdown annual ET_g of 86.5 mm, when the water table was 2.5 m below the soil surface, is within the range of values reported in similar vegetation types at similar water table depths (Eakin, 1960; Everett and Rush, 1964; Eakin et al., 1967; Robinson, 1970; Nichols, 1993; Nichols, 1994; Nichols, 2000).

4.4. Site vegetation changes

Matched ground photographs from the pre- and post-drawdown periods indicate that site vegetation has undergone a significant change in species composition and shrub distribution (Fig. 6). During the pre-drawdown period a vegetation mosaic was present, with shrubs on coppice mounds and herbaceous plants dominating playas. The high water table and periodic flooding in playas allowed wetland plants such as rush to occur within

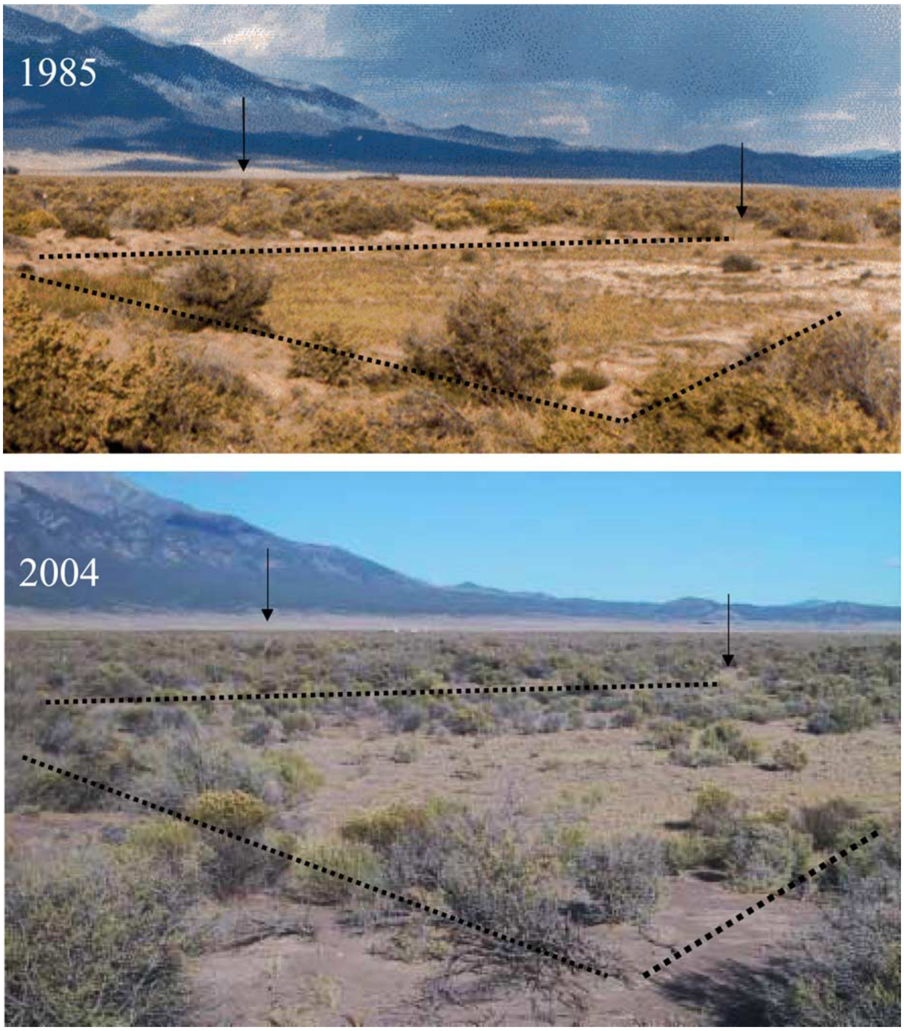

Fig. 6. Matched photographs from pre-drawdown (1985) and post-drawdown (2004) periods, looking east from the study site. The left arrow on each photograph identifies a fence post, and the right arrow identifies a gap in the vegetation. The dotted line on the lower photograph outlines the area of playa that occurs in the upper photograph and highlights the area of shrub invasion.

populations of saltgrass, while preventing colonization of the playas by greasewood and rabbitbrush, which are intolerant of periodic inundation and waterlogged soils (Groeneveld and Crowley, 1988; Groeneveld and Or, 1994). In the post-drawdown period, only sparse patches of arctic rush and saltgrass remained, while greasewood and rabbitbrush have invaded playas homogenizing site vegetation to a greater degree.

