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Key Points:

- Spatial pattern of diurnal groundwater table fluctuations (GTFs) is tightly related to vegetation
- Seasonal variations of diurnal GTFs is related to temperature-controlled plant phenology
- Depth to water table is the dominant control on groundwater evapotranspiration at daily time scale

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Spatiotemporal patterns of water table fluctuations and evapotranspiration induced by riparian vegetation in a semiarid area

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Abstract Groundwater evapotranspiration (ET_g) links various ecohydrological processes and is an important component in regional water budgets. In this study, an extensive monitoring network was established in a semiarid riparian area to investigate various controls on the spatiotemporal pattern of water table fluctuations (WTFs) and ET_g induced by riparian vegetation. Along a vegetation gradient (~1200 m), diurnal WTFs were observed during a growing season in areas covered by woody species (*Populus sect. Aigeiros* and *Juniperus virginiana*) and wet slough vegetation (*Panicum virgatum* and *Bromus inermis*) with deeper root systems; whereas, no diurnal WTFs were found in the middle section with shallower-rooted grasses (*Poa pratensis* and *Carex sp.*). The occurrence of diurnal WTFs was related to temperature-controlled plant phenology at seasonal scales and to radiation at subdaily scales. Daily ET_g in the mid-growing season was calculated using the White method. The results revealed that depth to water table (DTWT) was the dominant control on ET_g, followed by potential evapotranspiration (ET_p). By combining the effects of DTWT and ET_p, it was found that at shallower depths, ET_g was more responsive to changes in ET_p, due to the closer linkage of land surface processes with shallower groundwater. Finally, exponential relationships between ET_g/ET_p and DTWT were obtained at the study site, although those relationships varied considerably across the sites. This study demonstrates the complex interactions of WTFs and ET_g with surrounding environmental variables and provides further insight into modeling ET_g over different time scales and riparian vegetation.

1. Introduction

Riparian ecosystems play crucial roles in a range of ecohydrological and environmental processes [*Hill*, 1996; *Naiman and Décamps*, 1997; *Newman et al.*, 2006; *Capon et al.*, 2013]. Meanwhile, riparian vegetation is shown to be tightly linked to underlying groundwater systems through complex feedback mechanisms [*Dawson and Ehleringer*, 1991; *Stromberg et al.*, 1996; *Loheide and Gorelick*, 2007]. From a hydrological perspective, phreatophyte-induced groundwater evapotranspiration (ET_g) can be an important component of regional water budgets, especially in arid and semiarid regions [*Nichols*, 1994; *Butler et al.*, 2007; *Loheide*, 2008; *Lautz*, 2008; *Martinet et al.*, 2009; *Yin et al.*, 2013]. Thus, it is important to quantify ET_g for the purpose of water resources managements [*Goodrich et al.*, 2000; *Newman et al.*, 2006]. Although a number of techniques are available to measure surface evapotranspiration (e.g., pan evaporation and eddy covariance methods), those techniques are generally not suitable for direct measurements of ET_g [*Loheide et al.*, 2005]. Instead, the methods of stable isotope, water balance, and water table fluctuations (WTFs) have attracted more attention for directly estimating ET_g [cf. *Orellana et al.*, 2012]. Compared to the methods of stable isotope and water balance, the WTF-based method possesses several advantages for quantifying ET_g, including low operational costs and suitability for long-term continuous measurements [*Loheide et al.*, 2005].

In areas with a shallow water table, well hydrographs usually exhibit a distinct pattern of diurnal fluctuations, which can be attributed to the daily pattern of water use by phreatophytes if the impacts of other influencing factors (e.g., cyclical pumping and changes in barometric pressure) on diurnal WTFs are negligible [*White*, 1932; *Meyboom*, 1967; *Butler et al.*, 2007; *Gribovszki et al.*, 2010]. As phreatophytes directly tap groundwater for transpiration, daytime root water uptake causes water tables to decline during the day, while water tables recover at night when transpiration essentially ceases. Based on the above reasoning, *White* [1932] proposed to use the information derived from diurnal WTFs to estimate ET_g. In spite of the uncertainties associated with the White method [*Loheide et al*., 2005; *Orellana et al*., 2012; *Yin et al*., 2013], it has received increasing attention in the recent literature to estimate ET_g, largely due to the simplicity of the method [e.g., *Bauer et al*., 2004; *Gribovszki et al*., 2008; *Lautz*, 2008; *Soylu et al*., 2011; *Zhu et al*., 2011; *Cheng et al*., 2013; *Carlson Mazur et al*., 2014; *Wang et al*., 2014]. Later studies also attempted to improve the reliability and accuracy of the White method by modifying the original White equation [e.g., *Engel et al*., 2005; *Loheide et al*., 2005; *Gribovszki et al*., 2008; *Soylu et al*., 2012]. However, the application of the White method relies on a thorough understanding of the factors that control the diurnal WTFs [*Yin et al*., 2013], and relevant experimental studies are still limited [e.g., *Butler et al*., 2007; *Lautz*, 2008]. In addition, the knowledge of different controls on ET_g rising from field investigations can offer valuable insight into formulating the relationships employed by groundwater models for simulating ET_g [*McDonald and Harbaugh*, 1988; *Banta*, 2000; *Shah et al*., 2007].

Moreover, the information obtained from WTFs can be used as a diagnostic tool to investigate the interdependence between groundwater and riparian vegetation, which is largely modulated by meteorological conditions [*Engel et al*., 2005; *Butler et al*., 2007; *Loheide and Gorelick*, 2007; *Fan et al*., 2014]. For instance, *Engel et al*. [2005] observed a diurnal WTF pattern during a growing season in a 40 ha area covered by woody species; however, no diurnal WTFs were found in neighboring grasslands during the same time period. *Butler et al*. [2007] revealed that the amplitude of diurnal WTFs was mostly controlled by vegetation type, meteorological conditions, and specific yield of sediments. In particular, the authors showed that diurnal WTFs abruptly disappeared after the occurrence of the first frost event in fall that significantly reduced ET_g. *Fan et al*. [2014] found that the spatial ET_g distribution was highly correlated with the spatial distribution of vegetation. By comparison, *Loheide and Gorelick* [2007] showed that depth to water table (DTWT) largely determined the spatial distribution of riparian vegetation (e.g., xeric versus mesic species) along a river corridor. Overall, previous field studies underscore the close linkage of groundwater-dependent riparian vegetation with surrounding environments.

