Groundwater uptake by woody vegetation in a semiarid oak savanna

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[1] Groundwater can serve as an important resource for woody vegetation in semiarid landscapes, particularly when soil water is functionally depleted and unavailable to plants. This study examines the uptake of groundwater by deciduous blue oak trees (*Quercus douglasii*) in a California oak savanna. Here we present a suite of direct and indirect methods that demonstrate its occurrence and quantify its rates. The study site is underlain by a thin soil layer and fractured metavolcanic bedrock. Typical depth to groundwater is approximately 8 m. A variety of water storage and flux measurements were collected from 2005 to 2008, including groundwater levels, soil moisture contents, sap flows, and latent heat fluxes. During the dry season, groundwater uptake rates ranged from 4 to 25 mm month^{-1} and approximately 80% of total ET during June, July, and August came from groundwater. Leaf and soil water potentials supported these results, indicating that groundwater uptake was thermodynamically favorable over soil water uptake for key portions of the growing season. These findings strongly suggest that blue oaks should be considered obligate phreatophytes and that groundwater reserves provide a buffer to rapid changes in their hydroclimate, if these assets are not otherwise depleted by prolonged drought or human consumption. While groundwater uptake may provide for short-term protection, it should be viewed not as a mechanism for continued plant growth. It allows the woody vegetation to subsist during the summer but not to flourish.

1. Introduction

[2] California's oak savanna ecosystems experience profound summer drought every year [*Major*, 1988] and are water limited, with evaporative demand far exceeding annual rainfall [*Lewis et al.*, 2000]. The question of how these ecosystems regulate water use has important implications for how they will handle increased water stress, which may occur as climate change begins to alter hydrological patterns in the region [*Kueppers et al.*, 2005; *Lenihan et al.*, 2008].

[3] *Baldocchi and Xu* [2007] hypothesized that blue oak trees (*Quercus douglasii*) are able to function despite severe water limitations using a combination of mechanisms. The oaks have developed tight physiological controls and ecological adaptations to limit water loss at the leaf and landscape levels. Loss-limiting mechanisms include the down-regulation of stomatal conductance and photosynthesis and the establishment of a sparse canopy with widely spaced trees and low leaf area. However, the growing season of the trees is out-of-phase with the bulk of precipitation. Because of the Mediterranean climate, over 60% of the annual rainfall occurs from October to March, when the trees are dormant or beginning leaf-out. It is postulated that to make use of the winter rains, the oaks tap deep water stores that are more permanent and less seasonal than soil moisture.

[4] Previous studies of these water-limited, blue oak savanna ecosystems have focused on soil moisture as the sole hydrologic regulator of transpiration [*Baldocchi et al.*, 2004; *Chen et al.*, 2008; *Miller et al.*, 2007], although circumstantial evidence pointed to some limited groundwater use. However, the rock layer under the shallow soil was thought to be relatively impenetrable to roots, and the water table was assumed to be too deep for a significant number of them to reach. Additionally, groundwater uptake in similar, albeit coastal, species was precluded [*Blumler*, 1991; *Griffin*, 1973].

[5] Current research into groundwater uptake by woody vegetation has focused on plants accessing the shallow aquifers associated with riparian zones [*Butler et al.*, 2007; *Lamontagne et al.*, 2005; *Lautz*, 2008; *Loheide*, 2008; *O'grady et al.*, 2006b; *Scott et al.*, 2008b] and in other humid land systems [*Rodríguez-Iturbe et al.*, 2007], while groundwater has been largely considered "out of reach" for many semiarid ecosystems. However, several studies have shown that woody vegetation in upland areas can tap groundwater 7 m or more below the land surface [*Burgess et al.*, 2001b; *Jewett et al.*, 2004; *McElrone et al.*, 2003; *O'grady et al.*, 2006a; *Scott et al.*, 2004].

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[6] From tracer studies conducted on a similar California oak ecosystem, we know that this is true of blue oaks; *Lewis and Burgy* [1964] demonstrated that their roots can penetrate down to 24 m of fractured rock in order to access groundwater. However, previous research in this ecosystem has not directly addressed the role of plant groundwater uptake in the system's overall water budget and in its functioning, leading to a potentially incomplete understanding of water use. In this paper, we explore the uptake of groundwater resources by woody vegetation in one such ecosystem and discuss its ecohydrological implications, asking, "Are blue oaks dependent on groundwater for their survival?"

[7] Determining if, and to what extent, an ecosystem is groundwater dependent can be difficult. *Eamus et al.* [2006a] suggested that an ecosystem may be reliant on the subsurface presence of groundwater if it meets one or more of the following criteria: (1) The vegetation, or a portion of it, continues fixing carbon during extended dry periods. (2) Within areas of similar rainfall inputs, some ecosystems show large changes in leaf area index while others do not. (3) Daily changes in groundwater depth are observed which are not due to lateral flows, percolation to depth, or atmospheric pressure changes. (4) The annual rate of plant transpiration is larger than the rate of water entering the area, i.e., sum of the precipitation and run-on rates. (5) Significant surface expressions of groundwater are present, for example, springs or gaining streams, and the vegetation associated with these expressions is substantially different from other nearby vegetation. Additionally, the rooting depth of the vegetation must be at or below the water table or its capillary fringe, although this feature is often the most difficult to determine in practice.