5. Discussion

5.1. Water table decline and response of ET_g

The water table from 1980 through 2003 experienced annual and interannual variation due to natural patterns of precipitation and ground water recharge. Large winter snow pack in the Sangre de Cristo Mountains during the mid-1990s caused the regional water table to rise (Fig. 3), while drought in the late-1990s and early 2000s lowered the water table and reduced its annual variability. In addition to this natural variation, a steady water table decline began in 1986 due to ground water pumping by closed basin project wells. This decline and the lowered water table will persist as long as ground water pumping continues. Leonard and Watts (1989) modeled the maximum potential closed basin project drawdown to be greater than 6 m after 20 years. However, this rate is dependent upon pumping rates, ground water availability, and project operations, and in our study area the drawdown after nearly two decades is ~2.5 m.

Many researchers have found that ET and ET_g rates and annual totals are lower in phreatophyte communities with deeper water tables. For example, Scott et al. (2000) estimated that annual ET was 374 mm on a site with ~50% mesquite cover and a water table depth of 10 m depth in the southwestern US, while on a site with 80% mesquite cover and a water Table 1–2 m deep, Unland et al. (1998) estimated ET to be 848 mm/year. Nichols (1994) presented models of ET_g from non-riparian Great basin phreatophyte communities, which indicated that ET_g decreased as an exponential function of water table depth for any vegetation cover class. In contrast, Scott et al. (2004) saw a significant decrease in ET and ET_g from a stand of mesquite despite a slight rise in mean water table depth, probably as a consequence of a decrease in leaf area following an extended drought.

A negative correlation between ET and water table depth was measured at our site. A water table decline from a mean of 0.92 m in the pre-drawdown period to 2.50 m depth in the post-drawdown period resulted in a 32% decrease in annual ET, and a 62% decrease in annual ET_g. During three rainless periods at comparable times of year, ET was an average of 48.3% lower during the post-drawdown than pre-drawdown period. The reduction in ET rates likely resulted from lowering the water table with respect to plant roots. During the pre-drawdown period, the water table was within 1.3 m of the soil surface and occasionally was within 0.5 m of the surface, so that wetland plants with shallow root systems could grow at the site. The phreatophytic shrubs that dominate the site have the majority of their root biomass within the upper 0.4 m of the soil (Cooper et al. unpublished data). A water table within ~2 m of the soil surface may have sufficient capillary rise to supply water to these plants (Chen and Hu, 2004; Chimner and Cooper, 2004). However, as the water table drops below ~2 m, only plants with deeper roots can exploit ground water. During the post-drawdown period, the water table was always greater than 2 m depth and exceeded 2.8 m in 2003.

At shallow water table depths, capillary rise of ground water also contributes to ET through direct evaporation from the soil surface (Charles, 1987). This results in both water loss and the deposition of dissolved salts on the soil surface, which increases soil salinity and site albedo, both of which can decrease ET.

Our data over the first 18 years of water table drawdown support a general relationship between water table depth and ET, however we also found that existing models based on this simple relationship may result in large errors in the estimation of ET_g. For example, curves developed by Emery (Emery, 1970, 1991) have been used for decades to model ET_g in the SLV, but both Emery models over-estimated total annual ET_g from our study site, as well as the reduction in ET_g that occurred due to the water table drawdown (Table 3, Fig. 7). The measured mean annual pre-drawdown ET_g was 226.6 mm, while the 1970 Emery curve and 1991 modified Emery curve predicted total annual ET_g of 577.8 and 374.8 mm,

Table 3
Water table depth (m), predicted ET_g using Emery's 1970 and 1991 curves, and measured ET_g for the pre-decline (1985–1987) and post-decline (1999–2003) periods

