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On evapotranspiration and shallow groundwater fluctuations: A Fourier-based improvement to the White method

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Evapotranspiration (ET) is a significant component of the water and energy balance in wetlands and riparian zones, yet it is also one of the most challenging components to estimate. Diurnal water table fluctuations can be used to directly measure groundwater consumption by phreatophytes, which are often important contributors to the total ET in riparian systems. Although such methods are cost effective, significant uncertainties usually exist, and more accurate techniques continue to be developed. In this study we present a new “Fourier method” for calculating daily (and longer) groundwater ET consumption using a moving, multiday sine function to capture robust, diurnal water table fluctuations. The technique is tested and calibrated in Tamarix chinensis and Populus deltoids-dominated riparian areas in the Middle Rio Grande region of New Mexico and in a Phragmites australis-dominated riparian wetland in south-central Nebraska (using independent, energy balance estimates of ET). The results show that—at both field sites—the new Fourier technique performs significantly better than the commonly used White method, regardless of the length of the moving window that is employed. The Fourier method presented here provides a step toward increasing the accuracy of ET estimates from diurnal water table fluctuations. Guidelines are defined for applying the new and improved method in the most accurate fashion, based on groundwater hydrographs and solar radiation data (or theoretical clear-sky estimates).


1. Introduction

Evapotranspiration (ET) of shallow groundwater is a crucial component of both the surface and subsurface water balance in riparian systems. Previous studies have shown that groundwater has a significant effect on the energy and water balance of riparian zones and wetlands, where groundwater elevates soil moisture and/or ET rates from phreatophytic plants [Chen and Hu, 2004; Maxwell and Kollet, 2008; Soylu et al., 2011]. An upward capillary flux of groundwater, as well as uptake by phreatophytes result in a significant increase in latent heat flux, which subsequently modifies other components of the energy and water balance and plays an important role in land-atmosphere interactions. Understanding the surface energy and water balance requires proper quantification of ET. However, determining the amount of groundwater that contributes to surface ET is challenging [Shah et al., 2007; Martinet et al., 2009]. Moreover, many of the ET estimation methods are difficult to implement in areas of phreatophyte plant communities and groundwater-fed wetlands, particularly in narrow riparian corridors [Loheide et al., 2005; Lautz, 2007].

The primary meteorological driver of ET is solar radiation, which has a pronounced diurnal cycle. In response to ET, shallow water tables also show similar diurnal fluctuations, particularly where significant phreatophytic vegetation is present. Therefore, the main advantage of estimating ET by means of diurnal water table fluctuations is that the water loss due to evapotranspirative water consumption by phreatophytes is directly measured through water level change [White, 1932; Meyboom, 1965; Gerla, 1992; Loheide et al., 2005]. Cost effectiveness and relatively simple numerical calculations are other important advantages of this ET estimation method. Even though this technique has some advantages over other methods, it is hindered by a number of sources of uncertainty. Even the most widely used ET estimation technique that employs diurnal water table fluctuations—the White method [White, 1932]—has undergone numerous modifications due to a variety of uncertainties and deficiencies [e.g., Meyboom, 1965; Engel et al., 2005; Gribovszki et al., 2008; Loheide, 2008], many
of which relate to the estimation of specific yield in shallow water table environments [e.g., Loheide et al., 2005; Shah and Ross, 2009].

[4] In the current study we propose a new groundwater ET estimation method that utilizes a 24 h sine function along a moving, multiday window to more effectively capture the full diurnal cycle associated with water table fluctuations. This “Fourier” technique is tested and calibrated in Tamarix chinensis and Populus deltoids-dominated riparian areas along the Middle Rio Grande River of New Mexico, USA (referred to hereafter as the “New Mexico” site), as well as in a Phragmites australis-dominated riparian wetland in south-central Nebraska, USA (the “Nebraska” site). In both locations, independent energy balance measurements of ET are used to test the new Fourier method, which is found to perform better than the White method, both on the “standard” daily time scale and when using a 3 day (or longer) moving average. Application of the new technique requires measurements of diurnal ground water table fluctuations, an estimate of specific yield, and the use of a scaling factor that is largely dependent on the ambient solar cycle at the study site (which can be approximated using clear-sky values). We discuss some of the background and theory for estimating ET from water table fluctuations in section 2, followed by a description of the new methodology in section 3, an application of the technique to the riparian study sites in sections 4 and 5, and a discussion of the results and conclusions in section 6.

2. Background and Theory: The White Method

[5] As noted earlier, the primary diurnal control on plant water use is solar radiation, particularly in energy-limited regions such as riparian zones. The daytime portion of this diurnal cycle can be significantly modified by the presence of cloud cover, often showing complex temporal patterns. In response to solar radiation, plants transpire water during the day, causing an upward flow of groundwater due to plant water consumption that is (generally) more rapid than the rate of groundwater recovery. This then leads to a decline in water table during the daytime [White, 1932]. At nighttime, however, photosynthesis ceases, thereby halting the transpiration-driven decline in water table, allowing the water level to increase gradually in response to groundwater recovery (a process which is not limited to just the nighttime period). Thus, it is important to note that both plant water use and groundwater recovery contribute to the pattern of diurnal fluctuations in water table depth.

[6] In many shallow groundwater environments, ET from phreatophytic plants is associated with water withdrawals from both the vadose and saturated zones since the plant root depth generally extends into both regions [Shah and Ross, 2009]. Typically, vadose zone and groundwater sources of total transpiration are not explicitly distinguished, and so T is often assumed to be equal to ETG. For intermediate water table depths, direct measurements of ETG can sometimes lead to an underestimate of the total transpiration, due to neglect of the vadose zone contribution (e.g., for depths of 80–160 cm [Shah and Ross, 2009]).

[7] The traditional characterization of water storage in unconfined aquifers, which assumes a constant value of specific yield, can be invalid when the time scale of water release is too short or when the water table is very near the surface. Thus, important modifications to the calculation of specific yield are often required in shallow water table environments, which leads to complex dependencies of specific yield on depth-to-groundwater [Shah and Ross, 2009]. Taking such modifications into consideration, however, ETG and groundwater recovery lead to a net change in water storage that can be quantified according to the following governing equation [Loheide, 2008]:

$$\frac{dZ_{gt}}{dt} = r(t) - ET_G(t).$$  \hspace{1cm} (1)

where \(Z_{gt}\) is the specific yield, \(dZ_{gt}/dt\) is the rate of change in depth-to-groundwater. This equation is found to perform better than the White method (equation (4)) to estimate 24 h total ETG:

$$ETG:\Delta t = integral\ of\ r/Sy\ over\ \Delta t.$$  \hspace{1cm} (2)

where \(ETG\) is the mean transpiration rate (\(L \cdot T^{-1}\)) during the time interval \(\Delta t = t - t_0\) (which is assumed to be short enough that \(Sy\) is constant), and \(\Delta Z_{wt}\) is the observed change in water table height \(L\) during the same time interval. Note that equation (2) can also be written as

$$ETG:\Delta t = Sy(\frac{1}{\Delta t}\ integral\ of\ \frac{r}{Sy}dt) + Sy(-\Delta Z_{wt}).$$  \hspace{1cm} (3)

where \(r_{gw} = r/Sy\) is the rate of change in water table depth due solely to the effects of groundwater recovery (\(L \cdot T^{-1}\)), \(s = -\Delta Z_{wt}\) is the observed decrease in water table \(L\) (i.e., increase in depth-to-water table, positive downward), and the overbar indicates a temporal average over the time period \(\Delta t\). In the rare instance that \(r_{gw} = 0\) (i.e., no groundwater recovery), it is evident from equation (3) that the daily total \(ET_G\) is simply the product of the specific yield \(Sy\) and the daily drop in groundwater storage \((s > 0)\).