Here we extended previous field studies by setting up an extensive monitoring network along a vegetation gradient ($\sim$1200 m) in a semiarid riparian area, including two transects of shallow observation wells and a meteorological station. The primary goals of this study were to (1) identify the major factors that control the spatial (e.g., along the vegetation gradient) and temporal (e.g., from subdaily to seasonal scales) patterns of diurnal WTFs, and (2) assess different controls on daily ET_g calculated with the White method and the relationships of ET_g with potential evapotranspiration (ET_p) and DTWT. To this end, hourly measurements were made at the study site for groundwater levels and meteorological variables in 2014. In the following sections, the spatiotemporal patterns of diurnal WTFs and their influencing factors are first analyzed, and the estimated daily ET_g is then compared to the various controlling factors. The results of this experimental study provide further insight into the mechanistic functioning of groundwater-dependent riparian ecosystems as well as formulating the relationship of ET_g with different influencing factors for modeling purposes.

2. Materials and Methods

2.1. Study Site and Experimental Setup

This study is a part of the Platte River Recovery Implementation Program (https://www.platteriverprogram.org/Pages/Default.aspx), which aims to restore and protect riparian habitats for endangered species along the Platte River. The Platte River, originating from the Rocky Mountains and flowing through Nebraska, drains an area of $\sim$220,000 km^2 and plays a significant ecohydrological role in the central United States [*Johnson*, 1994; *Joeckel and Henebry*, 2008]. The Platte River provides crucial water resources for municipal and agricultural uses in the region, and serves as a vital habitat for a number of endangered aquatic species and migratory water birds [*Krapu et al*., 1984; *Henszey et al*., 2004]. Therefore, for the purposes of water resources management and riparian habitat protection, it is essential to understand the interdependence between riparian ecosystems and underlying groundwater aquifers, and water consumption (e.g., ET_g) by different riparian vegetation species in the area [*Chen*, 2007].

The study site, Shoemaker Island, is located within a riparian area of the Platte River near Grand Island, in south central Nebraska, USA (Figure 1). The climate in the area is continental semiarid, with the mean annual precipitation of 662.0 mm and the mean annual temperature of 10.5°C (1971–2000 means for Grand

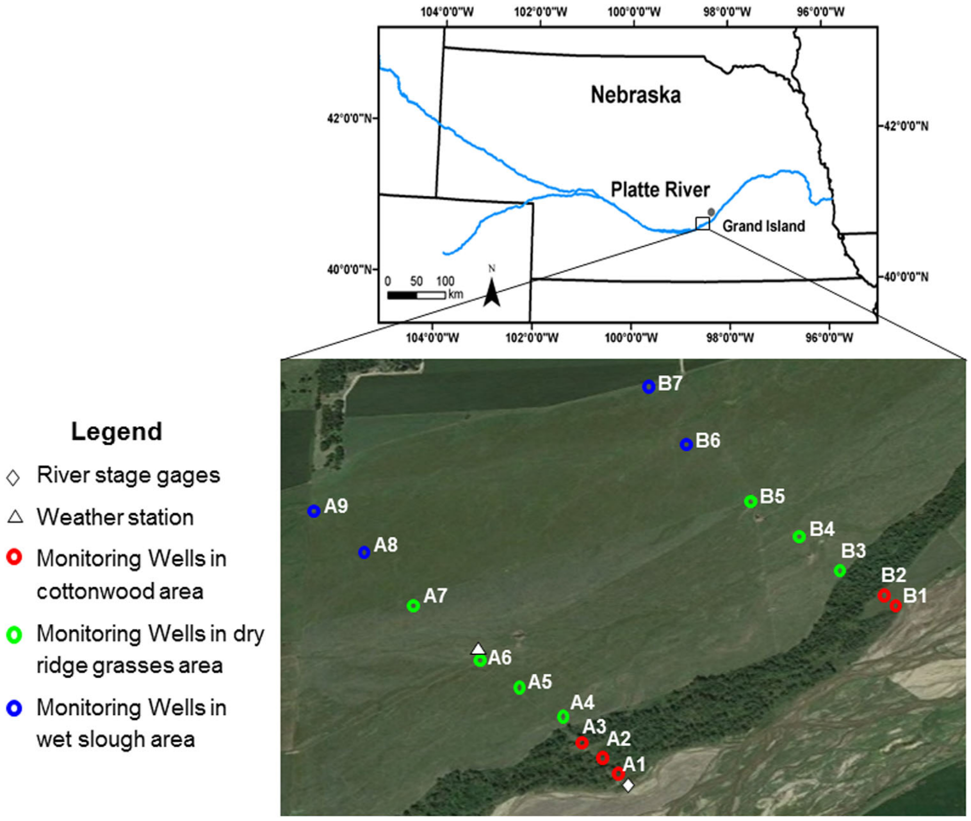

Figure 1. Location of the study site and the experimental layout of the monitoring wells.

Island; data were retrieved from the High Plains Regional Climate Center (HPRCC) at http://www.hprcc.unl.edu/). On average, over 70% of the annual precipitation is received between April and September. The Shoemaker Island site lies in the Platte River Valley above an alluvial aquifer, which extends approximately 24 m in depth based on the well logs in the area. In mid-2013, a total of 16 shallow observation wells with depths up to 3 m were installed along two parallel transects ($\sim$1200 m) at the study site (Figure 1). The distances between neighboring wells vary from 15 to 300 m within each transect. Except for small amounts of silty sand near the surface, sediments at the study site mainly consist of well-graded sand with occasional gravels. A grain size analysis of the borehole samples (the depth between 1 and 2 m below the surface) showed little textural differences with over 70% of the particles between 0.5 and 1.0 mm. The site topography is flat with an average slope of 0.001 m/m. Hourly groundwater levels in the wells were recorded using vented pressure transducers of Level TROLL 500 (In-Situ Inc., Fort Collins, Colorado, USA), which do not require barometric pressure corrections. In addition, a meteorological station operated by the HPRCC was setup at the center of the study site, which measures hourly global irradiance, air temperature, relative humidity, wind speed, and precipitation. Daily meteorological data were then obtained by integrating hourly data and used to calculate ET_p with the Penman-Monteith equation [*Allen et al*., 1998].

As shown in Figure 1, a vegetation gradient existed along the well transects, making it ideal for studying the response of water tables to the water use by different riparian vegetation species. Field surveys showed that the south part of the study area was mainly covered by woody species (a mixture of cottonwood (*Populus sect*. *Aigeiros*) and red cedar (*Juniperus virginiana*); Figure 2a), and for the purpose of simplicity, this area is referred as the cottonwood area hereafter. In the middle section, dry ridge grasses were dominant (e.g., *Poa pratensis* and *Carex sp*.; Figure 2b); whereas, the northern section was mainly covered by wet slough vegetation (e.g., *Panicum virgatum* and *Bromus inermis*; Figure 2c).