Period	Depth	Predicted ET_g 1970 Emery	Predicted ET_g 1991 Emery	Measured ET_g
Pre-decline	0.92	577.8	374.8	226.6
Post-decline	2.50	178.9	178.9	86.5
ET_g decrease		398.9	195.9	140.1

All ET values are in mm.

over-estimates of 155 and 65%. The post-drawdown mean annual ET_g was 86.5 mm, while both Emery curves predicted annual ET of 178.9 mm, an over-estimate of 92.4 mm, or 107%. The actual reduction in ET_g (ET salvage) resulting from the water table decline has been an average of 140.1 mm/year, while the 1970 and 1991 Emery curves predicted an annual reduction in ET_g of 398.9 mm and 195.9 mm, over-estimates of 185 and 40%.

The overestimates predicted by the Emery curves could have resulted from several sources. The curves could represent the correct form of the response, an exponential decline, but with an incorrect intercept. A line segment between the two data points we present has a slope similar to the 1991 Emery curve, suggesting that a revised intercept for that curve may be sufficient for modeling ET_g. However, evidence from several studies indicates that water table depth alone does not control phreatophyte community ET_g rates, as suggested by Weeks et al. (1987). Harr and Price (1972) determined that ET from a greasewood-cheat grass community was a function of water table depth when the water table was within 2.3 m of the ground surface, but at water table depths from 2.3 to 14 m the factors controlling evapotranspiration were more complex. Nichols (1994, 2000) suggested that plant density should be used in combination with water table depth to predict ET_g, and analyses of phreatophytic *Tamarix* communities indicated that stand leaf area was an important control on ET rates (Sala et al., 1996).

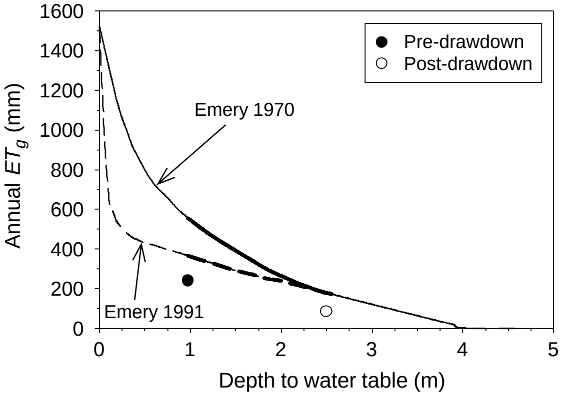

Fig. 7. Estimated annual ground water ET (ET_g) at the study stie along with Emery's 1970 and 1991 curves of ground water consumption as a function of water table depth. Bold sections on the Emery curves show the 1.58 m water table decline we measured at our study site.

5.2. Vegetation response to water table decline and implications for ET_g

The lower water table likely decreased soil evaporation due to capillary rise, as well as water availability in the upper soil horizons, where most plant roots occur. This could trigger changes in plant species at the study site. Because ET_g is largely through transpiration, changes in plant species composition or plant cover at any site could change long-term ET rates, but vegetation changes due to hydrologic changes are difficult to predict (Sorenson et al., 1989; Scott et al., 1999). Drought tolerant plant species may survive decades under conditions of a declining water table with only reduced leaf area (Cooper et al., 2003), while other plants may experience a significant canopy dieback or death (Stromberg et al., 1996; Scott et al., 1999; Williams and Cooper, 2005). Some plant species could grow roots to access deeper water tables (Sorenson et al., 1991), but in cases of substantial hydrologic changes, the entire plant community can change from phreatophytes or facultative phreatophytes to plants with no dependency on the water table (Merritt and Cooper, 2000). Many riparian phreatophytes respond to relatively small changes in water table depth. For example, a water table decline of 1 m caused leaf and twig death, reduced leaf area, and whole plant death in plains cottonwood (Scott et al., 1999; Cooper et al., 2003). However, greasewood and rabbitbrush on our study sites are likely less sensitive to water table declines of this magnitude.

