Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment

Steven P. Loheide II

Department of Geological and Environmental Sciences, Stanford University, Stanford, California, USA

James J. Butler Jr.

Kansas Geological Survey, University of Kansas, Lawrence, Kansas, USA

Steven M. Gorelick

Department of Geological and Environmental Sciences, Stanford University, Stanford, California, USA

Received 3 January 2005; accepted 12 April 2005; published 27 July 2005.

[1] Groundwater consumption by phreatophytes is a difficult-to-measure but important component of the water budget in many arid and semiarid environments. Over the past 70 years the consumptive use of groundwater by phreatophytes has been estimated using a method that analyzes diurnal trends in hydrographs from wells that are screened across the water table (White, 1932). The reliability of estimates obtained with this approach has never been rigorously evaluated using saturated-unsaturated flow simulation. We present such an evaluation for common flow geometries and a range of hydraulic properties. Results indicate that the major source of error in the White method is the uncertainty in the estimate of specific yield. Evapotranspirative consumption of groundwater will often be significantly overpredicted with the White method if the effects of drainage time and the depth to the water table on specific yield are ignored. We utilize the concept of readily available specific yield as the basis for estimation of the specific yield value appropriate for use with the White method. Guidelines are defined for estimating readily available specific yield based on sediment texture. Use of these guidelines with the White method should enable the evapotranspirative consumption of groundwater to be more accurately quantified.

Citation: Loheide, S. P., II, J. J. Butler Jr., and S. M. Gorelick (2005), Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment, *Water Resour. Res.*, *41*, W07030, doi:10.1029/2005WR003942.

1. Introduction

[2] Effective management of groundwater resources requires information about all components of the water budget. Evapotranspiration (ET) is often a significant component of the water budget in riparian environments. However, relatively little is known about the fraction of ET resulting from groundwater use by phreatophytes, plants such as cottonwood (*Populus* spp.), willow (*Salix* spp.), and salt cedar (*Tamarix* spp.) that grow in riparian areas and are capable of extracting water from the saturated zone [*Robinson*, 1958]. Since groundwater consumption by phreatophytes (henceforth ET_G) has become an issue of increasing importance in stream-aquifer systems undergoing groundwater development [*Woessner*, 2000; *Glennon*, 2002], there is a need to obtain better information about this component of the water budget.

[3] A number of methods are available for measuring ET, but few have proven effective in the relatively narrow riparian corridors where phreatophytes are most prevalent. Energy balance or eddy correlation methods are proven approaches for determining ET [*Shuttleworth*, 1993; *Dahm et al.*, 2002]. However, in addition to their complexity and the need for expensive micrometerological stations, their fetch requirements are too large for many riparian areas [*Goodrich et al.*, 2000]. Satellite-based methods for estimating ET, such as the surface energy balance algorithm for land (SEBAL) [*Bastiaanssen et al.*, 1998], have proved valuable on regional scales, but are difficult to apply to narrow riparian corridors where pixel mixing of bare ground, open water, riparian vegetation, etc, may introduce significant error. Measurement of pan evaporation could be a simple alternative for obtaining ET estimates, but the choice of an appropriate crop coefficient is problematic, as thermal and resistive properties of pans and plants can be quite different [*Allen et al.*, 1998]. Weighing lysimeters [*Aboukhaled et al.*, 1982; *Allen et al.*, 1991] provide a direct measure of ET, but are not practical for estimating transpiration from large riparian phreatophytes such as cottonwood and willow. Direct measurements of transpiration can be obtained from porometer [*Monteith et al.*, 1988; *McDermitt*, 1990] and sap-tracer [*Baker and Nieber*, 1989; *Smith and Allen*, 1996; *Schaeffer et al.*, 2000]

0043-1397/05/2005WR003942$09.00

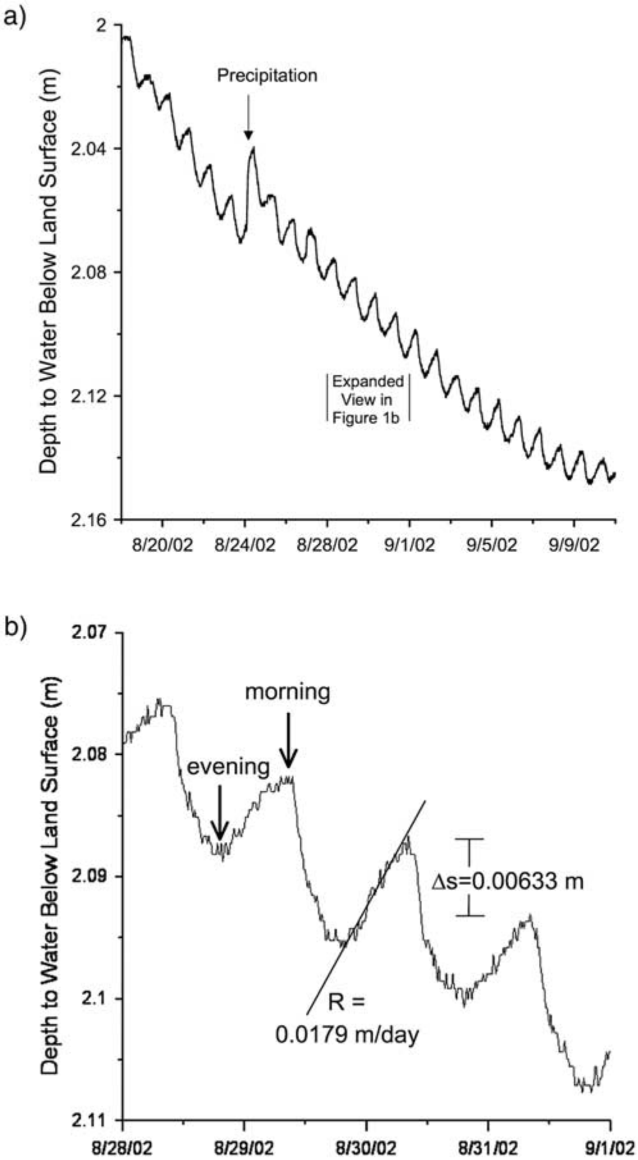

Figure 1. Depth to the water table recorded at a well in the riparian zone of the Arkansas River near Larned, Kansas. (a) Period from 18 August 2002 to 11 September 2002 (tickmarks at 12 A.M.). Note the impact of the 23 August 2002 precipitation event on the water table elevation, no other precipitation occurred during this period. (b) Expanded view of the 4 days from 28 August 2002 to 1 September 2002 (major and minor tickmarks at 12 A.M. and noon, respectively). When the White method is applied to the water level data recorded on 30 August 2002, the transpiration rate is 3.6 mm/d assuming the specific yield is 0.15.

approaches, but result in uncertain estimates when scaling from single leaves or plants to the riparian zone as a whole.

[4] Quantifying ET_G, the component of ET resulting from groundwater consumption by phreatophytes, has proven to be particularly difficult. Most previous work has involved isotopic tracers, water balance residuals, or water table fluctuations. Isotopic tracers [*Dawson and Ehleringer*, 1991; *Brunel et al.*, 1995; *Chimner and Cooper*, 2004] can be used to determine the fraction of transpired water contributed by groundwater when that water can be isotopically differentiated from other sources, but this technique must be used in combination with a method for determining transpiration in order to quantify the rate of groundwater consumption by plants. Phreatophyte consumption of groundwater has also been estimated using the water balance residual from field studies in which the other components of the water balance have been calculated from monitoring data [*Weeks and Sorey*, 1973]. However, the large uncertainty regarding subsurface inflows and outflows, among other aspects of the water budget, makes it difficult to have confidence that the water balance residual is primarily a function of plant water use.

[5] Methods based on water table fluctuations arise from the idea that if plants are using groundwater as a significant source of their water supply, wells screened across the water table should display diurnal fluctuations in water table elevation in response to the daily pattern of water use by phreatophytes. Analysis of those fluctuations should enable the consumption of groundwater by phreatophytes to be estimated [*White*, 1932; *Troxell*, 1936; *Gatewood et al.*, 1950; *Meyboom*, 1967; *Tromble*, 1977; *Gerla*, 1992; *Rosenberry and Winter*, 1997; *Lewis et al.*, 2002]. Such an approach has several advantageous characteristics: (1) It results in continuous daily estimates of ET_G, a quantity that is difficult to obtain with any other method. (2) The water table variations on which it is based are the integrated response to phreatophyte stresses that are highly heterogeneous and difficult to characterize. (3) The approach is generic in nature and not dependent on any particular mix of phreatophytes. (4) The approach can be readily implemented at a relatively low cost. The most commonly used method for analyzing well hydrographs to estimate groundwater consumption by phreatophytes is that of *White* [1932]. The further investigation of that method is the primary objective of the study described in this paper.

2. Diurnal Water Table Fluctuations and the White Method

[6] In areas where plants directly tap groundwater for their water supply, hydrographs from wells screened across the water table typically display diurnal fluctuations superimposed on some larger trend during the growing season. Figures 1a and 1b show diurnal water table fluctuations recorded in a well screened across the water table in an alluvial aquifer located within the riparian zone of the Arkansas River in central Kansas. The fluctuations, which are not produced by variations in pumping, barometric pressure, or temperature, begin in April at this site and continue through the first killing frost, and are limited to the zone of phreatophytic vegetation. Similar diurnal water table fluctuations have been reported by *White* [1932], *Troxell* [1936], *Tromble* [1977], *Farrington et al.* [1990], *Laczniak et al.* [1999], *Dulohery et al.* [2000], *Scott et al.* [2002], and *Dahm et al.* [2002], among others, and diurnal fluctuations have also been observed in tensiometer [*Remson and Randolph*, 1958] and streamflow data [*Bond et al.*, 2002].

