On groundwater fluctuations, evapotranspiration, and understory removal in riparian corridors

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[1]   This study utilizes 7 years of continuously monitored groundwater-level data from four sites along the Río Grande riparian corridor in central New Mexico to calculate evapotranspiration from groundwater and assess impacts of understory vegetation removal during a restoration project. Diurnal groundwater fluctuation measurements were used to compare the well-known White method for estimating evapotranspiration from groundwater (ET_g) to colocated measurements of total riparian evapotranspiration (ET) measured using the eddy covariance method. On average, the two methods were linearly correlated and had similar variability, but groundwater hydrograph estimates of ET_g tended to be larger than tower ET estimates. Average ET_g estimates for two wells at one site ranged from 91.45% to 164.77% of measured tower ET estimates, but were also shown to range from 57.35% to 254.34% at another site. Comparisons between the methods improved with deeper water tables, reduced groundwater and river connectivity, and where soil profiles were dominated by coarse-sized particles. Using a range of texture-based estimates of specific yield (S_y) with water table position improves the field application of the White method. River-induced fluctuations in groundwater increased the variability of ET_g measurements. Removal of understory vegetation at one site resulted in a small but significant reduction in diel groundwater fluctuation amplitude of 19–21%. Caution is required when understory vegetation removal is used as a means to decrease overall riparian ET. Diel groundwater fluctuation amplitudes can be useful in gauging the hydrological effects of vegetation removal. Riparian groundwater hydrographs are critical to investigating the hydrologic connectivity between river and shallow groundwater, the temporal patterns of vegetative consumption, and monitoring changes to the vegetation community.

1. Introduction

[2]   Groundwater hydrographs can provide insights into the ecohydrological processes occurring in riparian ecosystems. The spatial and temporal dynamics of groundwater-level position have been shown to control vegetation composition and nutrient processing in riparian corridors [*Burt et al.*, 2002; *Hefting et al.*, 2004; *Leyer*, 2005]. Groundwater wells within floodplain areas can provide information regarding ecosystem hydrological and biogeochemical processes [*Peterjohn and Correll*, 1984; *Smith et al.*, 1991; *Brunke and Gonser*, 1997; *Morrice et al.*, 1997; *Sjodin et al.*, 2001; *Schilling et al.*, 2004, 2006; *Davis et al.*, 2007].

[3]   Deployment of monitoring wells along groundwater gradients is an effective means to assess hydrological controls on the processing of nutrient fluxes in riparian ecosystems [*Lowrance et al.*, 1997; *Hedin et al.*, 1998; *Clément et al.*, 2003; *Butturini et al.*, 2003; *Vellidis et al.*, 2003; *Wigington et al.*, 2003; *Dhondt et al.*, 2006]. Furthermore, analysis of groundwater and surface water hydrographs can be used to estimate aquifer hydraulic properties, which influence riparian ecosystem processing [*Ferris*, 1951; *Smith*, 1999; *Jha et al.*, 2004; *Jung et al.*, 2004; *Woessner*, 2000; *Vivoni et al.*, 2006]. While wells in riparian areas have allowed improved understanding of hydrological and biogeochemical processes, there is still a need to further explore groundwater observations as ecosystem research tools. One important area of investigation is the use of well hydrographs to assess the interaction of riparian vegetation dynamics and water table fluctuations.

[4]   Riparian evapotranspiration (*ET*), which combines transpiration from overstory and understory plants and evaporation from soil surfaces and open water, is a critical ecohydrological flux which can be used to assess impacts of vegetation on surface and groundwater resources [*Newman*

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et al., 2006; *Cleverly et al.*, 2006a; *Zhang and Schilling*, 2006; *Rodríguez-Iturbe et al.*, 2007]. Several studies have analyzed groundwater well hydrographs in an attempt to estimate water consumption from phreatophytic vegetation whose roots directly access groundwater [e.g., *White*, 1932; *Troxell*, 1936; *Meyboom*, 1964; *Gerla*, 1992; *Loheide et al.*, 2005; *Butler et al.*, 2007; *Lautz*, 2008; *Loheide*, 2008]. Direct consumption of groundwater by phreatophytes (ET_g) represents an explicit link between ecosystem processes and subsurface hydrological dynamics. Evidence for groundwater evapotranspiration has been frequently observed in the diurnal fluctuations of shallow water tables in vegetated riparian zones [e.g., *Dahm et al.*, 2002; *Healy and Cook*, 2002; *Schilling et al.*, 2006; *Steinwand et al.*, 2006; *Zhang and Schilling*, 2006; *Butler et al.*, 2007, *Gribovszki et al.*, 2008]. Groundwater hydrographs in riparian corridors exhibit distinct diurnal patterns during the summer growing season corresponding to phreatophyte transpiration. Vegetation-induced groundwater fluctuations are characterized by an oscillating pattern of a high water table during the early morning and a low water table during the late afternoon. Seasonal variations in ET_g-induced fluctuations may serve as a tool for tracking vegetation consumption patterns as well as the effects of vegetation removal on riparian evapotranspiration.

[5] Estimating vegetation consumption of groundwater using well hydrograph records was proposed by *White* [1932] and has been used widely in different riparian settings [e.g., *Troxell*, 1936; *Farrington et al.*, 1990; *Gerla*, 1992; *Rosenberry and Winter*, 1997; *Loheide et al.*, 2005; *Butler et al.*, 2007; *Lautz*, 2008; *Loheide*, 2008]. The White method provides estimates of groundwater transpiration (ET_g) based on the analysis of diurnal water table fluctuations and an estimate of the specific yield near the water table position. A principal assumption of the White method (described in detail in section 3) is that diurnal fluctuations of an unconfined water table are a direct response of the diurnal pattern of phreatophyte transpiration, and not a response to groundwater temperature, atmospheric pressure, or local pumping, or to changes to boundary conditions such as a nearby river or water body. In addition, the method applies to circumstances where the dominant source of water used by riparian vegetation is groundwater and not vadose zone water. *Butler et al.* [2007] argue that measurements of riparian evapotranspiration (ET) should only be attempted when the evapotranspirative consumption of groundwater (ET_g) is a dominant term, as neither soil nor open water evaporation are considered in the White method.

[6] One practical advantage of the White method is that the technique can be applied to a set of inexpensive wells deployed in a riparian corridor to understand variations in ET_g and the groundwater response to vegetation changes. Recent studies have evaluated the White method to improve its application in field settings and provide guidelines for parameter estimation [*Loheide et al.*, 2005; *Butler et al.*, 2007]. *Loheide et al.* [2005] used numerical modeling to explore the effects of drainage time, depth to water table, specific yield, and flow geometry on ET_g estimates using the White method. The study showed that for depths to groundwater exceeding 1 m and sediments with >10% fine particles, a reasonable estimate of specific yield can be obtained using sediment texture. *Butler et al.* [2007] showed

that the major controls on phreatophyte-induced groundwater fluctuations depend on weather conditions, plant density, and species type, as well as on the specific yield of the sediments near the water table. These advances motivated our study by providing techniques to appropriately use the White method in riparian corridors.

[7] Our study is focused primarily on comparing the White method estimates of ET_g with measurements of riparian evapotranspiration (ET) in different plant communities found within a vegetated riparian corridor of a large, semiarid river system. Several methods are available to estimate total ET along riparian corridors, with the three-dimensional sonic eddy covariance (3SEC) method being a popular technique [e.g., *Shafroth et al.*, 2005; *Nagler et al.*, 2005; *Cleverly et al.*, 2002, 2006a]. The 3SEC method (described in detail in section 3) requires the deployment of expensive meteorological equipment and careful site placement [cf. *Cleverly et al.*, 2006a]. Because of its inexpensive nature, the White method is an appealing alternative that requires analysis of only well hydrographs and aquifer properties near the water table position. To our knowledge, however, comparisons of the White and 3SEC methods have not been carried out in vegetated riparian corridors. Direct comparison of these techniques at colocated sites is important for evaluating the usefulness of the White method in riparian corridors where groundwater transpiration is a major ET component. Long-term comparisons in a range of riparian communities would also allow use of groundwater wells to estimate ET in areas lacking meteorological data or where tower deployment is not feasible.

[8] Groundwater hydrographs also provide insights into the impact of riparian vegetation removal on aquifer processes, as well as insights on how water table fluctuations may affect ecosystem restoration efforts [e.g., *Qashu and Evans*, 1967; *Matheussen et al.*, 2000; *Tabacchi et al.*, 2000; *Swank et al.*, 2001; *Biggs et al.*, 2004; *Cooper et al.*, 2006; *Neill et al.*, 2006; *Newman et al.*, 2006; *Scott et al.*, 2005]. Removal of phreatophyte plants is increasingly used as a means to reduce consumptive water demand in riparian corridors [*Parker et al.*, 2005; *Newman et al.*, 2006; *Wilcox et al.*, 2006]. Nevertheless, few studies have assessed the effectiveness of restoration projects in riparian ecosystems [*Shah et al.*, 2007]. This is particularly important in arid and semiarid regions where removal of invasive phreatophytes is considered an effective management technique [*Swank et al.*, 2001; *Shafroth et al.*, 2005; *Cooper et al.*, 2006]. Analysis of groundwater hydrographs before and after a restoration project can potentially provide an estimate of the aquifer response to the vegetation change. To achieve this, long-term groundwater measurements are needed in a riparian restoration zone, along with estimates of plant biomass or leaf area index to track vegetation removal and recovery, if any.

[9] In this study, we utilize long-term groundwater hydrographs at four instrumented sites along a vegetated riparian corridor in the Río Grande floodplain to achieve two major objectives. First, we compare the White and 3SEC methods for estimating riparian evapotranspiration and its groundwater component using 7 years of meteorological flux and groundwater data. To our knowledge, this is the first extensive comparison between these two methods using long-term field data. Second, we use groundwater data that

were collected before and after an understory removal project to evaluate its impact on the groundwater resource. We hypothesize that estimates of daily evapotranspiration from the White method are similar to estimates from the 3SEC method, and that plant-induced diurnal fluctuations in the groundwater can successfully track vegetation removal.

2. Study Sites and Instrumentation

[10] Four long-term research sites (Albuquerque, Belen, Sevilleta, Bosque del Apache) were established in the middle Río Grande riparian corridor to measure evapotranspiration, biodiversity, and the temporal dynamics of groundwater level (Figure 1) [e.g., *Molles et al.*, 1998; *Dahm et al.*, 2002; *Cleverly et al.*, 2002; *Cleverly et al.*, 2006a]. As Figure 1 illustrates, the middle Río Grande flows from Otowi Bridge to Elephant Butte Reservoir in central New Mexico.

[11] Each site has a distinct vegetation composition. Albuquerque (ALB) and Belen (BLN) are dominated by native cottonwoods (*Populous deltoids* spp. *wislizeni*) with densities of 122 and 278 trees ha^{-1}, respectively [*Cleverly et al.*, 2006a, 2006b]. Understory vegetation at the ALB site was a dense thicket of salt cedar (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*) that was removed in late 2003 and early 2004 during a riparian restoration project. The understory vegetation at the BLN site is mostly native shrubs. Conversely, Sevilleta (SEV) and Bosque del Apache (BDA) sites are dominated by invasive salt cedar communities. SEV also has a mixture of various native halophytes such as mesquite (*Prosopsis pubescens*) and saltbush (*Atriplex L.* spp), while BDA is a dense, monospecific salt cedar stand. The four sites are representative of the middle Río Grande riparian ecosystem, which currently occupies land in the river floodplain.