2.2. The White Method

The primary goal of this study was to investigate the major abiotic controls on daily ET_g. The method of *White* [1932] was adopted here to calculate daily ET_g [*Gribovszki et al*., 2008; *Lautz*, 2008; *Soylu et al*., 2011;

Figure 2. Photos of (a) the cottonwood area near well A2-cotonwood, (b) the dry ridge grasses area near well A6-dry grasses, and (c) the wet slough area near well A9-wet slough (taken on 30 March 2015).

Zhu et al., 2011]. The White method utilizes hourly (or higher temporal resolution) groundwater level data to calculate daily ET_g:

$$ET_g = S_y(24r \pm s) \tag{1}$$

where S_y is the specific yield of sediments, r [L/T] is the hourly rate of the groundwater level rise from midnight to 4 A.M., and s [L] is the net rise or fall of the groundwater level over the day. For demonstration purposes, Figure 3 illustrates an example of diurnal WTFs in well A3-cottonwood, along with the parameters needed in equation (1). Several assumptions are needed to ensure the validity of equation (1) for calculating phreatophyte-induced ET_g [*Loheide et al.*, 2005]: (1) the decline in groundwater levels is only due to plant root water uptake, (2) ET_g caused by vegetation is negligible from midnight to 4 A.M., (3) the average rate of the water table rise between midnight and 4 A.M. is the same as the average recovery rate during the day, and (4) the specific yield S_y is known at the site of interest.

As pointed out previously [*Loheide et al.*, 2005; *Gribovszki et al.*, 2010; *Zhu et al.*, 2011], additional processes may cause diurnal WTFs and affect the calculation of ET_g, such as cyclical pumping, and changes in barometric pressure and temperature. At the study site, there was no groundwater pumping from the local aquifer in the surrounding area. The effects of barometric pressure and temperature were also negligible, which could be attested by the abrupt changes in the diurnal WTF patterns along the transects as shown in the next section. Figures 4a and 4b show the comparison between groundwater levels in wells near the river channel and stream water levels recorded at the gauging station close to well A1-cottonwood (Figure 1). Although groundwater consumption by vegetation was expected to be low in early May at the study site (about 1.3 mm/d at well A3-cottonwood based on the White method), there was a diurnal fluctuation pattern in the stream water levels. Note that the water table fluctuations in the wells lagged behind the ones in the stream water levels. Unlike evapotranspiration-induced fluctuations [*Gribovszki et al.*, 2010], this diurnal pattern was suspected to be caused by upstream water releases for hydropower generation. Figure 4c displays the flow rate of the Platte River at the USGS gauging station (#06770200) near Kearney, Nebraska, which is located about 40 km upstream of the study site. Clearly, the streamflow at #06770200 exhibited a diurnal pattern. More importantly, with the increasing distance from the river channel (e.g., along the direction from A1-cottonwood to A3-cottonwood or from B1-cottonwood to B2-cottonwood), the impact of diurnal stream level fluctuations on the diurnal WTFs significantly decreased, particularly in wells A3-cottonwood and B2-cottonwood. Given the fact that summer streamflow rates in the Platte River are lower (the stream periodically dried up during the summer of 2014), it was assumed that the impact of diurnal stream level

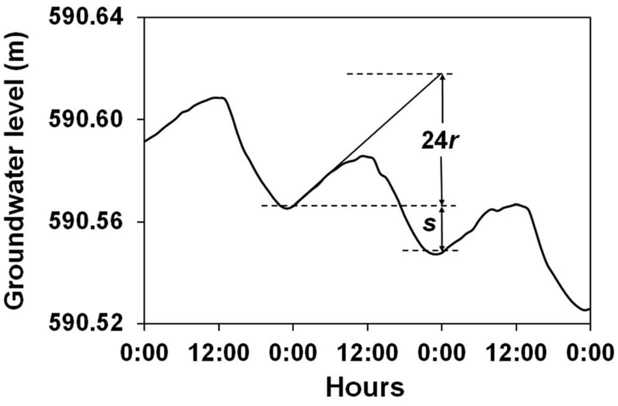

Figure 3. An example of diurnal water table fluctuations in well A3-cottonwood from 3 July 2014 to 5 July 2014.

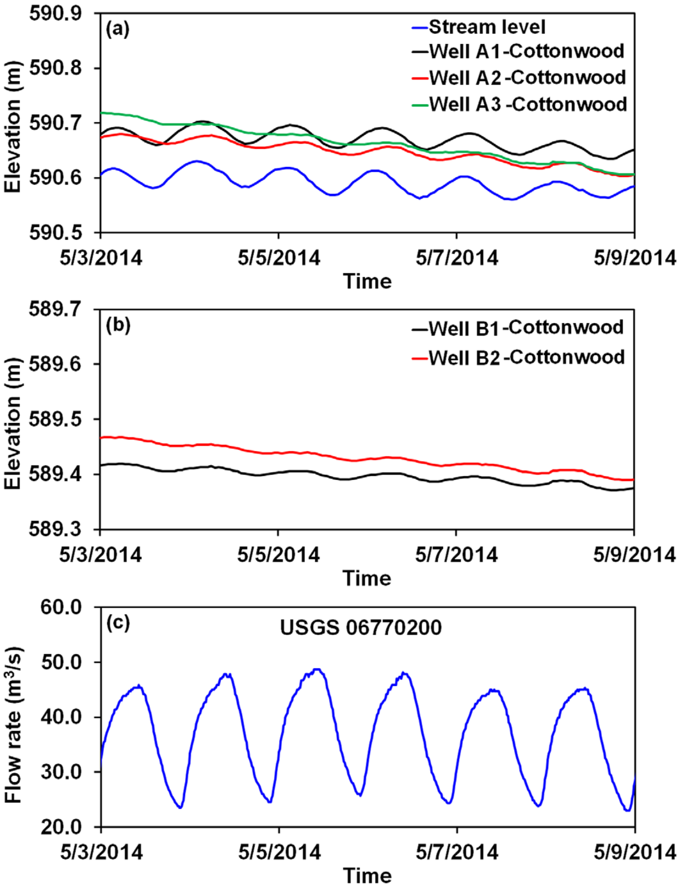

Figure 4. Comparison of well hydrographs with stream level at the study site and the USGS gauging station #06770200 (see Figure 1 for detailed information about the locations of the wells and gauging station).

fluctuations was only important in wells A1-cottonwood, A2-cottonwood, and B1-cottonwood. As such, the data from those three wells are removed from the following analysis.