[8] Blue oak ecosystems have been shown to meet the first criteria; the trees do not experience drought deciduousness. Photosynthesis and evaporation continue throughout the dry summer, even with predawn water potentials reaching −4 to −7 MPa. However, we aim to find more direct evidence of groundwater dependence and to quantify groundwater uptake rates. Therefore, the objectives of this research are (1) to integrate two measurement strategies for quantifying groundwater uptake; water balance closure at the stand level and diurnal water table fluctuations; (2) to use indirect lines of evidence for groundwater uptake, including water potential measurements, to support our conclusions about if and when uptake is occurring; and (3) to estimate the measurement error associated with each direct and indirect method and to suggest ways this error may be minimized.

[9] Specifically, we ask the following questions: What percentage of transpired water comes from deep groundwater sources? Does this vary over time? What driving force (hydraulic gradient) is necessary to move water from the aquifer to the top of the canopy? Do our water potential measurements indicate whether this force is present and when? How fast will water move under this gradient and will this affect the time scale over which we need to quantify hydrologic fluxes? Do indirect measurements, such as water potential data, corroborate the conclusions supported by direct hydrological measurements?

[10] We hypothesize that mature oaks have a seasonal, yet obligate, dependency on groundwater for their survival during the dry summer months and that the percentage of transpired water from groundwater is nonzero during the spring months and increases during times of soil water scarcity.

Water potential levels reached in the leaves will create a hydraulic gradient sufficient to transport water the 20 m between the groundwater table and the top of the canopy, and these potentials will suggest the percentage of roots tapping deepwater sources. By using multiple direct methods, we intend to obtain results that are consistent on the timing of uptake, although magnitude of uptake may vary due to differences in sampling scale.

2. Data Collection

2.1. Site Description

[11] The site, Tonzi Ranch, is an oak savanna located in the western Sierra Nevada foothills near Ione, California (latitude: 38.4311°N, longitude: 120.966°W, altitude: 177 m). The site is a member of AmeriFlux and Fluxnet micrometeorological observation networks, and half-hourly water vapor flux, soil moisture, and precipitation measurements have been collected near-continuously since spring 2001.

[12] In this oak savanna ecosystem, trees cover approximately 40% of the landscape [*Chen et al.*, 2007]; they are predominately blue oaks (*Quercus douglasii*) with occasional grey pines (*Pinus sabiniana*). The mean height of the canopy is 7.1 m, with approximately 194 stems per hectare, a mean diameter at breast height of 0.199 m, and a basal area of 18 m^2 ha^{-1} [*Baldocchi et al.*, 2004]. In 2008, the understory cover consisted primarily of nonnative herbs and grasses, with approximately 31% false brome (*Brachypodium distachyon*), 15% soft brome (*Bromus hordeaceous*), 7% redstem filaree (*Erodium cicutarium*), 5% smooth cat's ear (*Hypochaeris glabra*), 12% other unidentified grasses, 16% oak litter, 8% other litter, and 6% bare ground (Wenk, 2008, unpublished data).

[13] The site's hydroclimate is Mediterranean and semiarid; between 2004 and 2008, it received 370–780 mm of rain per year and lost between 350 and 485 mm of this to evapotranspiration. Historical records for the region indicate that precipitation has ranged from 200 to 1200 mm per year, with an average 548 mm per year and a standard deviation of 196 mm per year [*Baldocchi et al.*, 2010]. Most rainfall occurs during the cool wet season (November to April), with almost no precipitation occurring during the hot dry season (May to October). During the dry years included in this study (2007–2008), no surface water features were observed near the tower; however, during extremely wet years, ephemeral streams can occur. These, as well as precipitation, feed a small, man-made reservoir approximately 500 m from the tower. These hydrological features can be seen on a relief map of the site (Figure 1).