[12] Climate in the region is classified as semiarid with an annual precipitation ranging from 20 to 31 cm, with approximately 50% occurring during the summer monsoon period (July–September) [e.g., *Milne et al.*, 2003; *Weiss et al.*, 2004]. Hydrological conditions differ at each site based upon the proximity to the river and its seasonal flooding during spring snowmelt and the North American monsoon [e.g., *Dahm et al.*, 2002; *Vivoni et al.*, 2006]. To assess flood conditions, we gathered river stage and discharge data from the closest U.S. Geological Survey (USGS) stream gauges near the four riparian sites at 30-min intervals (Figure 1b). BLN and BDA are flood-prone sites with recurrence intervals of ~3 years, while ALB and SEV are considered nonflooding sites as significant inundation has not occurred since 1942 [*Molles et al.*, 1998]. Flood-prone sites reflect a high degree of surface water connection between the Río Grande and its floodplain. Differing hydrologic conditions at these sites have allowed monitoring long-term effects of flooding on riparian biodiversity and ecological processes [*Ellis et al.*, 1993; *Crawford et al.*, 1996; *Molles et al.*, 1998].

[13] To monitor subsurface hydrologic conditions, each riparian site has a network of five shallow groundwater wells installed across the water table, with an average depth of 3.5 m below the surface. Groundwater wells consist of a 5.0 cm ID polyvinyl chloride (PVC) tubing with a screened lower section (0.25 mm screen slot size). Figure 1 presents the arrangement of the five wells at each site, with the center well located next to the meteorological flux tower and the other four wells at 40 m distance in each cardinal direction. Depth to groundwater was measured every 30 min at three of the five wells using automated pressure transducers (EEI, Las Cruces, New Mexico, and Solinst Canada Ltd., Georgetown, Ontario). Instrumentation sites at the ALB, BLN, SEV, and BDA locations are placed approximately at 123, 122, 806, and 268 m, respectively, from the Río Grande bank, as measured from the center well (Figure 1).

[14] Meteorological flux tower instrumentation at each site was placed between 2 and 2.5 m above the vegetation canopies, which are ~25 m tall for cottonwood stands (ABQ and BLN) and ~10 m tall for the salt cedar sites (SEV and BDA). The eddy covariance (3SEC) technique is the benchmark method for measuring turbulent fluxes over tall vegetation and under the advective conditions experienced in riparian corridors [e.g., *Drexler et al.*, 2004]. Core flux instrumentation includes a high-frequency (10 Hz sampling with a 30-min integration period) sonic anemometer (CSAT3) to measure three-dimensional wind velocity fluctuations, a krypton hygrometer (KH20) or open-path infrared gas analyzer (IRGA) to measure fluctuations in humidity, and a thermocouple to measure air temperature fluctuations (see *Dahm et al.* [2002] and *Cleverly et al.* [2002, 2006a] for details). Since a simplified energy balance ($R_n - G = H + \lambda ET$) can be tested using the eddy covariance technique, measurements were also made of the net radiation (R_n) and ground heat flux (G) at each site to complement the sensible (H) and latent (λET) heat flux estimates. The latent heat flux (λET) represents conditions in a time-variable footprint upwind of the meteorological tower that depends on the horizontal wind speed and direction [e.g., *Cooper et al.*, 2003; *Drexler et al.*, 2004]. Supporting instruments were also deployed at each site to measure surface soil moisture and soil temperature as well as precipitation and atmospheric pressure.

[15] In 2003, the nonnative understory vegetation at the ALB site was removed using mechanical masticators and direct herbicide application. The removed wood was primarily chipped and spread over the ground. To track changes induced by the restoration project, the leaf area index (LAI), defined as the projected area of the leaves per unit ground area, was measured using an LAI2000 (Li-Cor, Lincoln, Nebraska). Measurements were made each June at the ALB site during the 3 years prior to 2000–2002, during 2003, and the third year after complete vegetation removal (2006). LAI measurements were collected near each of the five wells under the canopy and in the open sky on the nearby road. The year following vegetation removal (2004) showed a 9% decrease in annual *ET*, as measured by the 3SEC method, compared with an increase of 12% at all other sites [*Cleverly et al.*, 2006b]. However, if the nonnative understory is allowed to regrow, then the decreases in annual *ET* have been hypothesized to be short-lived [*Shafroth et al.*, 2005; *Cleverly et al.*, 2006b].

3. Evapotranspiration Estimation Methods

[16] In this study, we compare the daily riparian evapotranspiration (*ET* in mm d^{-1}) obtained using the 3SEC method to the daily groundwater evapotranspiration (ET_g in mm d^{-1}) from the White method. Currently, the 3SEC technique is the most direct method for measuring *ET* as a
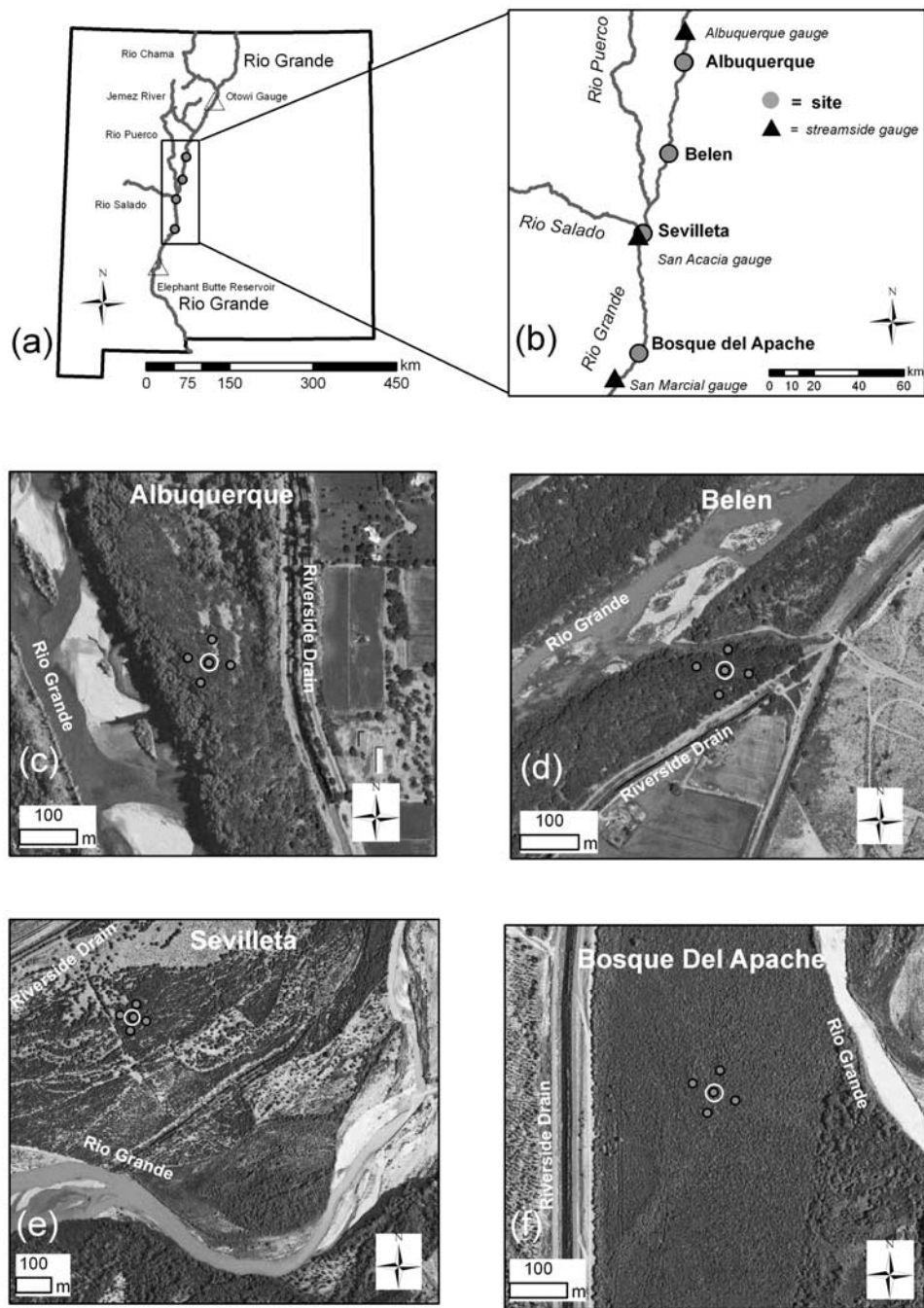
Figure 1. (a) Location of the study sites in New Mexico with the major tributaries to the Río Grande. Circles are locations of the study sites. Triangles are the U.S. Geological Survey (USGS) Otowi streamflow gauge and Elephant Butte Reservoir that delimit the northern and southern extents of the Middle Río Grande. (b) Close-up of the four sites (circles) with location of USGS stream gauges (triangles), Albuquerque (08330000), San Acacia (08354900), and San Marcial (08358400). Gray color composite orthophotos (1 m resolution) of study sites show location of monitoring wells, river, drainage canals, and other riparian features at (c) Albuquerque (ALB), (d) Belen (BLN), (e) Sevilleta (SEV), and (f) Bosque del Apache (BDA). Circles are the locations of the five shallow groundwater monitoring wells. Center well is outlined with a circle in proximity to the meteorological flux tower.