[7] The diurnal water table fluctuations shown in Figures 1a and 1b are produced by diurnal fluctuations in plant water use. Plants transpire water during the daylight hours, so the water table declines through most

of that period if the plants are utilizing groundwater to any significant extent (Figure 1b). Similarly, during the night, when transpiration significantly diminishes or ceases, the water table will rebound because of net inflow. Twice per day, the plant water use is balanced by net inflow, producing the peak and trough in the water level record in the morning and evening, respectively. In the absence of frequent precipitation events, stream-stage changes, or cycling of nearby pumping wells, the diurnal pattern of water use by plants produces a readily observable pattern of fluctuations in the elevation of the water table (Figures 1a and 1b).

[8] As part of a study of arid wetlands in Escalante Valley of Utah, *White* [1932] recognized that the diurnal water table fluctuations were a product of plant water use and proposed a method to estimate that use from an analysis of well hydrographs. The White method uses the following expression (Figure 1b):

$$ET_G = S_Y(\Delta s/t + R) \qquad (1)$$

where ET_G is the rate of evapotranspirative consumption of groundwater averaged over a 24-hour period (L/T), S_Y is the specific yield (dimensionless), Δs is the daily change in storage (L), R is the net inflow (recovery) rate (L/T), and t is the time period of one day expressed in the appropriate time units (e.g., 86400 s when rate terms are expressed in m/s). We added the subscript G in ET_G to emphasize that in this work we are calculating the component of ET that is derived from the saturated zone (i.e., groundwater). In the hydrologic setting where the White method was developed, groundwater was essentially the only source of water for vegetation so ET and ET_G were equivalent. In other environments, however, vadose zone water may often be the dominant water source for vegetation, in which case ET_G will be a negligible component of ET.

[9] The change in storage term in equation (1) is calculated as the difference between the daily maximum on the day of interest and that same quantity on the following day. This difference can be either positive or negative depending on whether the overall trend is one of falling (positive) or rising (negative) water levels. The net inflow term is determined from the rate of change in the water table elevation resulting from all flows into or out of the near-well region during a period (night) when it is assumed that transpiration is negligible. In this work, the net inflow rate is calculated from the slope of the best fit line to the hydrograph between midnight and 4 A.M. *White* [1932] hypothesized that the source of the recovery is inflow from depth, while *Davis and De Wiest* [1966] imply that the recovery is caused by lateral inflow from outside the riparian zone. As our analysis will show, one of the most attractive features of the White method is that the particulars of the flow system need not be known since the net inflow rate can be quantified from the well records alone.

[10] The major assumptions of the White method include the following: (1) Diurnal water table fluctuations are a product of plant water use. (2) Groundwater consumption by plants is negligible between midnight and 4 A.M. (3) A constant rate of flow into the near-well region occurs over the entire day; that is, impacts of recharge events, cyclic pumping, etc. are assumed negligible. (4) A representative value of specific yield can be determined. As we will show, the fourth assumption has proven particularly problematic.

[11] The White method has been compared with other estimates of ET_G by *Gatewood et al.* [1950], *Tromble* [1977], and *Farrington et al.* [1990]. These studies found reasonable agreement between the methods except that *Gatewood et al.* [1950] determined that salt cedar transpiration was nonzero during the night, which violates the second assumption of the White method. *Troxell* [1936], *Nichols* [1993], and *Laczniak et al.* [1999] have criticized the White method for being overly simplistic, while *Gerla* [1992] and *Rosenberry and Winter* [1997] state that the method often overestimates ET_G because of the uncertainty regarding specific yield. A modification of the method that results in hourly estimates of ET_G was proposed by *Troxell* [1936], but has seen little use in practice. *Qashu* [1966] and *Bleby et al.* [1997] have used variants of the White method, but these methods do not appear to properly account for the net inflow term.

[12] Despite the reasonable agreement found in comparisons with other methods, the inherent beneficial characteristics described earlier, and the fact that it has been presented in several introductory textbooks [*Davis and De Wiest*, 1966; *Freeze and Cherry*, 1979; *Todd*, 1980], the White method has not been widely adopted. Thus there is a need for a further assessment of this potentially useful approach for estimation of ET_G. Although numerical simulation of saturated-unsaturated flow processes would be an expected element in any rigorous evaluation of the White method that apparently has not been done previously. In this paper, we describe and report the results of a simulation-based assessment of the White method.

3. Methods

3.1. Quantitative Evaluation of the White Method

[13] Numerical simulation was used here to investigate the diurnal water table oscillations that serve as the basis for the White method. In the simulations, we investigated five issues: (1) Does the geometry of the flow system affect the ET_G estimates? (2) Does monitoring well placement within the riparian zone affect estimates of ET_G? (3) Are the nighttime recovery rates representative of those occurring throughout the entire day? (4) Are water exchanges between the saturated and unsaturated zones consistent with the concept of time-invariant specific yield for all sediment textures? (5) To what degree does additional water extraction by roots in the vadose zone affect estimates of ET_G?

[14] To address the above issues, water level fluctuations driven by diurnal transpiration patterns were simulated with a saturated-unsaturated flow model. The variably saturated two-dimensional numerical model (VS2D [*Lappala et al.*, 1987; *Healy*, 1990; *Healy and Ronan*, 1996; *Hsieh et al.*, 2000]) was used to solve the transient Richards equation in the presence of distributed sinks representing phreatophytes in a vertical cross section. Vertical discretization in the vadose zone was $\leq$5 cm (finest near the water table), and time steps never exceeded 0.01 days. The position of the water table was determined as the internodal elevation where the pressure head is zero. Hydrographs were created from the simulation results by interpolation at 15-min intervals and were then analyzed using the White method. The resulting ET_G estimates were compared with the

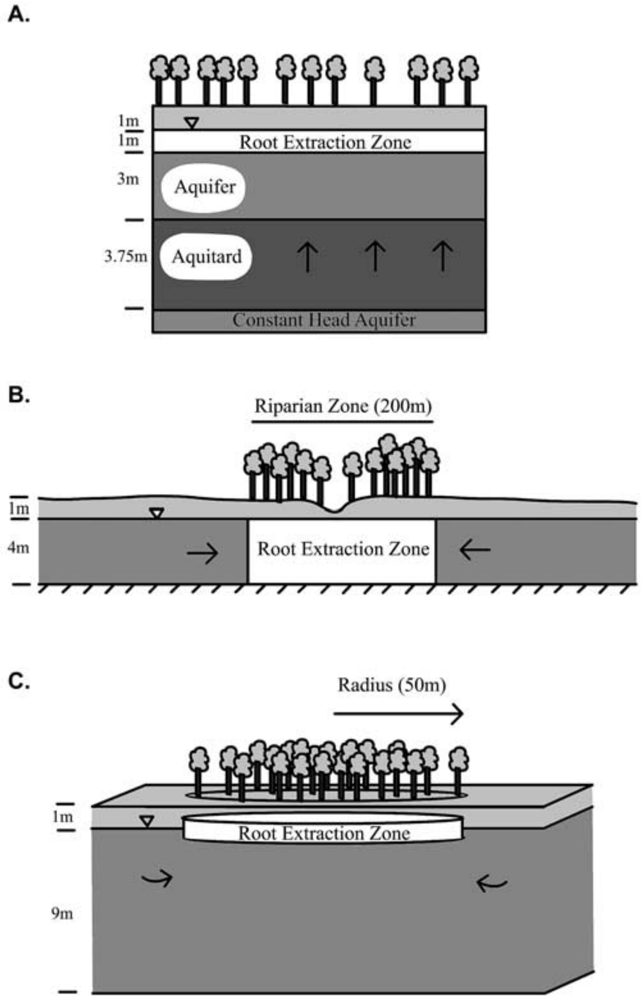

Figure 2. Schematic diagrams of the three conceptual models considered here: case A, groundwater supplied to phreatophytes through vertical flow from a deeper aquifer; case B, groundwater supplied to phreatophytes by lateral flow toward a riparian zone; and case C, groundwater supplied by radial and vertical flow to a circular patch of phreatophytes.

extraction rates used to simulate the diurnal fluctuations in the model.

[15] In the simulations, the *van Genuchten* [1980] model was used to represent water retention in the vadose zone:

$$\theta = \theta_R + \frac{\theta_S - \theta_R}{[1 + (\alpha|\psi|)^n]^m} \tag{2}$$

$$K(\theta) = K_S\left\{\frac{\theta - \theta_R}{\theta_S - \theta_R}\right\}^{1/2}\left\{1 - \left[\left(\frac{\theta - \theta_R}{\theta_S - \theta_R}\right)^{1/m}\right]^m\right\}^2 \tag{3}$$

where θ is the water content (dimensionless), θ_R is the residual water content (dimensionless), θ_S is the water content at saturation (dimensionless), ψ is the pressure head (L), K is the hydraulic conductivity (L/T), K_S is the saturated hydraulic conductivity (L/T), and α ($1/L$), n (dimensionless), and m (dimensionless) are empirical coefficients with m = 1 − 1/n. Parameter values used in the simulations are discussed in sections 3.2 and 3.3.

3.2. Dependence on Flow System Geometry

[16] A series of simulations was performed to assess the first three issues discussed in the previous section, the most important of which is whether the geometry of the flow system affects the ET_G estimate. In these simulations, we examined flow in the conceptual models illustrated in Figure 2. Although the aquifer properties and extraction rates are identical, the flow systems have different geometries and boundary conditions. Case A represents a lower aquifer supplying water to an upper aquifer tapped by phreatophytic vegetation, case B represents lateral inflow toward a riparian zone, and case C represents convergent radial and vertical flow to a circular cluster of phreatophytes. In all three cases, the aquifer properties are the same and are representative of clean, medium-grained sand. The hydraulic conductivity (K_S) is 50 m/d, specific storage (S_S) is 2×10^{-4} m^{-1}, θ_S is 0.43, θ_R is 0.045, α is 14.5 m^{-1}, and n is 2.68.