Based on numerical modeling experiments, *Loheide et al*. [2005] showed that S_y was the most important factor determining the accuracy of the White method for estimating ET_g. In order to minimize the uncertainty associated with S_y, it was measured directly using the laboratory method of *Chen et al*. [2010]. For measuring S_y, soil samples with the depths approximately from 0.4 to 0.8 m below the surface were taken from the study site. The experimental results showed that the average S_y in the cottonwood, dry ridge grasses covered, and wet slough areas was 0.06, 0.03, and 0.03, respectively, during a 12 h drainage period. The results were similar to the ones obtained by *Fan et al*. [2014].

3. Results and Discussion

3.1. Spatial Patterns of Diurnal WTFs Along the Vegetation Gradient

Spatial variations in diurnal WTF patterns reflect the differences in groundwater consumption by different vegetation species [*White*, 1932; *Engel et al*., 2005; *Butler et al*., 2007; *Fan et al*., 2014], provided that other factors exert negligible impacts on diurnal WTFs. For illustration purposes, Figure 5 shows the diurnal WTFs from all the wells (except for wells A1-cottonwood, A2-cottonwood, and B1-cottonwood) during a rainless period in the growing season of 2014. It can be seen from Figure 5 that the amplitude of diurnal WTFs varied considerably among the wells along both transects. The diurnal pattern of WTFs was obvious in the cottonwood area (e.g., A3 and B2) and wet slough area (e.g., A8, A9, B6, and B7); whereas, a similar diurnal pattern of WTFs could not be clearly observed in the area covered by dry ridge grasses (e.g., A6, A7, and B4). In addition, for the wells located within the transition zones (e.g., A4-dry grasses, B3-dry grasses, and B5-dry grasses; for instance, well A4-dry grasses was only about 20 m away from the cottonwood area), the diurnal pattern of WTFs was still noticeable, but with smaller amplitudes. Despite the relatively short distance of each transect (~1200 m) and between neighboring wells (from 15 to 300 m), there was a strong spatial correlation between the diurnal WTFs and vegetation pattern at the study site, which was in general agreement with previous studies [*Rosenberry and Winter*, 1997; *Engel et al*., 2005; *Zhang and Schilling*, 2006; *Butler et al*., 2007].

The contrasting diurnal WTF patterns at the study site can be largely attributed to the different vegetation rooting depths [*Butler et al*., 2007]. For instance, the wells with similar DTWTs in Figure 5 (e.g., A5-dry grasses versus A8-wet slough and A7-dry grasses versus B2-cottonwood) showed considerably different diurnal WTF patterns under different vegetation conditions. The most likely explanation for the diminished diurnal WTFs in wells under grass-covered conditions is that the roots of the dry ridge grasses were not deep enough to reach water tables for transpiration; whereas, the deeper root systems of cottonwoods could directly tap groundwater for transpiration and cause diurnal WTFs. This is consistent with root distributions observed for cottonwoods and natural grasses [*Canadell et al*., 1996; *Jackson et al*., 1996; *Wang et al*., 2009;

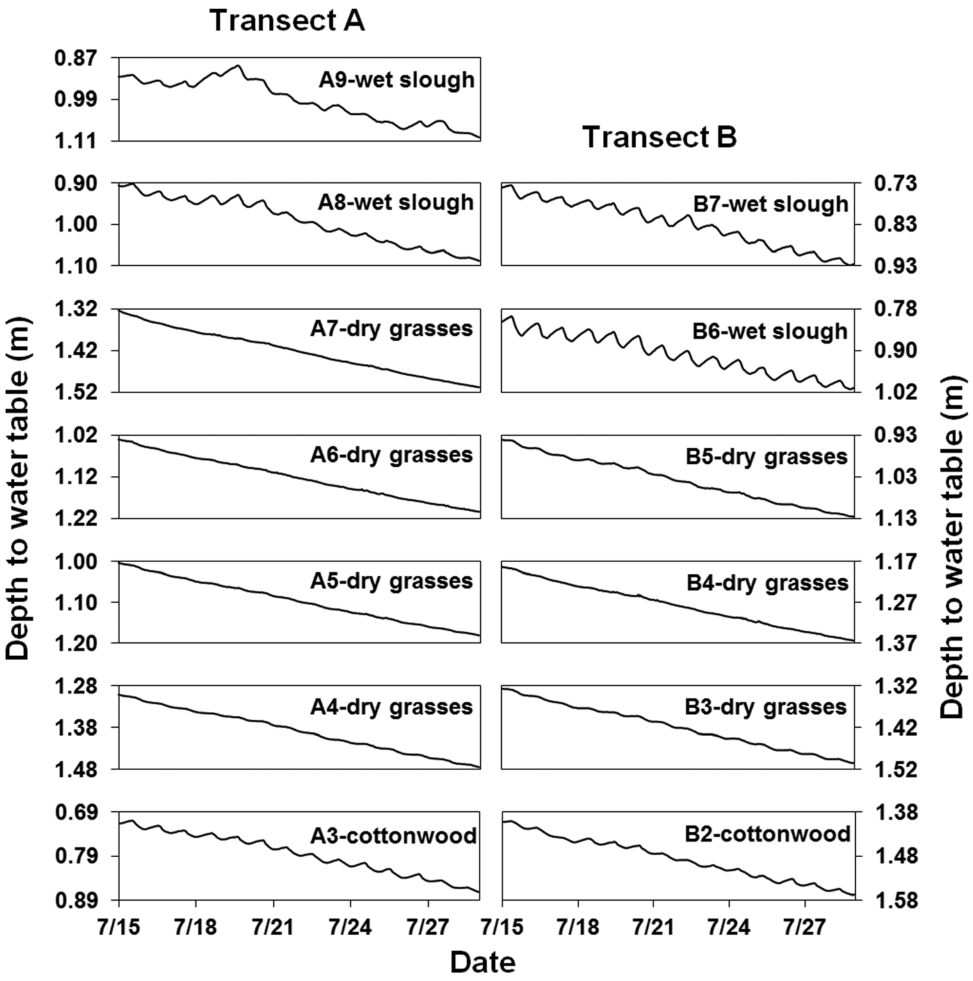

Figure 5. Diurnal water table fluctuations in all the observation wells (except for wells A1-cottonwood, A2-cottonwood, and B1-cottonwood) from 15 July 2014 to 28 July 2014.

Rood et al., 2011]. The control of roots on the diurnal WTFs is also evident in Figure 6, which shows the impact of DTWT on the amplitude of diurnal WTFs. In general, with increasing DTWT, the amplitude of diurnal WTFs became smaller in the wells, as fewer roots were available for extracting groundwater for transpiration. Particularly, when the DTWT exceeded ~1.1 m, the amplitude of diurnal WTFs was significantly reduced in well A8-wet slough. Meanwhile, the WTFs in well B6-wet slough still exhibited a strong diurnal pattern during the same time period, indicating that other factors (e.g., meteorological conditions) did not affect vegetation activities. By comparing the diurnal WTF patterns in Figures 5 and 6, it also appears that the wet slough vegetation had deeper roots than the dry ridge grasses (e.g., B5-dry grasses versus A8-wet slough in Figure 5), but shallower than the cottonwoods (e.g., B2-cottonwood versus A8-wet slough in Figure 6).