[14] The site's hydrogeology is typical of the Sierra Nevada foothills [*Duffield and Sharp*, 1975]. It has a thin layer of surface soil, 60–100 cm, which is classified as silt loam to rocky silt loam [*Sketchley*, 1965]. Approximately 4–8 m of saprolite (weathered rock) follows until reaching the bedrock, which consists of fractured, metamorphosed volcanic rocks (greenstone), and sedimentary rocks (slate) of the Jurassic period. The depth to groundwater ranges between 7 and 12 m below ground surface, and the groundwater is contained within a fractured rock "aquifer." Preliminary pumping tests estimated a maximum groundwater yield between 0.015 and 0.063 L s^{-1} (0.25 and 1 gpm), making the area unsuitable for groundwater extraction for
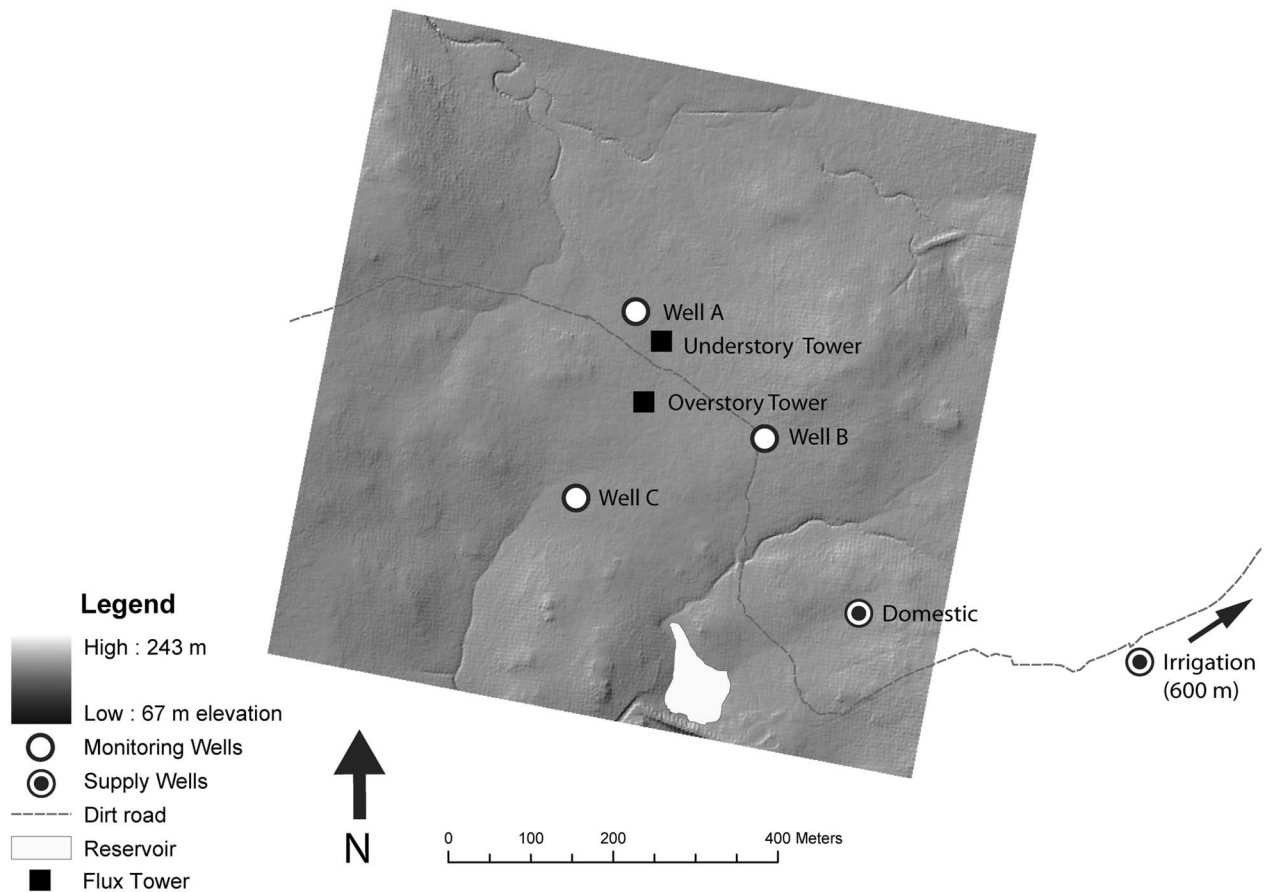
Figure 1. Tonzi Ranch site map. Relief map showing the location of hydrological features, monitoring and supply wells, and the eddy-covariance towers.

domestic or agricultural use. Slug tests performed using the Dagan method [*Butler*, 1997; *Dagan*, 1978] indicated a saturated hydraulic conductivity of 6×10^{-7} to 3×10^{-6} m s^{-1}.

2.2. Hydrologic Measurements

[15] A suite of hydrological measurements have been collected at the site, in order to characterize the vertical fluxes of water into and out of the study area and its water storage. Figure 1 shows a map of the site and instrument locations. All measurements were obtained every half-hour, unless otherwise noted. Precipitation was measured using a tipping bucket range gauge (Texas Electronics, TE 5252 mm), air pressure was measured with a capacitance barometer (model PTB101B, Vaisala, Helsinki, Finland), and air temperature and relative humidity were measured with a platinum resistance thermometer and a solid state humicap (model HMP-45A, Vaisala, Helsinki, Finland), shielded from the sun and aspirated.

[16] The eddy-covariance method [*Baldocchi*, 2003] was used to measure latent heat flux (and by proxy, evapotranspiration). As part of the method, wind velocity fluctuations were measured with a three-dimensional ultrasonic anemometer (Windmaster Pro, Gill Instruments, Lymington, UK), and water vapor density was measured using an open-path infrared absorption gas analyzer (model LI-7500, LICOR, Lincoln, NE). Two eddy-covariance towers are present at the site, an overstory tower located at 23 m above ground (16 m

above the canopy) and an understory tower located at 2 m above the ground surface. The extent of the flux footprint for the upper tower has been estimated to be on the order of 30 m during strongly unstable atmospheric conditions to 1 km during mildly unstable to near neutral conditions [*Kim et al.*, 2006]. Under the most common conditions, the footprint length is likely around 300 m. Although a site specific analysis has not been conducted for the shorter tower, *Baldocchi* [1997] estimated that a 2 m tower in a savanna or open woodland would have a footprint extending 60 m upwind. The combination of towers allows the total, stand-scale tree transpiration to be calculated by taking the difference in latent heat flux from the understory (representing the evaporation from the soil and the grasses) and the flux from the overstory (representing the total stand flux). During the summer, understory evapotranspiration is near zero; the annual grasses and herbs die out and the surface soil approaches its hygroscopic point.

[17] Biweekly measurements of depth to groundwater have been manually recorded in three observation wells since their installation in Fall 2006, with automated half-hourly measurements collected in one well. Manual measurements were made with a water level indicator tape (Model 101, Solinst, Georgetown, CA), while a cable vented pressure transducer and data logger was used for the continuous measurements (Model WL16U-15, Global Water Instrumentation, Gold

River, CA). Biweekly groundwater hydraulic gradients were calculated from these measurements.