[17] Case A is similar to the conceptual model of *White* [1932] based on his studies in the Escalante Valley of Utah, and consists of a thin vadose zone (1-m thick), an upper unconfined aquifer (4-m thick, K_S = 50 m/d), an aquitard (3.75-m thick, K_S = 0.001 m/d), and a lower constant head aquifer. The head in the lower aquifer is set to 0.5 m below the land surface. An equilibrium profile with hydrostatic conditions below a water table located 1 m from the land surface (d = 1 m) defines the initial condition in the upper aquifer and aquitard. The pressure head in the unsaturated zone is initially set equal to the negative of the distance above the water table [*Hsieh et al.*, 2000]. As a result of these initial conditions, the head in the lower constant head aquifer is above the elevation of the water table. Thus that lower aquifer, which serves as an infinite source of groundwater, contributes water to the upper aquifer even before transpiration begins. No-flow (zero-gradient) conditions are defined at the land surface and the lateral boundaries. ET_G is simulated by extraction that occurs over a 1-m thick root zone that extends 1 m beneath the initial water table. The extraction is distributed uniformly throughout this zone at a rate totaling 0.002 m^3/m^2/d, or 2 mm/d water depth equivalent, for the period from 8 A.M. to 8 P.M. Transpiration rate is set to zero during the night (8 P.M. to 8 A.M.), so the average daily ET_G rate is 1 mm/d.

[18] The conceptual model in case B represents conditions encountered along the Arkansas River in central Kansas. The riparian zone is 200 m in width, the aquifer is 4-m thick with an impermeable base, and the model domain is sufficiently wide (2000 m) so that daily effects of transpiration will not be observed at the lateral boundaries. Riparian vegetation occupies a swath extending 100 m on either side of a centrally located dry streambed. During the daylight hours, water is extracted at a rate of 0.002 m^3/m^2/d from the root zone that underlies the riparian area from the initial water table to the base of the aquifer (Figure 2b). Initial conditions are as defined in case A for the unsaturated zone and unconfined aquifer. The observation well for which a simulated hydrograph is generated is located 45 m from the dry streambed.

[19] Case C is based on conditions encountered by *Meyboom* [1966, 1967] in south central Saskatchewan. In this region dominated by rolling topography, groundwater

Table 1. Summary of Mean Textural and Hydraulic Properties Utilized in This Study and Specific Yield Values Obtained From Various Sources[a]

									S_Y			
Sediment Texture	θ_S	θ_R	α	n	$K_{S,\ m/d}$	$S_{S,\ 1/m}$	Sand, %	Clay, %	$\theta_S - \theta_R$	Depth Compensated	From *Johnson* [1967]	Readily Available
Sand	0.43	0.045	14.5	2.68	7.1	0.0002	92.7	2.9	0.385	0.38	0.34	0.32
Loamy sand	0.41	0.057	12.4	2.28	3.5	0.0003	80.9	6.4	0.353	0.34	0.26	0.26
Sandy loam	0.41	0.065	7.5	1.89	1.1	0.0004	63.4	11.1	0.345	0.29	0.19	0.17
Loam	0.43	0.078	3.6	1.56	0.25	0.0005	40.0	19.7	0.352	0.19	0.095	0.075
Silt	0.46	0.034	1.6	1.37	0.060	0.0006	5.8	9.5	0.426	0.11	0.06	0.026
Silt loam	0.45	0.067	2.0	1.41	0.11	0.0006	16.6	18.5	0.383	0.12	0.07	0.037
Sandy clay loam	0.39	0.100	5.9	1.48	0.31	0.0008	54.3	27.4	0.290	0.17	0.05	0.072
Clay loam	0.41	0.095	1.9	1.31	0.062	0.0008	29.8	32.6	0.315	0.078	0.038	0.021
Silty clay loam	0.43	0.089	1.0	1.23	0.017	0.0007	7.6	33.2	0.341	0.041	0.029	0.012
Sandy clay	0.38	0.100	2.7	1.23	0.029	0.0010	47.5	41.0	0.280	0.068	0.025	0.015
Coarse sand	0.43	0.045	14.5	2.68	200	0.0002	-	-	0.385	0.38	-	0.38
Medium sand	0.43	0.045	14.5	2.68	50	0.0002	-	-	0.385	0.38	-	0.36
Fine sand	0.43	0.045	14.5	2.68	12.4	0.0002	-	-	0.385	0.38	-	0.33
Very fine sand	0.43	0.045	14.5	2.68	3.1	0.0002	-	-	0.385	0.38	-	0.31

[a]Depth-compensated specific yield, as well as the readily available specific yield obtained from equation (1), is for a water table depth of 1 m. Note that differences in packing, sorting, grain shape, and other factors can result in a significant range of values for any parameter within a given textural class, but only mean values were used in this study.

flows to low-lying areas where it may or may not discharge onto the surface. Groundwater is consumed in the low-lying area by patches of phreatophytic vegetation such as the willow rings described by *Meyboom* [1966]. In case C, we consider convergent flow toward a circular cluster (50-m radius) of phreatophytic vegetation that extracts water at 0.002 $m^3/m^2/d$. The roots extract the water uniformly between the depths of 1 and 2 m below the ground surface. Initial conditions are as defined in case A for the unsaturated zone and unconfined aquifer. The observation well for which a simulated hydrograph is generated is located 12.5 m from the center of the circular cluster of phreatophytic vegetation.

3.3. Dependence on Sediment Texture

[20] A second set of simulations was performed to assess whether the concept of time-invariant specific yield is appropriate for all sediment types under phreatophyte stresses. These simulations used hydraulic properties that span a range of sediment textures. *Carsel and Parrish* [1988] present descriptive statistics of unsaturated flow parameters based on thousands of samples that have been divided into textural types. The mean of each of these parameters for a particular textural class was used in the simulation for that texture (Table 1). Table 1 also shows typical values of specific yield given by *Johnson* [1967] for each of these textural classes. The textural types found in the soil classification triangle (sand, sandy loam, sandy clay loam, sandy clay, silt, silt loam, silty clay loam, clay loam, loamy sand and loam) and four additional sediment types (very fine sand, fine sand, medium sand, and coarse sand) were used here. The unsaturated hydraulic properties for these additional sand types were the same as those given for sand by *Carsel and Parrish* [1988], except that values of K_S were estimated using the Kozeny-Carman equation [*Bear*, 1972]. A value for the specific storage coefficient was estimated for each sediment class based on values given by *Anderson and Woessner* [1992]. Clay and silty clay textures were not considered because simulations suggested that it is not possible for sediments of these textures to provide water to the roots at the rates of interest in our study. In this suite of simulations, the model configuration is the same as case B but the aquifer and vadose zone properties vary between simulations.

3.4. Dependence on Water Uptake by Roots in the Vadose Zone

[21] A final set of simulations was used to investigate the effect of water uptake by roots in the vadose zone. In particular, we were interested in how water extraction in the vadose zone affects water table fluctuations and resulting ET_G estimates obtained using the White method. To investigate this issue, we redistributed the water extraction used in the case B simulations to form three new extraction scenarios. First, we assumed water was extracted at a uniform rate over the aquifer (4-m thick) and vadose zone (1-m thick), such that 1 mm was extracted from the saturated zone and 0.25 mm was extracted from the vadose zone each day. Next, we doubled the rate in the vadose zone, such that 0.50 mm was extracted from the vadose zone, while maintaining the 1 mm extraction from the saturated zone. We then considered a case of 0.50-mm extraction from the vadose zone and zero extraction from the saturated zone in order to isolate the impact of vadose water extraction. Each of these extraction configurations was simulated for medium-sand, loam, and silt sediment textures.

4. Results

4.1. Dependence on Flow System Geometry

[22] The simulated water table hydrographs for cases A, B, and C are shown in Figure 3. The general character, most importantly the diurnal oscillations, of the simulation results is comparable to that of actual groundwater hydrographs (Figures 1a and 1b). Although the simulated hydrographs capture the salient features of the diurnal fluctuations, they

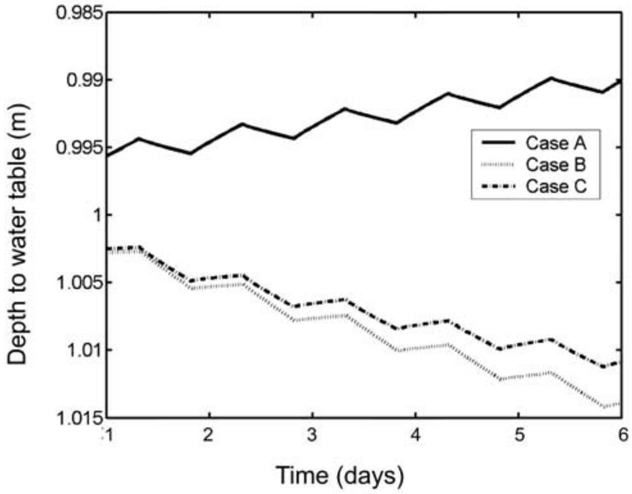

Figure 3. Simulated water table fluctuations for cases A, B, and C.

have a sharper transition between the falling (day) and rising (night) portions of the record. This sharper transition is due to our simplified representation of the onset and termination of transpiration as step functions, when, in reality, the transpiration function is smoother in time.

[23] The most important similarity among the simulated hydrographs is, as stated above, the pronounced fluctuations in the water table; the water table drops during the day because of transpiration, but rises during the night as a result of inflow. The most striking difference among the simulated hydrographs is that there is a net rise in the water table in case A, but a net drop in cases B and C. The inflow rate in case A is greater than the daily rate of ET_G because vertical flow is forced upward through the aquitard as a result of the higher head in the lower constant head aquifer. Such a situation would occur when a larger-scale flow system transmits water toward the riparian zone at rates greater than the transpiration demand. This phenomenon has been observed in field data [e.g., *White*, 1932; *Troxell*, 1936].

