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Ground water discharge by evapotranspiration in wetlands of an arid intermountain basin

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Summary To improve basin-scale modeling of ground water discharge by evapotranspiration (ET) in relation to water table depth, daily ET was measured using the Bowen ratio energy balance method during 1999–2005 in five herbaceous plant dominated wetlands in an arid intermountain basin in Colorado, USA. Three wetlands were wet meadows supplied primarily by regional ground water flow and two were playas supplied primarily by local stream flow. In wet meadows, mean daily water table depth (WTD) ranged from 0.00 m (ground surface) to 1.2 m, with low inter-annual variability. In wet meadows, annual actual ET (ET_a) was 751–994 mm, and ground water discharge from the shallow aquifer (ET_g) was 75–88% of ET_a. In playas, mean daily WTD ranged from −0.65 to 1.89 m, with high inter-annual variability. In playas, annual ET_a was 352–892 mm, and ET_g was 0–77% of ET_a. The relationship of annual ET_g to WTD was compared to existing ET_g–WTD models. For wet meadows, ET_g decreased exponentially as WTD increased from 0.13 to 0.95 m ($r^2 = 0.83$, CV = 5%, $p < 0.001$). In comparison with our findings, existing models under- and over-estimate ET_g by −30% to 47% at WTD of 0.13 m, and they under-estimate ET_g by −12% to −42% at WTD of 0.95 m. This study found that as the water table declined from near the soil surface to 0.95 m, ET_g decreased only ~26% versus 39–55% estimated by existing models. The magnitude of ET_g decrease was 220 mm, whereas existing models predicted decreases up to 700 mm (218% greater). In playas, there was no clear ET_g–WTD relationship. Instead, ET_g was strongly dependent on the surface water supply. When sufficient surface water inputs occurred to meet ET demand, ET_g was ≈0 mm/yr and independent of WTD. When inputs did not meet ET demand, ET_g was positive though highly variable at WTD up to 1.68 m.

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Introduction

In arid region intermountain basins, evapotranspiration (ET) is often the primary mechanism of water loss from shallow aquifers (Emery, 1970; Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; DeMeo et al., 2003; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007). In hydrologically closed basins (Snyder, 1962) virtually all water loss is through ET (Huntley, 1979), and a large proportion of this may be ground water from the shallow aquifer. In parts of the Great Basin of the western US, for example, 73–100% of actual evapotranspiration (ET_a) is ground water (Laczniak et al., 1999).

The ground water fraction of ET_a, termed ET_g, is a critical component of hydrologic models used to estimate water fluxes and storage in shallow aquifers. Since ground water models such as MODFLOW (Harbaugh et al., 2000; McDonald and Harbaugh, 2003) estimate WTD, relationships between ET_g and WTD are valuable for estimating ET_g across large landscapes. Several models have been proposed relating ET_g to WTD (Emery, 1970, 1991; Nichols, 2000). However, these models are based on relatively few studies and vegetation types (Emery et al., 1973).

ET data are particularly lacking for wetlands in arid regions (Laczniak et al., 1999, 2001; DeMeo et al., 2003). Despite extremely low mean annual precipitation on the floor of intermountain basins, abundant surface and ground water may flow into basins from adjacent high mountains (Walton-Day, 1996; Cooper et al., 2006) and support large wetland complexes with high ET rates (Drexler et al., 2004; Sanderson, 2006; Sanderson et al., in press). Potential ET (ET_p) can exceed mean annual precipitation by up to 10–30 times (Mifflin, 1988) and wetland ET rates can be >10 times greater than that of surrounding uplands (Laczniak et al., 2001) making wetland ET an important component of arid region water budgets. Wetland ET rates are influenced by the short- and long-term presence of surface water, variations in WTD controlled by climate variation, and human alterations of stream flow and ground water pumping (Cooper et al., 2006).

Wet meadows (Gosselink and Turner, 1978; Cooper, 1986; Carsey et al., 2003; Moreo et al., 2007) and playas (Malek et al., 1990; Laczniak et al., 2001; DeMeo et al., 2003; Sanderson, 2006; Sanderson et al., in press) are two major types of wetlands common in arid regions such as the western US. Wet meadows are ground water supported and typically have shallow WTDs throughout the year (Cooper, 1986; Carsey et al., 2003). Ground water storage varies gradually and subsequently inter-annual changes in WTD are typically small. Wet meadows are often seasonally shallowly flooded (Carsey et al., 2003), but surface ponding is only infrequently deep or prolonged. Playas occur in depressions with fine-grained soils and are filled by streams and surface runoff from snow melt or rain events (DeMeo et al., 2003; Kappen, 2004; Sanderson, 2006). In playas, surface runoff and variation in WTDs can be highly variable between years (Sanderson et al., in press). In some years water may pond deeply (up to 0.65 m in this study) for weeks or months, yet in other years there may be no ponding (Laczniak et al., 2001; Sanderson et al., in press).

Accurate estimates of ET rates are required for modeling the water budget of individual wetlands and entire intermountain basins (Poiani and Johnson, 1993; Devitt et al., 2002; CDSS, 2005), and methods and models have been developed for estimating ET_a in wetlands, many based on estimates of potential evapotranspiration (ET_p) (Winter et al., 1995; Rosenberry et al., 2004; Drexler et al., 2004). Models of ET_p have been derived using theoretical principles (Penman, 1948, 1963; Monteith, 1965), empirical relationships (Blaney and Criddle, 1950; Thornthwaite, 1948), and a combination of theory and empiricism (Priestley and Taylor, 1972). Independent measurements of ET_a for calibrating ET_p are performed using a variety of field methods (Drexler et al., 2004), including the Bowen ratio energy balance method (BREB), which is among the most commonly used and robust (Winter et al., 1995; Rosenberry et al., 2004).

Several models of ET_p have been successfully applied to wetlands (Drexler et al., 2004; Rosenberry et al., 2004) after calibration with independent measures of ET_a (Souch et al., 1996; Jacobs et al., 2002). Calibration is required for a variety of reasons. First, ET_a is strongly influenced by vegetation characteristics such as leaf area, plant height and roughness, and total plant cover and albedo (Peacock and Hess, 2004), all of which vary during the year. Second, ET_a is influenced by the presence of surface water, WTD, and soil water content, all of which vary by wetland type and may change during the year (Jacobs et al., 2002).

The objectives of this paper are to present data on ET_a and ET_g for wet meadows and playas in a large intermountain basin region of the western US, and to analyze ET_g as a function of water source and WTD. We specifically address the following questions: (1) What rates of ET_a and ET_g occur in intermountain basin wetlands? (2) How does ET_g vary with WTD? (3) Do ET_g–WTD relationships differ between wet meadows and playas? To address these questions, we measured daily ET_a and related environmental attributes over a period of 7 yr in five wetlands in Colorado's San Luis Valley (SLV).

Study area

Regional setting

The SLV is a high elevation intermountain basin covering ~8400 km^2 in southern Colorado, USA (Fig. 1; Huntley, 1979). The valley floor averages ~2350 m elevation and has little topographic relief. Peaks rise above 4000 m in both the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west. In the SLV, summers are warm (July mean = 17 °C), winters are cold (January mean = −9 °C), and insolation is high all year (Doesken and McKee, 1989; Western Regional Climate Center, 2005).

Orographic effects result in high mountain precipitation and low valley floor precipitation. Mean annual precipitation at Wolf Creek Pass (elevation 3290 m, Fig. 1) is 1153 mm, while at Center on the SLV floor (elevation 2350 m, Fig. 1) it is 177 mm (Western Regional Climate Center, 2005). The SLV is the most arid region in Colorado, and it also supports Colorado's highest concentration of wetlands (Walton-Day, 1996). This results from the abundant mountain snowfall contributing abundant surface and ground water inflows to the relatively flat valley floor.