[6] White [1932] proposed a method to estimate daily total \(ET_G\) from diurnal water table fluctuations using a formulation similar to equation (3):

$$ET_G = Sy(24r_{gw} \pm s).$$  \hspace{1cm} (4)

(Note that the daily total \(ET_G\) is technically equal to \(ET_G : \Delta t\), but we hereafter refer to this quantity as simply \(“ET_G”\) or “cumulative \(ET_G”\).) In applying the White method (equation (4)) to estimate 24 h total \(ET_G\), \(r_{gw}\) is simply taken to be the hourly rate of water table rise between midnight and 4:00 A.M. (using all available data points within that period), and \(s\) is the observed net rise or fall of the water table during the 24 h period (i.e., \(s = -\Delta Z_{wt}\)), and the + or – in equation (4) are used in the case...
of water table fall or rise, respectively). This methodology, therefore, assumes that the groundwater recovery rate is constant during the 24 h period and that the interval between midnight and 4:00 A.M. is an appropriate time period for estimating this “constant” rate (i.e., when any influence from ET is likely to be absent). Figure 1a illustrates the application of the White method for a sample groundwater time series observed at the Nebraska field site (described later).

[10] An inherent difficulty in applying the White method (and similar techniques) is an accurate determination of the specific yield $S_Y$. Duke [1972], Sophocleous [1985], Healy and Cook [2002], and many other studies have shown that specific yield is highly variable in shallow water table environments and that it depends not only on soil texture, but also on the water table depth and its rate of change. It is also possible for the groundwater recovery rate to vary within a 24 h period [Gribovski et al., 2008; Loheide, 2008]. Thus, the White method’s use of only a short, 4 h interval to estimate a constant rate of groundwater recovery can lead to large uncertainties. This is due not only to potential temporal variations in recovery rate, but also the fact that measurement errors can be exacerbated by the short observational interval, particularly if groundwater measurements are made at hourly or coarser time scales. These uncertainties are evident in the 4 day example shown in Figure 1a, which reveals large day-to-day variations in groundwater recovery estimates, as well as significant hour-to-hour variations in water table depth (which, in turn, affect the accuracy of the 4 h extrapolation to daily values). These and other limitations to the White method have been previously discussed in the literature [e.g., Meyboom, 1965; Healy and Cook, 2002; Loheide et al., 2005; Schilling, 2007; among others].

[11] Some studies have recommended modifications to the White method (and/or estimates of specific yield) in order to improve its performance [e.g., Meyboom, 1965; Engel et al., 2005; Loheide et al., 2005; Gribovski et al., 2008], while others have developed new techniques to estimate $ET_G$ [Loheide, 2008; Schilling, 2007; Czikowsky and Fitzjarrald, 2004]. Gribovski et al. [2010] provide a detailed historical review of $ET_G$ estimation methods that utilize diurnal fluctuations in water table depth and streamflow. We build on some of these earlier studies and propose an improved alternative for estimating $ET_G$, as described in section 3.

3. Improved Methodology: A Fourier Approach

[12] Despite the obvious periodic and (often) sinusoidal nature of diurnal fluctuations in shallow groundwater levels (e.g., Figure 1), relatively few studies have employed the use of Fourier techniques to examine rates of evapotranspiration. Most of these previous studies have focused on diurnal variations in streamflow [e.g., Czikowsky and Fitzjarrald, 2004; Lundquist and Cayan, 2002; Bren, 1997]. For example, Czikowsky and Fitzjarrald [2004] studied diurnal streamflow signals over small watersheds in the eastern U.S. and found that the diurnal variations could be adequately described using a Fourier methodology. In particular, they applied a partial Fourier series (namely a repeating, 24 h sine function) across a 3 day moving window of detrended streamflow

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**Figure 1.** Hourly water table elevation (relative to the land surface) observed at well-2 of the Nebraska field site for a 4 day sample period (21–24 August 2009), along with daily calculations of diurnal amplitude based on (a) the White method (equation 4) and (b) the Fourier method (equation 8). For the White method, $s$ represents the absolute change in water table (i.e., the distance between the horizontal black lines) over a full 24 h period, beginning and ending at midnight. The slope of the red line (i.e., $r_{gw}$) denotes the hourly rate of groundwater recovery, which is assumed to be constant and is calculated using a linear fit to the five hourly data points between midnight and 4:00 A.M. The equation for $ET_G$ uses $"+s"$ ("−s") in instances where the water table falls (rises) during the 24 h period. For the example using the Fourier method (panel b), a centered, 3 day moving window was applied. Window sizes used in this study vary from 1 to 7 days. A numerical curve-fitting routine was used to determine the black trend line $(D + A \cdot t)$, along with the other empirical parameters, $B$ and $E$. 

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data. Various coefficients were calculated by empirically fitting the streamflow data to the following time series function:

\[ Z(t) = A \cdot t + D + B \sin \left[ \frac{(t + E)}{24} \right]. \]  

(5)

where \( Z \) is the stream discharge or stage (\( L \)), \( t \) is time (in units of hours), \( A \) is the 3 day trend (\( L \ T^{-1} \)), \( D \) is the mean bias (\( L \)), \( B \) is the diurnal amplitude (\( L \)), and \( E \) is the diurnal signal phase (\( T \)). Czikowsky and Fitzjarrald [2004] used this method to quantify daily to seasonal changes in the magnitude of diurnal fluctuations in streamflow. Together with other methods and observations, they used this information to infer seasonal variations in ET, such as the changes that occur at the onset of spring (e.g., leaf emergence).

[13] The approach used by Czikowsky and Fitzjarrald [2004], as described by equation (5), is relatively simple to apply and has been found to provide a good characterization of seasonal variations in ET for various watersheds. To our knowledge, however, this method has not been used in conjunction with estimates of specific yield to directly calculate the rate of \( ET_G \) in riparian systems. Czikowsky and Fitzjarrald [2004], for example, used the magnitude of the diurnal streamflow fluctuations to infer relative variations in ET (by normalizing the diurnal fluctuations by the daily total streamflow), but they did not utilize this method to explicitly calculate absolute rates of ET (e.g., in mm d\(^{-1}\)).

[14] In the current study, we adopt this “Fourier method” of Czikowsky and Fitzjarrald [2004] and modify it to estimate daily (and longer) \( ET_G \) from diurnal fluctuations in shallow groundwater. We then apply the method to field data collected at the two previously mentioned riparian field sites (New Mexico and Nebraska) and compare the results to those obtained from the White method. The goals of this study, therefore, are to: (1) develop a technique for estimating daily to seasonal \( ET_G \) from diurnal water table fluctuations by means of a moving Fourier function, (2) calibrate and test the White and Fourier methods using independent energy balance observations of \( ET_G \) from the two field sites (a process which also leads to estimates of specific yield), and (3) evaluate and compare the relative performance of the two methods.

[15] Similar to the approach of Czikowsky and Fitzjarrald [2004]—and supported by observations such as Figure 1b—we assume that groundwater levels can be properly represented using a multiday, moving 24 h sine function with a bias and trend, as described by equation (5). By empirically fitting this equation to the observed groundwater levels, the mean bias and trend over the multiday period can be effectively removed, leaving just the main parameter of interest—the diurnal amplitude \( B \). An example of the results of this fitting procedure is shown in Figure 1b for a 3 day moving window. In contrast to Czikowsky and Fitzjarrald [2004], however, we do not restrict our study to 3 day periods, but instead apply the method across a variety of window sizes (from 1 to 7 day intervals) to test their relative effectiveness. Given this multiday approach, our analysis does not resolve subdaily variations in \( ET_G \), but instead focuses on variations that range across time scales of days to weeks (or longer). There is, of course, a trade-off in utilizing longer or shorter time windows in applying the Fourier method. Larger time windows provide more opportunity for diurnal signal “detection,” but at the expense of not resolving higher frequency variations in \( ET_G \) (e.g., daily), which are either muted or not detected at all. Smaller time windows, on the other hand, are more effective at resolving day-to-day variability, but have fewer data points with which to detect a robust diurnal amplitude.