[24] Several second-order differences are apparent in the hydrographs for cases B and C. In both cases, the hydraulic gradient is induced solely by the transpiration beneath the zone of phreatophytic vegetation. As transpiration cycles on and off over the course of several days, the hydraulic gradient toward that zone increases. Correspondingly, the recovery rate increases as indicated by the subtle steepening of slopes between midnight and 4 A.M. over successive nights (Figure 3). The water table in case B drops slightly more during the day and recovers slightly less during the night in comparison to case C. This is a result of the monitoring well in case C being closer to the edge of the phreatophyte zone, and therefore nearer the source of the inflowing groundwater.

[25] For all three cases, reasonable estimates of daily ET_G rates were obtained when the White method was applied to the simulated hydrographs of Figure 3 using a standard definition of specific yield calculated as $S_Y = \theta_S - \theta_R$. The average estimated daily ET_G rates for cases A, B, and C, respectively, were 1.19 ± 0.02, 1.08 ± 0.01, and 0.95 ± 0.01 mm/d, for a simulated ET_G value of 1.0 mm/d. The error estimates are the standard deviation about the mean of the estimates from the five days displayed in Figure 3. Changes in the net inflow with time are the predominant cause of the variability, which decreases as the system approaches a dynamic equilibrium. Although none of these cases predict the ET_G value used in the simulation exactly, they are all within 20% of that value with an average absolute error of less than 11%. Note that the first day is neither displayed in Figure 3 nor included in the average because there is no inflow preceding the onset of transpiration and there is continually increasing inflow throughout that day. This highly transient initial behavior is not representative of field situations and is therefore not included in our analysis.

[26] Simulated water table fluctuations and resulting estimates of ET_G varied across the phreatophyte zone. In general, the diurnal fluctuations were greatest in wells at the center of the phreatophyte zone, dampened slightly in wells near the border, and eventually disappeared in wells at some distance outside of the zone. In order to obtain accurate estimates of ET_G with the White method, wells must be located at a sufficient distance from the edge of the phreatophyte zone to minimize edge effects. For example, consider the effect of well position on estimates of ET_G for case C. Using simulated hydrographs for wells located at 47.5 m, 37.5 m, 27.5 m, 17.5 m, and 7.5 m from the edge of the circular zone of phreatophytes, estimated average ET_G rates were 0.95 mm/d, 0.95 mm/d, 0.95 mm/d, 0.95 mm/d, and 0.88 mm/d, respectively. For this example, boundary effects cause significant (>10%) underestimation of ET_G at distances less than 7.5 m from the edge of the zone of phreatophytic vegetation.

4.2. Dependence on Sediment Texture

[27] Simulated water table fluctuations for select textural types are shown in Figure 4. Although only the textural and hydraulic properties of the media are varied between simulations, there are considerable differences in the hydrographs. Most significantly, the finer-grained textural types produce much larger water table fluctuations and greater recovery rates.

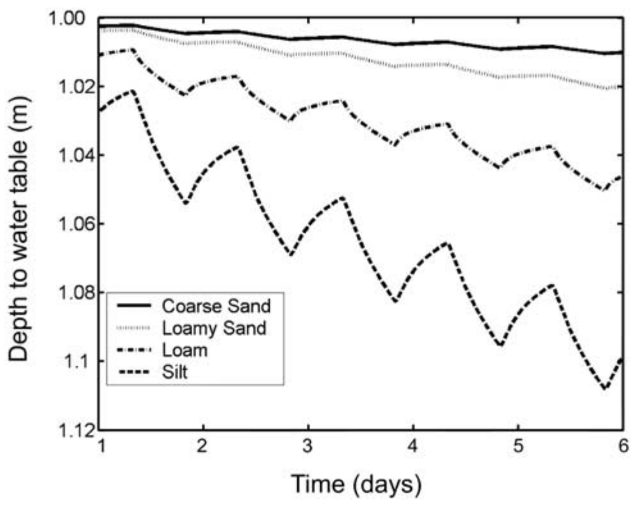

Figure 4. Simulated water table fluctuations for coarse sand, loamy sand, loam, and silt textures (geometry of case B).

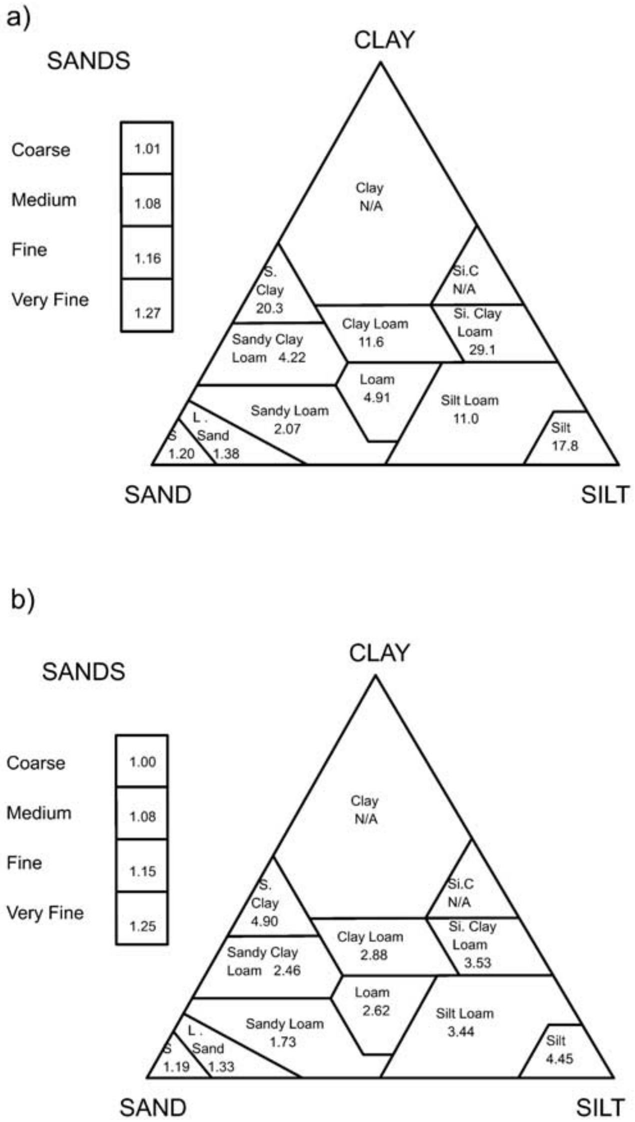

Figure 5. Textural classification triangle with estimated ET_G values (mm/d) for each texture obtained by applying the *White* [1932] method to the simulated water table fluctuations using (a) $S_Y = \theta_S - \theta_R$ and (b) the depth-compensated specific yield defined by equation (5). The actual value of ET_G should be 1 mm/d in all cases.

[28] Initially in this work, the White method was used to predict ET_G from the simulated hydrographs using the standard definition of specific yield ($S_Y = \theta_S - \theta_R$). This resulted in estimates of ET_G ranging from 1.01 to 29.1 mm/d compared to the actual value of 1.0 mm/d. Figure 5a shows these ET_G estimates as a function of textural type; as the percentage of sand decreases and the percentage of clay increases, the overestimation of ET_G increases.

4.3. Dependence on Water Uptake by Roots in the Vadose Zone

[29] The simulations discussed in the two previous sections focused on water uptake from the saturated zone, thereby ignoring the role of uptake by roots in the vadose zone. Figure 6 depicts computed water table fluctuations from a series of simulations for a loam sediment texture in which different proportions of uptake by roots in the vadose zone were considered. Not surprisingly, adding extraction from the vadose zone to the base case of saturated zone extraction causes increases in the rate of decline of the water table. After nearly 6 days of transpiration (t = 5.83 days), the water table has dropped 5.02 cm in the base case, 5.58 cm when 0.25 mm/d of vadose zone extraction is added to the base case, 6.12 cm when 0.50 mm/d of vadose zone extraction is added to the base case, and 1.13 cm when only 0.50 mm/d of vadose zone extraction is considered. For the loam sediment texture, the drop in the water table increases by 11% and 22%, and ET_G estimates increase by 6% and 11% when vadose zone extraction is added to the base case in the amounts of 0.25 mm/d and 0.50 mm/d (25% and 50% increases in total extraction), respectively. When only vadose zone extraction is considered, the water table drops continuously. Since diurnal fluctuations with alternating periods of rising and falling water table are not observed, the White method cannot be applied in its current form. Table 2 summarizes the results for the three sediment textures considered in the simulations of vadose zone extraction.

5. Discussion

[30] Both the overestimates of ET_G (Figure 5a) and the differences in the simulated hydrographs for the various textural types (Figure 4) can be explained by the transient behavior of specific yield. Specific yield is the volume of water released from storage per unit land surface area per unit drop in the water table [*Freeze and Cherry*, 1979]. However, this definition makes no mention of how quickly that water is released. For example, a sediment allowed to drain will release more water in a day than it will in an hour. In addition, under conditions of a shallow water table, a thicker vadose zone will release more water than a thinner

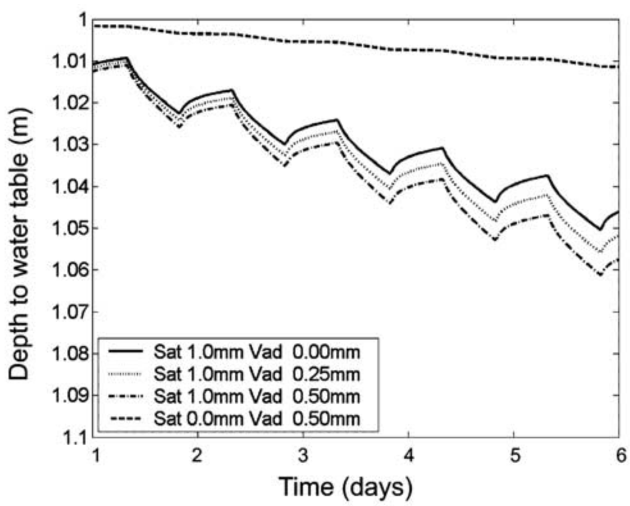

Figure 6. Simulated water table fluctuations for a sediment with a loam texture and the geometry of case B. The five cases shown simulate extraction of water by roots in the saturated and vadose zones, respectively, in the following quantities: 1.0 mm/0.00 mm, 1.0 mm/0.25 mm, 1.0 mm/0.50 mm, and 0.0 mm/0.50 mm.