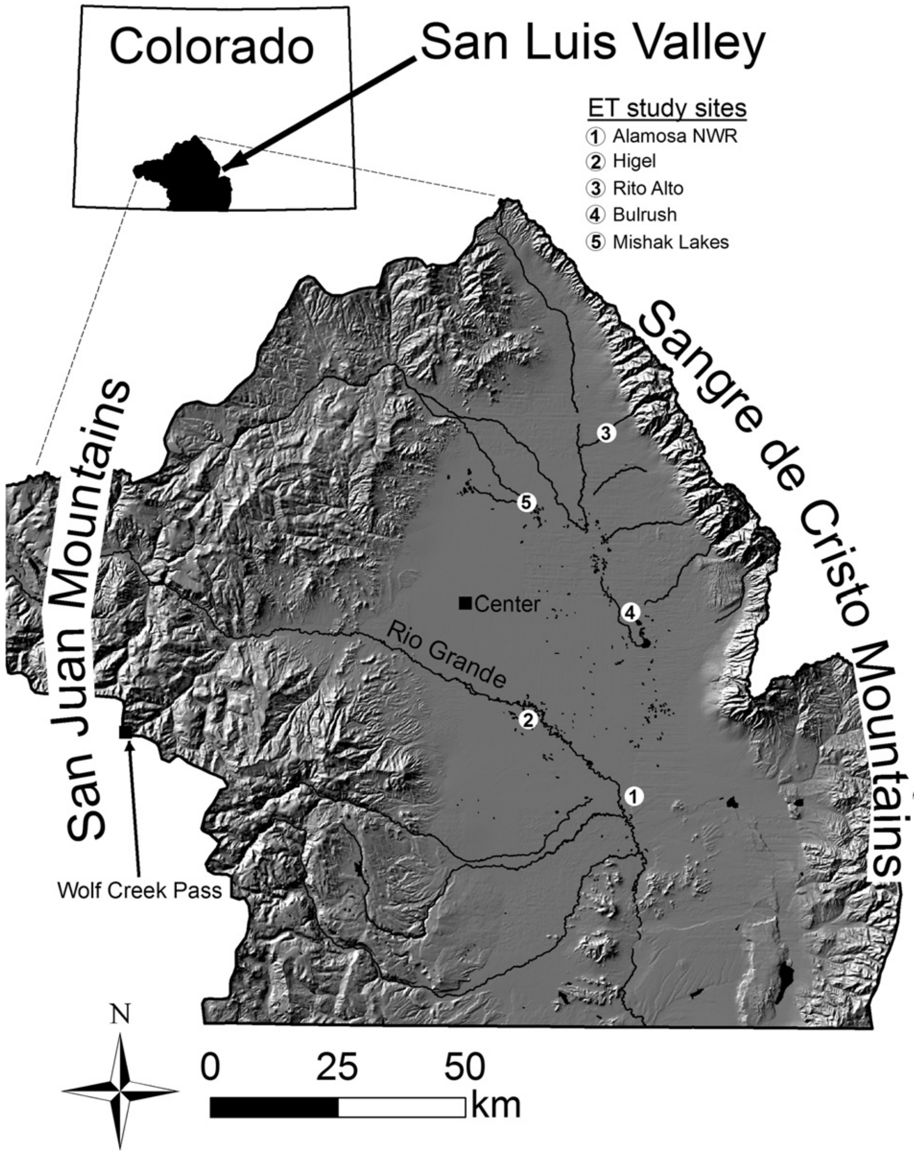

Figure 1 Study area and site locations.

The study years, 1999—2005, spanned a range of climatic conditions. In the late 1990s, the second-longest sustained wet period on record and the most drought-free period since 1890 were ending (McKee et al., 2000). Several months of moderate drought occurred in 2000, followed by a wet period from late 2000 through July of 2001. A severe drought lasted from the second half of 2001 through 2004. High snowmelt runoff and moderate rainfall followed the winter of 2004—2005, but water levels did not return to 2000 levels.

Our five study sites represented two wetland types. Three study sites (Alamosa National Wildlife Refuge, Higel, and Rito Alto; Fig. 2a—c) were wet meadows (Gosselink and Turner, 1978; Cooper, 1986; Carsey et al., 2003) that had no surface water inflow or outflows, were supported by subsurface flows, and had a water table within 1 m of the ground surface. When WTD was near zero, water was present in small (<0.2 m) pockets across the hummocky sites (Alamosa NWR and Higel), but standing water was at no time observed covering more than ~5% of the ground surface. In wet meadows, observed seasonal changes in WTD ranged from 0.40 m (at Higel) to 0.96 m (at Alamosa NWR) (Table 1), and the rate of WTD change was up to 1.6 cm/d (at Alamosa NWR). Patterns of WTD change in wet meadows were similar across years (Fig. 3).

Two study wetlands (Bulrush and Mishak Lakes; Fig. 2d and e) were playas (Laczniak et al., 2001; DeMeo et al., 2003; Kappen, 2004; Sanderson, 2006; Sanderson et al., in press), shallow basins (<1.25 m deep) with distinct stream inlets that had intermittent surface water inflow and outflow. Surface water covered the entire ground surface of both playa wetlands for at least some time during the years of this study to a depth of 0.24 m at Bulrush and 0.65 m at Mishak Lakes (Table 1). Bulrush also experienced 2 yr with no surface water inflow. In the absence of surface water, WTD was >1.0 m. The rate of WTD change in playas was up to 2.6 cm/d (at Bulrush). Patterns of WTD change were highly variable across years (Fig. 3).

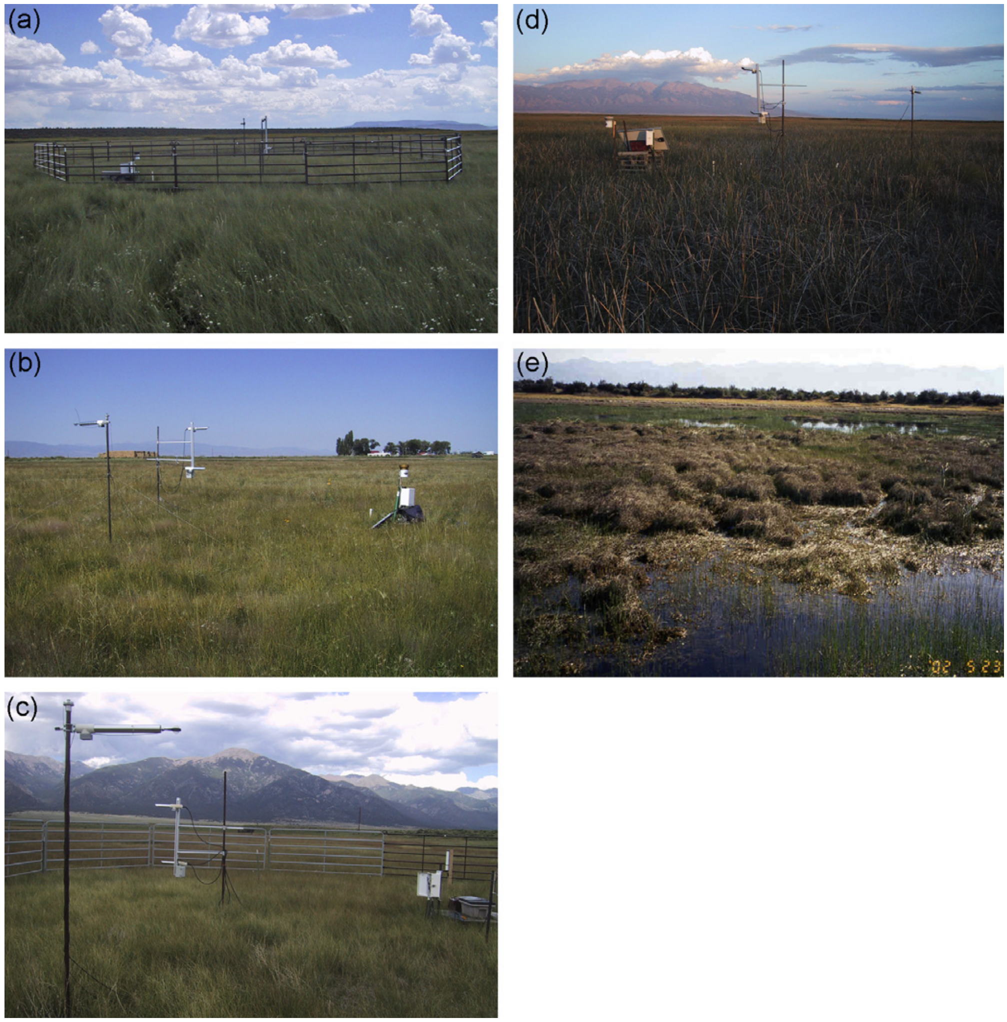

Figure 2 Photos of wetland study sites. Wet meadows are (a) Alamosa NWR, (b) Higel, and (c) Rito Alto. Playas are (d) Bulrush and (e) Mishak Lakes. The sets of equipment shown are the Bowen Ratio Energy Balance stations. The highest pieces of equipment are ~2.5 m above the ground surface.