Initial site conditions may influence how a water table decline affects site vegetation. At our study site the pre-decline water table was near the ground surface (Weaver et al., 1986), creating wet-soil conditions that supported rush and saltgrass. In the western US, such wet areas are shrub-free due to high water tables and periodic inundation, which greasewood and rabbitbrush cannot survive (Groeneveld and Crowley, 1988). A water table decline creates perennially dry soils, and the deeper water table precludes salt accumulation at the soil surface, allowing precipitation to leach salts to deeper soil depths, resulting in drier, less saline soils, and creating conditions where rabbitbrush and greasewood can survive. Both of these species have invaded the former playas at our study site.

Greasewood and rabbitbrush can extend roots to considerable depth for ground water acquisition. Greasewood rooting depths of 11 (Robertson, 1983; Mozingo, 1987) to 18 m (Robinson, 1952) have been reported. In the Great basin desert of Nevada, rabbitbrush grows where the water table is within 10.5 m of the ground surface (Nichols, 1994), but in the SLV rabbitbrush also occurs on sites where the water table is more than 15 m deep. In the formerly shrub-free playas, the invading shrubs may have the capacity to acquire ground water from a much deeper water table than the herbaceous plants that previously dominated the site.

As the shrubs mature and their size increases, site leaf area also will increase, and they may grow roots that can acquire water from the water table. Thus, it is possible that the ET decrease we have measured in the post-drawdown period could be a short-term phenomenon. Shrubs invasion into the former playas, and their growth and development of deep root systems over several decades, could result in a rise in ET rates, and the difference between pre-drawdown and post-drawdown period ET could diminish, thus reducing water available for ET salvage.

6. Conclusions

During our 19-year study period, the water table dropped from an annual mean of 0.92 to 2.50 m below the ground surface, and resulted in decreases of 32% in ET, and 62% in ET_g. While this reduction in ET_g is large, it is considerably less than would be predicted using ET/water table depth curves that have been developed for our study area (Emery, 1970; Emery, 1991). Along with the decrease in ET, the lowered water table triggered changes in site vegetation composition, coverage, and likely rooting characteristics. Flood-intolerant shrubs with different water acquisition and water use patterns have invaded playas formerly dominated by wetland grasses and other non-woody species, and these changes will likely continue for several decades because the invading shrubs are slow growing. While the leaf area of shrublands may be lower than grasslands in some portions of the world (Mahfouf et al., 1996), yielding lower ET rates, it is unclear that this is the case at our study site, where the former plant community had relatively low leaf area. The invading shrubs have deeper roots than the herbaceous plants they are replacing, and have a greater capacity to access deeper water tables. It is unclear how quickly the roots of shrubs can elongate to access the declining water table. These ongoing site changes suggest that the long-term pattern of site ET will likely continue to change and it is impossible to predict how the long-term, post-drawdown ET rates will compare to the pre-drawdown ET rates. Our analyses indicate that simple hydrologic changes, such as a directional water table drawdown, may trigger a complex set of changes in site soil water dynamics and vegetation succession that will ultimately control site ET rates and processes.

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References

Bowman, D.H., King, K.M., 1965. Determination of evapotranspiration using the neutron scattering method. Canadian Journal of Soil Science 45, 117–126.

Busch, D.E., Ingraham, N.L., Smith, S.D., 1992. Water uptake in woody riparian phreatophytes of the southwestern United States: a stable isotope study. Ecological Applications 2, 450–459.

Charles, F.L., 1987. Evapotranspiration of phreatophytes in the San Luis Valley, Colorado. MS Thesis. Colorado State University, Fort Collins, CO.

Chen, X., Hu, Q., 2004. Groundwater influences on soil moisture and surface evaporation. Journal of Hydrology 297, 285–300.

Chimner, R., Cooper, D.J., 2004. Using stable oxygen isotopes to quantify the water source used for transpiration by native shrubs in the San Luis Valley, Colorado USA. Plant and Soil 260, 225–236.

Cooper, D.J., D'Amico, D.R., Scott, M.L., 2003. Physiological and morphological response patterns of populus deltoides to alluvial groundwater pumping. Environmental Management 31, 215–226.