specific function of covariance between turbulent fluctuations in vertical wind velocity (w') and specific humidity (q'). Along riparian forests in the Río Grande, the footprint can range from 40 to 60 m around the salt cedar sites and up to 200 m around the cottonwood-dominated sites [see *Cleverly et al.*, 2006a]. Various standard corrections are applied to account for limitations of the 3SEC technique, as detailed by *Cleverly et al.* [2006a]. Closure of the energy balance has been ensured by utilizing the Bowen ratio ($H/\lambda ET$) to force thermodynamic equilibrium [see *Cleverly et al.*, 2002, 2006a].
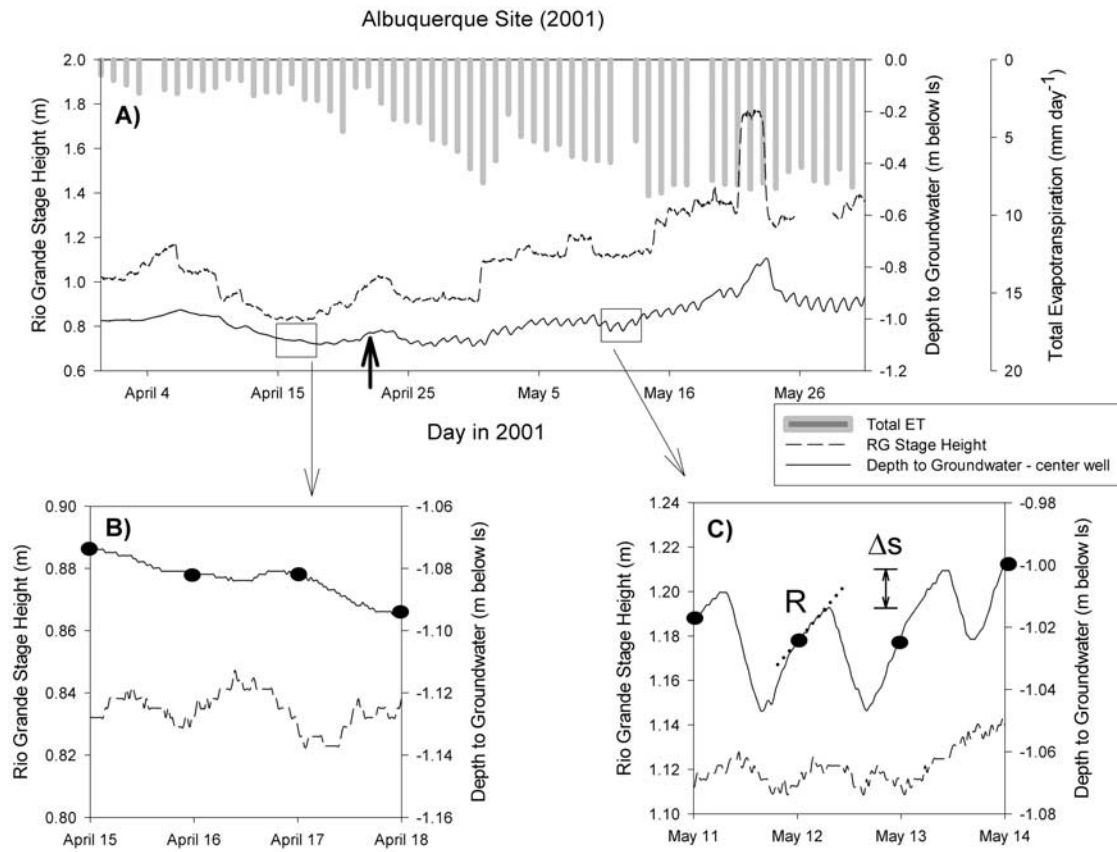
Figure 2. (a) Río Grande stage height, depth to groundwater, and total evapotranspiration at center well at the ALB site, 1 April to 31 May 2001. The arrow marks the beginning of the diurnal oscillations in water table. (b and c) Three-day intervals of river stage and depth to groundwater prior to and after the fluctuations commence. Dots mark midnight. Note how the diurnal groundwater oscillations cannot be explained by the river stage fluctuations. Minimum depth to groundwater typically occurs before the Sun rises, corresponding to the period of day during which photosynthesis is negligible and little groundwater consumption occurs. Maximum depth to water table typically occurs in the late afternoon, corresponding to high photosynthetic activity. R and Δs are variables used in the White method and estimated from the groundwater observations.

[17] Daily ET_g estimates using the White method are based on diurnal fluctuations in water table [*White*, 1932; *Loheide et al.*, 2005; *Butler et al.*, 2007]. As a result, the method only accounts for one component of the total riparian evapotranspiration (*ET*), generally defined as,

$$ET = ET_g + E_o + E_i + ET_s, \qquad (1)$$

where E_o and E_i are evaporation from open water and intercepted canopy water, and ET_s is evapotranspiration from the unsaturated soil. The groundwater phreatophyte transpiration component is estimated using the White method as (see Figure 2c)

$$ET_g = S_y(\Delta s/t + R), \qquad (2)$$

where ET_g is the rate of evapotranspirative consumption of groundwater averaged over a 24-h period (mm d^{-1}), S_y is the specific yield (dimensionless), Δs is the daily change in aquifer storage (mm), R is the net inflow (recovery) rate (mm d^{-1}), and t is the time period of 1 day. The daily storage change (Δs) is computed from the difference in the maximum water table elevations of two consecutive days. A positive Δs value indicates the water table is falling over a 24-h period and a negative value indicates a rising water table. The net inflow or recovery rate (R) is calculated as the rate of change (e.g., slope) in the water table elevation in a period with negligible transpiration, typically assumed between midnight and 0400 LT [*Loheide et al.*, 2005; *Butler et al.*, 2007].

[18] Figure 2 illustrates the seasonal differences in diurnal fluctuations in water table observed during the transition from spring to summer seasons in the Río Grande riparian corridor, and the application of the White method. While these data are specifically from the ALB site for the year 2001, similar patterns are observed for other years in the record and at the other riparian sites. Note that the depth to groundwater (m) from the center well (closest to the 3SEC tower) begins to show diurnal fluctuations around 22 April 2001 (arrow). The water table elevation at this site generally follows trends in the river stage as measured at a nearby USGS gauging station. Daily oscillations in river stage are minimal and show little in common with the seasonal differences in groundwater fluctuations that are characteris-

tic of riparian transpiration. Although river stage fluctuations are minimal, it is unclear whether the periodicity in river stage corresponds to a diurnal pattern of thermal expansion and contraction or is an equipment-induced artifact. Onset of the diel groundwater oscillations is coincident with an increase in the daily riparian evapotranspiration measured by the 3SEC method at the site (increasing from ~2 to ~7 mm d^{-1} during 22–30 April). To further illustrate the changes in groundwater response during the transition into the growing season, Figures 2b and 2c present river stage and groundwater elevations for two 3-day periods in the record (15–18 April and 11–14 May). Note that diurnal fluctuations are absent in the early period, while transpiration from the cottonwood overstory and nonnative understory at the site induces oscillations in the water table elevation for the later period.

[19] To accurately calculate ET_g using the White method, we removed periods of groundwater fluctuations that were induced by rapid changes in river stage. This issue has not been previously addressed since most prior studies focus on nonflowing channels or short-term periods of steady channel flow [*Loheide et al.*, 2005; *Steinwand et al.*, 2006; *Butler et al.*, 2007]. In addition, daily ET_g data were inspected for consistency by removing any negative ET_g values resulting from spurious water table fluctuations. Furthermore, short-term ET_g values exceeding twice the standard deviation above the annual mean ET_g were filtered from the record. Taken together, these three processing steps ensured the removal of ET_g outliers that corresponded to water table fluctuations during river pulses. Prior to calculating ET_g, pressure transducer data were filtered for spikes and noise. The data also were frequently calibrated in the field with manual measurements of depth to groundwater. Precipitation events during this study were not shown to affect groundwater dynamics directly due to soil infiltration. Precipitation events only affected groundwater dynamics through precipitation-induced river pulses, which we accounted for in our data processing procedures. This data processing was essential to ensure a consistent set of ET_g values across all sites and years.

[20] The only variable in the White method not estimated directly from groundwater fluctuations is the specific yield (S_y), defined as the water volume released from storage per unit drop in the water table height per unit land area. S_y is a property of depth to water table, antecedent moisture conditions, duration of drainage, and the sediment texture [e.g., *Hornberger et al.*, 1998; *Healy and Cook*, 2002]. Estimating S_y in a field setting is challenging due to heterogeneities in aquifer properties that interact with a fluctuating water table. Recent papers have explored techniques to estimate specific yield by characterizing the soil horizon properties near the water table [*Loheide et al.*, 2005; *Butler et al.*, 2007]. Using a numerical simulation, *Loheide et al.* [2005] showed that the specific yield of a substrate with high porosity decreases as the percent of fines increases and is a function of depth to groundwater. The authors propose a method to estimate the readily available specific yield using sediment texture [see *Loheide et al.*, 2005, Figure 10] that we adopt in this study. Given the uncertainties inherent in this technique, we account for possible variations in S_y for each soil texture (details provided in section 4.2). Soil texture analyses (% clay, sand, silt) were performed on samples taken during

installation of two of the five wells at each site using the hydrometer method [*Birkeland*, 1984]. At each site, soil analysis was performed on the first 10 cm, with subsequent analysis performed when there was a visible difference in soil type. We estimated the readily available specific yield at each well using the soil properties at depths over which the water table was observed to occur during the long-term monitoring effort (2000–2006).

4. Results

4.1. Surface Water and Groundwater Hydrographs

[21] Peak river flows in the Río Grande typically occur during the snowmelt (April–May) and monsoon (July–September) periods (Figure 3). River stage height is used here to describe river flows instead of discharge because stage height represents the hydraulic head in the river channel and can be directly related to groundwater elevations. The timing and magnitude of the peak flows varied annually during the period of this study (2000–2006). As shown in Figure 3, annual maximum flows at the ALB stream gauge occurring in 2000, 2002, and 2003 were significantly reduced as compared with 2001, 2004, 2005, and 2006. For convenience in our study, sampling years with lower snowmelt and monsoon flood pulses are labeled as dry years (2000, 2002, 2003), while the remaining years are considered wet (2001, 2004, 2005, 2006). The only wet year lacking snowmelt-derived peak flow was 2006, in which spring streamflow was significantly muted due to the relatively dry winter, while intense monsoon rainfall led to large summer flows [*Gutiérrez-Jurado et al.*, 2007]. River stage data at the three gauging stations (see Figure 1b) revealed spatial heterogeneity in how this river reach responded to wet and dry years (Figure 3). Downstream river response varies due to hydrologic inputs from the Río Salado and Río Puerco tributaries (Figure 1) as well as losses to the shallow aquifer [*Vivoni et al.*, 2006] and irrigation diversion dams.