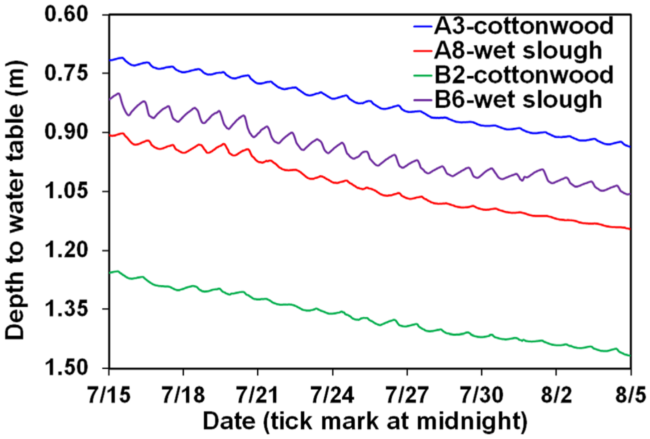

Figure 6. Diurnal patterns of water table fluctuations in wells A3-cottonwood, A8-wet slough, B2-cottonwood, and B6-wet slough from mid-July to early-August of 2014.

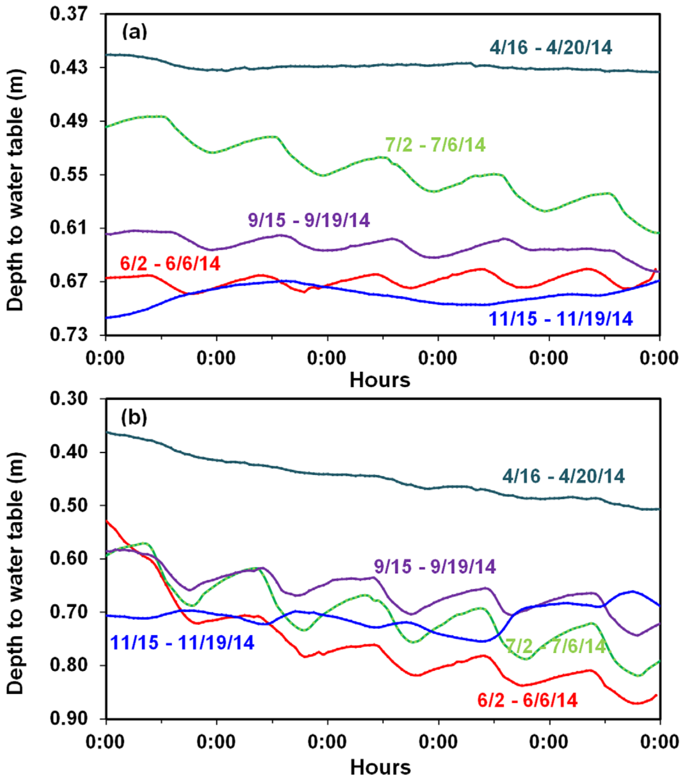

Figure 7. Seasonal variations in diurnal water table fluctuations in well (a) A3-cottonwood and (b) B6-wet slough.

It should be stressed that other factors may also affect the amplitude of diurnal WTFs, such as meteorological conditions and sediment properties (e.g., S_y) [*Cooper et al.*, 2006; *Lautz*, 2008; *Martinet et al.*, 2009]. Due to the small size of the study area, it is reasonable to assume that meteorological conditions were spatially invariant at the site. In addition, given the smaller S_y ($=0.03$) in the dry ridge grass area (e.g., $S_y = 0.06$ for the cottonwood area), the diminished diurnal WTF pattern in the dry ridge grass area was not likely due to the spatial variation in S_y [*Lautz*, 2008]. Overall, based on the tight spatial correlation between the vegetation and diurnal WTF patterns, Figures 5 and 6 provided strong field evidence of the dominant control of vegetation on diurnal WTFs at the study site.

3.2. Temporal Variations in WTFs

With the influence of root water uptake, the temporal variation in diurnal WTFs is the result of complex interactions of vegetation with surrounding environments, such as climate, soil moisture, and groundwater dynamics [*Butler et al.*, 2007; *Lautz*, 2008; *Orellana et al.*, 2012; *Fan et al.*, 2014; *Gou and Miller*, 2014]. Previous studies showed that diurnal WTFs were affected by a range of factors on different time scales (e.g., long-term groundwater dynamics on annual scales [*Cooper et al.*, 2006] and vegetation phenology on seasonal scales [*Butler et al.*, 2007]). To have a full understanding of the temporal variations in diurnal WTFs at the study site, the diurnal WTFs in wells A3-cottonwood and B6-wet slough during five rainless periods were plotted in Figure 7. In mid-April, the diurnal WTFs were unnoticeable as the vegetation was still in dormancy due to the low air temperatures (average daily maximum (T_{max}) and minimum (T_{min}) temperature of 19.5°C and 4.4°C, respectively, from 16 to 20 April). It is clear from Figure 7 that the diurnal WTF pattern occurred throughout the growing season from June to September, when the groundwater consumption by phreatophytes was high. In particular, with similar DTWTs, the amplitude of diurnal WTFs tended to be larger in July, mainly due to the higher meteorological demands for evapotranspiration. In mid-November, the diurnal WTFs disappeared again as the root water uptake ceased due to the low air temperatures (average daily T_{max} and T_{min} of -0.3°C and -15.2°C, respectively, from 15 to 19 November).

Growing research efforts have also been devoted to quantifying subdaily ET_g using variant models from the White method [*Schilling*, 2007; *Loheide*, 2008]. In order to refine the temporal resolutions (e.g., at hourly time steps) of groundwater and land surface models for computing ET_g, it is also important to understand the factors that affect subdaily WTF patterns. *Butler et al.* [2007] showed a tight correlation between subdaily global irradiance and sapflow velocity; however, the impact of global irradiance on subdaily WTFs remained unclear. Figure 8 shows hourly groundwater levels in wells A3-cottonwood and A9-wet slough along with global irradiance during two rainless periods in July. Between 2 and 5 June, the peak time of the hourly groundwater levels occurred in the early morning around 8 and 9 A.M., while it was significantly delayed to approximately 2 P.M. from 16 to 19 July. For instance, the peak time on 18 July in wells A3-cottonwood and A9-wet slough occurred in the afternoon around 2 and 5 P.M., respectively. The delay in the peak time can be clearly attributed to the subdaily variations in global irradiance at the study site.