Table 1 Site characteristics

Wetland	Dominant vegetation	Vegetation height (m)	Daily water table elevation (m)[a]	Site elevation (m above MSL)	Location[b]
Alamosa NWR	*Carex simulata* Mackenzie and *C. aquatilis* Wahlenb.	0.50	0.0 to −0.90	2291	43°37′17″E, 414°04′12″N
Higel	*Carex simulata* Mackenzie and *Juncus balticus* Willd. var. *montanus* Engelm.	0.60	0.0 to −0.40	2310	41°31′22″E, 415°48′50″N
Rito Alto	*Carex simulata* Mackenzie and *Juncus balticus* Willd. var. *montanus* Engelm.	0.50	−0.24 to −1.20	2324	42°85′58″E, 421°02′84″N
Bulrush	*Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla	1.0–2.0[c]	+0.24 to −1.89	2296	43°32′48″E, 417°59′29″N
Mishak Lakes	*Eleocharis palustris* (L.) Roemer & J.A. Schultes	0.50	+0.65 to −1.26	2302	41°32′43″E, 419°70′31″N

[a] Relative to ground surface; positive is above the ground surface, negative is below.
[b] NAD1983 UTM Zone 13N.
[c] Bulrush height varies depending on amount of water supplied to the wetland in any given year.

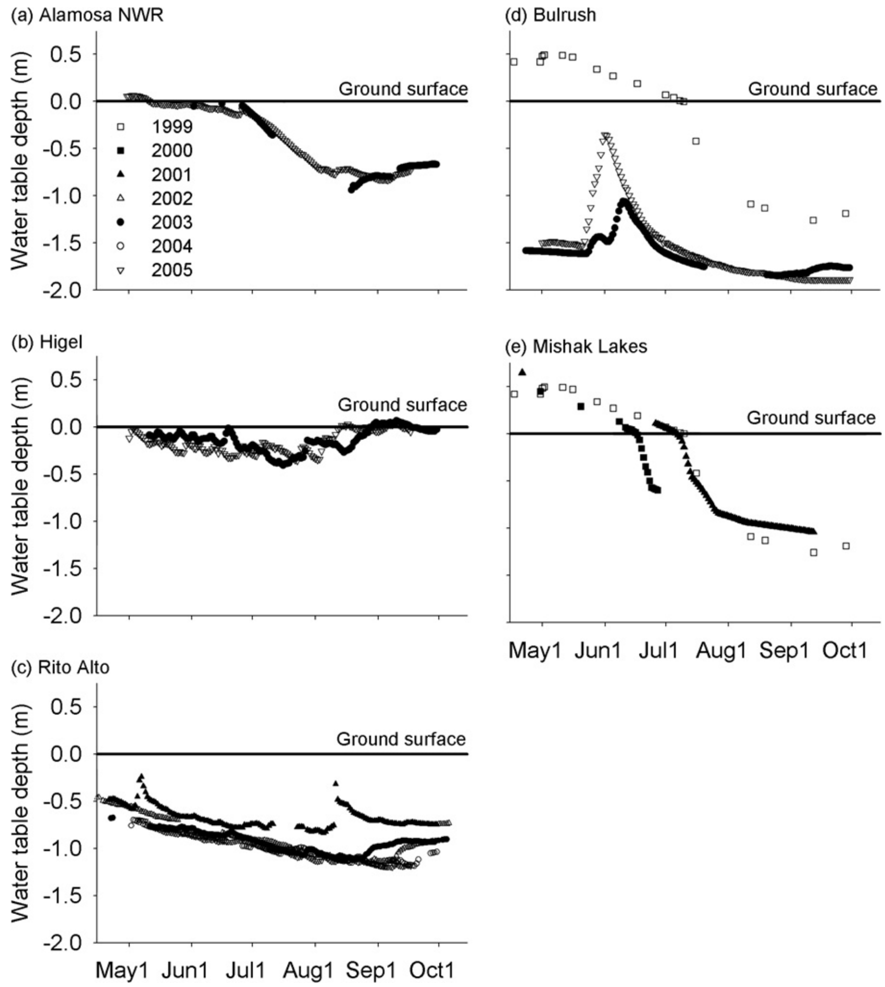

Figure 3 Water table position for wet meadows (a—c) and playas (d and e).

Uplands surrounding all of the sites are dominated by the desert halophytic shrubs greasewood (*Sarcobatus vermiculatus* (Hooker) Torrey) and rabbitbrush (*Ericameria nauseosa* (Pallas ex Pursh) Nesom & Baird), with a grass understory dominated by saltgrass (*Distichlis spicata* (L.) Greene) and alkali sacaton (*Sporobolus airoides* (Torr.) Torr.). Species nomenclature follows the USDA (2005).

Wet meadows

Alamosa National Wildlife Refuge

The Alamosa NWR site (Fig. 2a) is located on the margin of the broad Rio Grande floodplain. The site is a relatively homogeneous 13 ha area densely vegetated by grasses and sedges (Table 1). The wetland is supported by regional ground water flow through sandy alluvium (the Alamosa formation; Siebenthal 1910). During this study, the water table was within 0.3 m of the soil surface for ~85 d at the beginning of each growing season, and after ~July 1 the water table declined to ~0.8 m depth through the fall (Fig. 3a). In early summer, small (<0.2 m across) pools created by ground water discharge were present between hummocks that were up to 0.2 m high. The upper 1.4 m of soil is partially decomposed organic matter (peat).

Higel

The Higel site (Fig. 2b) is located on the edge of the broad Rio Grande floodplain. The site is a relatively homogenous 14 ha area dominated by grasses, sedges, and *Juncus balticus* (a rush) (Table 1). This wet meadow is maintained by ground water flows from the Rio Grande as well as irrigation ditches on the upper floodplain margin. During this study, the WTD was <0.3 m for 2—3 months at the beginning of the growing season, and another 2 months at the end of the growing season. The greatest WTD observed was 0.41 m (Fig. 3b). Hollows between 0.30 m tall hummocks fill with discharging ground water when WTD is near 0, but standing water did not cover more than a small fraction of the site. Soil water content in the silt loam soils remained close to saturation all summer.

Rito Alto

The Rito Alto site (Fig. 2c) is located near the small perennial stream Rito Alto, ~5 km west of the Sangre de Cristo Mountains. The site is a relatively homogenous 3.7 ha wet meadow dominated by sedges and *J. balticus* (Table 1). The water table is supported by ground water flow through the mountain front alluvial fan of Rito Alto, and the water table responds to both high discharges in Rito Alto and local rain events. During most study years, the water table high occurred in March or April, and declined through the summer (Fig. 3c). During July and August the water table elevation increased following summer thunderstorms. WTD was <0.3 m for only 2 d among all years of the study (minimum WTD = 0.24 m). Soils are silt loams, with high organic matter content in the upper 5 cm.

Playas

Bulrush

The Bulrush site (Fig. 2d) is a playa located at the terminus of a distributary of Sand Creek, ~5 km west of the Sangre de Cristo Mountains. The site is a nearly circular, shallow (<1 m deep) basin ~100 ha in size with a relatively homogenous cover of bulrush (*Schoenoplectus tabernaemontani*) (Table 1). During this study, inter- and intra-annual variability of inflowing surface water was very high, creating high variability in WTD (Fig. 3d). In 1999 WTD was <0.30 m for 23 d, with water up to 0.24 m deep ponded on the surface for 18 d. During 2003 and 2005, minimum WTD was >0.3 m. Soils are sandy clay loams.

Mishak Lakes

Mishak Lakes (Fig. 2e) is a complex of shallow (1.25 m depth) interconnected basins supporting a near-monoculture of ~0.5 m tall spikerush (*Eleocharis palustris* (L.) Roemer & J.A. Schultes) in the basin bottoms (Table 1). No basin is larger than ~2.0 ha, but the contiguous area represented by the study site covers ~200 ha. During the years ET was measured at Mishak Lakes, the wetland complex received ~80% of its water as flow in Russell Creek (Sanderson 2006; Sanderson et al. in press). When sufficient surface water entered the Mishak complex, surface water outflow also occurred. Little net infiltration of surface water occurred (Kappen, 2004). Water ponded for 62–86 d in early summer to a depth of 0.4–0.6 m (Fig. 3e). Once surface water disappeared, WTD increased rapidly to >1.0 m. Soils are sandy loams underlain by a 0.12 m thick low-permeability (vertical hydraulic conductivity = 3.6×10^{-10} m/s) clay layer ~0.5 m below ground surface (Kappen, 2004).