[16] In order to apply the Fourier method to the estimation of \( ET_G \), we must first relate equation (5) to the governing equation for shallow groundwater fluctuations (equation (1)). To do this we start with the time-integrated form of equation (1) (namely equation (2), solved for \( S_Y \Delta Z_{sw} \)) to relate the height of the water table (\( Z_{sw} \)) to the cumulative effects of groundwater recovery and transpiration, as a function of time:

\[ S_Y \Delta Z_{sw}(t) = S_Y[Z_{sw}(t) - Z_0] = \int \frac{r - ET_G}{\Delta t} dt = \int \frac{ET_G}{\Delta t} dt, \]

\[ \text{(6)} \]

where \( Z_0 \) is an arbitrary initial water level. Similar to the White method, equation (6) assumes that the groundwater recovery rate is constant over the time period of interest (\( \Delta t = t - t_0 \)), which has allowed \( r \) to be pulled out of the integration on the right hand side. Although this assumption can potentially be problematic (as noted earlier), we would argue that this drawback is more than made up for by the fact that the Fourier method takes into account the full diurnal cycle (in some cases, even over multiple days). The White method, on the other hand—while also assuming a constant daily recovery rate—does so by simply extrapolating to a 24 h period using a small number of data points, and over a short, 4 h interval.

[17] Combining equation (6) with equation (5) by setting \( Z = Z_{sw} \) (and \( t_0 = 0 \)), we arrive at

\[ Z_{sw}(t) = Z_0 + r_{gw}t - \frac{1}{S_Y} \int_0^t \frac{ET_G}{\Delta t} dt = D + A \cdot t + B \sin \left[ \frac{(t + E)}{24} \right]. \]

\[ \text{(7)} \]

At first glance, it might appear from equation (7) that the mean and trend, \( D + A \cdot t \), are entirely accounted for by the initial water level and accumulated groundwater recovery, \( Z_0 + r_{gw}t \). This would leave the cumulative \( ET_G \) term \( \int ET_G/\Delta t \) to be associated solely with the sine function on the right hand side (i.e., a diurnal fluctuation in water level with a peak-to-trough “range” of 2B). Importantly, however, this is not the case. Rather, the observed water level trend \( A \cdot t \) actually represents the combined effects of both groundwater recovery and cumulative transpiration. Thus, \( ET_G \) contributes significantly to the trend in water level and, in fact, is responsible for the entire trend when the groundwater recovery rate is zero. As a result, the process of detrending the water level time series—by removing \( D + A \cdot t \) in equation (7) (and any associated trend on the left hand side)—actually removes a significant portion of the cumulative \( ET_G \) signal, thereby weakening the diurnal rise and fall that is subsequently observed in the detrended \( Z_{sw} \) time series. The only term on the right hand side of
equation (7) that remains after the detrending process, then, is the aforementioned sine function, with amplitude $B$ (i.e., peak-to-trough range $= 2B$). Although this diurnal amplitude is precisely what the Fourier method is intended to measure, we demonstrate in the remainder of this section that simply equating the daily total transpiration to $Sy(2B)$ results in a significant underestimation of $ET_c$. This artifact of the detrending process, however, can be easily corrected through the use of a simple scaling factor, as described below.

To illustrate the effects of trend removal (as well as groundwater recovery) on the diurnal amplitude, we examine two idealized scenarios in Figure 2, which shows the hourly transpiration rate, cumulative $ET_c$, hypothetical water level (multiplied by specific yield), and detrended water level time series. The two synthetic water level time

Figure 2. Sample calculations illustrating the origin of the “scaling factor,” $k$ (equation 8), for two idealized scenarios using a repeating, 12 h square wave (left panels) and a theoretical clear-sky solar radiation curve (right panels). (a) and (b) show the hourly $ET_c$ rate for four consecutive days, with each curve scaled to produce 6 mm of daily total $ET_c$. (c) and (d) show the hourly cumulative $ET_c$ loss, while (e) and (f) represent the hypothetical water table elevation (multiplied by specific yield), assuming a constant groundwater recovery rate of $r = 0.2$ mm h$^{-1}$ (see equation 6). (g) and (h) show the final, detrended time series of water table elevation (multiplied by specific yield), as well as the resulting scaling factor required to recover the daily $ET_c$ amplitude of 6 mm d$^{-1}$. 
series (i.e., $Sy \cdot Z_o$) were created from equation (6) by assuming $Z_o = 0$, $t_o = 0$, and $r = 0.2 \text{ mm h}^{-1}$ (i.e., constant), while applying an $ET_G$ that varied on an hourly basis but maintained a constant daily rate of 6 mm $d^{-1}$. These specific numerical values were chosen for the sake of illustration purposes only and do not have an impact on the resulting calculation of the $ET_G$ “scaling factor,” which depends only on the shape and duration of the diurnal transpiration curve. In theory, a similar correction factor to adjust for diurnal variations in groundwater recovery rate $r$ could be introduced as well, but this is beyond the scope of the current study and is likely to be of less importance than accounting for the overall impacts of detrending on the inferred $ET_G$ diurnal amplitude.

In both scenarios shown in Figure 2, it is clear that the amplitude of the diurnal fluctuations in each of the various time series gets progressively weaker as groundwater recovery is added and detrending is applied. For example, when a periodic, 12 h square wave (Figure 2a) is used to simulate transpiration (at a maximum rate of 0.5 mm h$^{-1}$), the cumulative $ET_G$ time series shows a daily range of 6 mm (Figure 2c), as would be expected. Ultimately this is the parameter that the Fourier method seeks to recover since it represents the total daily transpiration. However, this daily range is reduced to 3.6 mm when a constant groundwater recovery rate of 0.2 mm h$^{-1}$ is applied (Figure 2d). Detrending the overall time series reduces the diurnal range even further (to $2B = 3$ mm), resulting in a value which is exactly half the original diurnal range of 6 mm. Thus, a “scaling factor” of $k = 2.0$ must be applied to recover the initial $ET_G$ (i.e., the actual diurnal transpiration). This can be represented by the following simple equation:

$$ET_G = Sy \cdot k(2B) \quad (8)$$

It turns out that $k = 2.0$ is the appropriate scaling factor for any 12 h square wave, regardless of the transpiration rate or constant $r$ value that is chosen (since $r$ is also removed in the detrending process). Clearly, without the explicit inclusion of $k$ in equation (8), either $ET_G$ would be significantly underestimated, or—in cases where specific yield is the quantity of interest (e.g., determined from independent estimates of $ET_G$ and $B$)—$Sy$ would be significantly overestimated.