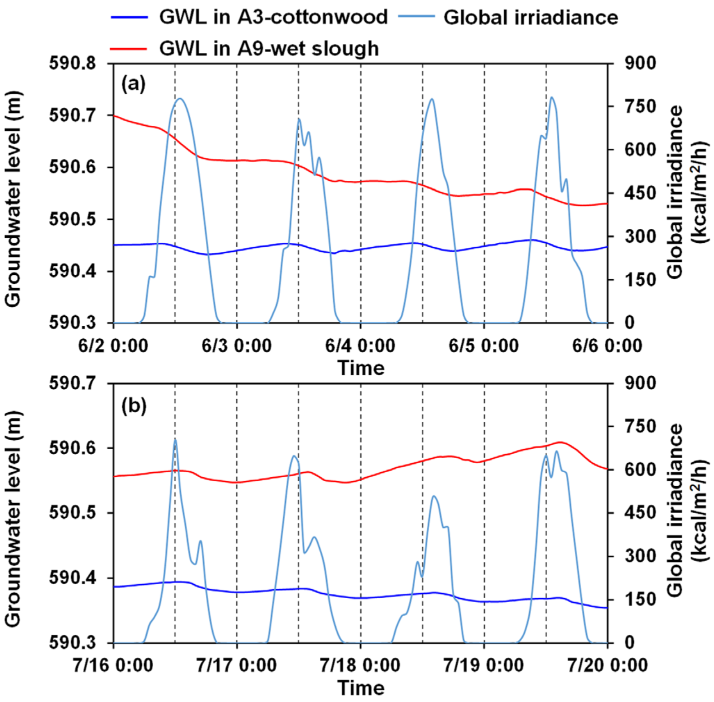

Figure 8. The responses of diurnal fluctuations of groundwater level (GWL) to different levels of global irradiance in (a) early-June and (b) mid-July in 2014.

Without sufficient radiation in the early morning (Figure 8b), the use of groundwater by vegetation for transpiration was low. Thus, the declining rate of groundwater tables caused by root water uptake was still smaller than the recovery rate due to groundwater inflows, which led to the delayed peak time of the hourly groundwater levels. Figure 8 highlights the importance of radiation in controlling subdaily WTFs and future studies are still needed to elucidate the effect of subdaily variations in radiation on calculating subdaily ET_g; however, it was beyond the scope of this study.

3.3. Controls on Daily ET_g Estimated From Diurnal WTFs

Quantifying different controls on ET_g under field conditions can provide critical information for the purposes of modeling

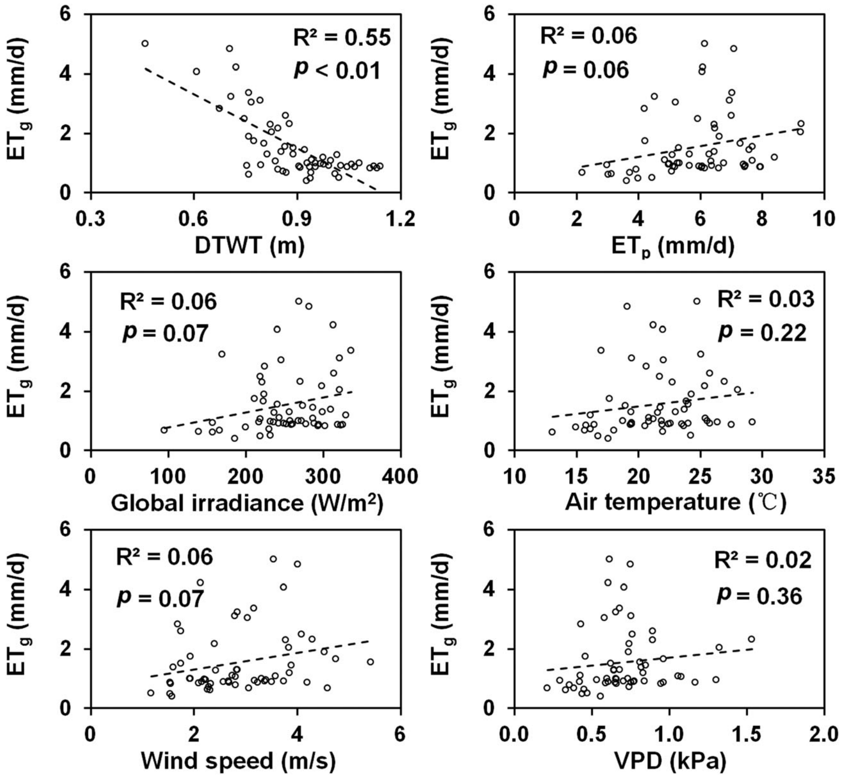

Figure 9. The relationships of daily groundwater evapotranspiration (ET_g) with depth to water table (DTWT), potential evapotranspiration (ET_p), wind speed, vapor pressure deficit (VPD), global irradiance, and air temperature at well A8-wet slough.