Methods

Field measurements

Daily ET_a was measured using the Bowen Ratio Energy Balance (BREB) method (Tanner, 1960; Fritschen and Simpson, 1989; Moncrieff et al., 2000; Drexler et al., 2004). Data were collected using a micrometeorological system from Radiation Energy Balance Systems Inc. (REBS Inc., Bellevue, WA). Platinum resistance elements were used to measure temperature in the atmosphere and in the cavity where humidity was measured. Humidity was measured with a hydroscopic polymer capacitance chip. Humidity and temperature sensor pairs were vertically separated by 1 m. To remove bias between sensors, their positions were exchanged every 15 min using an automated system. Net radiation (R_n) was measured with a REBS, Inc. Q*7.1 net radiometer deployed and leveled ~2.5 m above the ground surface and oriented due south. For settings without surface water, 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 an angle to measure heat storage in the top 5 cm of soil. For settings with surface water, temperature sensors were suspended in the water column, and soil heat flux plates were positioned at the soil surface. Measurements were made every 15 s, and averaged and stored on a data logger every 15 min. ET_a was calculated at 30-min intervals and summed over each 24-h period.

Requirements for fetch (the upwind distance to which the uniform vegetation extends) at three sites (Alamosa NWR, Higel, and Bulrush) exceeded the generally accepted minimum fetch to upper sensor ratio of 100:1 (Stannard, 1993; Moncrieff et al., 2000). At Rito Alto and Mishak Lakes, minimum fetch-to-height ratio was met in and near the direction of the prevailing wind, but was less in other directions. The 80% cumulative source area for turbulent flux was ~1.5 ha at all sites except Bulrush, where the source area was ~3.8 ha (Stannard, 1997).

The BREB method failed under specific combinations of available energy, temperature gradient, and vapor pressure gradient (Ohmura, 1982; Perez et al., 1999), and during advective inversions (Verma et al., 1978). These failures typically occurred around sunrise or sunset, when ET_a is low, and they generally lasted for only one or two 30 min intervals, so it is expected that they did not introduce significant error in daily ET_a totals. Failures were identified in the data set, and 30 min ET values were interpolated from temporally proximate values.

WTD was measured using a GE Druck 1–5 psi water level sensor at one location at each site. Precipitation was measured using an unshielded Texas Instruments 20.3 cm tipping-bucket rain gage with a sensitivity of 0.254 mm. Beginning in 2001, soil water content was measured by time domain reflectometery using Campbell Scientific CS615 probes at 0–30 cm. Probes were calibrated in the lab for each specific soil using known soil water contents.

Estimating ET_a and ET_g

For basin-scale studies of ground water discharge, ET_a and ET_g are commonly expressed as annual totals (Emery, 1970, 1991; Huntley, 1979; Hearne and Dewey, 1988; Duell, 1990; Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; DeMeo et al., 2003; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007). We measured ET at five sites during multiple years at each site; we thus estimated annual ET_a and ET_g for a total of 14 site-year combinations.

Total annual ET_a was estimated by summing daily values of ET_a. Measured values were used where available. Growing-season days without a measured value were modeled. Winter ET_a was estimated by calculating monthly means using at least seven daily measurements for each month from the Rito Alto site, and these means were applied to all sites. The approach to winter ET is realistic because winter ET_a rates are similar across sites during that season, when solar radiation is low, plants are leafless, frozen soils inhibit capillary movement of ground water to the surface, and frontal rather than convective weather patterns prevail.

Table 2 Number of days (percent of growing season) from April 15 to October 15 with measured daily ET for each site from 1999 to 2005

Site	1999	2000	2001	2002	2003	2004	2005
Alamosa	0	0	0	0	60 (33%)	0	140 (76%)
Higel	0	0	0	0	144 (78%)	0	140 (76%)
Rito Alto	0	0	151 (82%)	118 (64%)	162 (88%)	144 (78%)	132 (72%)
Bulrush	0	0	0	0	123 (67%)	0	101 (55%)
Mishak	13 (7%)	19 (10%)	55 (29%)	0	0	0	0

Equipment failures caused the loss of measured ET_a values for some growing-season days. Measured daily ET_a was available for 55–88% of the growing season for 10 of 14 study-year combinations, and for 7–33% of the growing season for the remaining four study-year combinations (Table 2). For days lacking ET_a measurements, daily ET_a was modeled by calibrating the Priestly–Taylor ET_p (P–T ET_p) model and using regional weather data as input.

Calibrating the Priestley–Taylor ET_p model

The P–T ET_p model was chosen because it produces a reasonable approximation of ET_a under a variety of well-watered conditions (e.g., Priestley and Taylor, 1972; Jacobs et al., 2002; Rosenberry et al., 2004). P–T ET_p is:

$$ET_p = \alpha[s/(s+\gamma)][(R_n - G)/\lambda] \quad (1)$$

where α is the Priestly–Taylor coefficient (no units), s the slope of the saturated vapor pressure–temperature curve (mb/°C), γ the psychrometric constant (mb/°C), R_n the net radiation (MJ/m^2/d), G the change in heat stored in surface soil or water (MJ/m^2/d), and λ is the latent heat of vaporization (MJ/kg).

Several authors have argued that α has theoretical significance for well-watered surfaces, where it has a value of 1.26 (Priestley and Taylor, 1972; McNaughton, 1976; de Bruin, 1983). For situations where water may be limiting, α has been related to measures of water availability. A relationship to soil moisture has been demonstrated in some settings (Davies and Allen, 1973; Flint and Childs, 1991); however, Stannard (1993) found that α did not relate to soil moisture but instead was related in a non-linear fashion to leaf area and recent rain. Without assuming any particular relationship, we used multiple linear regression analysis to determine the dependence of α on water limiting variables. Using the form of Eq. (1), the regression was modeled as

$$ET_a = f(\text{water limiting variables}) \cdot 1.26 \cdot [s/(s+\gamma)] \cdot [(R_n - G)/\lambda] \quad (2)$$

where f(water limiting variables) was a function of season, WTD, soil water content, recent precipitation, and the year of measurements.

Season represented seasonal changes in leaf area, plant cover, surface roughness, and other plant canopy-related factors that affect ET (Peacock and Hess, 2004). It was expressed as a log-normal function with the form:

$$\text{season} = [1/(x \cdot s \cdot \sqrt{2\pi})] \exp(-0.5[(ln(x) - m)/x]^2) \quad (3)$$

where x is day-of-year, and m and s are constants (5.44 and 0.533, respectively) determined through iteration so that season ranges from 0 (no green leaves) on April 15 and October 15 to 1 (full canopy) on June 22 (summer solstice). Soil water content was volumetric water content (VWC) in the upper 30 cm (cm^3/cm^3). Cumulative precipitation was the sum of weighted daily precipitation for the previous 7 d (7d_ppt) calculated as

$$\text{7d\_ppt} = \sum_{i=1}^{7} (D - i) \exp[(1 - i)/2] \quad (4)$$

where D is the day for which ET is being modeled, so that, for example, $(D - 1)$ is the amount of precipitation on the previous day and $(D - 7)$ is the amount 1 week ago. Using this formula, yesterday's precipitation was weighted more heavily than the day before yesterday, and so on until 7 d previous, beyond which the effect of precipitation was assumed negligible. This assumption is supported by our data collected during a rainy period in the San Luis Valley that shows ET matches or exceeds precipitation over 7-d intervals (Cooper et al., 2006); thus, most precipitation is returned to the atmosphere within days of its falling. In another intermountain basin, Malek et al. (1990) found that the affect of rain on ET_a lasted about 7 d. Any precipitation remaining in the soil after 7 d is likely a small fraction of total soil water content, so it is expected to have a minimal effect on our modeling approach. Cumulative precipitation was square-root transformed before use in model development.

For the analysis, Eq. (2) was re-written as

$$ET_a/ET_p = f(\text{season} + \text{WTD} + \text{VWC} + \text{7d\_ppt} + \text{year}) \quad (5)$$

Using this model, a calibration function was developed for each site using linear regression. Some relationships between ET_a/ET_p and water-limiting variables may be non-linear (Flint and Childs, 1991; Stannard, 1993). As such, linear regression may not be capable of accurately capturing all aspects of these relationships across the range of their possible manifestations on the landscape. However, since the linear model yielded a good fit to the data and the model was only applied within the range of data used to create it, we assumed the error introduced by using a linear model was minimal.