[18] To measure individual tree transpiration and soil environment, a network of nine "sap flow stations" were located across the site [*Miller*, 2009]. Each station measured the sap velocity at four points within one tree, using the heat ratio method [*Burgess et al.*, 2001a] calibrated using a previously developed inverse modeling method [*Chen*, 2009]. Each station was equipped with five ECH$_2$O EC-5 soil moisture sensors (Decagon, Pullman, WA), three located immediately adjacent to the tree at depths of 5, 20, and 50 cm, one at the tree's drip line at a depth of 20 cm and one at the nearest canopy opening at a depth of 20 cm. One station was also outfitted with two gypsum blocks (Model 227, Delmhorst, Towaco, NJ) to measure soil water potential at a depth of 20 cm. Fourteen MoisturePoint time domain reflectometer probes (Environmental Sensors Inc., Sidney, British Columbia) were previously in place at the site, distributed throughout the woodland. These sensors were placed 60 cm deep, had four 15 cm segments, and were manually measured on a weekly basis. During 2008, tree diameter was also recorded on a biweekly basis using manual band dendrometers (Series 5 Low Tension, Agricultural Electronics Corporation, Tucson, Arizona).

[19] To complement these measurements, midday and predawn leaf water potentials were measured every 10–14 days during the growing season, using a portable plant water status console (Model 3005, Soil Moisture Corp, Santa Barbara, CA). Three leaves were collected from each tree, and three trees were sampled per event, in order to find representative values. Predawn leaf water potentials that are less negative than soil water potentials can serve as a crude indicator that plant roots are currently exposed to groundwater [*Eamus et al.*, 2006b], although several plant water use processes conflate the issue, particularly nighttime transpiration and refilling of internal water storage [*Bucci et al.*, 2004; *Donovan et al.*, 1999; *Fisher et al.*, 2007].

[20] Stable oxygen and hydrogen isotope methods [*Dawson et al.*, 2002] can also yield information on the relative use of water sources. An estimate of the proportion of groundwater used by a plant can be found by comparing the groundwater's isotopic composition to that of the plant's xylem water and of the surrounding surface or soil water [*Cramer et al.*, 1999; *Dawson*, 1993; *Snyder and Williams*, 2000]. Stable isotope testing was conducted at the site in 2008 and 2009. The results were inconclusive due to the lack of differentiation between the values found in the groundwater and those found in the deep soil moisture samples. Thus, the ratios could not be used to confirm or deny the possibility of groundwater uptake by vegetation.

2.3. Data Analysis

[21] In this work, we consider two methods for estimating groundwater use from direct hydrological measurements. The first method uses diurnal fluctuations in depth to groundwater to isolate the daily change in groundwater (driven by vegetative uptake) from the overall, seasonal trends in the water table level. The second is the flux tower water budget closure method, a technique which compares favorably to more traditional hydrological water balance methods [*Wilson et al.*, 2001]. This method takes measurements of canopy evapotranspiration and site precipitation using established micrometeorological techniques and calculates the groundwater uptake that must occur based on the deficit between incoming, outgoing, and stored water in the system.

2.3.1. Stand-Level Uptake From Water Balance Closure

[22] To estimate the stand-level uptake, a water budget is formed by specifying a control volume centered on the flux tower, creating a 200 m by 200 m square area which extends vertically from the soil/rock interface to the top of the flux tower. In this control volume, the water budget can be defined as

$$G_w + P - \mathrm{ET} = z\frac{\partial \theta}{\partial t} + \frac{h_t}{\rho_w}\frac{\partial \rho_v}{\partial t} + \frac{V_b}{A}\frac{\partial m_c}{\partial t}, \qquad (1)$$

where the fluxes, shown on the left-hand side of the equation, are G_w, the net groundwater source or sink (m d^{-1}); P, the precipitation (m d^{-1}); and ET, the stand evapotranspiration (m d^{-1}). On the right-hand side of the equation, the system storage terms are represented by z, the soil depth (0.6 m); θ, the soil volumetric water content (m^3 m^{-3}); and t, the time (d), h_t, the height of the eddy-covariance tower (23 m); ρ_w, the density of water at 20° C (998 kg m^{-3}); ρ_v, the density of water vapor in atmosphere (g m^{-3}); V_b, the volume of woody biomass (estimated as 61 m^3); A, the area of stand (4.0×10^4 m^2); and m_c, the stem volumetric water content (m^3 m^{-3}). This equation assumes that no net lateral movement of water occurs, i.e., lateral flow rates of runoff, water vapor in atmosphere, and soil water are equal to zero. In practice, the last two terms in the equation, representing the change in atmospheric and stem water storage, are much smaller than the soil moisture storage term and can be neglected. In this water balance formulation, a half-hourly time step is used for the calculations, as the data are collected at this interval, and the results are reported at daily or monthly intervals.

[23] Here G_w is found as a remainder on the water balance. It is the difference between the precipitation entering the control volume, the moisture escaping through evapotranspiration, and the amount of water stored in the soil over a given period in time. During periods when no runoff occurs, this difference is the vertical flux of water to or from the aquifer. It can be further decomposed into two component fluxes: groundwater uptake by vegetation (U) and leakage (L) from the soil layer (where $G_w = U - L$). The value of G_w indicates a net loss from the aquifer when it is positive and a net gain or recharge to the aquifer when it is negative. While the inability to segregate U and L based on the water balance is a major drawback to the method, the net groundwater uptake can still be an informative measure. During the long summer dry season, soil is far below its field capacity, leakage is nonexistent, and runoff is very unlikely to happen. Under these conditions, G_w is equal to the rate of groundwater uptake. The term G_w also provides a measure of monthly groundwater recharge, a quantity useful for water resources planning, although this value may be overestimated during periods when runoff is nonnegligible (i.e., the wet season during wet years).