Table 2. Water Extraction Patterns and Results From Simulations Considering Extraction From the Saturated Zone, the Vadose Zone, or Both[a]

Water Extraction			Ratio of ET_G to Base Case ET_G			
Groundwater, mm/d	Vadose, mm/d	Total, mm/d	Expected Ratio	Medium Sand	Loam	Silt
1.00	0.00	1.00	1.00	1.00	1.00	1.00
1.00	0.25	1.25	1.00	1.07	1.06	1.05
1.00	0.50	1.50	1.00	1.14	1.11	1.09
0.00	0.50	0.50	N/A	N/A	N/A	N/A
5.00	0.00	5.00	5.00	4.97	5.34	5.67

[a]The base case ET_G is the estimate from the first case listed in Table 2 (extraction only from below the water table). The ratio of the estimated ET_G to that found for the base case is shown for medium-sand, loam, and silt textures. When only vadose zone extraction was considered, the water table dropped continuously, and the White method was not applicable (N/A).

vadose zone. A more complete definition of specific yield, assuming there are no sources or sinks of water in the vadose zone, is the area between the initial and final water content profiles divided by the water table change [*Bear*, 1972; *Nachabe*, 2002]:

$$S_Y = \frac{1}{\Delta h}\int_0^{z'} \theta(z,t_1)\mathrm{d}z - \frac{1}{\Delta h}\int_0^{z'} \theta(z,t_2)\mathrm{d}z \tag{4}$$

where Δh is the change in water table elevation between times t_1 and t_2 (L), z is depth below land surface, $\theta(z, t)$ is the moisture content at time t and depth z (dimensionless), and z' is an arbitrary depth that is below the water table at all times (L). This alternative definition demonstrates that specific yield is not only a property of the porous media, but is also dependent on the depth to the water table, the duration of drainage, and the antecedent moisture conditions. The dependence of specific yield on these additional factors will be briefly discussed here; additional discussion is given by *Healy and Cook* [2002].

[31] We first consider the impact of the depth to the water table. Specific yield calculated as $S_Y = \theta_S - \theta_R$ is a simplification that is only valid for homogeneous sediments when the water table is sufficiently deep such that $\theta_{Surface} = \theta_R$, and when sufficient drainage time is allowed to maintain a moisture content profile with a constant shape. Even when an equilibrium moisture content profile is maintained, $S_Y \neq \theta_S - \theta_R$ if the water table is near the surface. Under these conditions, the specific yield can be defined as $S_Y = \theta_S - \theta_{Surface}$ [*Duke*, 1972; *Nachabe*, 2002], a quantity that we will refer to as the depth-compensated specific yield ($S_Y^{d\text{-}comp}$). Assuming an equilibrium profile and the van Genuchten water retention curves in equation (2), we obtain the following expression for the depth-compensated specific yield as a function of depth (d) to the water table in a manner analogous to that used by *Duke* [1972]:

$$S_Y^{d-comp}(d) = \theta_S - \left[\theta_R + \frac{\theta_S - \theta_R}{[1+(\alpha|d|)^n]^m}\right] \tag{5}$$

The depth-compensated specific yield defined by (5) is plotted as a function of depth to the water table for several sediment textures in Figure 7.

[32] The *White* [1932] method was used with the depth-compensated specific yield (equation (5)) to obtain ET_G estimates for the textural types of Figure 5a. In this case, the range of estimates of ET_G was much smaller (1.00 to 4.90 mm/d, Figure 5b). For the various types of sands, the estimated ET_G was always within 25% of the input value (1.0 mm/d). Thus the White method appears reliable for clean sands. However, for sediments with more than 10% fines, ET_G is still significantly overestimated.

[33] We next consider the impact of delayed drainage from the vadose zone on specific yield estimates. Use of a constant value for specific yield is strictly valid only when the moisture content profile maintains a time-invariant shape as it moves up or down through homogeneous media in response to changes in the elevation of the water table. The time-invariant shape of the profile is maintained when the velocity (v) of the change in elevation of the water table meets the following condition [*Raats and Gardner*, 1974; *Hinz*, 1998]:

$$\mathrm{v} > -\frac{dK(\theta)}{d\theta}\bigg|_{\theta_{Surface}} \tag{6}$$

If this condition is not met, the specific yield is a function of the duration of drainage.

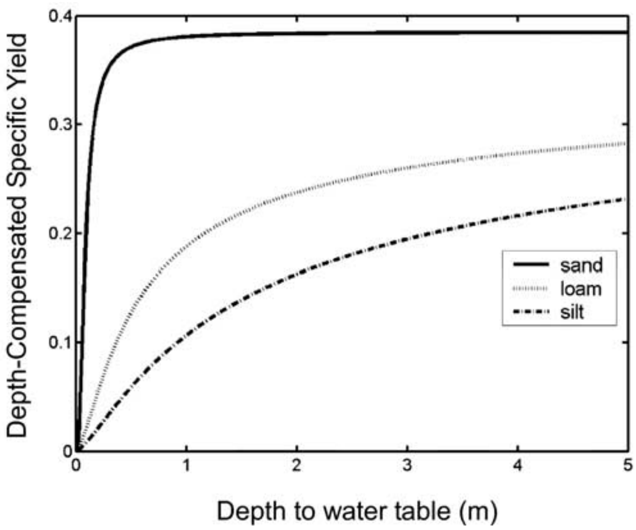

Figure 7. Depth-compensated specific yield as a function of depth to the water table for sand, loam, and silt textures. Specific yield calculated as $\theta_S - \theta_R$ is 0.385, 0.352, and 0.426 for the sand, loam, and silt textures, respectively.

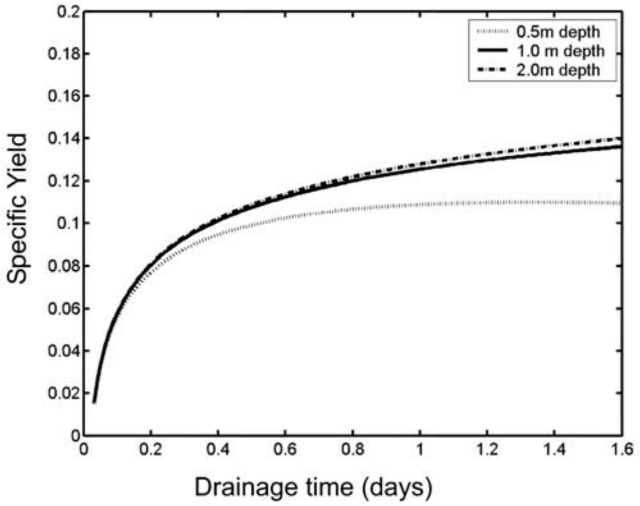

Figure 8. Specific yield as a function of duration of drainage for a loam sediment texture. Curves were generated using equations (8a) and (8b) with the following parameters: $h_a = 0.14$ m, $\lambda = 0.26$, $\theta_S = 0.41$, $\theta_R = 0.02$, $K_S = 0.0168$ m/s, $\Delta h = 0.025$ m, and d = [0.5 m, 1.0 m, 2.0 m].

[34] *Zacharias and Bohne* [1997] and *Nachabe* [2002] provide methods for determining specific yield given the depth to the water table and the duration of drainage after a step change in the elevation of the water table. Although transpiration causes the water table to rise and fall continuously rather than as a step function, the results of *Nachabe* [2002] can provide insight into the dependence of specific yield on the duration of drainage. *Nachabe* [2002] used the *Brooks and Corey* [1964] model for water retention:

$$\theta(\psi) = \theta_R + (\theta_S - \theta_R)\left(\frac{h_a}{\psi}\right)^{\lambda} \tag{7}$$

where h_a is the soil air entry value (L), and λ is the pore size distribution index (dimensionless). Given that model, an approximate closed-form solution for specific yield can be obtained [*Nachabe*, 2002]:

$$S_Y(t) = \frac{K_S}{\Delta h}\left[\left(\frac{\theta_B - \theta_R}{\theta_S - \theta_R}\right)^{\frac{(2+3\lambda)}{\lambda}} - \left(\frac{\theta_{Surface} - \theta_R}{\theta_S - \theta_R}\right)^{\frac{(2+3\lambda)}{\lambda}}\right] t + (\theta_S - \theta_R)\left(1 - \frac{\theta_B - \theta_R}{\theta_S - \theta_R}\right) \tag{8a}$$

where θ_B (dimensionless) is a parameter of the water content profile defined by *Nachabe* [2002] as

$$\theta_B = \theta_R + (\theta_S - \theta_R)\left(\frac{\Delta h(\theta_S - \theta_R)}{\left(\frac{(2+3\lambda)}{\lambda}\right)K_S}\right)^{\frac{1}{\left(\left(\frac{(2+3\lambda)}{\lambda}\right)-1\right)}}\left(t^{\frac{1}{\left(1-\left(\frac{(2+3\lambda)}{\lambda}\right)\right)}}\right) \tag{8b}$$

Equation (8) indicates that the specific yield will be a function of drainage time, depth to the water table, and the properties of the porous media. Specific yield is a function of the depth to the water table in equation (8) because $\theta_{Surface}$ decreases with increasing depth. The increase in specific yield with increasing duration of drainage is shown in Figure 8 for a hypothetical loam sediment texture. A point of particular importance illustrated in Figure 8 is that the specific yield is essentially independent of depth to the water table when the water table is deeper than 1 m for durations of drainage less than half a day.