[22] The hydrologic connectivity between the river and shallow groundwater varies for each of the study sites (data shown only for ALB and SEV). At the daily timescale, groundwater at three sites, ALB, BLN, and BDA, is highly responsive to changes in river stage, responding on average about 14–24 h, 24–34 h, and 4–8 h after the change in river stage, respectively (not shown). On the other hand, groundwater at the SEV site is comparatively unresponsive to immediate changes to the river stage (Figures 3d and 3e) with a longer 3- to 4-day delay. Although groundwater at the SEV site does not respond rapidly to changes in the river stage, it does follow the annual runoff cycles within the Río Grande (i.e., annual groundwater oscillations clearly shown in Figure 3e). As in other sites, the water table rises during the snowmelt runoff period and decreases steadily during interstorm periods prior to monsoon activity. Groundwater at both ALB and SEV sites exhibit short-term responses to large individual flow events as shown in 2006. During that year, both ALB and SEV sites responded slowly to low snowmelt runoff but demonstrated a dramatic increase in water table position due to the high monsoon rainfall and runoff [e.g., *Gutiérrez-Jurado et al.*, 2007].
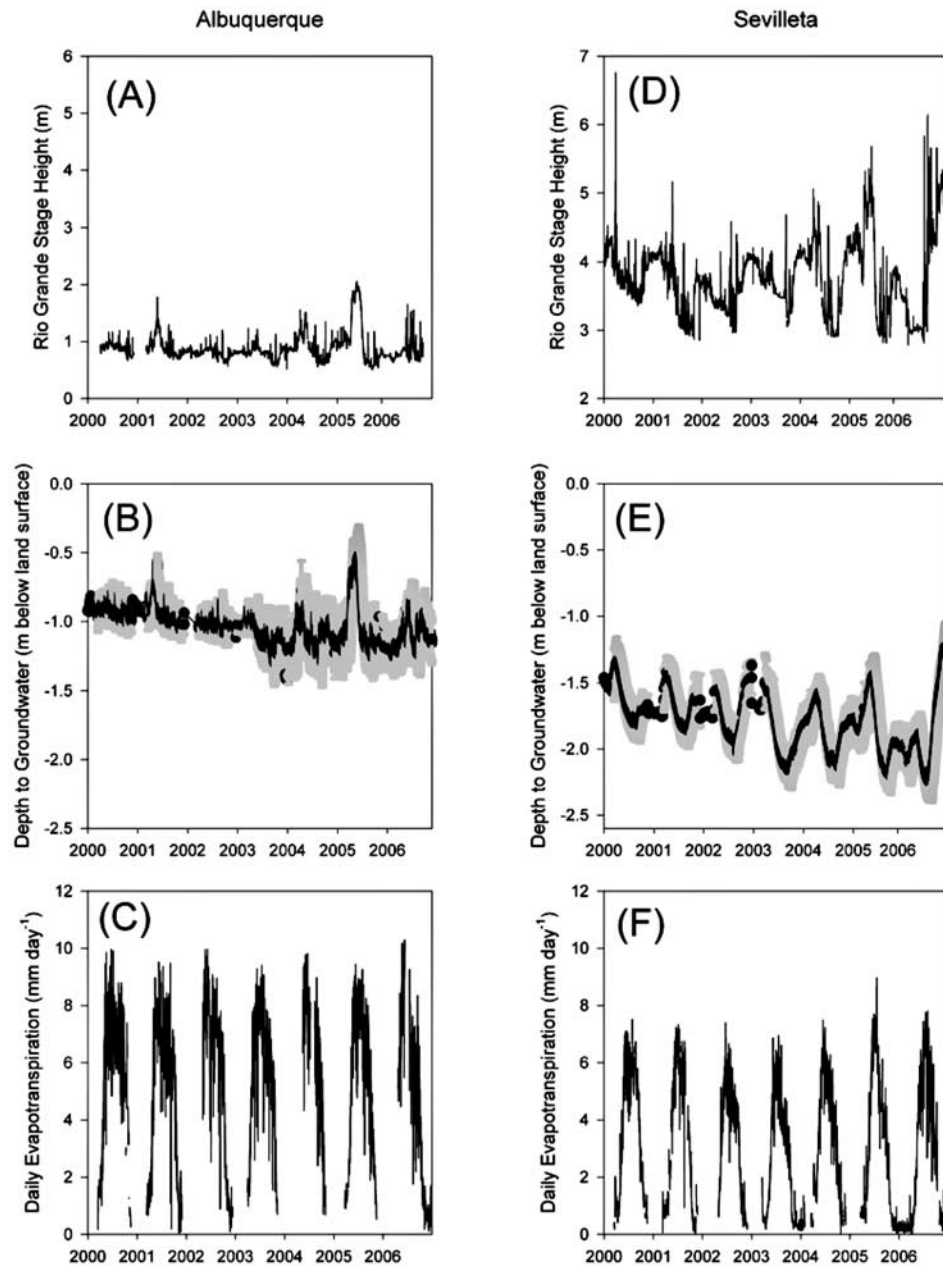
Figure 3. Río Grande stage height (m), average depth to groundwater (m below land surface), and daily evapotranspiration (mm d^{-1}) during the 2000–2006 period for (a–c) ALB site and (d–f) SEV site. The depth to groundwater is averaged (solid curve) over the four wells at the site. The shaded area represents the range (±1 standard deviation) in the four wells. Note that the depths to groundwater are given in negative values where the land surface is $z = 0$. Daily evapotranspiration (ET) data (mm d^{-1}) are derived from the meteorological towers using the three-dimensional sonic eddy covariance (3SEC) method. Blank regions indicate that no data are available. Year begins at the hatch mark.

[23] The shallowest depth to groundwater occurred at the two flooding sites, BLN and BDA, which exhibited ponded water on the land surface during some periods in wet years. The annual depth to water table at these sites, averaged across the study period and using all wells on site, was 0.78 and 0.75 m, respectively, below the land surface. Deeper groundwater occurred at the nonflooding sites, ALB and SEV, with annual averaged depths of 1.03 and 1.78 m below the surface. Interestingly, dry and wet years did not result in significant difference in the averaged depth to groundwater at each of the four sites. Nevertheless, the occurrence of wet

or dry years did affect the pattern of groundwater fluctuations. Specifically, the average daily ranges of the water table position were reduced during the dry years as compared with the wet years. This finding was only statistically significant (P < 0.06) at the two flooded sites.

4.2. Using Groundwater Well Hydrographs to Estimate ET_g

4.2.1. Specific Yield Estimates

[24] Figure 4 presents the soil texture estimates (% sand, % silt, % clay) at the available wells in each study site for
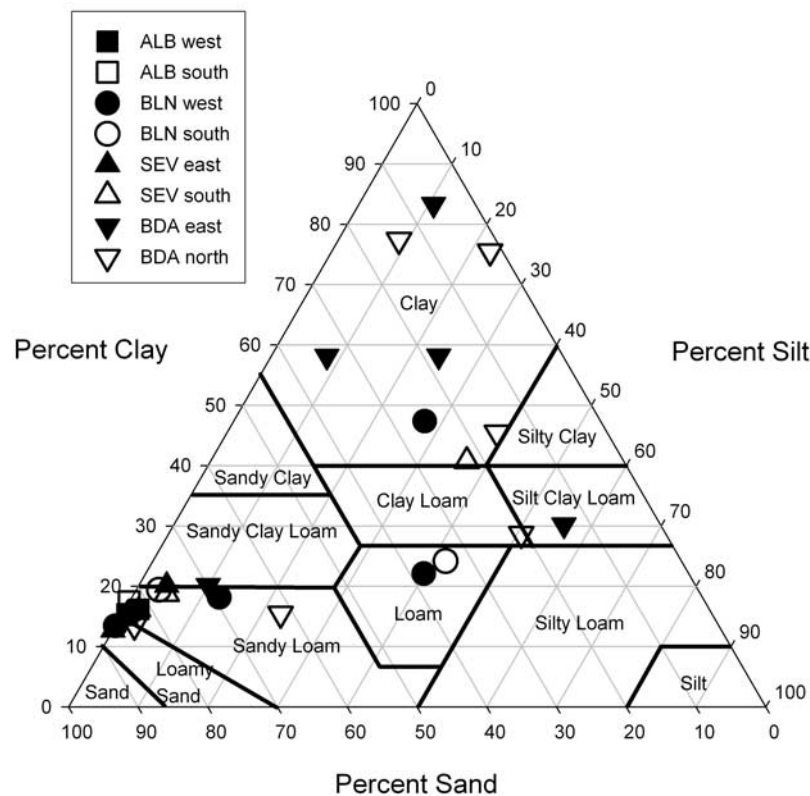
Figure 4. Soil texture classification (% silt, % clay, % sand) of sediments within the zone of groundwater fluctuations at all four sites. Solid and open symbols for ALB and BLN sites correspond to west and south wells. Solid symbols for SEV and BDA sites are east wells, while open symbols are south and north wells, respectively.

the groundwater fluctuation intervals. For each soil classification, we used the high and low estimates of the readily available specific yield values given by *Loheide et al.* [2005, Figure 10]. Because of the uncertainties inherent in the S_y estimates, a range of values for each soil texture classification was considered more appropriate than a single value of S_y. As a result, ET_g estimates from the White method at each well in our study represent a range that corresponds to high and low S_y estimates for each soil classification.

[25] Sediment profiles at the ALB site revealed sandy loam texture at both the west and south wells across the
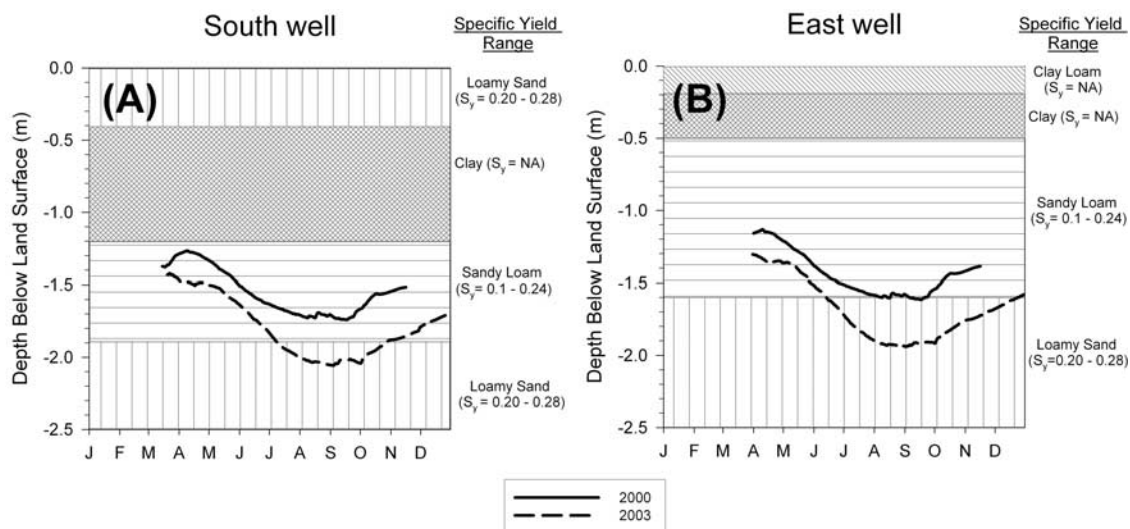

Figure 5. Vertical profile of soil texture and daily mean depth to groundwater at the (a) south and (b) east wells at the SEV site during 2000 and 2003. Major soil texture classification and estimated range of readily available specific yield are also shown.
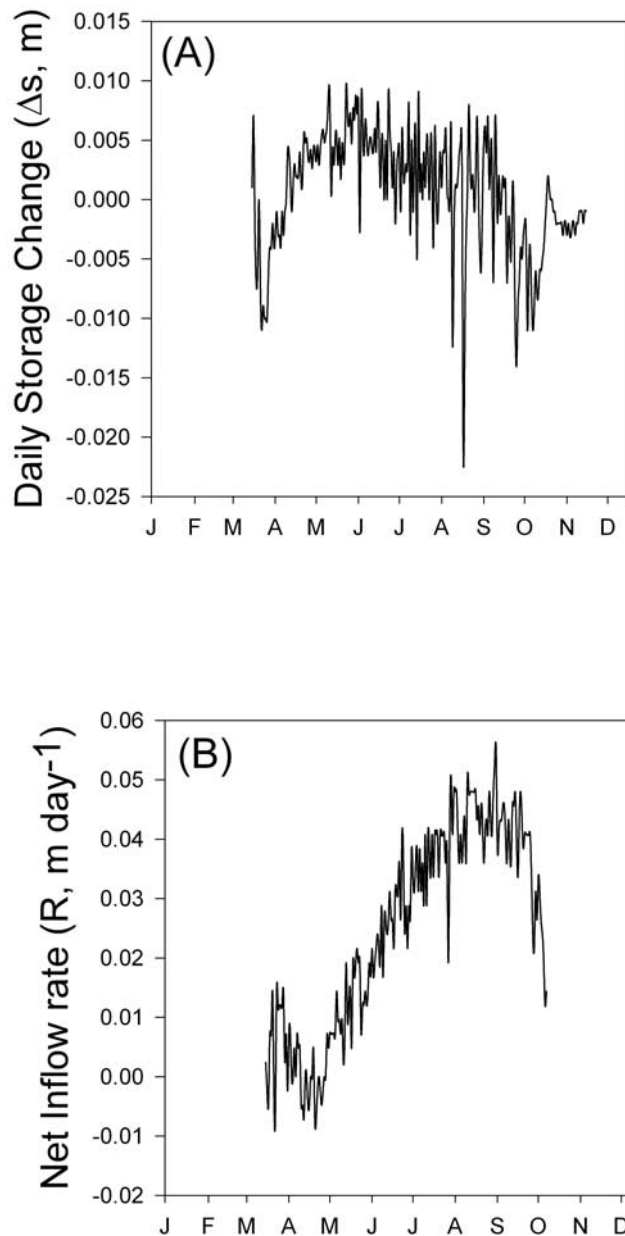
Figure 6. (a) Daily storage change (Δs, m), and (b) net inflow rate (R, m d^{-1}) at the SEV south well during 2000.

water table fluctuation zone (WTFZ) (between 0.74 and 1.21 m below the land surface) with a range of readily available specific yields of 0.10–0.24. Measurements at the west and south wells of the BLN site revealed loam to sandy loam textures within the WTFZ (0.05–1.25 m), with a range of S_y increasing with depth from 0.04 to 0.24 (data not shown). Clay sediments near the surface of the west well prevented estimation of S_y in 2004 using this method [see *Loheide et al.*, 2005]. At the SEV site, sediment profiles within the WTFZ (1.4–2.06 m) at the east and south wells are predominately sandy loam and loamy sand, with S_y values ranging from 0.10 to 0.28 (Figure 5). Figure 5 shows the daily mean depth to groundwater and sediment textures at the south and east wells at the SEV site during

2000 and 2003. The SEV south well had a clay lens with a small S_y at depths of 40–120 cm. The east and north wells of the BDA site exhibited more clay lenses within the WTFZ (0.62–1.79 m) relative to the other sites, limiting S_y estimates. Nevertheless, a range of soil textures was identified at BDA, including silt clay loam, clay loam, sandy loam, and loamy sand, with S_y from 0.01 to 0.28. An increase in finer-sized sediments was observed at the BLN and BDA sites as compared with ALB and SEV.