2.3.2. Uptake From Groundwater Measurements

[24] We have measured the groundwater levels in all wells on a biweekly basis since December 2006 (Figure 2). Continuous measurements have been collected on a half-hour cycle in Well A since May 2007 (Figure 1). To calculate the
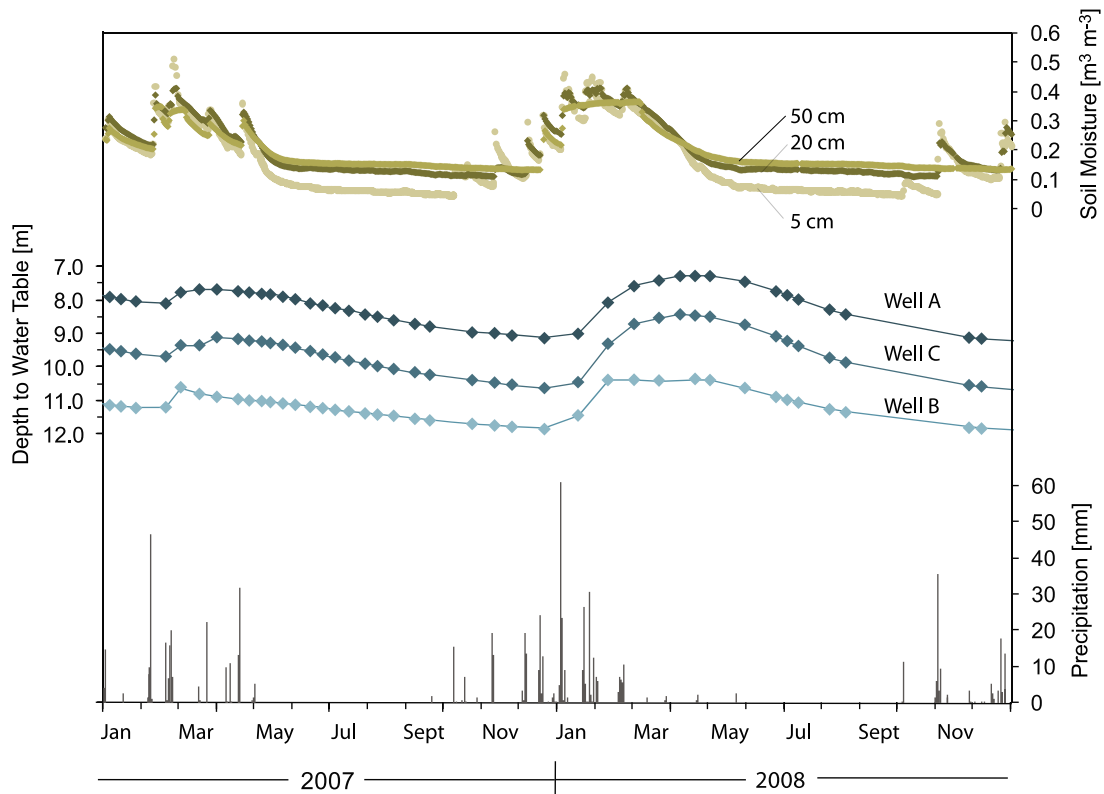
Figure 2. Temporal patterns of water flux and storage. Groundwater table elevations during the study period, with daily precipitation and soil moisture values. The wells are located in a triangular pattern, centered on the flux tower. Soil moisture sensors are buried within 10 m of the tower.

daily vegetative groundwater uptake (ET_g), we used the method developed by *White* [1932] and later refined [*Butler et al.*, 2007; *Loheide et al.*, 2005],

$$ET_g = S_y^*(\Delta s/t + R), \quad (2)$$

where S_y^* is the readily available specific yield of the aquifer and is dimensionless; Δs is the daily change in storage, in m; t is the time period over which the change in storage occurs, i.e., 1 day; and R is the rate of aquifer recharge, in m d^{-1}. The term Δs is the change in groundwater head over the span of a day, which is found by computing the difference between the peak head on the initial day, H_1, and the peak head on the subsequent day H_2, so that $\Delta s = (H_1 - H_2)$. The recharge rate R is calculated from the slope of the water table plot between 10 P.M. at night and 7 A.M. the next morning, when evapotranspiration is at a minimum; to find R for any given day, the values from the previous night and the subsequent night are averaged.

[25] *Loheide et al.* [2005] discussed the major assumptions made with this method: "(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."

[26] To address the validity of these assumptions for the Tonzi site, we first examined other possible sources of the observed diurnal fluctuations. The main, alternate sources of such fluctuations are tides from nearby water bodies, anthropogenic groundwater extraction, changes in atmospheric pressure, and changes in temperature [*Freeze and Cherry*, 1979]. The first two causes were eliminated. The largest water body in the vicinity is the small, man-made reservoir, over 500 m away, and the only nearby groundwater pumping is minimal (<0.063 L s^{-1} or 1 gpm) and takes place in the landowner's personal well, over 200 m away (Figure 1). The fluctuations observed did not match those that would occur if these factors were influential. A year-round signal would be present from pumping, and tides would cause the groundwater levels to peak twice per day. The effect of barometric pressure changes on the water level measurements should be minimal. Fluctuations due to pressure changes are not commonly seen in unconfined aquifers [*Domenico and Schwartz*, 1998], and the use of a vented pressure transducer would minimize their occurrence. This does not preclude the possibility of barometric pressure changes acting on the aquifer itself, a condition we test for in section 3.2.