Crouch, T.M., 1985. Potentiometric surface, 1980, and water-level changes, 1969–80, in the unconfined valley-fill aquifers of the San Luis Basin, Colorado and New Mexico. US Geological Survey Hydrologic Investigations Atlas HA-683. 2 Sheets.

DeMeo, G.A., Laczniak, R.J., Boyd, R.A., Smith, J.L., Mylund, W.E. 2003. Estimated ground-water discharge by evapotranspiration from Death Valley, California, 1997–2001. US Geological Survey Water-Resources Investigations Report 03-4254.

Devitt, D.A., Donovan, D.J., Katzer, T., Johnson, M., 2002. A reevaluation of the ground water budget for Las Vegas Valley, Nevada, with emphasis on ground water discharge. Journal of the American Water Resources Association 38, 1735–1751.

Doesken, N.J., McKee, T.B., Richter, B.D., 1984. Analysis of Colorado average annual precipitation for the 1951–1980 period. Climatololgy Report No. 84-4. Colorado Climate Center, Colorado State University, Fort Collins.

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

Eakin, T.E., 1960. Gound-water Appraisal of Newark Valley, White Pine County, Nevada. Nevada Department of Conservation and Natural Resources, Carson City, NV.

Eakin, T.E., Hughes, J.L., Moore, D.O., 1967. Water-resources Appraisal of Steptoe Valley, White Pine and Elko Counties, Nevada. Nevada Department of Conservation and Natural Resources, Carson City, NV.

Emery, P.A., 1970. Electric Analog Model Evaluation of a Water-Salvage Plan, San Luis Valley, south-central, Colorado. Colorado Water Conservation Board, Denver.

Emery, P.A., 1991. Testimony in Case No. 86CW46, District Court, Water Division No. 3, State of Colorado. November 19, 1991, transcript page 5741.

Emery, P.A., Snipes, R.J., Dumeyer, J.M., Klein, J.M., 1973. Water in the San Luis Valley, South-central Colorado. Colorado Water Conservation Board, Denver, Colorado.

Everett, D.E., Rush, F.E., 1964. Ground-water Appraisal of Smith Creek and Ione Valleys, Lander and Nye Counties, Nevada. Nevada Department of Conservation and Natural Resources, Carson City, NV.

Fritschen, L.J., Simpson, J.R., 1989. Surface energy and radiation balance systems: general descriptions and improvements. Journal of Applied Meteorology 28, 680–689.

Groeneveld, D.P., Crowley, D.E., 1988. Root system response to flooding in three desert shrub species. Functional Ecology 2, 491–497.

Groeneveld, D.P., Or, D., 1994. Water-table induced shrub-herbaceous ecotone: hydrologic management implications. Water Resources Bulletin 30, 911–920.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the US Geological Survey modular ground-water model–User guide to modularization concepts and the ground-water flow process. US Geological Survey Open-File Report 00-92.

Harr, R.D., Price, K.R., 1972. Evapotranspiration from a greasewood-cheatgrass community. Water Resources Research 8, 1199–1203.

Horton, J.L., Kolb, T.E., Hart, S.C., 2001. Physiological response to groundwater depth varies among species and with river flow regulation. Ecological Applications 11, 1046–1059.

Kurc, S.A., Small, E.E., 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico. Water Resources Research 40, 9–22.

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.

Leonard, G.J., Watts, K.R., 1989. Hydrogeology and simulated effects of ground-water development on an unconfined aquifer in the Closed Basin Division, San Luis Valley, Colorado. US Geological Survey Water-Resources Investigations Report 87-4284.

Mahfouf, J.F., Ciret, C., Ducharne, A., Irannejad, P., Noilhan, J., Shao, Y., Thornton, P., Xue, Y., Yang, Z.L., 1996. Analysis of transpiration results from the RICE and PILPS workshop. Global and Planetary Change 13, 73–88.

Malek, E., Bingham, G.E., McCurdy, G.D., 1990. Evapotranspiration from the margin and moist playa of a closed desert valley. Journal of Hydrology 120, 15–34.