In the second, and more realistic scenario shown in Figure 2 (right-hand panels), the hourly transpiration time series was given the same shape as a theoretical clear-sky solar radiation curve (based on the latitude of the Nebraska field site, but scaled to produce the same daily total $ET_G$ of 6 mm). In this case, the original diurnal amplitude in Figure 2d was reduced even further by the detrending process (Figure 2h), resulting in a larger scaling factor of $k = 2.12$. Thus, the magnitude of $k$ is found to be dependent on the shape and duration of the diurnal transpiration curve, which is largely a function of solar radiation (particularly in well-watered regions, such as riparian zones). To examine the range of potential values that may exist for this scaling factor, we repeated the above process using observed, hourly incoming solar radiation data to represent the diurnal shape of the $ET_G$ curve. The radiation data were obtained from the Nebraska site for the 2009 growing season. A given day’s hourly solar radiation values were accumulated iteratively over multiple days, then the time series was detrended, and the scaling factor was calculated. This was repeated for each day of the growing season, and the resulting scaling factors are shown in Figure 3. The magnitude of the scaling factor was found to range from a minimum of $\sim 1.6$ to a maximum of $\sim 2.2$, with a mean value of 1.9. Larger scaling factors tend to occur during days that have a “flatter” diurnal pattern or longer length-of-day, as evidenced by the obvious seasonal cycle (Figure 3), which peaks in late June. The observed scaling factors in Figure 3 are used later in the analysis, together with equation (8) and energy budget-derived observations of $ET_G$, to arrive at estimates of specific yield for the Nebraska site. Similarly, observed

![Figure 3. Daily observed shortwave radiation, $SW_{obs}$ (right axis; gray bars), and daily scaling factors for the Fourier method, $k-SW_{obs}$ (solid black line) and $k-SW_{clr}$ (dotted line), which were estimated from accumulated hourly values of observed solar radiation and theoretical clear-sky values, respectively. Dashed line represents a third-order polynomial fit to $k-SW_{obs}$.](image-url)
incoming solar radiation data with 30 min intervals were used to calculate scaling factors at the New Mexico sites. [21] Since observations of incoming solar radiation may not always be available for applying the Fourier method described here, we also tested the accuracy of simply using an hourly theoretical clear-sky curve to calculate the scaling factor for each day of the growing season. The results are compared with the actual daily values from 2009 (Figure 3). As might be expected, the clear-sky scaling factors are generally found to lie along an upper envelope of the observed daily values (roughly 8% higher than the polynomial fit to the observations). Thus, we find that it would be suitable to use scaling factors generated from theoretical clear-sky values, so long as a reduction of ~8% is applied. According to Figure 3, these “reduced” clear-sky estimates are typically within 10% of the actual daily values, and even a constant, mean scaling factor of 1.9 would be off by no more than ~18% on any given day. The option of using clear-sky values is obviously desirable since such calculations only require knowledge of the latitude of the field site in question (and day of year). On the other hand, direct observations of incoming solar radiation provide a more accurate determination of the daily scaling factor and are also valuable for estimating cloud cover, potential ET, etc.

4. Study Sites and Instrumentation

4.1. Middle Rio Grande Region, New Mexico

[22] The Fourier and White methods were first compared using data collected in the riparian corridor of the middle Rio Grande River basin of New Mexico [Cleverly et al., 2002, 2006a; Martinet et al., 2009], a study region which includes three research sites, located north-to-south in Belen, Sevilleta, and Bosque del Apache. While Belen is dominated by native cottonwoods (Populous deltoids), the Sevilleta and Bosque del Apache research sites are dominated by invasive salt cedar communities (Tamarix chinensis). The climate of the area is semiarid, with an annual mean precipitation ranging from 200 to 310 mm [Martinet et al., 2009].

[23] Instrumentation at each of the three New Mexico research sites includes multiple groundwater wells and a meteorological flux tower, which uses the eddy covariance technique to measure 30 min turbulent fluxes above the plant communities over multi-year periods (from 2000 onward). Detailed information about the climate, hydrologic conditions, vegetation cover, and instrumentation at each of the research sites is discussed in a series of papers by Cleverly et al. [2002], Dahm et al. [2002], Cleverly et al. [2006a], and Martinet et al. [2009]. ET and groundwater data for the New Mexico sites were obtained from Cleverly et al. [2006b], and we focus on the period 1 July–15 September 2001 for the purposes of this study.

4.2. South-Central Nebraska

[24] The second study site is a riparian wetland located in south-central Nebraska, roughly 6 km west of the town of Arapahoe, and at an elevation of 664 m above sea level (Figure 4). The climate of the site is subhumid to semiarid [Lenters et al., 2011], with a mean annual precipitation of 600 mm. Approximately 80% of the annual precipitation occurs between April and September. Perennial standing water exists in the wetland channel, which is approximately 900 m long and 50 m wide, with a water depth that ranges (seasonally) from approximately 10–60 cm. The wetland receives a limited amount of water from a spring along the western end and occasionally loses water through a narrow channel to the east (but only during periods of high water level). In general, the flow of surface water into or out of the wetland is minimal, as most of the water enters through groundwater discharge or direct precipitation and leaves through ET and groundwater recharge [Lenters et al., 2011]. A tall, invasive grass—P. australis, or “common reed” (maximum height 4.2 m)—is the dominant vegetation type in the wetland. Some native reeds are also present, as well as small patches of open water (Figure 4). P. australis

Figure 4. Map showing the study area (black rectangle) in south-central Nebraska, as well as the wetland land cover and locations of the meteorological station, LAS transmitter and receiver, and three groundwater wells (labeled W-1, W-2, and W-3).
grows well in water-logged soils due to the very low oxygen consumption of its roots, which is similar to other flood-tolerant plants [Gries et al., 1990]. The rooting depth of *P. australis* has been reported to be over 2.5 m [Kohzu et al., 2003], and the soil in the vicinity of the wetland is classified as a Gibbon soil (fine-silty, mixed, superactive, calcareous, mesic Fluvaquentic Endoaquolls [Soil Survey Staff, 2010]).

[25] Instrumentation at the Nebraska field site includes numerous piezometers (Figure 4), water/soil temperature loggers, pressure transducers (for measuring surface and groundwater level), and a meteorological tower for monitoring the surface energy and water balance of the wetland. The tower height is 6.3 m, and it is positioned near the middle of the wetland. Atmospheric measurements include incoming solar radiation, wind speed and direction, precipitation, air temperature and relative humidity, net shortwave and longwave radiation, and barometric pressure. A large aperture scintillometer (LAS) system was also installed above the wetland to measure sensible heat flux. The LAS transmitter and receiver are positioned in such a way that the midpoint of the transect is near the meteorological tower (Figure 4). Most measurements were sampled every 10 s (1 s, in the case of the LAS data) and averaged to 10 min, hourly, and daily means. Data were collected throughout the 2009 growing season (roughly mid April to early October). Additional details regarding the energy balance instrumentation, measurements, and data analysis can be found in the study by Lenters et al. [2011].

[26] Three polyvinyl chloride (PVC) piezometers were installed at various locations in the unsaturated region of the wetland to monitor subsurface hydrologic conditions (Figure 4), with one positioned in the western portion of the wetland (well-1), and the other two located along the north bank (well-2) and the south bank (well-3) of the central section of the wetland. Two additional wells (not shown) were deployed in saturated portions of the wetland. In the current study, we only use data from the three wells that did not experience inundation since, to our knowledge, the White method has not been applied to conditions with fully saturated soil and standing surface water (due to complications related to water table measurement and the interpretation of specific yield, as discussed below and by Soylu [2011]). Each of the three wells that were not in saturated regions of the wetland contains a screen in the lower section that is 20 cm long (with a slot width of 0.2 mm), and the wells were deployed at an average depth of 200 cm (measured from the upper portion of the screen to the soil surface). The hydraulic head within each piezometer $h_{wt}$ was measured every 15 min using automated pressure transducers (Level TROLL 300, In-Situ Inc.), and the data were averaged to 1 h intervals to match the temporal resolution of the barometric pressure observations. For the purposes of this study we use the soil surface as our water level datum and convert the hydraulic head measurements to an approximate “depth-to-water table,” $D_{wt} = -Z_{wt} = D_{well} - h_{wt}$, where $D_{well}$ is the well depth. The three wells had a mean hydraulic head of $h_{wt} = 148$ cm, yielding an average depth-to-water table of $D_{wt} = 52$ cm. Hydrographs from all three observation wells show a distinct pattern of diurnal fluctuations in $D_{wt}$ during the 2009 growing season, especially between mid-June and the end of September (Figure 5).