Data collected on site were used to develop the model. Values of ET_a were those measured during the growing season (April 15–October 15). Values of ET_p were calculated using on-site daily means of temperature, net radiation (R_n) and energy storage (G). Available daily values were randomly split into two equal-sized data sets, and one data set was used for model development. The best regression model was selected using a stepwise procedure with α_{entry}

and $\alpha_{exit} = 0.05$ (SAS Institute, 2003). WTD and VWC content in particular were, in some instances, highly correlated. Because WTD was of primary interest, preference was given to WTD during model development when WTD and VWC were equally good predictors.

Model fit was evaluated using a cross-validation approach. Data withheld during the model development step were used to calculate goodness-of-fit statistics. Statistics included a coefficient of determination (r^2) of modeled and measured values of ET_a, a coefficient of variation (CV) calculated as the standard error of the model divided by the mean of the measured values of ET_a (Stannard, 1993), and a mean-bias error defined as the mean difference between modeled and measured values (Kaygusuz, 1999). Also, slopes of best-fit lines through modeled versus measured ET_a were calculated to assess deviation from one; deviation from a slope of one indicates that the error in the modeled value varies as a function of the size of the value, possibly causing systematic under- or over-estimation of daily ET_a.

Modeling available energy (R_n–G)

For days lacking on-site measurements, available energy (R_n–G) for use in the Priestley–Taylor ET_p equation was modeled as a function of variables measured at a regional weather station. Total solar radiation (Q_s) can be used to model R_n–G with reasonable results (Stewart and Rouse, 1976). However, changes in plant cover alter the relationship between Q_s and R_n–G by changing albedo and surface temperatures, so the season function (Eq. (3)) was also used in developing the model for R_n–G. Yesterday's precipitation was also considered for models of R_n–G, because our data suggest that where vegetation is sparse (such as the Bulrush site) rain wets the soil, temporarily making it darker and lowering its albedo relative to dry soil.

Development and validation of the R_n–G model was done using the same cross-validation approach described for the ET_a model. On-site data were used for the dependent variable and weather station data for the independent variables. Weather station data were obtained principally from the CoAgMet Ctr01 station at Center, Colorado (Colorado Climate Center, 2005). Precipitation data from the Alamosa NOAA weather station (NOAA, 2005) and the Blanca, Colorado CoAgMet station were used when they were the nearest stations with available data.

Estimating ET_g

Annual ET_g was estimated in two ways, depending on the presence or absence of surface inflows: (i) when no surface inflow occurred, ET_g was estimated by subtracting precipitation from ET_a (Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007), and (ii) when there was surface inflow, ET_g was estimated by subtracting both precipitation and net surface water fluxes to the site (DeMeo et al., 2003). Situation (i) assumed negligible runoff, a reasonable assumption when the water table was not at the surface, given the limited vertical relief but high surface roughness of the sites, and the infrequent and small magnitude of most precipitation events. When the water table was at the surface and soils were fully saturated, rain events may have resulted in runoff, reducing the precipitation fraction of ET_a. Runoff was not quantified, so ET_g at sites where these conditions occurred (Alamosa NWR and Higel) may be underestimated by as much as ~9%. Situation (ii) required detailed quantification of surface water fluxes so the surface water fraction of ET_a could be estimated. At Mishak Lakes, the only site where this situation occurred, precipitation, surface inflows and outflows, and seepage were quantified in detail (Kappen, 2004; Sanderson, 2006; Sanderson et al., in press).

Calculating water table depth (WTD)

ET data were summed on an annual basis to eliminate the effects of weather and season, which can confound the ET_g–WTD relationship. For example, on July 25 and 26, 2005 at the Higel site, measured ET_a was 2.9 and 6.8 mm, respectively, when insolation was 15.4 and 28.4 MJ/m^2, respectively, yet the WTD depth difference between these two adjacent days was only 0.02 m.

There are many ways to calculate annual WTD for a site, each of which may be suitable for certain watersheds. For sites where the water table varies little between seasons, a simple annual average may be useful. However, where there is considerable seasonal variability in WTDs and ET rates, a weighted average may be most useful. We weighted each month's WTD based on the proportion of annual ET that occurred in that month, calculating weighted annual WTD as

$$\text{weighted WTD}_x = \sum_{i=1}^{12} \text{WTD}_i \cdot \text{ET}_i / (\text{annual ET}_x) \qquad (6)$$

where weighted WTD_x is WTD for site x, WTD_i is the mean of daily WTD for month i, ET_i, is the sum of daily ET for month i, and annual ET_x is annual ET_a for site x.

Results

Patterns of daily ET_a

The three ground water wetlands shared a characteristic daily pattern of ET_a during the growing season (Fig. 4a–c), yet during any season anomalously high and low daily ET_a rates occurred, illustrating the variability in ET_a driven by short-term weather patterns. For example, in early May of 2005, Alamosa NWR experienced unusually warm and windy conditions, with daily ET_a rates as high as 8.2 mm/d, near the annual maximum. More typically, in spring and early summer when water tables were highest, daily ET_a increased following leaf emergence in late April and seasonal increases in insolation. ET_g remained high through June and July, with maximum single day ET rates ranging from 8.1 mm/d at Rito Alto to 9.6 mm/d at Higel. Minimum mid-summer (the 2 weeks centered on the summer solstice) rates occurred on cloudy days and ranged from 3.2 mm/d at Alamosa NWR to 3.9 mm/d at Higel. ET_a decreased steadily from August through early October as solar radiation decreased, and water tables and soil water content was declining. Leaf senescence typically occurred by mid-October, and during the leafless period mean daily ET_a was less than 1 mm/d.

In playas, the pattern of daily ET_a differed between Bulrush and Mishak Lakes. At Bulrush, the water table was deep

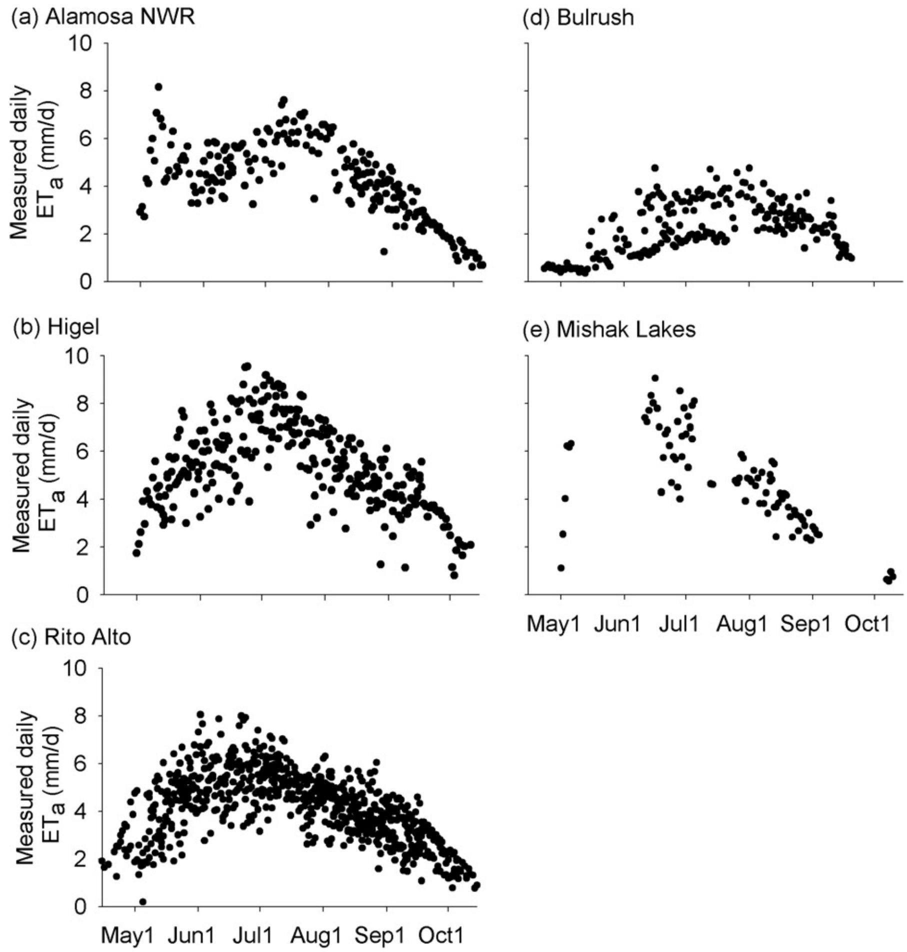

Figure 4 Measured daily actual evapotranspiration (ET_a) in wet meadows (a—c), and in playas (d and e). The number of years of data for each figure is: (a) two, (b) two, (c) five, (d) two, and (e) three. Some daily values are missing in all years for all sites (see Table 2).

through May of both 2003 and 2005, and ET_a rates increased slowly from April 15 through early June (Fig. 4d), reaching a maximum of 4.8 mm/d. In contrast, Mishak Lakes was inundated at the beginning of each growing season, and ET_a increased in spring to a late June maximum of 9.1 mm/d (Fig. 4e), similar to the peak rate at the Higel wet meadow (Fig. 4b). Minimum mid-summer rates ranged from 1.2 mm/d at Bulrush to 4.0 mm/d at Mishak Lakes.