[27] The second assumption that no tree uptake is occurring overnight is more problematic. Previous studies have shown that trees at the site continue to transpire during the nighttime [*Fisher et al.*, 2007], as indicated by positive sap flows during the night. These flows continue to be observed and amount to approximately 10%–20% of daytime values [*Miller*, 2009]. The apparent violation of this assumption could cause the underprediction of R, the aquifer recharge term in equation (2), leading to an underestimation of the daily value of ET_g when overnight transpiration is occurring.

[28] As suggested by the third assumption, in shallow aquifers, this analysis must be confined to days when no precipitation occurs, as it can interfere with the signal. This consideration is minimal at the Tonzi Ranch, due to its long dry summers with few or no rainfall events. Additionally, since the aquifer is over 8 m below the ground surface, when precipitation events do happen, they are only rarely seen in the fluctuations.

[29] The final assumption is that a representative specific yield, the sole parameter in equation (2), may be found. According to *White* [1932], its value is "exceedingly difficult to determine," a problem which has historically prevented more widespread application of the method. Even the definition of specific yield itself is subject to uncertainty and interpretation [*Healy and Cook*, 2002; *Vincke and Thiry*, 2008]. However, in this context, it is typically considered to represent the depth of water entering or leaving the porous matrix as a percentage of the change in height of the water table [*White*, 1932]. For instance, if the specific yield is 0.10, and a groundwater decline of 2 cm is observed over the course of a day, then the calculated groundwater uptake would be 0.2 cm d^{-1}. Field measurements for unconfined aquifers require either core samples of the porous matrix or multiwell pumping tests. Neither approach is appropriate here: core samples cannot capture the dual-porosity nature of the fractured rock; the long duration required of pumping tests may not capture the short-term specific yield values needed; and the well configuration is not appropriate for conducting a pump test.

[30] To circumvent these constraints, we used information available from the water balance method to help estimate a representative specific yield value. During dry periods, the method provides direct measurements of uptake alone, which are not influenced by recharge. These uptake values, combined with the fluctuations, allowed us to invert equation (1) to find an effective specific yield value which could then be applied to calculations over all time periods.

[31] In the inversion, the minimum residual sum of squares method was used,

$$\mathrm{RSS} = \sum_{i=153}^{244} \left[\mathrm{ET}_{g,i} - \beta(\Delta s_i/t + R_i) \right]^2, \tag{3}$$

where i represents the day of year, from 1 June to 31 August in 2007 and 2008; ET_g represents the daily groundwater uptake calculated by the tower; $(\Delta s_i/t + R_i)$ represents the daily groundwater level fluctuation attributable to groundwater uptake; and β is a coefficient that equals S_y^*, when RSS is minimized. The results of this inversion are reported in section 3.2.

2.3.3. Water Potential Data

[32] Assuming that the Dixon cohesion-tension theory of sap water ascent is correct [*Dixon and Joly*, 1894; *Tyree*, 1997], the water potential measured in the leaves must be sufficiently negative to overcome the forces of both the gravitational potential caused by the change in height from the roots to the leaves and the matric potential associated with hygroscopic forces in the soil. By comparing the water potential measured in the leaves to the total of the gravitation potential and the matric potential needed to obtain water from various sources, we can theoretically determine which water sources would be favored thermodynamically.

[33] For example, if soil matric potential at a depth of 50 cm is −2 MPa, then we can calculate that it will require at least a leaf water potential of −2.8 MPa to use this water: −2 MPa for roots to extract water from the soil, −0.1 MPa to move the water against a 10.5 m gravitation head from the soil to the leaf, and another −0.7 MPa to overcome the frictional resistance of water flowing against the xylem walls. Alternately, if groundwater is to be used, a gravitational head and frictional resistance over approximately 17 m needs to be overcome, requiring a driving pressure of approximately −1.4 MPa. In this case, extracting groundwater would be more energetically favorable than extracting soil moisture.

[34] In order to directly compare groundwater, soil, and leaf water potential measurements, we adjusted all values to account for gravitational and frictional resistance, using the following equation,

$$\Psi_{i,\mathrm{t}} = \Psi_i - \Delta P_\mathrm{x}. \tag{4}$$

Here $\Psi_{i,\mathrm{t}}$ is the total adjusted potential at a measured location, in MPa; Ψ_i is the direct potential measurement, for example, soil matric potential, in MPa; and ΔP_x is the maximum theoretical change in potential associated with overcoming gravity and the frictional resistance of the stem in order to reach a leaf at 3 m above the ground. It is calculated using an appropriately modified version of Darcy's law,

$$\Delta P_\mathrm{x} = \rho_\mathrm{w} z \left(\frac{q_\mathrm{max}}{K_\mathrm{s}} + g \, 10^{-6} \right), \tag{5}$$

where ρ_w is the density of water at 20°C, 998 kg m^3; z is the length of the stem segment from the measurement point to the leaf height, in m; q_max is the maximum rate of sap ascent in the xylem measured by the sap flow sensors, 30 cm h^{-1} or 8.3×10^{-5} m s^{-1}; K_s is the hydraulic conductivity of the stem, 1.10 kg s^{-1} m^{-1} MPa^{-1} for deciduous *Quercus* trees [*Cavender-Bares and Holbrook*, 2001]; g is the gravitational acceleration constant, 9.81 m s^{-2}; and 10^{-6} converts from Pa to MPa. These figures indicate that a maximum of 0.075 MPa of resistance must be overcome per meter of xylem for friction and 0.0098 MPa per meter of elevation change for gravity.