4.2.2. Daily Change in Storage (Δs) and Net Inflow Rate (R) Estimates

[26] Figure 6 shows the Δs and R at the SEV south well during 2000. In general, Δs and R measurements were similar between wells within a site (data not shown), especially at ALB and SEV. There were slight variations in Δs and R measurements between wells at the BLN site, and larger variations at the BDA site. Large spikes in Δs and R, as shown in Figure 6 during the month of August, were subsequently removed from the data after processing ET_g for outliers that corresponded to water table fluctuations during river pulses (refer to methods for details). In general, all sites exhibited similar curve shapes for annual Δs and R measurements. The shape of the Δs curve typically was flat with an annual mean of 0 and variability predominately within ±0.05 m. The annual curve of R measurements typically was more bell shaped, with greater recovery rates occurring during the growing season, and reduced rates during the winter months. Peak recovery rates for all sites did not exceed 0.1 m d^{-1}.

4.2.3. Visual Comparisons of Evapotranspiration Estimates

[27] ET_g ranges were similar for each well within a site, indicating similarity in the groundwater hydrographs and sediment profiles. Figures 7 and 8 show the comparison of the well ET_g and ET at the ALB site (west well) and the SEV site (south well), respectively, over the study period. At both sites, the annual onset and cessation of ET_g closely tracked the ramp-up (April–May) and ramp-down periods (September–October) in ET. The range of ET_g is reduced during the rising and falling limbs, as compared with the peak season (June–August), due to the lower values of R and Δs. Although ET_g and ET measure two different quantities in equation (1), they both appear to track each other well.

[28] At the ALB site, ET_g tended to be larger than tower ET even when accounting for potential uncertainties in S_y. Note that the ALB site experienced understory vegetation removal in 2003 (see section 4.3), which would affect both ET_g and ET at the riparian site. It appears that the difference between the two ET estimates decreased after understory removal (2003). In contrast, comparisons at the SEV site between the south well ET_g and tower ET exhibited a closer agreement for most of the record (Figure 8). Groundwater ET_g estimates at the SEV site clearly envelope the colocated tower ET estimates during peak season, suggesting that the White method can provide moderate estimates of riparian evapotranspiration. Note that the uncertainty captured in S_y allows the ET_g estimates to bound the tower ET for the peak growing season. ET_g overestimates ET (September through October) in 2003–2005 (Figure 8). These time periods correspond to a transition in water table elevation from sandy loam texture to loamy sand texture. As a result, the
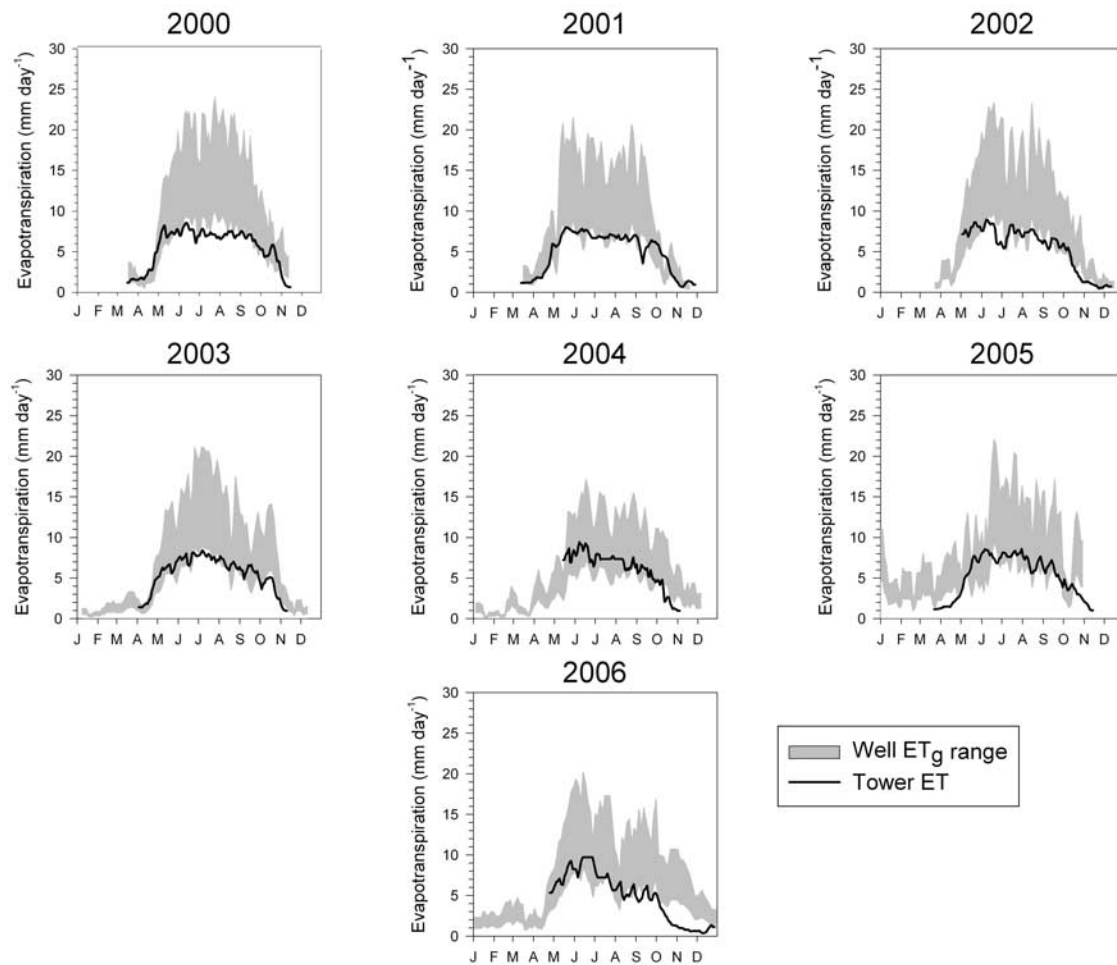
Figure 7. Multiple-year comparison of *ET* (solid curve) and west well ET_g range (gray region) for the ALB site for years 2000–2006. Estimates of *ET* and ET_g are represented as 10-day running averages. Units are in mm d^{-1}.

modeled range in S_y went from 0.1–0.24 to 0.2–0.28 (Figures 4 and 5), reducing well ET_g range and overestimating *ET*. ET_g estimates at the SEV site (salt cedar) are significantly reduced as compared with the ALB site (Figures 7 and 8).

[29] At the BLN site, the west well ET_g exhibits lower variations and encompasses the tower *ET*, while the south well overestimates *ET* and shows large fluctuations (data not shown). At the BDA site, neither well ET_g estimate captures the tower *ET* (data not shown). During most of the year, ET_g at the BDA east well could not be calculated because the water table was located within sediments composed of 40% clay or more, and when possible, the values were extremely low due to corresponding low S_y estimates. While soil profile conditions at the BDA north well did not limit ET_g estimates, these exhibited erratic behavior that overestimated or underestimated tower *ET* and did not capture the ramp-up and ramp-down periods.

4.2.4. Statistical Comparisons of Evapotranspiration Estimates

[30] Table 1 shows the percent coefficient of variation (CV%) calculated over the peak growing season (June–August) for the daily tower *ET* and ET_g estimates. CV% was calculated by dividing the standard deviation over the season (σ) by the seasonal mean (μ) for ET_g and *ET* during each year (CV% = 100 σ/μ). The CV% values for ET_g were averaged between high and low estimates of S_y. Yearly values of CV% were then averaged over the 2000–2006 period. At all four sites, CV% of ET_g is greater than CV% of *ET*. Wells within a site have similar variability in ET_g estimates, except at the BDA site where the east well has larger CV%. At ALB and SEV, CV% of ET_g was closer to the CV% of *ET*, whereas the BLN and BDA sites have nearly 3–6 times more variability in ET_g than in *ET* (Table 1). It should be noted that east well CV% at BDA represent only 1 year, whereas CV% at the north well represents a 6-year average.