Models of ET_a

For wet meadows, P—T ET_p generally provided good estimates of ET_a (r^2 = 0.73—0.86; coefficient of variation, CV = 14—24%) (Fig. 5a—c, left column). At Alamosa NWR and Rito Alto, P—T ET_p overestimated ET_a across the range of measured values. At Higel, P—T ET_p overestimated ET_a at low values and underestimated at high values. Slopes of P—T ET_p versus measured ET_a were 0.65—0.74.

The use of field ET_a measurements for calibrating ET_p improved estimates for all sites (r^2 = 0.87—0.92; CV = 9—12%) (Fig. 5a—c, right column). Slopes of calibrated ET_p versus measured ET_a were 0.89—0.94. Calibration functions included season and WTD for Alamosa NWR and Rito Alto, but only season for Higel (Table 3).

For playas, P—T ET_p more poorly estimated ET_a than for wet meadows (r^2 = 0.36 and 0.62, for Bulrush and Mishak Lakes, respectively; Fig. 5d and e, left column). For Bulrush, P—T ET_p greatly overestimated daily measured ET_a (CV = 126%; Fig. 5d). Calibrating ET_p for water availability improved the fit for both Bulrush and Mishak Lakes (r^2 = 0.76—0.87; CV = 12—25%; Fig. 5d and e, right column). The calibration function for Mishak Lakes was similar to that for wet meadows, but the function for Bulrush differed substantially and included VWC, precipitation, and year (Table 3). The calibrated ET_p for Bulrush yielded the poorest fit to measured ET_a when compared to other sites.

Modeled daily ET_a using off-site energy flux data from a regional weather station compared well to measured ET_a (r^2 = 0.70—0.84, CV = 15—25%, slopes = 0.81—0.91; Table 4). The model for Bulrush produced the greatest average error in daily estimates (CV = 25% versus 15—18% for the other sites). Mishak Lakes yielded the poorest fit of modeled to measured ET_a (r^2 = 0.70). For all sites modeled daily ET_a underestimated at low measured ET_a and overestimated at high measured ET_a. Slopes of modeled versus measured were 0.78—0.82 for wet meadows versus 0.70—0.71 for playas.

Modeling daily ET_a for days when on-site data were not collected was possible because available energy (R_n−G) at each site was significantly related to solar radiation as measured at Center ($p < 0.001$, Table 5). Thus, ET_p could be calculated even when on-site energy flux data were missing.

Annual ET

In wet meadows, the calculated annual ET_a ranged from 751 mm at Rito Alto in 2005 where WTD was 0.95 m, to 994 mm at Higel in 2003 where WTD was 0.13 m (Table 6). Annual ET_g in wet meadows ranged from 629 mm at Rito Alto in 2004 and 2005 to 866 mm at Higel in 2005.

In playas, annual ET_a ranged from 352 mm at Bulrush in 2003 where WTD was 1.68 m, to 892 mm at Mishak Lakes in 2001 where WTD was 0.18 m. ET_g at these sites ranged from 0 mm at Mishak Lakes in 1999—2001, to 571 mm at Bulrush in 2005 (Table 6). At Mishak Lakes, ET_g was estimated to be $\approx$0 mm during all years because measured annual stream inflow to the wetland complex in combination with on site precipitation supplied 36% more surface water to the wetland than was consumed by annual ET_a (Sanderson, 2006; Sanderson et al., in press) and there was little net seepage (Kappen, 2004). Of this 36%, most was lost as surface water outflow, although a small amount may have entered the shallow aquifer via ground water recharge

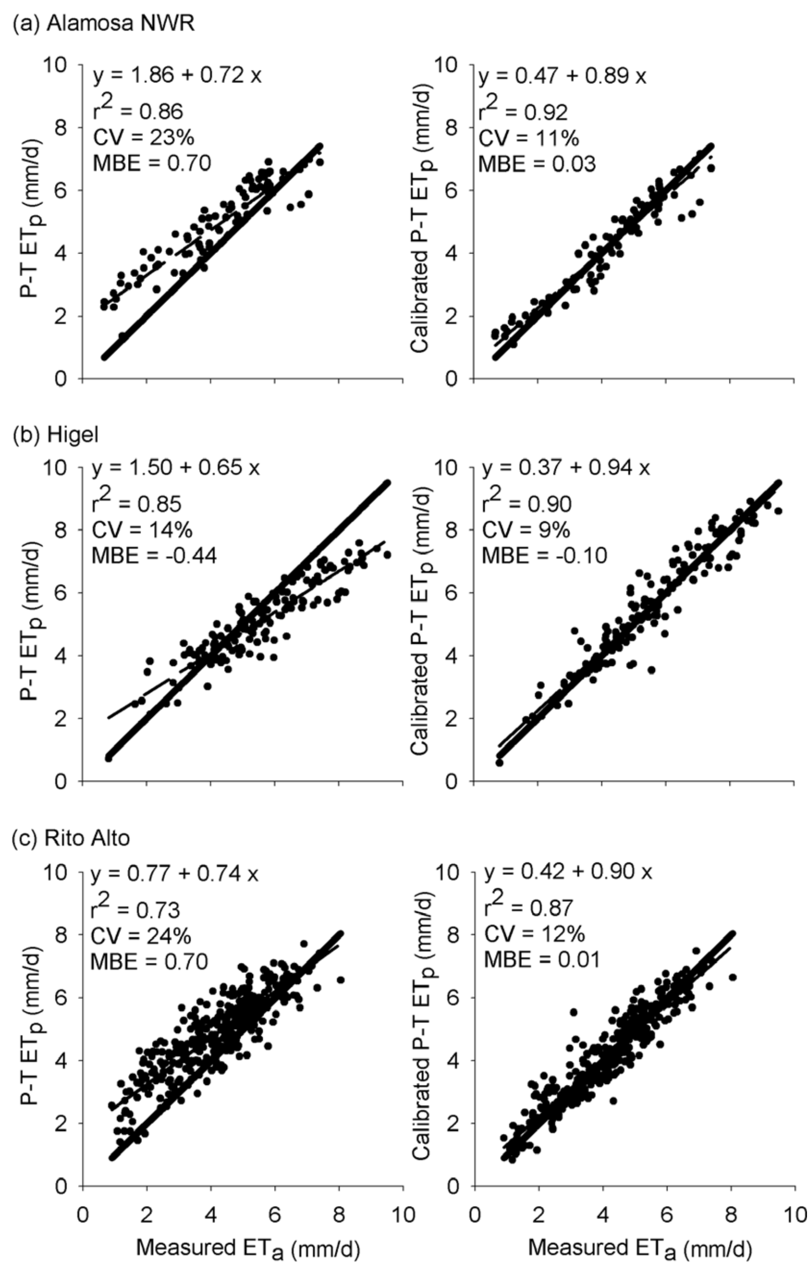

Figure 5 Priestley—Taylor potential evapotranspiration (P—T ET_p) (left) and calibrated P—T ET_p (right) for wet meadows (a—c), and for playas (d and e). r^2 is the coefficient of determination, CV the coefficient of variation, and MBE is the mean bias error. The light line through the data points is the least-squares best fit. The heavy line shows the 1:1 relationship.