[35] As discussed above, specific yield is not only a property of the porous media, but is also a function of the depth to the water table, the duration of drainage, and the antecedent moisture conditions. In this work, we use the term "readily available specific yield" introduced by *Meyboom* [1967] to denote the amount of water that is released from the vadose zone during the time frame (<12 hours) of the diurnal fluctuations. The readily available specific yield can be significantly less than that predicted by $S_Y = \theta_S - \theta_R$ in finer-grained sediments because the moisture profile may be truncated at the land surface and the finer-grained materials release water slowly from the vadose zone. It is this significantly smaller readily available specific yield that produces the larger water table fluctuations, larger daily changes in storage, and greater recovery rates observed in the simulated hydrographs for the finer-grained textural types (Figure 4).

[36] Figure 9 shows a series of simulated water content profiles for a silt sediment texture. Although initially at equilibrium conditions, the water content profile changes shape during the course of seven days of transpiration cycling on and off. The water table moves downward during this period, but the moisture content profile cannot shift downward as quickly. Thus, as predicted by *Raats and Gardner* [1974], the profile shape changes because water is not released quickly enough to maintain a constant shape. The result is that the readily available specific yield is smaller than the depth-compensated specific yield, causing the White method to overpredict ET_G when the depth-compensated specific yield is used.

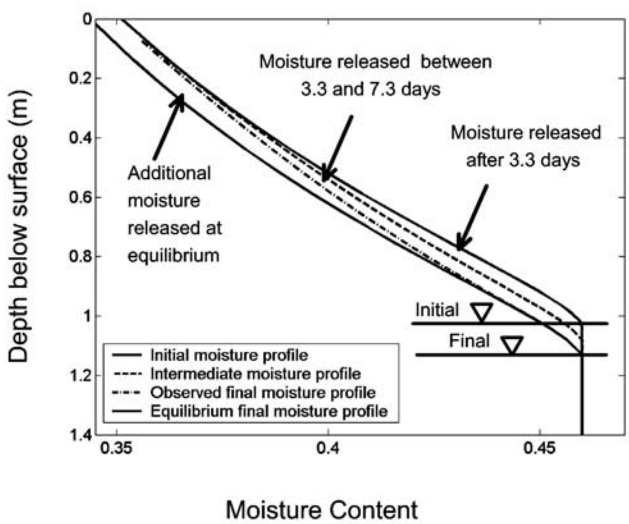

Figure 9. Simulated transient and equilibrium water content profiles for a media with a silt texture and the geometry of case B. Only a fraction of the water that would be released after an infinite duration of drainage is actually released over the course of 3.3 and 7.3 days (inverted triangles mark the position of the water table).

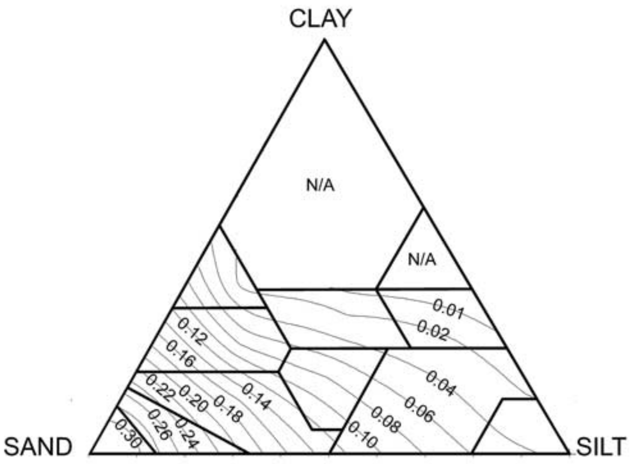

Figure 10. Trilinear diagram for estimating readily available specific yield based on sediment texture when the depth to water table is greater than 1 m. Contours were created using the data presented in the last column of Table 1.

[37] *Meyboom* [1967] suggested that the value of the readily available specific yield should be 50% of the standard definition for specific yield. However, our simulations indicate that this suggestion is not appropriate for all sediment types. From the suite of water table hydrographs simulated for a wide range of sediment textures, we computed the value of the readily available specific yield that is appropriate for each texture. This was done by using the simulated hydrographs and the actual value of ET_G in equation (1), and solving for the readily available specific yield. These computed values are given in the last column of Table 1 for each textural type, and are plotted with contours of equal specific yield on the trilinear textural classification graph in Figure 10. If little is known about a site except the sediment texture, these values for the readily available specific yield can be used to estimate ET_G from water table hydrographs. However, these values are based on average properties for a given textural type and may not be representative of sediment properties at all sites. In addition, these values are based on the assumptions that the water table is deeper than 1 m, and that the readily available specific yield is essentially independent of the magnitude of the diurnal fluctuations and antecedent moisture conditions. The dependence on the magnitude of the diurnal fluctuation was assessed in additional simulations in which ET_G was increased by a factor of 5. This large increase in ET_G only resulted in a 0.6% increase, 6.8% decrease, and 13.4% decrease in the estimate of readily available specific yield for medium sand, loam, and silt textures, respectively, demonstrating that the specific yield estimate was only weakly dependent on the magnitude of the diurnal fluctuations (Table 2). ET_G estimates do not appear to be strongly influenced by antecedent moisture conditions. As shown in Figure 9 for a silt texture, the moisture profiles at the start of transpiration on days 3 and 7 are different. However, the ET_G estimates only differ by 3.7% (only the silty clay loam texture resulted in a larger discrepancy between the ET_G estimates for days 3 and 7).

[38] One of the most attractive features of the White method is that it quantifies only that component of ET that is intimately tied to the saturated zone, a quantity we refer to as ET_G. As shown here, extraction of water by roots in the vadose zone will have some impact on estimates of ET_G. Simulation results revealed that the White method estimates of ET_G included not only the saturated zone extraction, but also 28%, 23%, and 19% of the vadose zone extraction for the medium-sand, loam, and silt textures, respectively. This indicates that direct extractions from the saturated zone are not solely responsible for the water table fluctuations. Thus the ET_G estimates from the White method are not just quantifying water extracted directly from the saturated zone. More accurately, these estimates are the summation of root extraction of water via the following four mechanisms: (1) direct extraction of water from below the water table, (2) direct extraction of water from the capillary fringe, (3) interception of water that would have otherwise drained to the saturated zone as a result of a dropping water table, and (4) indirect extraction from the saturated zone by pulling water upward to supply roots in the vadose zone a short distance above the capillary fringe. Water removed from storage in the vadose zone at a distance from the top of the capillary fringe does not appear to be incorporated in the estimates of ET_G (Figure 6). The ET_G estimate obtained with the White method is therefore useful for management of groundwater resources because it quantifies the transpiration component of discharge extracted both directly and indirectly from the saturated zone. It is imperative that this concept of ET_G be applied in groundwater resource management instead of the more routinely measured quantity, ET, because of the parallel definitions of recharge and ET_G. Both recharge and ET_G quantify fluxes across the water table, whereas ET and infiltration quantify fluxes across the land surface. This distinction allows transpirative ecosystem needs to be more fully characterized, as called for by *Gleick* [2000]. Currently, the White method is the best available means of measuring the transpirative discharge from the saturated zone. As discussed earlier, standard methods for estimating evapotranspiration will give total ET, not just that portion intimately tied to the saturated zone as estimated with the White method.

[39] The single-phase flow model considered here does not account for hysteresis or air entrapment, both of which can cause the specific yield to be different for rising and falling water tables [*Dunn and Silliman*, 2003; *Nachabe et al.*, 2004]. If the rising and falling values of specific yield (S_Y^{rising} and S_Y^{falling}, respectively) are known, equation (1) could be modified as follows:

$$ET_G = \frac{S_Y^{\text{rising}}\left(t^{\text{falling}}R\right) + S_Y^{\text{falling}}(\text{Max} - \text{Min})}{t^{\text{rising}} + t^{\text{falling}}} \tag{9}$$

where t^{falling} is the time during a specific day when the water table is falling (T), t^{rising} is the time during a specific day when the water table is rising (T), Max is the morning maximum water table elevation (L), and Min is the evening minimum water table elevation (L). This proposed modification is not considered in more detail here because measurements of S_Y^{rising} and S_Y^{falling} are rare.

6. Estimation of Readily Available Specific Yield

[40] A variety of methods can be used to estimate the readily available specific yield from field and laboratory

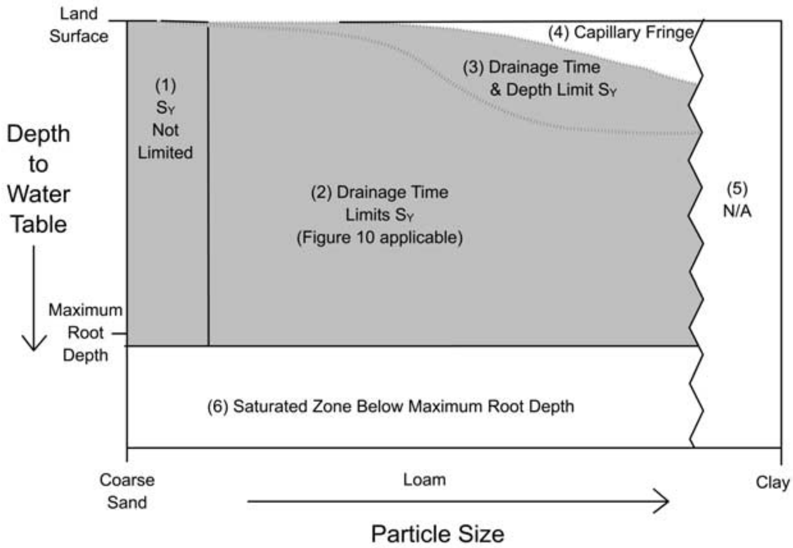

Figure 11. Guidelines for determining the readily available specific yield estimate to use in the White method. Descriptions of the processes affecting each region are noted below, and appropriate methods for determining the readily available specific yield are given in parentheses for the regions (shaded in gray) where the White method is valid: 1, region where the readily available S_Y is not limited by slow drainage or shallow depth to water (traditional estimates of S_Y are valid because the readily available specific yield is equal to $\theta_S - \theta_R$); 2, region where duration of drainage limits S_Y (Figure 10 valid because depth to water is not an important factor); 3, region where both slow drainage and shallow depth to water limit S_Y (equation (8)), numerical modeling, or the ratio of precipitation to water table rise are acceptable approaches); 4, region where the entire soil column is saturated (concept of S_Y not valid); 5, region of clay and silty textures (White method is prone to large errors because the readily available specific yield is near zero); and 6, region below the maximum root zone (diurnal fluctuations will be muted or nonexistent).

data [*Healy and Cook*, 2002]; Figure 11 provides guidelines for which method is most appropriate at any particular site. In general, if the depth to water is greater than 1 m, Figure 10 should provide reasonable estimates of specific yield for use with the White method in many settings. Additional approaches are summarized in the following paragraphs.