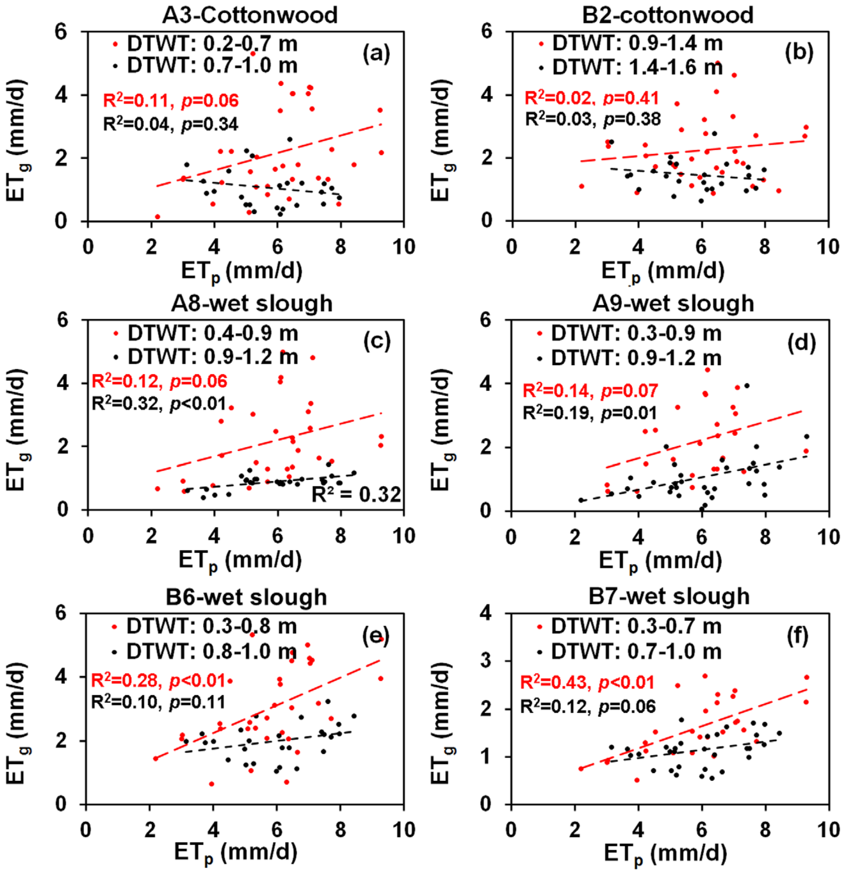

Figure 10. The relationships between daily groundwater evapotranspiration (*ET_g*) and potential evapotranspiration (*ET_p*) for different ranges of depth to water table (DTWT) in wells (a) A3-cottonwood, (b) B2-cottonwood, (c) A8-wet slough, (d) A9-wet slough, (e) B6-wet slough, and (f) B7-wet slough.

ET_g and interactions between groundwater and land surface processes. As discussed previously, a range of environmental factors could affect the diurnal WTF patterns at different temporal scales and subsequently ET_g. To further assess the impacts of those factors on ET_g, the White method (i.e., equation (1)) was used to calculate daily ET_g with measured S_y for each respective vegetation cover. As plant phenology controls seasonal variations in the amplitude of diurnal WTFs (e.g., Figure 7), only the rainless periods from June to September in 2014 with similar phenology are used in the following analysis.

As an example, Figure 9 shows the relationships of daily ET_g with DTWT, ET_p, wind speed, vapor pressure deficit, global irradiance, and air temperature at well A8-wet slough. A strong negative correlation emerged between daily ET_g and DTWT ($p < 0.01$), which was consistent with the conclusions made from Figure 6. Intuitively, owing to the decay of root biomass with depth [*Jackson et al.*, 1996], the ability of roots to extract groundwater for transpiration decreases with increasing DTWT, resulting in the negative correlation between ET_g and DTWT. By comparison, there appeared to be no significant correlations of ET_g with ET_p and individual meteorological variables (p values > 0.05). Although air temperature was shown to affect diurnal WTFs through controlling plant phenology at seasonal scales, its effect on daily ET_g during the growing season was less apparent as opposed to the effect of DTWT.

To further examine the correlations between ET_g and ET_p using field data, their relationships are displayed in Figure 10 for each individual well. Weak positive correlations between ET_g and ET_p were found at individual wells (R^2 ranged from 0.01 (B2-cottonwood) to 0.23 (B7-wet slough) and p values from 0.00 (B7-wet slough) to 0.44 (B2-cottonwood), not shown in Figure 10). Overall, the correlations of ET_g with ET_p were stronger than the ones with individual meteorological variables, as ET_p reflects the combined effect of individual meteorological variables for delineating the atmospheric demand for evapotranspiration. Similarly, *Lautz* [2008] also showed a weak positive relationship between ET_g and ET_p in a semiarid riparian area.

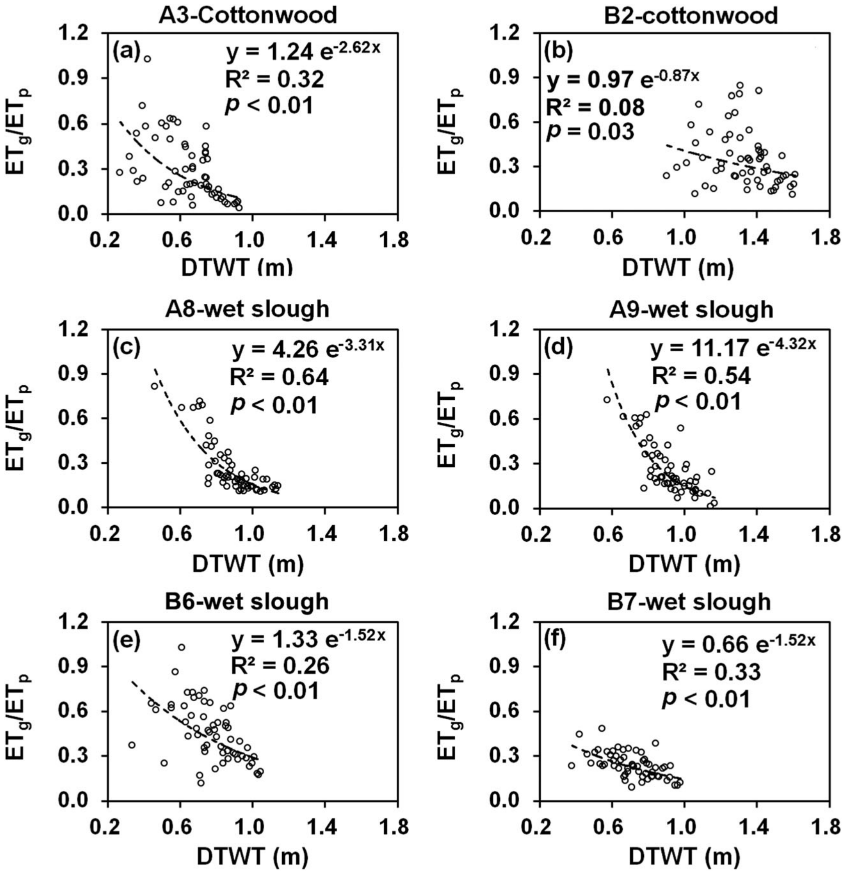

Figure 11. The relationships between the ratio of daily groundwater evapotranspiration (ET_g) over potential evapotranspiration (ET_p) and depth to water table (DTWT) in wells (a) A3-cottonwood, (b) B2-cottonwood, (c) A8-wet slough, (d) A9-wet slough, (e) B6-wet slough, and (f) B7-wet slough.