[31] Table 2 presents the ET_g and *ET* averaged over the 92-day peak growing season (June–August) over the record period. The range of ET_g estimated at each well at the ALB site overlapped with tower *ET* values in four (2003–2006) of the seven years. ALB peak season ET_g, averaged across the record and each well, captured 97.3–233.81% of average *ET* (7.20 mm d^{-1}). South and west well ET_g values at ALB were significantly correlated to *ET* (r = 0.5, p < 0.001), except in 2006 (Table 3). At the SEV site, south and east well ET_g had the highest average correlation with *ET* (r = 0.71 and 0.61, Table 3). The ET_g range of the south well overlapped with *ET* during 6 years, whereas the east well
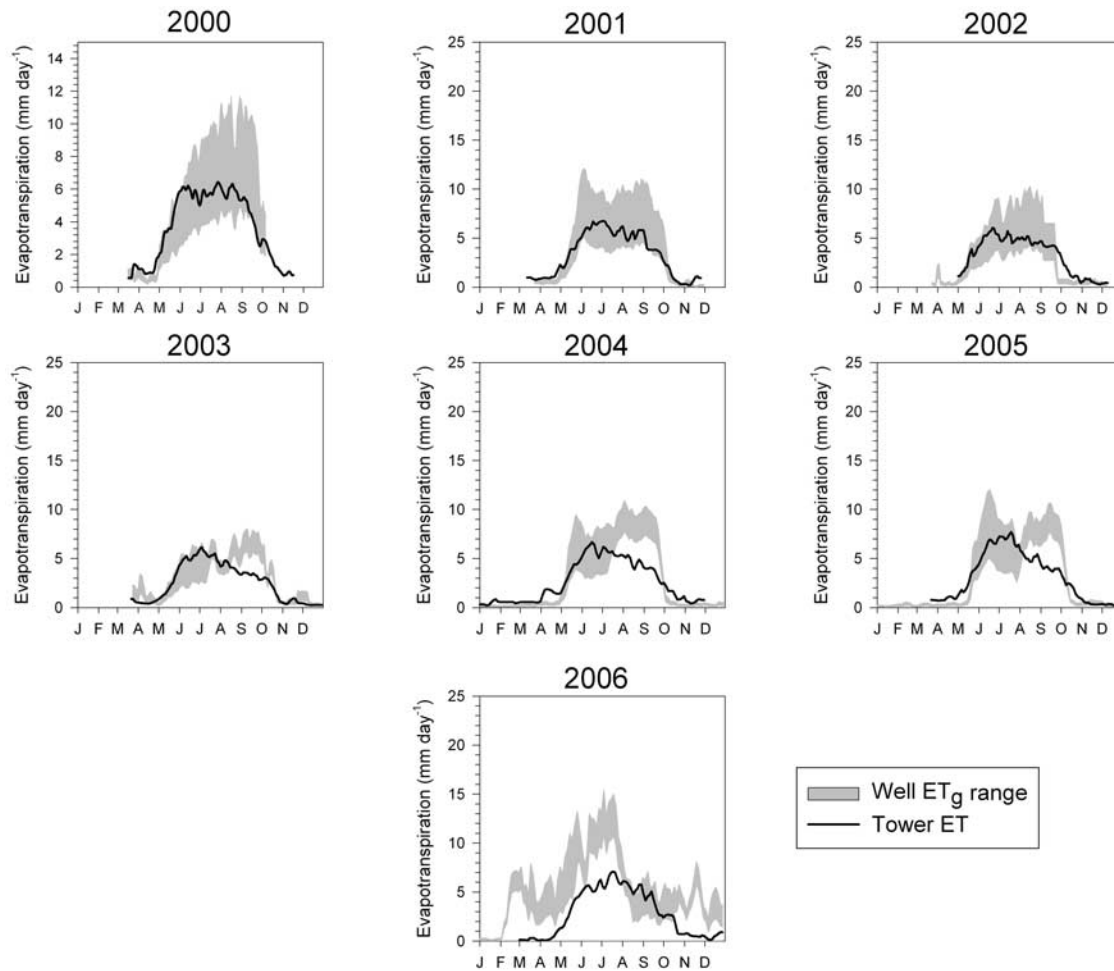
Figure 8. Multiple-year comparison of *ET* (solid curve) and south well ET_g range (gray region) for the SEV site for years 2000–2006. Estimates of *ET* and ET_g are represented as 10-day running averages. Units are in mm d^{-1}.

only overlapped 2 years (Table 2). South well ET_g values ranged from 79.7% to 155.2% of the tower measurement, while east well ET_g ranged from 103.2% to 174.3% of *ET*. At BDA, the north well ET_g overlapped the tower *ET* for 3 years, but on average was 113.5% to 273.6% larger. At BDA, 2001 was the sole year when ET_g was correlated to *ET* (r = 0.83). Correlation between the BDA north well and the *ET* was stronger (r = 0.31) across the record as compared with the east well (r = 0.01). At the BLN site, ET_g values at the west well enveloped the tower *ET* during the 4 years, whereas the south well overlapped for only 2 years (Table 3). On average, south and west well ET_g differed from *ET* by 120.9% and 81.3% for the low S_y range (Table 2). BLN peak season ET_g, averaged across the record and each well, captured 101.1–254.3% of average *ET* (6.17 mm d^{-1}). A weak correlation was found between *ET* and ET_g (r = 0.26). Among all the sites, ET_g estimates at the SEV site were closest to *ET*.

4.3. Using Groundwater Hydrographs to Assess Understory Vegetation Removal

[32] Figure 9 presents 10-day running averages of the diurnal amplitude (Δa) of groundwater fluctuations for three wells at ALB during 2001 (April–October). Also

depicted are the tower *ET* and range of ET_g derived from the west well. The diurnal amplitude (Δa) of a given day is calculated by subtracting the maximum and minimum water table elevations over a 24-h period. Note how Δa and ET_g closely track tower *ET* during the growing season and capture the onset and demise of seasonal ET_g. Leaf area index (LAI) declined from an average of 6.67 during the preremoval years to approximately 4 in 2003 (40% reduction) (Figure 10). Total LAI measured in 2006 remained 47% lower than preremoval estimates. Throughout the entire study period, the summer peak season average Δa

Table 1. Percent Coefficient of Variation for Estimates of ET_g and *ET* at ALB, BLN, SEV, and BDA Sites, Computed Over the Peak Growing Season (June–August) for 2000–2006[a]

Site	South ET_g	West ET_g	Tower *ET*
ALB	33 (±6)	34 (±7)	18 (±4)
BLN	65 (±25)	67 (±24)	19 (±3)
SEV	30 (±14)	40 (±11)	17 (±2)
	East ET_g	North ET_g	Tower *ET*
BDA	129 (nd)	74 (±48)	17 (±3)

[a]Standard deviations (SD) are given in parenthesis.

Table 2. Peak Season and Record Averaged ET_g and ET for the Two Wells and Tower at ALB, BLN, SEV, and BDA for 2000–2006[a]

Site	Well S_y Range[b]	2000	2001	2002	2003	2004	2005	2006	Record Average	SD
ALB	south	8.54–20.49	7.11–17.06	7.56–18.13	7.37–17.68	5.74–13.79	6.65–15.97	6.50–15.60	7.07–16.96	0.89–2.13
	west	8.34–20.23	7.05–16.92	7.75–18.60	7.13–17.11	5.67–13.61	6.37–15.29	6.33–15.19	6.95–16.71	0.91–2.24
	tower	7.28	7.02	7.26	7.29	7.53	7.55	6.48	7.20	0.36
BLN	south	7.44–17.87	5.98–14.36	8.82–21.17	6.55–15.73	8.51–20.42	N.D.	N.D.	7.46–17.91	1.22–2.93
	west	3.85–11.54	3.57–10.71	3.98–10.92	5.04–12.27	8.66–21.94	N.D.	N.D.	5.02–13.48	2.11–4.77
	tower	5.65	6.12	6.12	6.81	N.D.	N.D.	N.D.	6.17	0.48
SEV	south	3.86–9.26	4.15–9.97	3.40–8.17	3.40–5.79	5.12–8.72	4.65–8.93	6.48–9.67	4.44–8.64	1.10–1.39
	east	3.95–9.47	3.16–5.53	6.07–8.74	6.73–9.77	6.67–9.93	8.03–14.23	5.62–10.32	5.75–9.71	1.69–2.56
	tower	5.82	5.90	5.01	4.84	5.40	6.23	5.77	5.57	0.50
BDA	north	N.D.	10.31–24.74	0.24–1.41	4.98–11.59	10.47–25.14	4.33–10.40	20.70–49.67	8.50–20.49	7.13–16.95
	east	N.D.	N.D.	N.D.	0.09–0.26	N.D.	N.D.	N.D.	0.09–0.26	N.D.
	tower	7.37	7.59	6.29	7.37	7.89	7.93	8.02	7.49	0.59

[a]Record averages and standard deviations for each well and colocated tower were calculated by averaging peak season values over the 7-year period. Values are mm d^{-1}. N.D. means no data. Peak season is June–August.

[b]Well ET_g calculated using the low and high estimates of S_y given by *Loheide et al.* [2005].

ranged from 4.5 to 6 cm, whereas during the winter, Δa ranged from 0 to 1 cm. Note how vegetation removal is reflected in the reduction of daily amplitude of groundwater fluctuations, in particular during the year following removal (2004).

[33] Figure 11 presents 10-day running averages of diurnal Δa at the center, west, and south wells prior (2000–2002) and after (2004–2006) vegetation understory removal. Postrestoration Δa exceeded prerestoration Δa during April and October. Groundwater amplitude of the preremoval period ranged from 1.0 cm in winter to 6.0 cm during the growing season, while postremoval Δa varied from 2.0 to 5.5 cm (Figure 11). A Mann-Whitney test indicated that Δa was significantly reduced in postremoval years (p < 0.001). The difference in the median amplitude across the three wells was 0.32–0.86 cm (at 95% confidence level), which represents a 6.7–18.1% reduction in Δa. Peak season ET_g during the postremoval years showed a 19–21% reduction as compared with the preremoval years (Table 2).

5. Discussion

5.1. Riparian Evapotranspiration and Groundwater Hydrographs

[34] In the semiarid southwestern United States, there is a growing effort to construct regional water budgets to aid in water management decisions. A major component of the water budget in riparian ecosystems is evapotranspiration [e.g., *Dahm et al.*, 2002; *Cleverly et al.*, 2006a, 2006b; *Newman et al.*, 2006]. *Dahm et al.* [2002] estimated the annually averaged riparian ET in the Middle Río Grande as 150 to 250 × 10^6 m^3/a, which accounted for 20–30% of water consumption from Otowi gauge to Elephant Butte Reservoir. Although few studies have identified contributions of evaporation and transpiration, a significant portion of total evapotranspiration in semiarid riparian ecosystems can occur from vegetative consumption of groundwater [e.g., *Ferretti et al.*, 2003; *Yepez et al.*, 2003; *Scott et al.*, 2005; *Lauenroth and Bradford*, 2006; *Steinwand et al.*, 2006]. Research along the San Pedro River in Arizona revealed that transpiration accounted for close to 100% of the total riparian water loss during dry periods, and near 35% during large precipitation events that led to an increase in soil evaporation [*Corell et al.*, 1996; *Goodrich et al.*, 2000; *Yepez et al.*, 2003; *Leenhouts*, 2005; *Scott et al.*, 2005]. The majority of the total transpiration (71–94%) during the peak and late summer months was attributed to the overstory vegetation, whose primary source was groundwater [*Scott et al.*, 2005]. As a result, the dynamics of the riparian vegetation and its effect on groundwater are critical to understand local and regional water budgets in the southwestern United States.

[35] Exploring the relationships between groundwater dynamics, riparian evapotranspiration, and long-term trends in ecosystem structure and function is still difficult due to the lack of accurate ET measurements at appropriate scales in riparian zones of different widths [e.g., *Thorburn et al.*, 1993; *Tabacchi et al.*, 2000; *Dahm et al.*, 2002; *Cleverly et al.*, 2002; *Shafroth et al.*, 2005; *Wilcox et al.*, 2006]. In this study, we have used long-term meteorological flux tower and groundwater hydrograph data to compare the 3SEC and

Table 3. Annual and Record Correlation Coefficients of ET_g at Specific Wells and Tower ET for ALB, BLN, SEV, and BDA Sites Over 2000–2006[a]

Site	Correlation	2000	2001	2002	2003	2004	2005	2006	Record Average[b]	SD
ALB	south-west	0.99	0.48	0.99	0.76	0.99	0.49	0.86	0.79	0.23
	south-tower	0.59	0.61	0.61	0.56	0.37	0.27	0.513[c]	0.50	0.13
	west-tower	0.59	0.62	0.61	0.52	0.39	0.29	N.D.	0.50	0.13
BLN	south-west	0.42	0.44	0.15[c]	0.36	0.36	N.D.	N.D.	0.35	0.12
	south-tower	0.36	0.34	0.001[c]	0.34	0.261[c]	N.D.	N.D.	0.26	0.15
	west-tower	0.149[c]	0.28	0.20[d]	0.41	0.326[d]	N.D.	N.D.	0.27	0.10
SEV	south-east	0.959	0.82	0.79	0.48	0.55	0.66	0.51	0.68	0.18
	south-tower	0.753	0.818	0.832	N.D.	0.72	0.71	0.45	0.71	0.14
	east-tower	0.704	0.66	0.73	N.D.	0.51	0.63	0.413	0.61	0.12
BDA	north-east	N.D.	N.D.	N.D.	0.87	N.D.	−0.108[c]	N.D.	0.38	0.69
	north-tower	0.285[c]	0.827	−0.149[c]	0.03[c]	0.47[c]	−0.127[c]	0.82	0.31	0.42
	east-tower	N.D.	N.D.	N.D.	−0.01[c]	0.3[c]	0.157[c]	−0.396[c]	0.01	0.30

[a]The Pearson correlation tests for linear correlation between both wells and tower. All coefficients are significant at p < 0.001, unless noted otherwise. N.D. means no data.
[b]Values are averaged for all years data are available.
[c]Not significant.
[d]Significant at p < 0.05.