McDonald, M.G., Harbaugh, A.W., 2003. The history of MODFLOW. Ground Water 41, 280–283.

Merritt, D.M., Cooper, D.J., 2000. Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regulated Rivers: Research and Management 16, 543–564.

Moncrieff, J., Jarvis, P., Valentini, R., 2000. Canopy fluxes. In: Sala, O.E., Jackson, R.B., Mooney, H.A. (Eds.), Methods in Ecosystem Science. Springer, New York, pp. 161–180.

Mozingo, H.N., 1987. Shrubs of the Great Basin: Reno. University of Nevada Press, Reno.

Nichols, W.D., 1993. Estimating discharge of shallow groundwater by transpiration from greasewood in the northern Great Basin. Water Resources Research 29, 2771–2778.

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

Nichols, W.D., 2000. Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada. US Geological Survey Professional Paper 1628.

Ohmura, A., 1982. Objective criteria for refection data for Bowen ratio flux calculations. Journal of Applied Meteorology 21, 595–598.

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

Robertson, J.H., 1983. Greasewood (*Sarcobatus vermiculatus* (Hook.) Torr.). Phytologia 54, 309–324.

Robinson, T.W., 1952. Phreatophytes and their relation to water in Western United States. Transactions, American Geophysical Union 33, 57–61.

Robinson, T.W., 1958. Phreatophytes. US Geological Survey Water-Supply Paper 1423.

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

Sala, A., Smith, S.D., Devitt, D.A., 1996. Water use by *Tamarix ramosissima* and associated phreatophytes in a Mojave desert floodplain. Ecological Applications 6, 888–898.

SAS Institute, 2003. SAS for Windows, Release 9.1. The SAS Institute Inc., Cary, NC.

Scott, M.L., Shafroth, P.B., Auble, G.T., 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23, 347–358.

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. Agricultural and Forest Meteorology 150, 241–256.

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. Agricultural and Forest Meteorology 122, 65–84.

Shreve, F., 1942. The desert vegetation of North America. Botanical Review 7, 195–246.

Sorenson, S.K., Dileanis, P.D., Branson, F.A., 1989. Soil water and vegetation responses to precipitation and changes in depth to ground water in Owens Valley, California. US Geological Survey Open-file Report 89-260.

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.

Stannard, D.I., 1993. Comparison of Penman–Monteith, Shuttleworth–Wallace, and modified Priestly–Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. Water Resources Research 29, 1379–1392.

Stannard, D.I., Weaver, H.L., 1995. Measurements of evapotranspiration, surface-energy fluxes, weather variables, and water-table depths in the Closed Basin of the San Luis Valley, Alamosa County, Colorado, 1985–88. US Geological Survey Open-file Report 93–639.

Stromberg, J.C., Tiller, R., Richter, B., 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecological Applications 6, 113–131.

Tanner, C.B., 1960. Energy balance approach to evapotranspiration from crops. Soil Science Society of America Proceedings 24, 1–9.

Unland, H.E., Arain, A.M., Harlow, C., Houser, P.R., Garatuza-Payan, J., Scott, P., Sen, O.L., Shuttleworth, W.J., 1998. Evaporation from a riparian system in a semi-arid environment. Hydrological Processes 12, 527–542.

US Bureau of Reclamation, 1987. The San Luis Valley Project–Closed Basin Division, Design and Planning of the Project. Denver, CO.

Weaver, H.L., Weeks, E.P., Campbell, G.S., Stannard, D.I., Tanner, B.D., 1986. Phreatophyte water use estimated by eddy-correlation methods. Proceedings of the Water Forum ‘86, American Society of Civil Engineers Specialty Conference, Long Beach, California, August 4–6, 1986.

Weeks, E.P., Weaver, H.L., Campbell, G.S., Tanner, B.D., 1987. Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico. US Geological Survey Professional Paper 491-G.

Williams, C.A., Cooper, D.J., 2005. Mechanisms of riparian cottonwood decline along regulated rivers. Ecosystems 8, 382–395.