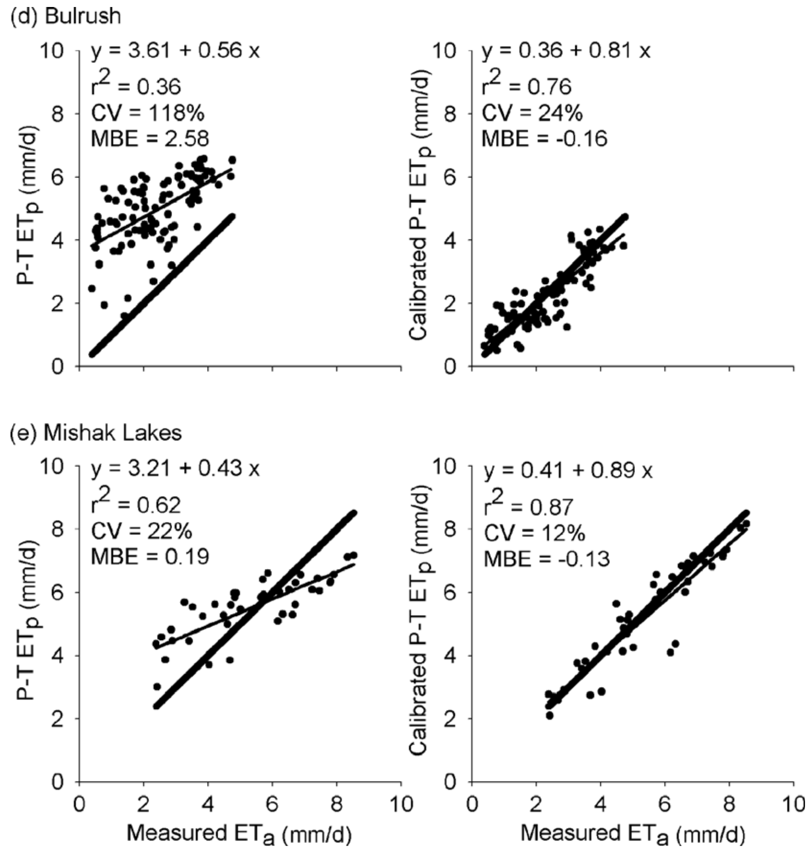

Figure 5 (*continued*)

Table 3 Models used to calibrate Priestly—Taylor potential evapotranspiration (ET_p) to measured actual evapotranspiration (ET_a)

Site	Variables included	Parameter estimate ± 1 s.e.	*p*-Value
Wet meadows			
Alamosa NWR	Intercept	1.14 ± 0.085	
	Season	−0.30 ± 0.100	0.003
	WTD	−1.02 ± 0.13	<0.001
	Season × WTD	1.50 ± 0.18	<0.001
Higel	Intercept	0.75 ± 0.027	
	Season	0.44 ± 0.035	<0.001
Rito Alto	Intercept	0.85 ± 0.042	
	Season	0.38 ± 0.026	<0.001
	WTD	−0.29 ± 0.041	<0.001
Playas			
Bulrush	Intercept	−356.2 ± 40.4	
	Soil water	0.73 ± 0.32	0.023
	7d_ppt	0.054 ± 0.011	<0.001
	Year	0.18 ± 0.020	<0.001
Mishak Lakes	Intercept	0.31 ± 0.069	
	Season	0.83 ± 0.071	<0.001
	WTD	−0.11 ± 0.29	0.001

WTD is water table depth. 7d_ppt is cumulative weighted precipitation over the previous 7 d.

Table 4 Statistics for modeled actual evapotranspiration (ET_a) versus measured ET_a using modeled available energy (R_n-G) and off-site regional weather station data

Site	r^2	CV (%)	MBE	Slope
Alamosa NWA	0.84	16	0.0	0.80
Higel	0.80	15	0.0	0.82
Rito Alto	0.75	17	0.0	0.78
Bulrush	0.76	25	−0.1	0.71
Mishak Lakes	0.70	18	+0.1	0.70

r^2 is the coefficient of determination, CV is the coefficient of variation, and MBE is the mean bias error (in mm).

Table 5 Models of available energy (R_n-G) as a function of off-site data

Site	Variables included	Parameter estimate ± 1 s.e.	*p*-Value	Model r^2	Model MBE
Wet meadows					
Alamosa NWR	Intercept	2.78 ± 0.85		0.79	0.14
	Solar radiation	0.37 ± 0.037	<0.001		
	Season	3.36 ± 0.72	<0.001		
Higel	Intercept	1.76 ± 0.58		0.56	−0.25
	Solar radiation	0.50 ± 0.023	<0.001		
Rito Alto	Intercept	2.57 ± 0.49		0.64	−0.04
	Solar radiation	0.36 ± 0.022	<0.001		
	Season	3.20 ± 0.42	<0.001		
Playas					
Bulrush	Intercept	3.24 ± 0.76		0.64	−0.32
	Solar radiation	0.33 ± 0.031	<0.001		
	Season	2.02 ± 0.65	0.003		
	1d_ppt	0.76 ± 0.24	0.002		
Mishak Lakes	Intercept	2.90 ± 1.01		0.76	−0.23
	Solar radiation	0.49 ± 0.040	<0.001		

1d_ppt is total rainfall on the previous day. See text for complete explanation of independent variables. r^2 is the coefficient of determination of modeled versus measured (R_n-G), and MBE (in $MJ/m^2/d$) is the mean bias error of the model.

Table 6 Annual estimated actual evapotranspiration (ET_a) and the annual estimated ground discharge via evapotranspiration (ET_g) for all sites and all years

Site	Year	WTD (m)	ET_a (mm)	Precipitation (mm)	ET_g (mm)
AL	2003	0.34	882	158	724
AL	2005	0.33	891	131	760
HI	2003	0.13	994	155	839
HI	2005	0.15	987	121	866
RA	2001	0.67	897	221	676
RA	2002	0.83	845	110	735
RA	2003	0.90	804	205	599
RA	2004	0.94	809	180	629
RA	2005	0.95	751	122	629
BU	2003	1.68	352	189	163
BU	2005	1.54	571	128	443
MI	1999	0.21	868	1199[a]	0
MI	2000	0.48	892	1258[a]	0
MI	2001	0.18	872	1232[a]	0

Wet meadows are AL = Alamosa National Wildlife Refuge, HI = Higel, and RA = Rito Alto. Playas are BU = Bulrush and MI = Mishak. WTD = water table depth.

[a] Includes precipitation and surface water inflows per unit area of wetland; the amount in excess of ET_a was lost from wetland primarily as surface water outflow (Sanderson, 2006; Sanderson et al., in press).

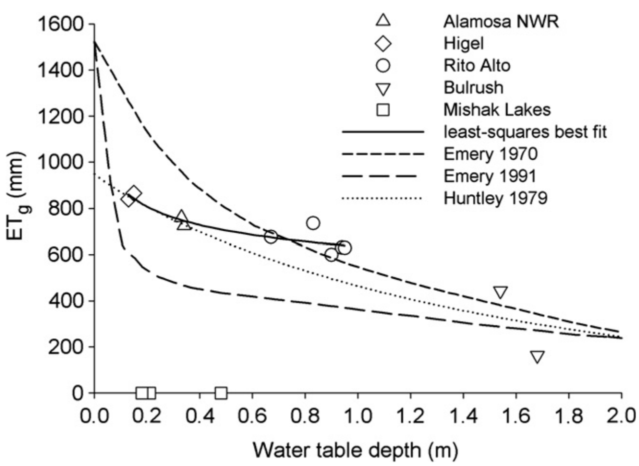

Figure 6 Total annual ground water component of evapotranspiration (ET_g) as a function of water table depth (WTD) for all sites and years, plus three existing models for comparison. The solid line shows the least-squares fit to the nine values for wet meadows.

(Kappen, 2004; Sanderson, 2006; Sanderson et al., in press). At Bulrush, ET_g in 2005 was 466 mm, which was 172% greater than ET_g in 2003, even though the mean annual WTD was only 0.14 m higher in 2005.

Annual ET_g was significantly related to WTD for wet meadows. The best-fit curve for the nine annual values for ET_g from ground water wetlands was

$$ET_g = 635.1\ \mathrm{WTD}^{-0.1488} \quad (r^2 = 0.83,\ p < 0.001) \tag{7}$$

This curve indicates that ET_g decreased exponentially as WTD increased, comparable to the shape of curves suggested by Emery (1970, 1991) and Huntley (1979) (Fig. 6). However, the magnitude of estimated ET_g differs from existing curves. At WTD = 0.13 m, Eq. (7) yields an annual ET_g of 860 mm, while ET_g from existing models ranges from 605 mm (−30%, Emery, 1991) to 1265 mm (+47%, Emery, 1970). At WTD = 0.95 m, Eq. (7) yields an annual ET_g of 640 mm, while ET_g from existing models ranges from 370 mm (−42%, Emery, 1991) to 565 mm (−12%, Emery, 1970).