[35] The groundwater table is, by definition, the location where soil or rock matric potential (Ψ_matric) equals zero. Volumetric soil water content measurements (θ) were converted to water potentials, using the following water retention curve,

$$\Psi_\mathrm{soil} = 0.1 \left(\frac{\theta}{0.44} \right)^{-2.8753}. \tag{6}$$

The curve was developed from water potential measurements collected with WP4 potentiometer (Decagon Devices, Inc., Pullman, WA) and using the pressure-plate method.

[36] The atmospheric water potential (Ψ_atmos) was calculated from

$$\Psi_\mathrm{atmos} = RT \ln \left(\frac{e}{e^\mathrm{o}} \right) \tag{7}$$

where R is the gas constant, 8.31 J g^{-1}; T is the air temperature in Kelvin; e is the water vapor pressure; e^o is the

Table 1. Components of the Annual Water Balance (mm)[a]

Year	2005	2006	2007	2008
Precipitation	700	880	440	380
Evapotranspiration (ET)	460	440	340	310
Change in soil storage	−120	−1	60	−20
Recharge/runoff	360	440	30	100
Tree transpiration	190	170	200	210
Grass and soil ET	270	270	150	100

[a]Note: balance is calculated for water year for the site, from DOY 296 to DOY 295 [*Ma et al.*, 2007]. For example, the 2006 water year spanned from 23 October 2005 through 22 October 2006.

saturation water vapor pressure at temperature T; e/e^o is the fractional relative humidity; and the resulting value is in MPa.

3. Results and Discussion

3.1. Groundwater Uptake From Water Balance

[37] During the four years analyzed (2005–2008), annual precipitation at the site was between 380 and 880 mm (Table 1). Of this, 310–460 mm was returned to the atmosphere through evapotranspiration; 170–210 mm from the trees and 100–270 mm from the soil and grass. Using the stand-scale water balance, we calculated that annual water loss (the combined value of runoff and recharge to the underlying groundwater) ranged from 30 to 440 mm. The annual change in soil storage ranged from -120 to 60 mm.

[38] Looking more closely at ET (Table 1), we find that its variability was primarily attributable to the variability in grass and soil evapotranspiration ($\sigma = 86$ mm) rather than to that of tree transpiration ($\sigma = 16$ mm). During the wet years (2005, 2006), additional precipitation created a longer grass growing season, allowing for higher ET rates. In 2006, the site received upward of 880 mm of precipitation, 50% of which was returned to the atmosphere through evapotranspiration from the soil and the vegetation. Of this 440 mm of ET, tree transpiration accounted for 170 mm (39%) while the grass and soil ET was 270 mm (61%). In contrast, during the dry years (2007, 2008), the site experienced significantly lower rainfall. Evapotranspiration, however, was not reduced correspondingly; in 2008, it dropped to 310 mm per year, around 80% of precipitation. This same year, the proportion of total ET from the grass and soil dropped dramatically to 100 mm (32%), while tree transpiration increased slightly, to 210 mm (68%). Comparing the wet and dry years, we see that the annual partitioning between tree and grass/soil fluxes was highly variable, as it depended on grass transpiration which was controlled by wet season rainfall. Despite these increases in grass/soil ET, the majority of the additional precipitation during wet years went to recharge and runoff processes; for example, their combined value was 440 mm in 2006 versus 100 mm in 2008.

[39] This water balance data suggest that trees are less susceptible to interannual variations in precipitation than grasses, hinting that they can access stored water sources that are deeper than soil moisture. At this annual time scale, though, groundwater uptake by woody vegetation was not readily apparent from the water balance. Thus, one of the possible metrics for identifying GDE was not useful (annual evapotranspiration losses did not exceed the amount of water entering the area) and the others needed to be explored.

[40] Because the oak active season (April–October) is out of phase with the bulk of the rainy season (November–

May), the trees must rely on stores of water built up over the wet winter. At the beginning of the dry season, the trees quickly deplete the soil moisture reserves (Figure 2), but they continue to transpire, albeit at much reduced rates, during the period of extremely high potential evaporation. During the summer, soil volumetric water content stays at a more or less constant rate, near 10% for most soil layers. While the soil moisture does decrease very slightly over the dry season, it does not appear that a sufficient volume of water is removed to account for the levels of water transpired. This pattern contrasts with that of the groundwater levels (Figure 2), which decrease steadily throughout the summer.