White methods for estimating riparian evapotranspiration and to monitor the hydrologic effects of changing vegetation density. However, the influence of river flood pulses on the White method must be accounted for in riparian corridors with perennial reaches and high levels of hydrologic connectivity between the river and shallow aquifer. Typically, these variations were caused by large river pulses during snowmelt and monsoon seasons. The BLN and BDA sites showed the largest river-induced groundwater fluctuations, while the SEV site was mostly unresponsive to short-term fluctuations (Figure 3). The surface water/groundwater connectivity at the ALB site, although less than BLN and BDA, did result in increased temporal variations in ET_g, especially during wetter years (e.g., 2004–2006).

[36] We found that ET_g estimates at all four sites along the Río Grande riparian corridor have large variability due to the inherent uncertainty in specific yield (S_y). We utilized the coefficient of variations (CV%) between the tower ET and groundwater ET_g estimates to determine whether a comparison of the methods was appropriate [*Lauenroth and Bradford*, 2006]. A greater similarity in CV% suggests that a closer relationship exists at the ALB and SEV sites, as compared with the BLN and BDA sites (Table 1). Differences in sediment composition in the zone of water table fluctuations may explain some of the observed variability in the groundwater ET_g estimates. As shown in previous studies, ET_g calculations using the White method can overestimate or underestimate actual ET depending on the values of the specific yield (S_y) assumed for the sediments that interact with the water table [e.g., *Healy and Cook*, 2002; *Loheide et al.*, 2005; *Butler et al.*, 2007; *Lautz*, 2008]. Various studies have documented how S_y estimates for coarse sediments have lower uncertainties [e.g., *Rosenberry and Winter*, 1997; *Healy and Cook*, 2002; *Loheide et al.*, 2005; *Butler et al.*, 2007]. Since coarser sediments drain more quickly, errors in estimating S_y related to drainage and retention times are minimized. Finer textures (i.e., silt and clay) tend to decrease hydraulic conductivity and increase water retention. As a result, estimates of ET_g may not respond as readily within a 24-h cycle if the water table is located within silt and clay dominated sediments. Both ALB and SEV sites had deeper water tables that interacted with

coarser sediments (loamy sand to sandy loam) as compared with BLN and BDA where shallower water tables were located in soils with finer particles (sandy loam to silty clay loam). The stronger correlation between ET_g and ET at ALB and SEV indicates these sites are more amenable for the White method. The SEV site was found as the best candidate to estimate ET_g as groundwater is typically deeper than 1 m from the surface and the connectivity between the river and shallow aquifer is minimal.

[37] We found that the range of ET_g values was larger than tower ET measurements at all four study sites. While ET_g can envelope tower ET at certain sites, the daily variations in water table can lead to greater variability in evapotranspiration estimates than the daily meteorological flux estimates. While this result may seem counterintuitive, it is clear that the White method is sensitive to potential errors in estimating S_y and can be influenced by periods of hydrologic fluxes from the nearby river. Nevertheless, we accounted for both sources of error by excluding periods of large diurnal changes not related to plant transpiration and by sampling a range of possible S_y. The two sites with the
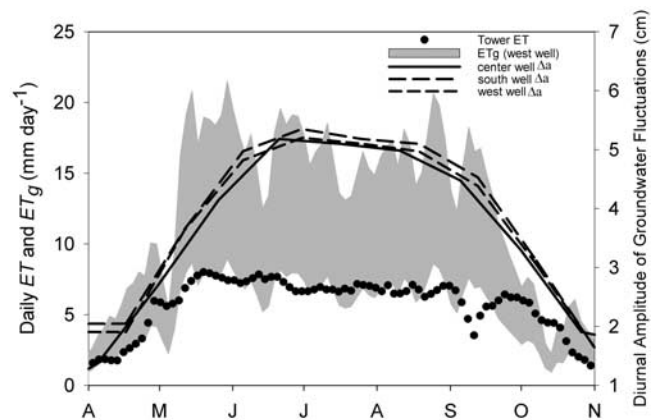

Figure 9. Diurnal amplitude Δa (cm) of groundwater fluctuations at center, south, and west wells (curves), daily ET (mm d^{-1}) (dots) at the ALB site, and ET_g (mm d^{-1}) (gray area) from the west well during 1 April to 31 October 2001.
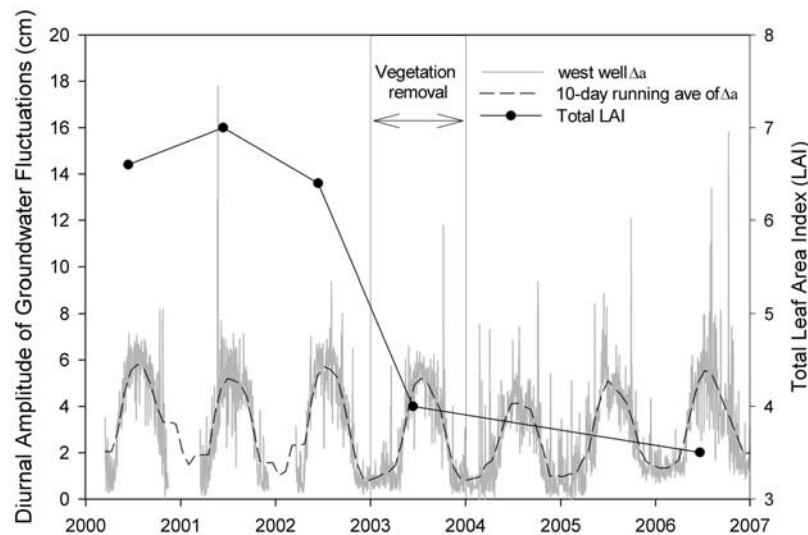
Figure 10. Diurnal amplitude Δa (cm) of groundwater fluctuations (gray curve) and field estimates of total leaf area index (LAI) (solid curve) at the ALB center well from 2000 to 2006. Diurnal amplitudes are shown with a 10-day running average (dashed curve). Box highlights the year that understory vegetation was removed.

strongest correlations between ET and ET_g were ALB and SEV (Figures 7 and 8). The lower range of ET_g estimates at the ALB and SEV sites were on average 97.3 and 101.1% of the tower ET estimates. While this result is encouraging, the higher ranges of ET_g estimates based on high S_y values were 233.8 and 164.8% of ET. ET_g appears to be the primary component of total ET compared with E_o, E_i, and ET_s (see equation (1)), especially at the ALB site. Compared with the ALB site, the groundwater at the SEV site is consistently deeper and less connected to the river, making vadose zone water (ET_s) a potentially more important component of total ET. Furthermore, salt cedar plants, the primary vegetation at the SEV site, have a greater ability to extract water from the vadose zone than do cottonwood plants, the primary vegetation at the ALB site. Thus combining both the White method and 3SEC method can help separate the ET_g component from total ET, and reveal how vegetation types can alter the balance of ET components.

[38] The SEV site exhibited the best correlation between ET and ET_g due to the improved measurements of available specific yield that can be obtained when the groundwater is deeper than 1 m and sediment texture is well known [Loheide et al., 2005; Butler et al., 2007]. While depth to groundwater at all four sites occasionally dropped below 1 m, only the SEV site had a water table position consistently below 1 m. As discussed by Loheide et al. [2005], the depth to groundwater, the degree of hydrologic connectivity, and the sediment composition are critical factors in applying the White method. In 2006, there was a clear increase in overestimation of ET and variability associated with ET_g. This variability between February and March can be explained by an increase in recovery rate (R) estimates, beginning suddenly in mid-February, which was not apparent during the previous years (data not shown). The sudden increase in R in mid-February is not explained by river stage fluctuations, which were relatively calm during this period. It is worth noting that during January and July of 2006, the

water level position was at its lowest depth on record (~-2.0 m). Even though the water table was located within a sandy loam texture from mid-March to June, ET_g still overestimated ET. There is insufficient evidence to determine whether the rapid fluctuations in R are caused by additional inflows, such as regional groundwater flows or an increase in capillary flow. In addition to the variability associated with S_y, another reason why ET_g overestimates ET could be artificially high recovery rates (R). While R
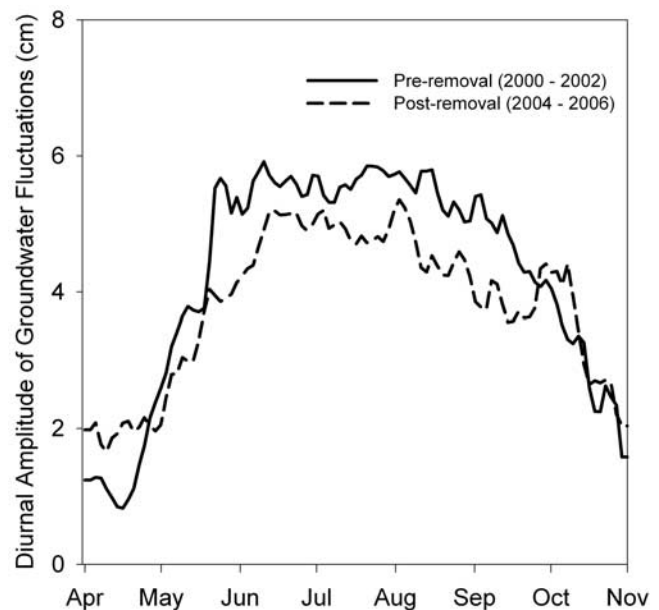

Figure 11. Diurnal amplitude Δa (cm) of groundwater fluctuations averaged for three wells at the ALB site during the growing season (1 April to 31 October). Solid curve represents the preremoval period, and the dashed curve represents the postremoval period. The data are shown as 10-day running averages.

appears to change with vegetation growth (increasing during the growing season) and local hydrologic conditions, it is not clear what factors influence R throughout the day. More research is needed on the diurnal changes of R in relationship to river stage height, groundwater fluctuations, and vegetation growth. This research is needed in order to know whether or not calculating R from midnight to 0400 LT. is an accurate approach to estimate R. Although daily groundwater hydrographs can be highly variable in both space and time, they have been shown to capture distinct patterns among different sites, and therefore can potentially be used to capture significant changes within a site.