5. Water Table Measurements and Interpretation of Specific Yield

[27] The proposed Fourier method is tested using data from two distinct regions (New Mexico and Nebraska) in order to demonstrate the generality of the proposed approach in areas with shallow groundwater. The New Mexico site uses conventional depth-to-groundwater observations (i.e., screened across the water table), as are typically required for diurnal water table fluctuation studies [e.g., Loheide et al., 2005]. Groundwater levels at the New Mexico research sites were not significantly variable and were generally deeper than 1 m during the time period of interest (July to mid-September 2001). Furthermore, the soil texture is generally quite coarse [Martinet et al., 2009]. Therefore, specific yield was assumed to be constant at each of the three New Mexico research sites.

Figure 5. Water table hydrographs from the three observation wells at the Nebraska field site (Figure 4) during the 2009 growing season. Gray shaded areas show dates which were excluded from the $ET_G$ estimation procedure due to precipitation events.
[28] The Nebraska field site, on the other hand, is a wetland, containing predominantly saturated soil and standing water throughout much of the growing season. Therefore, as indicated in section 4.2, continuous screening was not applied to the groundwater wells at the Nebraska site. Instead, the two wells that were located in regions with standing water were screened ~1–2 m below the water table since screening across the water table (as is traditionally done), would result in a measurement of the surface water elevation. For consistency, the three wells not located in inundated areas (i.e., the focus of the current study) were also screened at roughly the same depth below the water table (average $h_\text{wt} = 148$ cm).

[29] Thus, it is important to note that—for the Nebraska site only—we are applying the $ET_G$ estimation methods using diurnal fluctuations in hydraulic head, rather than the more traditional depth-to-water table. Our assumption is that variations in hydraulic head measured by the piezometer are nearly equivalent to changes in water table elevation, given the proximity of the screened interval of the piezometer to the actual water table. Any discrepancies between true water table variations and those estimated with measurements of hydraulic head would indicate that the concept of specific yield is not sufficient to describe the water storage and release mechanisms at the site. Under these nonhydrostatic conditions, where measured hydraulic head and actual water table position are different, water would not only be released through drainage of pores (which is represented by specific yield), but also by poroelastic effects (which are described using specific storage). Therefore, we suggest that a new variant of the White method (including a new definition of specific yield/storage) is needed in order to properly interpret hydraulic head fluctuations and water storage/release in these nonhydrostatic, shallow water table environments (i.e., a method which is applicable to both saturated and unsaturated conditions). Although we are developing an evolving framework to accommodate these conditions [Soylu, 2011], the work is beyond the scope of the current investigation and will be discussed in a future study in greater detail. For the purposes of the current study, we apply the traditional White method (and new Fourier method) at both field sites, while also adopting the term “apparent specific yield” for the Nebraska site, in order to recognize the unique considerations for this wetland location.

6. Results and Discussion

[30] To evaluate the $ET_G$ estimation methods, independent transpiration measurements are required for comparison. At the New Mexico sites, the total ET was simply assumed to be equal to $ET_G$ due to the fact that the high leaf area index (LAI) of the woody vegetation during the time period of interest (1 July–15 September 2001) attenuates a large amount of solar radiation and provides significant wind sheltering. These factors substantially reduce surface evaporation, particularly given the lack of surface moisture at the New Mexico sites. At the Nebraska site, however, where both standing water and tall vegetation are present, data from the meteorological station and LAS were used to calculate the overall rate of ET from the wetland (i.e., the total latent heat flux from transpiration and surface evaporation). This was accomplished by means of the energy balance method, with ET calculated as a residual [Lenters et al., 2011]. As explained in section 6.1, transpiration estimates were then determined by subtracting surface water evaporation rates from the energy budget-derived total ET. Intercepted evaporation is ignored at both the Nebraska and New Mexico study sites due to the episodic nature of summer precipitation, generally low precipitation amounts, and high transpiration rates.

6.1. Energy Balance Estimates of $ET_G$ (Nebraska Site)

[31] Total ET in a wetland environment ($ET_{\text{tot}}$) can be broken down into its various components, which includes transpiration ($ET_G$), open water evaporation ($E_{\text{ow}}$), intercepted water evaporation ($E_{\text{int}}$), evaporation from water beneath the canopy ($E_{\text{cw}}$), and soil water evaporation from the unsaturated zone ($E_{\text{unsat}}$). Observations from the Nebraska study site indicate that standing water was present throughout most of the wetland during the vast majority of the 2009 season. Thus, the soil was generally 100% saturated or—at most—had a very limited vadose zone (e.g., near the banks; Figure 4), indicating that $E_{\text{unsat}}$ can be ignored as an important contributor to the total ET. Intercepted evaporation ($E_{\text{int}}$) is also assumed to be negligible, as noted above. However, given the significant amount of standing water in the wetland—both beneath the vegetation and exposed to the open air—neither of the surface water evaporation terms can be ignored ($E_{\text{ow}}$ and $E_{\text{cw}}$). Therefore, we separated $ET_{\text{tot}}$ into three components according to the surface area occupied by each component:

$$A_{\text{tot}}ET_{\text{tot}} = A_{\text{ow}}E_{\text{ow}} + A_{\text{cw}}E_{\text{cw}} + T_{\text{vol}},$$  \hspace{1cm} (9)

where $A_{\text{tot}}$ (m$^2$) is the total area contributing to the energy balance-derived ET (i.e., roughly the “footprint” of the LAS and meteorological station), $A_{\text{ow}}$ is the area of open water contained within that footprint, $A_{\text{cw}}$ is the area of the standing water beneath the vegetation canopy, and $T_{\text{vol}}$ is the volumetric transpiration rate (L$^2$ T$^{-1}$) through the P. australis vegetation, whose stems occupy a (relatively small) portion of the total surface area, $A_{\text{stems}} = A_{\text{ow}} + A_{\text{cw}} + A_{\text{stems}}$. Dividing both sides of equation (9) by $A_{\text{tot}}$, and defining $ET_G$ as $T_{\text{vol}}/A_{\text{tot}}$, we arrive at

$$ET_G = ET_{\text{tot}} - f_{\text{ow}}E_{\text{ow}} - f_{\text{cw}}E_{\text{cw}},$$  \hspace{1cm} (10)

where $f_{\text{ow}}$ and $f_{\text{cw}}$ are the fractions of the wetland area occupied by open water and “under-canopy” water, respectively. (Note that, technically speaking, one could argue that the “transpiring area” for $ET_G$ should be defined as $A_{\text{tot}} - A_{\text{stems}}$, rather than simply $A_{\text{tot}}$.) Open water occupies approximately 9% of the total wetland area [Lenters et al., 2011], but the fractional coverage is much lower ($f_{\text{ow}} = 0.03$) in the portion of the wetland that lies within the footprint of the LAS (Figure 4). The remaining 97% of the wetland surface is composed of standing water beneath the canopy ($f_{\text{cw}} = 0.91$) and stems protruding from the water (which account for ~6% of the total surface area). It is important to note that the surface area occupied by the stems does not contribute to evaporation via $E_{\text{cw}}$, but rather to transpiration (i.e., $T_{\text{vol}}$ and, hence, $ET_G$).
[32] As noted earlier, ET_{cw} was determined from the wetland energy balance, based on the results of Lenters et al. [2011], and we applied a 7% reduction to the measured sensible heat flux to correct for a suspected high bias in the LAS data (which results in a slightly higher ET_{cw} than reported by Lenters et al. [2011]). In a similar, but slightly simpler fashion, both E_{cw} and E_{cw} were calculated using the Bowen ratio energy balance (BREB) method, which expresses the evaporation rate (in units of latent heat of vaporization, and