The percentage and magnitude of decrease in ET_g with increasing WTD also differ substantially between this study and existing models (Emery, 1970, 1991; Huntley, 1979). We found that in wet meadows ET_g decreased by 26% (220 mm) as the WTD dropped from 0.13 to 0.95 m, versus a 39–55% decrease estimated by existing models (Table 7). The magnitude of ET_g decrease estimated by two existing models (Emery, 1970; Huntley, 1979) was 69–218% greater than estimated by our model. Emery (1991) estimated a decrease in ET_g of 235 mm, only 7% greater than our model's estimate; however, Emery (1991) underestimated the magnitude of ET_g across the range of WTDs studied by up to 42% (Table 7).

Discussion

Annual ET_g versus WTD

This study illustrates that the relationship between ET_g and WTD is not a simple curve with lower ET rates when the water table is deeper, as proposed by other researchers (Emery, 1970, 1991; Huntley, 1979). The ET_g to WTD relationship is significantly different between wet meadows and playas, indicating that models must consider water source. Among wet meadows, ET_g has a consistent relationship with WTD, while for playas it does not.

ET_g versus WTD for wet meadows

For wet meadows, our results corroborate the general relationship that ET_g decreases as WTD increases. However, the magnitude of ET_g estimated by existing models when compared to results from this study is from 30% too low to 47% too high at WTD = 0.13 m and 12–42% too low at WTD = 0.95 m (Fig. 6). Over- and under-estimates of ET_g result in two significant problems for a basin-scale ground water model: (i) substantial over- and under-estimates of water flux from a shallow aquifer to the atmosphere via ET in a given cover type, and (ii) substantially larger estimates of the decrease in ET_g as the water table declines. Thus, existing models would estimate ET ''salvage'', i.e. a reduction in ET_g due to water table drawdown, that may be several times higher than is actually occurring as WTD changes from 0.13 to 0.95 m.

The existing ET_g–WTD models (Emery 1970, 1991; Huntley 1979; Hearne and Dewey 1988) are based on limited wetland ET and hydrology data, and studies such as ours that use local data and rigorous techniques result in more accurate quantification of ET rates and processes (Laczniak et al., 1999). For example, existing models that predict steep decreases in ET_g along a WTD gradient are based on ET from open water bodies and ET_g from a single vegetation type (saltgrass, *D. spicata* (L.) Greene) (White, 1932; Blaney

Table 7 Estimates from existing models and the current study of the ground water component of evapotranspiration (ET_g) in the San Luis Valley with water table depth (WTD) = 0.13 and 0.95 m, the range encountered during this study

	Estimated ET_g		Decrease in ET_g
	WTD = 0.13 m	WTD = 0.95 m	
This study	860	640	220 (26%)
Emery (1970)	1265 (+47%)	565 (−12%)	700 (55%)
Emery (1991)	605 (−30%)	370 (−42%)	235 (39%)
Huntley (1979)	851 (+1%)	479 (−25%)	372 (44%)
Hearne and Dewey (1988)	945[a] (+10%)	n/a	

ET_g values are in mm. Percentages show the difference from this study. Estimates from this study are for wet meadows only.
[a] For WTD <0.60 m.

et al., 1938; Blaney and Criddle, 1962; Robinson and Waananen, 1970; Dylla et al., 1972). However, saltgrass is not a typical wetland plant and often grows in alkaline soils where, despite a shallow water table, surface soil water content and plant productivity can remain low. It differs in many ways from highly productive sedges such as *Carex simulata*, *Carex aquatilis* and *Carex utriculata*, the rush *J. balticus*, and other emergent plants that dominate wetlands in mountain and intermountain basins throughout the western US. ET_g estimates from this study, which are based on ET_a measurements in a variety of wetland types, suggest that saltgrass poorly represents ET relationships of wetland vegetation in the western US.

The reduction in ET_g due to water table decline is lower than previous estimates because soil water content does not limit ET when the water table is within $\sim$1.0 m of the ground surface. Soil water content in the upper 0.3 m remained above 0.22 cm^3/cm^3 even at a WTD of 1.20 m, indicating that capillary water moved from the water table into upper soil horizons to support ET_g. This is consistent with other studies that documented significant capillary movement of water through fine textured soils into the root zone (Andersen, 2005), even on sites with a WTD of 2.5 m (Chimner and Cooper, 2004). It also suggests that wetland plants in the study area have well developed root systems that can utilize ground water and ground water recharged soils, even when WTD is 1.0 m.

ET_g versus WTD in playas

Unlike wet meadows, ET_g is highly variable in playas, and lacks a consistent relationship with WTD. For example, ET_g at Bulrush was 172% greater in 2005 than in 2003, despite a difference in WTD of only 0.14 m. The increase in 2005 over 2003 occurred because the water table rose abruptly to within 0.35 m of the ground surface, saturating the soil within the root zone of the plants that dominate the site, and then the water table dropped abruptly so that mean annual WTD did not vary substantially. The variability in WTD and subsequently ET_g arises from the variability in water supply to playas, which is driven by watershed scale precipitation patterns, especially winter snow in the adjacent high mountains. Inter-annual surface water inflows to intermountain basin wetlands may vary by >300% (Sanderson, 2006; Sanderson et al., in press).

In contrast to existing models (Emery, 1970, 1991; Huntley, 1979; Hearne and Dewey, 1988), our estimated ET_g rates in playas were $\approx$0 mm when WTD was <0.50 m (at Mishak Lakes) and were >0 mm when WTD was 1.54 and 1.68 m (at Bulrush). This counter-intuitive result occurred because surface water inflows to the wetland complex combined with precipitation were substantially greater than ET_a demand, eliminating the ground water fraction of ET_a (Sanderson, 2006; Sanderson et al., in press). This result is consistent with the work of DeMeo et al. (2003), who determined that when inflows are in excess of ET_a, calculated ET_g is <0 mm, indicating ground water recharge.

When drought prevails and snowmelt provides insufficient inflows to wetlands yet water tables are near the ground surface (e.g., at Bulrush), ET_a may be satisfied by ground water, thus ET_g is >0 mm. At the Bulrush site, which was not inundated in 2003 and 2005, ET_g was >0 mm despite a mean annual water table up to 1.68 m below ground surface. In playas, ET_g can also vary considerably for a given WTD.

The relationship between hydrologic variability and ET_g of playas is difficult to predict with the current state of knowledge. During long drought periods water tables drop, seepages losses from streams may be great, and playas may remain dry despite high runoff (Wurster et al., 2003), as occurred in 2005 at the Bulrush site. ET_g in this case would be >0 mm. Consecutive years of moderate runoff could also occur, possibly resulting in extensive flooding and causing ET_g to be $\leqslant$0 mm.

Role of vegetation in ET_g

This study could improve existing models of ET_g for wetland ecosystems with shallow WTDs because common wetland types were analyzed. Many previous researchers applied a single ET_g—WTD relationship to all vegetation types, irrespective of hydrologic dynamics and variability in vegetation type, growth, and physiology. We suggest that at any WTD, freshwater wetlands have higher ET_g rates than the saline wetlands and upland vegetation types used to develop existing ET_g—WTD relationships (White, 1932; Blaney et al., 1938; Eakin, 1960; Blaney and Criddle, 1962; Robinson and Waananen, 1970; Dylla et al., 1972; Nichols, 1994).

Water availability is a critical determinant of vegetation composition, and vegetation strongly influences rates of ET_g. As the patterns and rates of water use continue to change in intermountain basins of the western US, vegetation will also continue to respond dynamically, in both the short- and long-term. In the short-term, species dominance, leaf area, and stomatal conductance can respond to a changing water table, thus changing within-season ET rates. In the long-term, changes in water availability may trigger changes in site vegetation composition, cover, and rooting characteristics. For example, Cooper et al. (2006) documented flood-intolerant shrubs invading playas formerly dominated by wetland grasses and other non-woody species after a water table decline of 1.6 m. These upland shrubs have different water acquisition and use patterns than the wetland plants they replaced. These shrubs are deeply rooted and can access deep water tables, yet they have low productivity and low leaf area (Cooper et al., 2006). ET, water table position, and vegetation type are critically inter-related (Ridolfi et al., 2006), and efforts to predict changes in ET_g must consider both short- and long-term changes in these factors.

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