[39] Spatial variation in groundwater responses will influence the estimation of ET_g in riparian corridors, depending on the composition of alluvial aquifer sediments and spatial gradients in groundwater elevation. Spatial groundwater differences in wells 40 m apart at each site generally produced identical groundwater hydrographs, resulting in similar temporal patterns in depth to groundwater, storage (Δs), and recovery rate (R) (Figure 6). Although exceptions exist, differences between well estimates of ET_g at each site appear more correlated with spatial variability in S_y than with variations of Δs and R. At the ALB and SEV sites, the similarity between ET_g estimates at both wells is a result of similar sediment textures and groundwater well hydrographs (see Figure 5 for SEV). However, the correlation coefficients between ET_g estimates at the ALB and SEV site were relatively lower during some years (e.g., 2001 and 2005 for ALB, and 2003 for SEV). One possible explanation for the lower correlation coefficients at the ALB site is that 2001 and 2005 were both significantly wetter years (larger river flows). Significant river stage changes during these years are likely influencing the spatial groundwater dynamics at hydrologically connected sites such as ALB even after removing the effects of large river pulses on the groundwater. In the case of SEV, 2003 was a significantly drier year, which resulted in some of the deepest mean water table depths at this site (Figure 5). Perhaps the difference in spatial groundwater fluctuations between wells at the SEV site became more evident as the water table moved across heterogeneous sediment layers, as shown in Figure 5. The correlation coefficient of ET_g at both ALB and SEV sites suggests that nearby wells might respond differently to raised or lowered water table positions, as controlled by local hydrological conditions. In addition, estimates of ET_g using the White method should account for the temporal interactions of the water table with different S_y zones (and the uncertainty in S_y for each layer). It is therefore advisable to have multiple wells around a meteorological flux tower in order to select the most appropriate groundwater hydrograph records.

[40] In contrast, BLN west and south wells had similar hydrographs but interact with different soil horizons with varying S_y. In most years, the BLN west well had greater Δa values but nearly half of the ET_g variability than the south well. The larger ET_g fluctuations at the south well can further be explained by the greater S_y ranges at the south well compared with the west well. Because of finer textures, ET_g estimates at the west well may have higher time-dependent errors than the south well that may result in a decreased correlation with ET [*Rosenberry and Winter*, 1997; *Healy and Cook*, 2002]. However, record average correla-

tions between south and west well ET_g and ET were similar (0.26 and 0.27) despite the differences in coarse sediments and groundwater elevation. While this result suggests that readily available S_y [*Loheide et al.*, 2005] can be adequately predicted from soil texture at sites with a shallow water table and fine-textured sediments, it clearly does not hold true at the BDA site. In this study, the White method performed better in loam-dominated sediments, such as the BLN west well, compared with clay loam and silt clay loam sediments, as was the case at the BDA north well. In 2003, groundwater at the BLN west well transitioned during June from a loam layer to a sandy loam layer, while groundwater in the south well consistently occupied a sandy loam layer. This groundwater shift at the west well resulted in an increase in the range of ET_g. In 2004, the BLN wells showed larger groundwater fluctuations due to a relative increase in river stage variations, resulting in larger ET_g ranges. The increased river stage fluctuations might be explained by nearby irrigation operations. This indicates that caution must be taken in applying the White method in riparian areas where groundwater is highly responsive to surface water forcings, particularly during wetter periods, which include seasonal river pulses, daily phreatophyte water consumption, and surface water diversion and pumping effects. Overall, temporal variation in depth to the water table will influence estimation of ET_g as daily interactions occur with different soil horizons.

[41] It is apparent that ET_g estimates are sensitive to vertical heterogeneity in S_y and its possible spatial variations. It is therefore prudent to have at least two riparian wells located in close proximity to obtain a baseline understanding of site heterogeneity. Variations between ET_g and ET appear to increase as the water table approaches the land surface. At some sites, estimates of ET_g were limited by fine sediments and river fluctuations. In our study, BLN and BDA exhibited the weakest correlation between ET_g and ET, possibly due to the presence of fine sediments in the soil column. The erratic behavior at BDA north well was a result of very large fluctuations in Δs. Clearly, the application of the White method for estimating ET_g can fail under particular conditions. As demonstrated by comparing the SEV site with ALB and BLN sites, ET_g estimates using the White method improved when water table fluctuations stabilized at deeper positions, were located in coarser sediments, and were less hydrologically connected to local surface water fluctuations. In order to minimize the large uncertainties associated with specific yield estimates, in situ measurements (e.g., aquifer pump test or soil-moisture profile analysis) of specific yield might be needed, especially at sites where groundwater is shallower and interacts with finer sediments.

5.2. Understory Vegetation Removal and Groundwater Hydrographs

[42] Recent evaluations of vegetation restoration projects note a lack of monitoring data following the restoration activity [*Bernhardt et al.*, 2005; *Palmer et al.*, 2005], which limits the long-term evaluation of restoration efforts [e.g., *Wissmar*, 2004; *Wohl et al.*, 2005]. For example, restoration projects have not adequately tracked water salvage, if any, even though this was often cited as a motivating reason for the restoration [e.g., *Culler et al.*, 1982; *Bernhardt et al.*, 2005; *Palmer et al.*, 2005; *Wilcox et al.*, 2006; *Wilcox and*

Thurow, 2006]. *Culler et al.* [1982] evaluated evapotranspiration along a 24-km reach in southern Arizona before and after the removal of floodplain vegetation. Long-term hydrologic monitoring revealed that vegetation removal led to an increase in annual groundwater discharge to the river following removal, particularly during the summer. *Welder* [1988] analyzed 15 years of water table and base flow data following the cutting of 19,000 acres (7689 ha) of salt cedar along the Pecos River in New Mexico. Water salvage was detected along the reach but did not result in significant increases to river base flow. *Stednick* [1996] compiled the results from paired catchment studies that looked at the effects of timber harvesting on annual water yield and concluded that the hydrometeorological conditions and the basal extent of the timber harvest were critical factors.

[43] Monitoring daily groundwater fluctuations in riparian ecosystems can be an effective tool to assess impacts of vegetation removal on hydrological resources [*Steinwand et al.*, 2006; *Zhang and Schilling*, 2006]. Here, we analyzed 3 years of daily groundwater data at the ALB site prior to and after the removal of dense understory exotic vegetation, primarily salt cedar (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*). A small but significant change in groundwater dynamics was detected following vegetation removal. The reduction in groundwater fluctuation amplitude (Δa) by 6.7% to 18.1% is comparable to the 9% decrease in *ET* following understory removal, as reported by *Cleverly et al.* [2006a]. The water table at the ALB site did not rise after vegetation removal. The mean water table depth (1.38 m) was the same for both prevegetation and postvegetation removal years. Diurnal groundwater fluctuation amplitudes (Δa) can potentially be used as a technique to quickly inspect the effects of vegetation removal on riparian *ET*, if appropriately time averaged. The ($\Delta s + R$) term from equation (2) can also be used in conjunction with Δa to measure vegetation-induced changes to riparian *ET*. We found that comparing ($\Delta s + R$) and Δa at the ALB site produced similar variability (data not shown), which might not be the case at every riparian site. Using Δa is particularly useful at riparian sites where water table mean depths are controlled primarily by surface water dynamics, where groundwater storage (Δs) values tend to be low ($\Delta s \sim 0$; see Figure 6) and vegetation-induced diurnal groundwater fluctuations can be clearly determined. However, this technique will have to account for river stage influences on groundwater elevations to improve the application of Δa to monitor changes in *ET*. The increase in postremoval Δa during April and October compared with preremoval is a result of large snowmelt and monsoon events that occurred during the postremoval period. Using Δa to monitor restoration projects might not be appropriate at riparian sites where the groundwater is hydrologically disconnected from surface water recharge (very low R). More research is needed to explore the benefits of using Δa and ($\Delta s + R$) to measure the changes in riparian groundwater dynamics where vegetation removal has occurred.

[44] Interestingly, we found that the reduction in Δa is relatively small considering that the understory was a large portion of total LAI at the site. Even though LAI was significantly reduced, peak season *ET* showed a slight increase in 2004 and 2005 (Table 2). Furthermore, the correlation between ET_g and *ET* decreased in post restoration years (Table 3). Decreased transpiration resulting from understory vegetation removal could be offset by increased soil evaporation due to increasing the solar radiation reaching the ground surface, and could have a significant role in reducing measurable *ET* reductions [e.g., *Zhang and Schilling*, 2006]. We suspect that understory removal caused an increase in net radiation (R_n), which resulted in an increase in *ET*. This would help to explain the reduced correlations between *ET* and ET_g during postrestoration years. The contribution of soil evaporation to *ET* measurements at this site will more likely depend on available moisture within the mulch layer derived from precipitation, rather than evaporation from soil sediments below the mulch layer. These results suggest that the cottonwood overstory at this site dominates groundwater consumption, even though the understory made up a significant portion of LAI. However, without accounting for soil evaporation and transpiration from the vadose zone, we cannot completely evaluate water salvage and the different roles that understory and overstory vegetation have on water consumption [e.g., *Steinwand et al.*, 2006; *Zhang and Schilling*, 2006]. We hypothesize that in these phreatophyte-driven riparian ecosystems, ET_s will be generally negligible compared with ET_g (see equation (1)). Clearly, removing the dense understory of exotic vegetation at this riparian site has not resulted in large water savings, though measurable impacts are observed in groundwater diurnal fluctuations and ET_g measurements (Table 2). There was no evidence of any vegetation regrowth during this study. Until further research is performed, caution should be exercised when an increase in water resources is used to justify riparian vegetation restoration.

6. Conclusions

[45] In riparian corridors, groundwater hydrographs are useful in assessing the role that vegetation plays in local and regional water budgets. In this study, we have explored the use of diurnal groundwater fluctuations as a tool to measure riparian groundwater evapotranspiration and the impacts of understory vegetation removal. To estimate groundwater *ET*, we applied the White method using a range of specific yields based on soil texture properties. We compared groundwater hydrograph estimates of ET_g with *ET* measurements from the 3-D sonic eddy covariance (3SEC) method over a 7-year period at four sites in the Río Grande riparian corridor. In general, groundwater ET_g estimates tend to exceed *ET*. The accuracy of riparian ET_g values improved as compared with *ET* when the water table deepened and was decoupled from rapid hydrologic changes in the river channel. The SEV site, which exhibited these conditions, had ET_g values that were 0.91–1.65 times the values of tower *ET*. The differences between ET_g and *ET* increased at riparian sites with shallow water tables that are tightly coupled to changes in the river stage. While the White method appears to work better in certain riparian areas, ET_g estimates are sensitive to the vertical heterogeneity of alluvial sediments and its interaction with a fluctuating water table. Using the average textural sizes and the corresponding ranges of readily available specific yield, as we did in this study, might not be appropriate at sites where the water table fluctuates between heterogeneous sediment layers. The best correspondence between ET_g and *ET* values

occurred at the SEV site where the vertical soil heterogeneity was relatively lower compared with other sites. Thus application of the White method in riparian corridors can be limited by sediment layer composition and heterogeneity, depth to water table, and the degree of hydrological connectivity between the shallow aquifer and the nearby perennial river.

[46] Groundwater hydrographs also can serve as an important indicator of vegetation dynamics within riparian corridors. Vegetation-induced diurnal changes in groundwater fluctuations can be used to gauge patterns of vegetation growth and removal including changes in density, age structure, or species composition. Diurnal groundwater fluctuations should be complemented with measurements of vegetation characteristics, such as LAI and stand density. In this study, we used 3 years of diurnal groundwater fluctuations before and after the removal of understory vegetation. We observed a small but significant reduction in the diurnal groundwater amplitude ranging from 0.32 to 0.86 cm (6.7–18.1% reduction). Since groundwater amplitude captured the effect of understory vegetation removal, this simpler technique has potential field applications that could be further explored, particularly for studies seeking to quantify water salvage due to restoration activities.

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