\[
E_{cw} = \frac{R_n - \Delta S_{sw}/\Delta t}{\rho_e \lambda(1 + \beta_{cw})} \tag{11a}
\]

and

\[
E_{cw} = \frac{R_n - \Delta S_{sw}/\Delta t}{\rho_e \lambda(1 + \beta_{cw})}, \tag{11b}
\]

where \(R_n\) is net radiation, \(R_{nc}\) is the canopy-attenuated net radiation (i.e., the amount that makes it to the water surface), \(\Delta S_{sw}/\Delta t\) is the rate of heat storage in the water and underlying soil, \(\rho_e\) is the density of water, \(\lambda\) is the latent heat of vaporization, and \(\beta\) is the Bowen ratio (i.e., ratio of sensible to latent heat flux), which is calculated according to

\[
\beta_{cw} = \frac{(T_{cw} - T_{oa})}{(e_{cw} - e_{oa})} \tag{12a}
\]

and

\[
\beta_{cw} = \frac{(T_{cw} - T_{oa})}{(e_{cw} - e_{oa})}. \tag{12b}
\]

[33] In equations (12) \(\gamma\) is the psychrometric constant, \(T\) is temperature, \(e_{cw}\) is saturation vapor pressure, and \(e_\text{sat}\) is vapor pressure. The subscripts “ca” and “oa” refer to measurements of air temperature (or vapor pressure) at a “canopy-air” height of 2.2 m (i.e., within the canopy) and an “open-air” height of 4.1 m, respectively. Similarly, “cw” and “ow” refer to measurements of water surface temperature (or saturation vapor pressure) made in areas of “canopy water” (i.e., beneath the canopy) and “open water,” respectively. Canopy-attenuated net radiation in equation (11b) is calculated according to Beer’s law:

\[
R_{nc} = R_n \exp(-k_{ext} LAI), \tag{13}
\]

where \(k_{ext} = 0.6\) is the extinction coefficient (based on estimates for \(P. australis\) from Burba et al. [1999]), and LAI is the leaf area index (measured at the site at various intervals and interpolated to daily values). Measurements of net radiation, soil temperature, \(T_{cw}, T_{ca}, T_{oa}\), relative humidity (for both \(e_{cw}\) and \(e_{oa}\)), and heat storage rates were collected at the wetland field site during 2009, as described by Lenters et al. [2011] and Cutrell [2010]. Estimates of \(T_{cw}\) were obtained from \(T_{cw} = T_{cw} + \delta\), where \(\delta\) is a smoothly varying seasonal adjustment based on a second-order polynomial fit to \(T_{ca} - T_{cw}\) (with \(\delta\) assumed equal to zero at the beginning of the season, when LAI is at a minimum). In addition to daily mean values, 3 day (and longer) running means were applied to all variables to produce a more robust energy balance (particularly for the heat storage term), while additional gap-filling and 15 day smoothing was applied to the Bowen ratio calculations to reduce spurious noise. The resulting BREB estimates of sensible and latent heat flux (both within the canopy and over open-water areas) were found to be robust and physically consistent, yielding reasonable values for \(E_{cw}, E_{cw}, \text{and } E_{G}\).

[34] Figure 6 shows the final estimates of \(E_{G}\) (on a 3 day running mean time scale), along with \(E_{cw}\) and the various surface water evaporation components for May 2009 onward (i.e., the majority of the growing season). Around the time of leaf emergence (20 April [Cutrell, 2010]), transpiration from the \(P. australis\) was negligible, and \(E_{G}\) remained near zero until 22 April (not shown), when \(E_{cw}\) was roughly 2 mm d\(^{-1}\) (and, therefore, comprised entirely of evaporation from surface water). By early to mid May, \(E_{G}\) rates increased to become comparable to \(E_{cw}\) (Figure 6), although open-water evaporation rates were still much higher (\(E_{cw} \approx 5\) mm d\(^{-1}\)). Continued plant growth and increases in LAI eventually led to significant attenuation of incoming radiation by early to mid June, accompanied by reductions in “under-canopy” \(E_{cw}\) to generally less than 1 mm d\(^{-1}\). Open-water evaporation rates remained high throughout the summer (up to \(\sim 8\) mm d\(^{-1}\)), but did not contribute significantly to the total ET due to the small fraction of open-water area (3%). The end result, then, is that transpiration rates (\(E_{T_G}\)) were much lower than the total ET during the early part of the season (e.g., \(\sim 20\% - 50\%\) lower during May) but were only slightly lower (\(\sim 5\% - 20\%\)) from about mid-June onward (Figure 6). As described below, these \(E_{T_G}\) observations were then combined with measurements of diurnal fluctuations in \(D_{sw}\) (from the three observation wells at the Nebraska field site) to arrive at estimates of specific yield.

6.2. Specific Yield Calculations

[35] Determining specific yield in shallow-water table environments can be challenging, and our approaches for estimating specific yield (\(S_y\)) are different for the New Mexico and Nebraska field sites. As noted previously, \(S_y\) is assumed to be constant at each of the three New Mexico sites due to the fact that water levels were not significantly variable, soil textures are coarse, and the mean water table is generally deeper than 1 m during the period of interest [Lenters et al., 2005; Martinet et al., 2009]. To estimate \(S_y\) at the New Mexico sites, we calculated the optimum \(S_y\) for each groundwater well (and for each of the White and Fourier methods) by minimizing the root mean square error (RMSE) between the time series of observed and estimated \(E_{T_G}\) (right and left hand sides of equations (4) and (8)). Daily scaling factors \(k\) (or longer running means) were obtained from observed solar radiation data collected at the New Mexico sites. The mean \(S_y\) values (averaged across all groundwater wells at each site, and across both methods) were calculated to be 0.046, 0.110, and 0.035 for the Belen, Sevilleta, and Bosque del Apache research sites, respectively. These estimates are within the range of \(S_y\) values reported by Martinet et al. [2009] for the same field sites.

[36] At the Nebraska wetland site, a high degree of saturation and extensive areas of standing water are typically present. Poroeelastic storage effects are likely to be important, and the depth to water table (\(D_{sw}\)) and associated
The hydraulic head are quite variable throughout the 2009 growing season (Figure 5). Therefore, we do not assume $S_y$ to be constant, but rather, we explicitly investigate its dependency on $D_w$. To calculate “apparent” $S_y$ at the Nebraska field site, we used both the White and Fourier methods (equations (4) and (8), respectively) to solve for specific yield:

$$S_y = \frac{ET_G}{24r_{gw} s}$$  \hspace{1cm} (14a)

and

$$S_y = \frac{ET_G}{k(2B)}$$,  \hspace{1cm} (14b)

where $ET_G$ values were obtained from the partitioning of the total wetland ET (as described in section 6.1), and $k$ values were obtained from observed solar radiation data (Figure 3). Data from each of the three observation wells were used to create plots of daily $S_y$ versus $D_w$ for both the White method (Figure 7a) and the Fourier method (Figure 7b), with the latter technique also being applied across a variety of moving windows (i.e., 3, 5, and 7 day windows; Figures 7c–7e). The plots in Figure 7 not only illustrate the dependency of apparent $S_y$ on water table depth, but they also provide insight into the performance of the different methods (e.g., as determined by the degree of scatter in the data). The results of Figure 7 are discussed below.