However, compared with the effect of DTWT, the control of ET_p on ET_g was much less significant at the study site. To show the combined effect of DTWT and ET_p, the relationships between ET_g and ET_p for two different ranges of DTWT are also highlighted in Figure 10. For demonstration purposes, those separation depths were arbitrarily chosen at each well location. With similar ET_p, ET_g tended to be lower when water tables were deeper, indicating the larger impact of DTWT on ET_g. More interestingly, the larger slopes of the fitting curves for shallower DTWTs implied that ET_g was more responsive to the variations in ET_p; whereas, negative correlations between ET_g and ET_p even occurred under the deeper DTWT conditions (e.g., in well A3-cottonwood and B2-cottonwood). The closer linkage between ET_g and ET_p under the shallower DTWT conditions was likely due to more roots available for tapping groundwater for transpiration. When water tables became deeper, other factors (e.g., soil moisture content in the vadose zone) might also play important roles in the process of transpiration [*Lautz*, 2008]. By comparison, *Nichols* [1994] derived an exponential function describing the relationship between ET_g and DTWT, using an energy combination model. By comparing annual ET_g during predrawdown and postdrawdown periods, *Cooper et al*. [2006] reported lower annual ET_g with deeper mean annual DTWT. Overall, Figures 9 and 10 suggest that DTWT exerted a dominant control on ET_g, followed by ET_p at the study site.

Various model algorithms and numerical techniques have been used to calculate ET_g, including empirical relationships [*McDonald and Harbaugh*, 1988; *Banta*, 2000; *Shah et al*., 2007], analytical solutions under quasi steady state conditions [*Soylu et al*., 2011], and the coupling of process-based groundwater and land surface models [*Liang et al*., 2003; *Maxwell and Miller*, 2005]. In particular, the standard MODFLOW model employs a linear or a piecewise linear relationship of ET_g/ET_p with DTWT [*McDonald and Harbaugh*, 1988; *Banta*, 2000]; whereas, *Shah et al*. [2007] proposed an exponential decay function between ET_g/ET_p and DTWT, based on the results of numerical modeling. To be consistent with the modeling framework, the relationship between

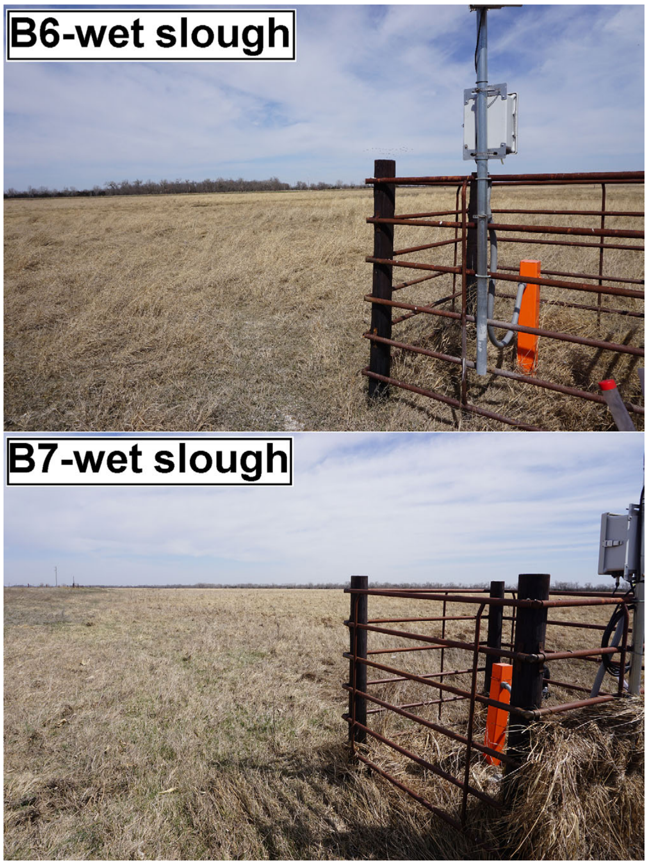

Figure 12. Vegetation cover at wells B6-wet slough and B7-wet slough.

ET_g/ET_p and DTWT is plotted in Figure 11 for individual wells. Significant scatters of the data points existed at some well locations. For example, at well B2-cottonwood, the ratio of ET_g/ET_p varied between 0.1 and 0.8, when the DTWT was ~1.3 m. However, an exponential relationship generally provided satisfactory correlations between ET_g/ET_p and DTWT at the study site (fitting equations with R^2 and p values are shown in Figure 11). Those results largely support the exponential function proposed by *Shah et al*. [2007].

Meanwhile, it is important to notice that the exponential relationship between ET_g/ET_p and DTWT varied considerably across the sites with a spatial scale of ~1200 m, even under similar vegetation conditions. It reflects the complex interactions of vegetation with surrounding environmental factors [*Nichols*, 1994; *Sala et al*., 1996; *Shah et al*., 2007; *Fan et al*., 2014]. For example, in the cottonwood area, the correlation of ET_g/ET_p with DTWT was more significant at well A3-cottonwood than at well B2-cottonwood. In the wet slough area, the response of vegetation to DTWT also differed at different well locations, most likely due to the spatial variations in local conditions (e.g., soil texture and vegetation). For instance, Figure 12 shows the vegetation cover around wells B6-wet slough and B7-wet slough. Although the vegetation type was similar at those two wells, the vegetation cover was denser at well B6-wet slough. Comparing Figures 11e and 11f, the larger ET_g/ET_p ratios at shallower depths (DTWT $<$ 0.6 m) at well B6-wet slough might be partly caused by the higher vegetation density at this location. As such, Figure 11 underscores the importance of assessing the uncertainties associated with the relationship between ET_g/ET_p and DTWT employed by different numerical models for calculating ET_g. Nonetheless, the observations from the study site provide field evidence, which suggests the exponential relationship between ET_g/ET_p and DTWT. We note that future analyses of this type should include more detailed local information about soil texture and vegetation characteristics.

4. Conclusions

An extensive observation network was established in a semiarid riparian area to monitor the spatial and temporal patterns of diurnal water table fluctuations (WTFs) induced by vegetation. Along a vegetation gradient (~1200 m), there was a tight spatial correlation between the vegetation and diurnal WTF patterns, which was related to the rooting depth of vegetation. The major factors that affected diurnal WTFs varied at the study site, depending on the temporal scale of interest. Specifically, air temperature played the most important role at the seasonal scale, as it controlled plant phenology and thus root water uptake from groundwater. Daily groundwater evapotranspiration (ET_g) during a time period with similar plant phenology in a growing season was calculated using the White equation. The results revealed the dominant control of depth to water table (DTWT) on ET_g at daily time scales, followed by potential evapotranspiration (ET_p) at the study site. In particular, with less roots available for directly tapping groundwater for transpiration, ET_g was less sensitive to the changes in ET_p under deeper DTWT conditions. Finally, exponential relationships between ET_g/ET_p and DTWT were obtained at the study site, although there was significant variability in those relationships. With the help of the newly established monitoring network, the results of this study provided further field evidence, demonstrating the close tie between diurnal WTFs induced by vegetation and various environmental factors that were related to vegetation characteristics (e.g., root distribution and plant phenology), as well as offered additional insight into modeling ET_g at different spatiotemporal scales.

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