[41] If the water retention characteristics of the sediment are known, the method of *Nachabe* [2002] can be used to calculate the readily available specific yield. However, the time (duration of drainage) to use in that calculation is uncertain. For the loam in Figure 8, the readily available specific yield is 0.075 after 4 hours of drainage, which is the same value as obtained by solving for the readily available specific yield using equation (1) as described earlier (Table 1). This duration of drainage is significantly less than the simulated 12-hour period of transpiration because the water table falls continuously through the period of transpiration, whereas the method of *Nachabe* [2002] describes the case of an instantaneous drop in the water table. Thus sediments near the water table maximum drain for a full 12 hours, while sediments slightly above the water table minimum will only drain for a few minutes. The 4-hour period should be considered as an effective drainage time for sediments with a loam texture, but is assumed to be a representative timescale for all textures.

[42] For sediments in which neither the depth to the water table nor slow drainage are important considerations (e.g., clean sands), the readily available specific yield is essentially equivalent to traditional estimates of specific yield ($\theta_S - \theta_R$). Under these conditions, laboratory drainage experiments can be used to determine the readily available specific yield by saturating a sediment sample and then allowing it to drain for at least 4 hours. Short-term pumping tests can also be performed to obtain an estimate of specific yield. However, more than one pumping test should be done at each site in order to partially compensate for the impact of media heterogeneity on specific yield estimates obtained from pumping tests [*Butler*, 2005].

[43] Numerical modeling also provides a means for determining the readily available specific yield. In this work, we used VS2D to simulate an approximately linear decline in water table elevation over a 12-hour period. The depth of water drained can be calculated by integrating the area between the initial and final soil moisture profiles. Dividing this quantity by the change in water table elevation results in an estimate of the readily available specific yield (equation (4)). For a 1.2-cm water table decline, a readily available specific yield of 0.073 was found for a loam soil. This compares well with the value of 0.075 (Table 1) determined using the White equation in an inverse manner as described earlier. Numerical simulation is recommended when both a shallow water table and slow drainage are limiting factors. The major drawback is that the unsaturated hydraulic properties of the media must be known.

[44] *Gerla* [1992] and *Rosenberry and Winter* [1997] suggest that the specific yield can also be calculated as the ratio of infiltrated precipitation to recorded rise in the

water table. This technique should work well in environments such as wetlands where the moisture content in the vadose zone is relatively high, the water table is very shallow, and overland flow is negligible or readily quantified. However, the technique may be inappropriate when a thicker vadose zone is present and the antecedent moisture conditions are below field capacity. In that situation, much of the precipitation may not reach the water table. In addition, the time that is needed for the wetting front to reach the water table may make it difficult to determine the timescale associated with the specific yield estimate. *Healy and Cook* [2002] discuss other factors that would impact the specific yield estimate obtained with this approach.

7. Considerations for Field Applications

[45] The following points must be considered to obtain reasonable ET_G estimates with the White method. First, water level records must reflect changes in the water table, so monitoring wells should be screened across the water table, and not over deeper intervals. Second, as these fluctuations are often on the order of 1 cm or less, high-resolution and high-accuracy pressure transducers are required, often at the expense of a reduced operating range. Even with such sensors, noise of various origins may impact the pressure measurements, so it may be necessary to filter out aberrant readings and/or use a moving average to smooth the data. Third, the White method can be modified slightly by using the average net inflow rate calculated from the hydrograph slopes for midnight to 4:00 A.M. on the day of interest and the following day. This modification results in a more appropriate average recharge value for the 24-hour period. Fourth, processes that are unsteady on a daily timescale, such as cycling on or off of nearby pumping wells, recharge events (Figure 1a), or stage changes in nearby streams, will violate the assumption that net inflow is constant over a 24-hour period. Under such conditions, the White method should not be applied until the system approaches a dynamic equilibrium. Fifth, because any error in specific yield translates directly into an error in estimated ET_G, readily available specific yield must be determined carefully. For relatively clean sands, standard laboratory and field methods should provide acceptable estimates of specific yield. When the depth to the water table is greater than 1 m and only sediment texture is known, we recommend that Figure 10 be used to estimate S_Y for sediments with more than 10% fines. If the water table is shallower than 1 m, equation (8), numerical modeling, or, in some cases, the ratio of infiltrated precipitation to recorded rise in the water table can be used to estimate S_Y (Figure 11). The dependence of specific yield on the depth to water is important because deeper water levels can result in larger specific yields (Figure 7) and thus smaller water table fluctuations. If the larger specific yield values are not accounted for in the White method, the estimated ET_G values will appear to decrease with depth to water, even if this is not the case. Thus care must be used so as not to confuse apparent decreases in ET_G with the decreases that are expected as the water table becomes deeper and it becomes more difficult for the vegetation to access the saturated zone. At sites where the depth to water is relatively shallow but changes significantly over time, it may be necessary to consider the dependence of specific yield on the depth to water.

8. Conclusions

[46] This study demonstrates that reasonable estimates of groundwater consumption by phreatophytes (ET_G) can be obtained through an analysis of well hydrographs with the method proposed by *White* [1932]. These estimates are necessary for effective management of groundwater resources, particularly when ecological considerations are incorporated into water policy [*Gleick*, 2000]. The White method uses the net inflow rate determined from the water table recovery during the overnight period of assumed zero transpiration, the net change in the elevation of the water table over a day, and an estimate of the readily available specific yield to quantify ET_G. The largest source of error is the uncertainty in the estimate of the readily available specific yield. Although this critical value is dependent on textural type, duration of drainage, and depth to the water table, we provide a means to estimate it for the timescale appropriate for this application. We also demonstrate that while the particulars of the groundwater flow system determine the net inflow rate, understanding those particulars is unnecessary for estimating ET_G using the White method.

[47] If the concept of readily available specific yield is ignored, the White method can significantly overpredict ET_G for sediments with more that 10% silts and clays. The readily available specific yield accounts for the fact that water is not released instantaneously from the vadose zone, which is the primary cause of the large overprediction of ET_G. Values of readily available specific yield were determined in this study through saturated-unsaturated flow simulation with hydraulic properties that are typical for each textural type. Using the guidelines presented here, a reasonable value can be determined for the readily available specific yield, making the White method a simple, cost-effective method for continuous assessment of daily groundwater consumption by phreatophytic vegetation.

Notation

α	empirical van Genuchten coefficient ($1/L$).
d	depth to the water table below land surface (L).
Δh	change in water table elevation (L).
Δs	daily change in storage (L).
ET	daily rate of transpiration (L/T).
ET_G	daily rate of groundwater consumption by transpiration (L/T).
h_a	soil air entry value (L).
K	hydraulic conductivity (L/T).
K_S	saturated hydraulic conductivity (L/T).
λ	pore size distribution index (dimensionless).
m	empirical van Genuchten coefficient (dimensionless).
Max	maximum daily water table elevation (L).
Min	minimum daily water table elevation (L).
n	empirical van Genuchten coefficient (dimensionless).
R	net inflow (recovery) rate (L/T).
S_Y	specific yield (dimensionless).
$S_Y^{falling}$	specific yield for a falling water table (dimensionless).

S_Y^{rising} specific yield for a rising water table (dimensionless).
$S_Y^{d\text{-}comp}$ depth-compensated specific yield (dimensionless).
$t^{falling}$ duration of the day that the water table is falling (L).
t^{rising} duration of the day that the water table is rising (L).
θ water content (dimensionless).
θ_B parameter of the water content profile defined by *Nachabe* [2002] (dimensionless).
θ_R residual water content (dimensionless).
θ_S water content at saturation (dimensionless).
$\theta_{Surface}$ water content at the land surface (dimensionless).
ψ pressure head (L).
v velocity of the water table (L/T).
z depth below the land surface (L).
z' arbitrary depth that is below the water table at all times (L).
t time (T).

[48] **Acknowledgments.** This material is based upon work supported by the National Science Foundation under grant EAR-0337393 (SMG PI). This research was also supported in part by the Kansas Water Resources Institute under grant 01HQGR0081 (subaward S04015, JJB PI) and a joint agreement between the Kansas Geological Survey and Groundwater Management District 5. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation, the Kansas Water Resources Institute, or Groundwater Management District 5. The authors would also like to thank three anonymous reviewers for helpful comments and suggestions that greatly improved this paper.

References

Aboukhaled, A., A. Alfaro, and M. Smith (1982), Lysimeters, *FAO Irrig. Drain. Pap.*, *39*, 68 pp.

Allen, R. G., T. A. Howell, W. O. Pruitt, and I. A. Walter (Eds.) (1991), *Lysimeters for Evapotranspiration and Environmental Measurements: Proceedings of the International Symposium on Lysimetry Held in Honolulu, Hawaii, July 23–25, 1991*, 456 pp., Am. Soc. of Civ. Eng., Reston, Va.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), Crop evapotranspiration— Guidelines for computing crop water requirements, *FAO Irrig. Drain. Pap.*, *56*, 300 pp.

Anderson, M. P., and W. W. Woessner (1992), *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Elsevier, New York.

Baker, J., and J. Nieber (1989), An analysis of the steady-state heat balance method for measuring sap flow in plants, *Agric. For. Meteorol.*, *48*, 93–109.

Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, and A. A. M. Holtslag (1998), A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation, *J. Hydrol.*, *212–213*, 198–212.

Bear, J. (1972), *Dynamics of Fluids in Porous Materials*, Dover, Mineola, N. Y.

Bleby, T. M., M. Aucote, A. K. Kennett-Smith, G. R. Walker, and D. P. Schachtman (1997), Seasonal water use characteristics of tall wheatgrass [*Agropyron elongatum* (Host) Beauv.] in a saline environment, *Plant Cell Environ.*, *20*, 1361–1371.

Bond, B. L., J. A. Jones, G. Moore, N. Phillips, D. Post, and J. J. McDonnell (2002), The zone of vegetation influence on baseflow revealed by diel patterns of streamflow and vegetation water use in a headwater basin, *Hydrol. Processes*, *16*, 1671–1677.

Brooks, R. H., and A. T. Corey (1964), Hydraulic properties of porous media, *Hydrol. Pap. 3*, Colo. State Univ., Fort Collins.

Brunel, J. P., G. R. Walker, and A. K. Kennett-Smith (1995), Field validation of isotopic procedures for determining source water used by plants in a semi-arid environment, *J. Hydrol.*, *167*, 351–368.

Butler, J. J., Jr. (2005), Hydrogeological methods for estimation of spatial variations in hydraulic conductivity, in *Hydrogeophysics*, edited by Y. Rubin and S. S. Hubbard, pp. 23–58, Springer, New York.

Carsel, R. F., and R. S. Parrish (1988), Developing joint probability distributions of soil water retention characteristics, *Water Resour. Res.*, *24*, 755–769.

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

Dahm, C. N., J. R. Cleverly, J. E. Allred-Coonrod, J. R. Thibault, D. E. McDonnell, and D. J. Gilroy (2002), Evapotranspiration at the land/water interface in a semi-arid drainage basin, *Freshwater Biol.*, *47*, 831–843.

Davis, S. N., and R. J. M. De Wiest (1966), *Hydrogeology*, John Wiley, Hoboken, N. J.

Dawson, T. E., and J. R. Ehleringer (1991), Streamside trees that do not use stream water, *Nature*, *350*, 335–337.

Duke, H. R. (1972), Capillary properties of soils—Influence upon specific yield, *Trans. ASAE*, *15*(4), 688–691.

Dulohery, C. J., R. K. Kolka, and M. R. McKevlin (2000), Effects of a willow overstory on planted seedlings in a bottomland restoration, *Ecol. Eng.*, *15*, S55–S66.

Dunn, A. M., and S. E. Silliman (2003), Air and water entrapment in the vicinity of the water table, *Ground Water*, *41*, 729–734.

Farrington, P., G. D. Watson, G. A. Bartle, and E. A. N. Greenwood (1990), Evaporation from dampland vegetation on a groundwater mound, *J. Hydrol.*, *115*, 65–75.

Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, Prentice-Hall, Upper Saddle River, N. J.

Gatewood, J. S., T. W. Robinson, B. R. Colby, J. D. Hem, and L. C. Halpenny (1950), Use of water by bottom-land vegetation in lower Safford Valley, Arizona, *U.S. Geol. Surv. Water Supply Pap.*, *1103*.

Gerla, P. J. (1992), The relationship of water table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands, *Wetlands*, *12*, 91–98.

Gleick, P. H. (2000), The changing water paradigm: A look at the twenty-first century water resources development, *Water Int.*, *25*, 127–138.

Glennon, R. J. (2002), *Water Follies: Groundwater Pumping and the Fate of America's Fresh Waters*, Island Press, Washington, D. C.

Goodrich, D. C., et al. (2000), Seasonal estimates of riparian evapotranspiration using remote and in situ measurements, *Agric. For. Meteorol.*, *105*, 281–309.

Healy, R. W. (1990), Simulation of solute transport in variably saturated porous media with supplemental information on modifications to the USGS's computer program VS2D, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *90-4025*, 125 pp.

Healy, R. W., and P. G. Cook (2002), Using groundwater levels to estimate recharge, *Hydrogeol. J.*, *10*, 91–109.

Healy, R. W., and A. D. Ronan (1996), Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media—Modification of the USGS computer program VS2DT, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *96-4230*.

Hinz, C. (1998), Analysis of unsaturated/saturated water flow near a fluctuating water table, *J. Contam. Hydrol.*, *33*, 59–80.

Hsieh, P. A., W. Wingle, and R. Healy (2000), VS2DI—A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *9-4130*.

Johnson, A. I. (1967), Specific yield-compilation of specific yields for various materials, *U.S. Geol. Surv. Water Supply Pap.*, *1662-D*, 74 pp.

Laczniak, R. J., G. A. DeMeo, S. R. Reiner, J. L. Smith, and W. E. Nylund (1999), Estimates of ground-water discharge as determined from measurements of evapotranspiration, Ash Meadows Area, Nye County, Nevada, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *99-4079*.

Lappala, E. G., R. Healy, and E. P. Weeks (1987), Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *83-4099*.

Lewis, K., D. Hathaway, and H. Shafike (2002), Evapotranspiration-driven diurnal fluctuations in groundwater levels at San Marcial, New Mexico, in *Ground Water/Surface Water Interactions, AWRA 2002 Summer Specialty Conference Proceedings*, edited by J. F. Kenny, pp. 115–119, Am. Water Resour. Assoc., Middleburg, Va.

McDermitt, D. K. (1990), Sources of error in the estimation of stomatal conductance and transpiration from porometer data, *HortScience*, *25*, 1538–1548.

Meyboom, P. (1966), Groundwater studies in the Assiniboine River drainage basin—part I: Evaluation of a flow system in south-central Saskatchewan, *Bull. Geol. Surv. Can.*, *139*.

Meyboom, P. (1967), Groundwater studies in the Assiniboine River drainage basin—part II: Hydrologic characteristics of phreatophytic vegetation in south-central Saskatchewan, *Bull. Geol. Surv. Can.*, *139*.

Monteith, J. L., G. S. Campbell, and E. A. Potter (1988), Theory and performance of a dynamic diffusion porometer, *Agric. For. Meteorol.*, *44*, 27–38.

Nachabe, M. H. (2002), Analytical expressions for transient specific yield and shallow water table drainage, *Water Resour. Res.*, *38*(10), 1193, doi:10.1029/2001WR001071.

Nachabe, M. H., C. Masek, and J. Obeysekera (2004), Observations and modeling of profile soil water storage above a shallow water table, *Soil Sci. Soc. Am. J.*, *68*, 719–724.

Nichols, W. (1993), Estimating discharge of shallow groundwater by transpiration from greasewood in the northern Great Basin, *Water Resour. Res.*, *29*, 2771–2778.

Qashu, H. K. (1966), Estimation of the elements of the water balance of an ephemeral stream channel with riparian vegetation, Ph.D. thesis, Univ. of Ariz., Tucson.

Raats, P. A. C., and W. R. Gardner (1974), Movement of water in the unsaturated zone near a water table, in *Drainage for Agriculture*, pp. 311–405, Am. Soc. of Agron., Madison, Wis.

Remson, I., and J. R. Randolph (1958), Root growth near tensiometer cups as a cause of diurnal fluctuations of readings, *Soil Sci.*, *85*, 167–171.

Robinson, T. W. (1958), Phreatophytes, *U.S. Geol. Surv. Water Supply Pap.*, *1423*.

Rosenberry, D. O., and T. C. Winter (1997), Dynamics of water table fluctuations in an upland between two prairie-pothole wetlands in North Dakota, *J. Hydrol.*, *19*, 266–289.

Schaeffer, S., D. Williams, and D. C. Goodrich (2000), Transpiration of cottonwood/willow forest estimated from sap flux, *Agric. For. Meteorol.*, *105*, 257–270.

Scott, R. L., C. Watts, J. Garatuza, E. Edwards, D. C. Goodrich, and D. Williams (2002), Measuring the distribution of surface energy and water fluxes in a riparian mesquite savannah-type ecosystem, paper presented at 2nd Annual Meeting, Semi-Arid Hydrol. and Riparian Areas (SAHARA), Tucson, Ariz.

Shuttleworth, W. J. (1993), Evaporation, in *Handbook of Hydrology*, edited by D. R. Maidment, pp. 4.1–4.53, McGraw-Hill, New York.

Smith, D. M., and S. J. Allen (1996), Measurement of sap flow in plant stems, *J. Exp. Bot.*, *47*, 1833–1844.

Todd, D. K. (1980), *Groundwater Hydrology*, 2nd ed., John Wiley, Hoboken, N. J.

Tromble, J. M. (1977), Water requirements for mesquite (*Prosopis juliflora*), *J. Hydrol.*, *34*, 171–179.

Troxell, H. C. (1936), The diurnal fluctuation in the ground-water and flow of the Santa Ana river and its meaning, *Eos Trans. AGU*, *17*(4), 496–504.

van Genuchten, M. (1980), A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, *44*, 892–898.

Weeks, E. P., and M. L. Sorey (1973), Use of finite-difference arrays of observation wells to estimate evapotranspiration from ground water in the Arkansas River Valley, Colorado, *U.S. Geol. Surv. Water Supply Pap.*, *2029-C*, 27 pp.

White, W. N. (1932), A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: Results of investigations in Escalante Valley, Utah, *U.S. Geol. Surv. Water Supply Pap.*, *659-A*.

Woessner, W. W. (2000), Stream and fluvial plain ground water interactions: Rescaling hydrogeologic thought, *Ground Water*, *38*, 423–429.

Zacharias, S., and K. Bohne (1997), Replacing the field capacity concept by an internal drainage approach—A method for homogeneous soil profiles, *Sci. Soils*, *2*, article 2.

J. J. Butler Jr., Kansas Geological Survey, University of Kansas, Lawrence, KS 66045, USA.

S. M. Gorelick and S. P. Loheide II, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305, USA. (sloheide@stanford.edu)