As noted earlier, our analysis of diurnal fluctuations in the observed hydrographs (Figure 5) focused on the peak of the growing season (15 June–30 September 2009), which is when the hourly variations in water table were most pronounced. It is clear from Figure 5 that the observed diurnal fluctuations increase in amplitude as the season progresses, during which time the depth-to-water table also increases by ~60–70 cm. As described by equation (8), this increase in diurnal amplitude (i.e., $2\beta$) is indicative of either an increase in $ET_G$ and/or a decrease in apparent $S_y$ (with the scaling factor $k$ playing a more limited role; Figure 3). Clearly $ET_G$ by itself cannot explain the seasonal increase in diurnal head fluctuations since transpiration is declining during this time (Figure 6), primarily in response to decreases in incoming solar radiation (Figure 3). Rather, the relationship between water table depth and the amplitude of the diurnal fluctuations mainly stems from changes in apparent $S_y$ (calculated according to equation (14) and plotted in Figure 7 as a function of $D_w$). As illustrated in Figures 7a and 7b, both the White and Fourier methods yield similar values of apparent $S_y$, ranging from ~0.04 (for deep water tables) to ~0.4 (for shallow water tables), with few outliers beyond these bounds. The mean $S_y$ values of 0.28 (well-1), 0.21 (well-2), and 0.21 (well-3) are generally higher than those found at the three New Mexico field sites. Both methods display an inverse, exponential relationship between daily values of apparent $S_y$ and $D_w$ at each of the three observation wells (Figure 7). These results indicate that—during periods of high water table—transpiration withdraws more soil water from storage than would be expected from the otherwise limited diurnal fluctuations in water table (e.g., early in the season; Figure 5). Conversely, when the water table deepens, apparent $S_y$ becomes smaller (Figure 7), and $ET_G$ decreases, despite the larger observed diurnal fluctuations in hydraulic head (Figure 5).

We primarily attribute this behavior (i.e., higher apparent $S_y$ values at shallower water table depths) to enhanced water availability and plant water use within the unsaturated zone, similar to the results of Shah and Ross [2009]. A second important factor is the distance between
the water table and the depth at which the head fluctuations are measured since this distance actually increases as the water table rises. This would likely lead to reductions in ETG diurnal amplitude, despite similar (or larger) rates of groundwater use by roots within the overlying saturated zone, which thickens as the vadose zone thins. Third, groundwater fluctuations may become muted if water is supplemented by other sources, most likely nearby standing surface water in this case. Thus, considering that all three wells are located near the bank of the wetland channel, the increased apparent Sy at shallower water table depths may be at least partially explained by enhanced ETG contributions from lateral water flow. In summary, one of the above explanations is related to the choice of measurement (hydraulic head versus depth-to-groundwater), while the other two factors relate to increased water availability for plant roots (within the unsaturated zone, as well as through enhanced connections with standing surface water). All three factors would result in reduced diurnal amplitudes of measured head fluctuations for similar rates of ETG, thereby leading to an increase in apparent Sy.

The exponential relationship between apparent Sy and water table depth (Figure 7) can be expressed as follows:

\[ Sy = a \cdot e^{-bD_{wt}}, \]  

(15)

where \(a\) and \(b\) are empirical coefficients determined individually for each observation well (based on the regressions between Sy and \(D_{wt}\), and listed in Figure 7). The functional relationship is especially robust in the case of the Fourier method (Figure 7b), which shows considerably less scatter than the White method (Figure 7a), and the regression is improved even further when the size of the Fourier window is increased to 3, 5, and 7 day moving windows (Figures 7b–7e). There are, however, “diminishing returns” as one expands the Fourier method beyond the 5 day time scale (presumably due to trade-offs between sample size and temporal smoothing). Thus, we conclude that the Fourier technique performs best when 3 day and (especially) 5 day moving windows are applied.
6.3. Evaluation of ETG Estimation Methods

[40] Final estimates of ETG for the New Mexico and Nebraska sites were calculated from the observed diurnal water table fluctuations using the White and Fourier methods (equations (4) and (8), respectively). Sy was determined individually for each observation well and each method at both study sites (as described in section 6.2). ETG estimates from all wells within a given site were then averaged together to create an overall time series of the mean transpiration rate at each of the four sites (three in New Mexico and one in Nebraska). For the Nebraska site, four time series were created via the Fourier method (using 1, 3, 5, and 7 day moving windows), while two time series were created via the White method (i.e., the standard, daily method and—for comparison purposes—a 3 day moving average).

[41] Figure 8 shows a comparison of the White-based and Fourier-based ETG estimates at each of the three New Mexico sites with the observed values derived from the energy balance measurements. (For brevity, we only show results using a 3 day moving window, as other averaging intervals yielded similar results.) In addition to the multiwell, "site-mean" ETG values shown in Figure 8 (i.e., the red squares), we also show the individual ETG estimates from each of the observation wells (i.e., the gray dots). Figure 9 shows similar plots for each of the six ETG estimates at the Nebraska site, including four different window lengths for the Fourier method, as well as daily and 3 day moving averages for the White method. It is important to note that one of the primary sources of uncertainty in the ETG estimates for the Nebraska site (Figure 9) and, to be fair—a source of agreement as well—is the calculation of Sy, which uses individual, empirically derived functions at each well to estimate Sy from \( D_{WT} \) (Figure 7). The New Mexico site, on the other hand, provides additional validation of the two ETG methods in a region with considerably less complexity and less uncertainty in Sy.

[42] The results of both Figures 8 and 9 clearly show that the Fourier method performs significantly better than the White method, regardless of the size of the moving window and the site location (climate, soil type, depth-to-groundwater, etc.). At the New Mexico site, for example, comparisons of estimated and observed ETG values show higher \( r^2 \) values for the Fourier method (0.40, 0.38, and 0.33 at Belen, Bosque del Apache, and Sevilleta, respectively) as compared to the White method (0.17, 0.20, and 0.03; Figure 8). The Fourier method also results in a 15%–25% reduction in ETG RMSE (from 1.02, 1.09, and 0.85 mm to 0.77, 0.92, and 0.64 mm, respectively). In addition, we measured the performance of the Fourier and White methods by comparing the ETG estimates with observations using the Nash-Sutcliffe efficiency (NSE) coefficient. The NSE parameter indicates how well the observed and estimated ETG values fit the 1:1 line, and the values range from \(-\infty\) to 1, with higher values indicating better agreement [Legates and McCabe, 1999]. Although the NSE coefficients are negative in five of the six examples shown in Figure 8 (indicating limited predictive skill), the ETG estimates from the Fourier method show higher NSE values at all three research sites. For the Nebraska field site, comparisons of White-based estimates of ETG with observed ETG show \( r^2 \) values of 0.19 and 0.28 for daily (Figure 9a) and 3 day (Figure 9b) time scales, respectively. The Fourier method, on the other hand, yields higher \( r^2 \) values of 0.51 (Figure 9e) and 0.57 (Figure 9d), respectively, and also results in a ~25% reduction in error, as measured by ETG RMSE values (1.81 and 1.29 mm, as compared to 2.33 and 1.77 mm for the White method). In both cases, ETG estimates from the Fourier method show higher NSE values than the White method (Figure 9).

[43] It is evident from Figure 9 that the use of 5 and 7 day moving Fourier windows shows the best correspondence with observed ETG values (\( r^2 = 0.63 \), RMSE = 1.11 mm, and NSE = 0.36, Figure 9e; \( r^2 = 0.61 \), RMSE = 1.09 mm, and NSE = 0.33, Figure 9d). Czinkosky and Fitzjarrald [2004] noted in their study of diurnal streamflow fluctuations that the optimal window length is dependent on the regional climate, and they chose a 3 day running mean time scale for the eastern U.S. Our own results suggest that the optimal window length for estimating ETG in the Nebraska study domain is 5 to 7 days, which is consistent with the time scale of synoptic weather variability in this region. It should also be noted that when we applied 5 and 7 day running means to the 1 day Fourier ETG values, the overall comparison with observations (\( r^2 = 0.73 \), RMSE = 1.12 mm, and NSE = 0.31, 5 day; \( r^2 = 0.75 \), RMSE = 1.06 mm, and NSE = 0.34, 7 day) was comparable to that of the 5 and 7 day moving window results noted above. However, some of the short-term anomalies (relative to the observations) tended to be more exaggerated. Thus, we conclude that the use of a broader Fourier window appears to be slightly more effective at estimating 5 to 7 day ETG values, rather than applying an “after-the-fact” moving average to 1-day ETG estimates (at least for this particular field site). Also evident in Figure 9 are a number of large anomalies for the shorter time windows (e.g., 1 and 3 day White method and 1-day Fourier method). The number of outliers is greatly reduced, however, once a 3 day (or longer) window is applied to the Fourier method. Once again, this argues for the use of a multiday, moving sine function for obtaining improved estimates of ETG on short-term to seasonal time scales.

[44] In summary, the results of Figures 7–9 indicate that the Fourier method provides an improved alternative to the “standard” White method in estimating ETG from water table fluctuations. This conclusion holds true even if a multiday moving window is applied to both methods, with 5 to 7 days being determined as the optimal time scale for employing the Fourier method (at least for the Nebraska site). The advantage of a multiday moving window is that it allows one to sample over consecutive diurnal periods, while also overcoming other difficulties that are often associated with measurements of water table fluctuation (e.g., coarse sampling intervals or high-frequency noise). Similar to the White method, the Fourier technique is relatively easy to apply and requires only water table observations, estimates of specific yield, and a local “scaling factor” \( k \) which can be calculated from observed solar radiation data (or estimated from theoretical clear-sky values).

7. Summary and Conclusions

[45] Water table hydrographs are useful tools for assessing rates of evapotranspiration from groundwater (ETG), which often occurs in shallow-water table environments
Figure 8. Comparison of observed \( ET_G \) values at the three New Mexico field sites (from energy balance measurements; \( x \) axis) with both of the diurnal water table fluctuation methods (\( y \) axis). \( ET_G \) comparisons from the 3 day White method and 3 day Fourier method are represented by panels in the left and right columns, respectively. Results from the (a) and (b) Belen site, (c) and (d) Bosque del Apache site, and (e) and (f) Sevilleta site are shown in the top, middle, and bottom rows, respectively. Red squares (and summary statistics) represent the average \( ET_G \) across all observation wells, while the gray dots denote \( ET_G \) values from individual wells.
with phreatophytic plants. However, the widely known White method that is used for estimating daily $ET_G$ (from diurnal fluctuations in water table depth) is associated with numerous uncertainties. Some of these uncertainties relate to temporal resolution, as well as errors in estimating groundwater recovery, while others relate to the estimation of specific yield (especially in conditions with shallow, varying water table depth). In this study, we developed a new “Fourier method” for more accurately estimating $ET_G$ (based, in part, on previous work by Czikowsky and Fitzjarrald [2004]), and this method applies a repeating, 24 h sine function over a detrended, multiday moving window to measure diurnal fluctuations in water table depth. The detrending process is a necessary step, but it also removes a significant fraction of the desired quantity, namely the diurnal amplitude. Thus, a daily-varying scaling factor was introduced to adjust the diurnal amplitude back to its original magnitude and arrive at reasonable estimates.

Figure 9. Similar to Figure 8, but for the Nebraska field site. (a) and (b) show the daily and 3 day running mean White method, respectively, while (c), (d), (e), and (f) show the Fourier method using 1, 3, 5, and 7 day moving windows, respectively.
of both specific yield and ETG. This scaling factor, which averages around 1.9, is dependent on the shape and duration of the hourly transpiration curve and can be easily estimated from observations of incoming solar radiation or approximate clear-sky values.

The new Fourier method—along with the White method—were applied and tested at three riparian research sites along the Middle Rio Grande River in New Mexico (USA) and at a riparian wetland site in south-central Nebraska (USA). Independent measurements of ETG (from energy balance and/or eddy covariance techniques) were used to validate the ETG estimation methods and provide estimates of Sy. At the New Mexico study site, conventional depth-to-groundwater observations from the peak of the 2001 growing season were used to estimate ETG (utilizing data from three different research sites along the Rio Grande River). At the Nebraska study site, diurnal water table fluctuations were measured at three observation wells during the 2009 growing season. Importantly, due to the prevalence of standing water and saturated soil throughout most of the field site, the piezometers were not screened across the water table, but rather were used to measure hydraulic head at specific, shallow depths (i.e., to calculate an approximate “depth-to-water table” that is similar to previous studies, but that does not simply measure the height of the standing water).

Comparison of the White and Fourier methods with observed daily to 7 day running mean ETG values shows that the Fourier method performs considerably better than the White method, regardless of the size of the moving window that is applied. At the New Mexico research sites, for example, 3 day ETG estimates showed significant improvements when applying the Fourier method instead of the White method (e.g., roughly 15%-25% reductions in the RMSE ETG, as compared to observations). At the Nebraska field site, the error in estimates of daily ETG was reduced by roughly 25%, from RMSE = 2.33 mm and $r^2 = 0.19$ (White method) to RMSE = 1.81 mm and $r^2 = 0.51$ (Fourier method). Applying a 3 day moving average to the White method improved the results considerably ($r^2 = 0.28$ and RMSE = 1.77 mm), but still did not match the accuracy of using a moving 3 day Fourier window ($r^2 = 0.57$ and RMSE = 1.29 mm). Although it was found that a 5 to 7 day moving window provided the best results for the Nebraska site when using the Fourier method to estimate ETG, it would be worthwhile to test different window sizes when applying the Fourier method to other study sites and in different climatic regions.

As should be noted that groundwater measurements at the Nebraska field site were collected at 15 min intervals and averaged to hourly values (to match the barometric compensation interval), and this coarse temporal resolution may be contributing to the relatively poor results for the White method. Nevertheless, 30 min data collection intervals were used for the New Mexico site, and this location also showed significant improvements in ETG estimates when using the Fourier method. Thus, the temporal sampling interval employed at these sites is not likely to be the primary reason for the improvements observed from the use of the Fourier method. On the other hand, one could certainly argue that the Fourier method would be a much-preferred alternative to the White method in cases where the groundwater sampling interval is particularly coarse (e.g., 1-3 h).

The Fourier method presented in this study is a step toward increasing the accuracy of ETG estimates from diurnal water table fluctuations. Additional studies should be performed to test these methods and ideas in other regions and under different environmental conditions (soil type, vegetation, climate, etc.). The empirical nature of the present study also highlights the need for model investigations to more clearly elucidate the physical mechanisms for some of the observed behavior, such as the apparent dependency of Sy on water table depth (particularly in saturated environments). Finally, we note the continued need for coupled models, which provide an integrated assessment of the interactions among groundwater, surface water, and land-atmosphere fluxes of mass and energy.

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References
Cutrell, G. J. (2010), Seasonal energy and water balance of a Phragmites australis-dominated wetland in the republican river basin (southwestern Nebraska, USA), Master’s Thesis, University of Nebraska, Lincoln, NE.
Gerla, P. J. (1992), The relationship of water table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands, Wetlands, 12, 91–98.