[41] Breaking the stand-scale water balance into monthly segments (Figure 3), we see this same pattern again; recharge of the aquifer occurs during the wet months, and uptake by the oaks occurs during the dry ones. Over the course of the year, total stand ET was highest when both the trees and grasses were active (March through May), reaching a maximum of 80–100 mm per month. After soil moisture is reduced and the grasses senesce, rates of transpiration decrease. They are around 30 mm per month in June and decrease to 6 mm per
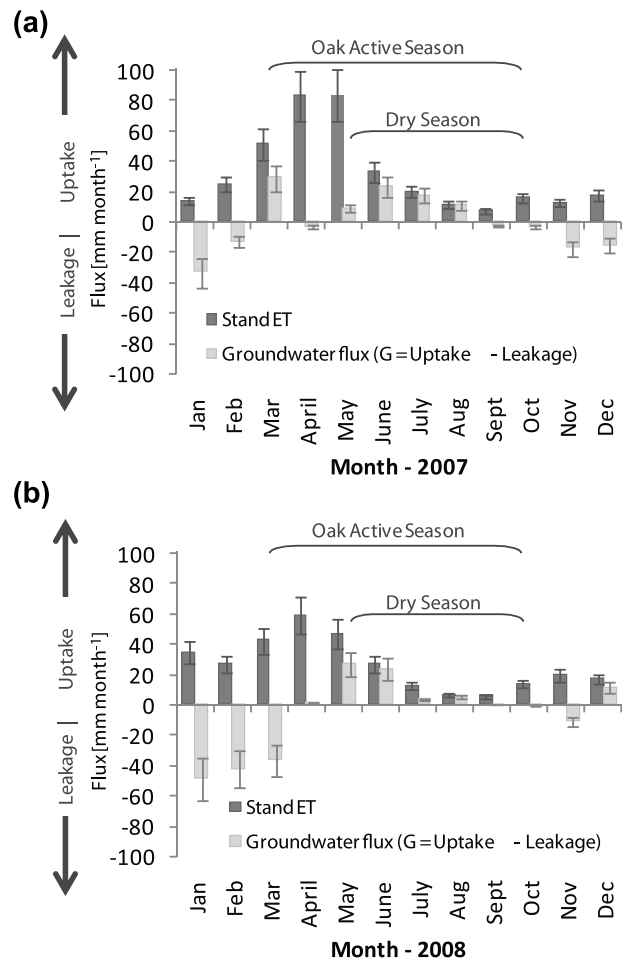

Figure 3. Groundwater uptake from stand water balance. Monthly groundwater uptake calculated using stand water balance for (a) 2007 and (b) 2008. Positive fluxes indicate that uptake is occurring; not enough soil moisture is removed to account for all stand transpiration. Negative fluxes indicate leakage from the soil, i.e., water is traveling out of the 60 cm soil column and recharging the groundwater.
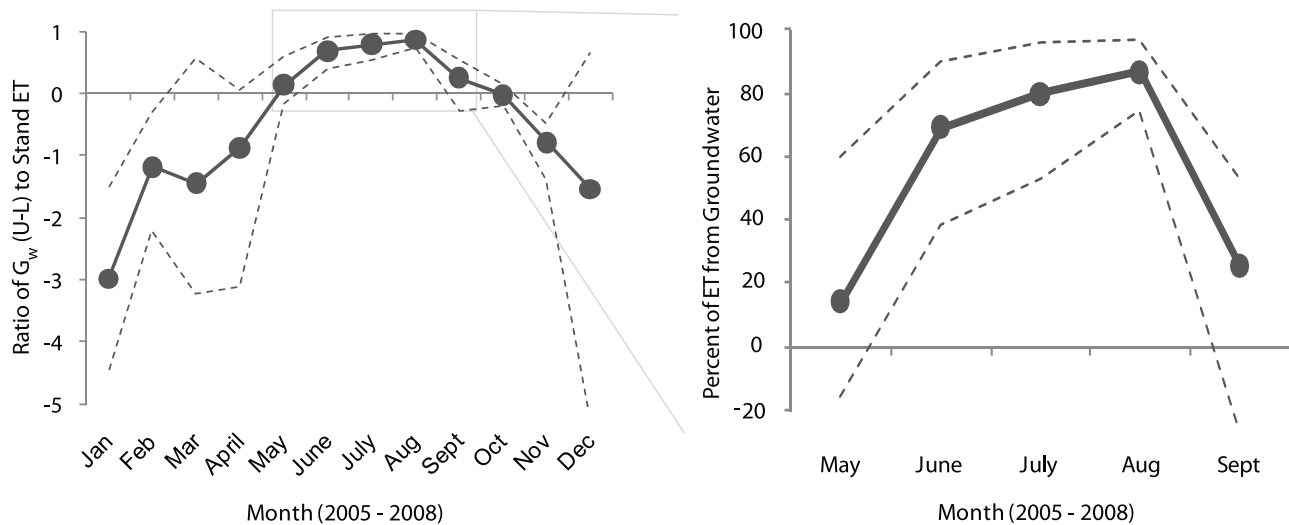
Figure 4. Annual variation in ratio of groundwater flux to ET. Groundwater flux (G_w) is computed as the remainder of the water balance and represents the difference between uptake by plants and leakage from the soil layer (U - L). When positive, this ratio represents the portion of the overall tower evapotranspiration that comes from groundwater uptake by woody vegetation (G_w/ET). When negative, the values denotes the net leakage from the soil zone, which can be up to 5 times that lost through evapotranspiration. The percent of ET from groundwater, shown in detail on the right, had high annual variability. For instance, it ranged from 55% to 95% during the month of July. However, despite being such a large fraction of ET, the actual value of G_w varied widely. For 2005 to 2008, it was between 3.7 and 40 mm per month in July and August.

month in August and September. However, this period is when groundwater uptake occurs. It begins in May or June, depending on the date of last precipitation, and lasts until September or October, when the rainy season starts. According to the water balance data, uptake from groundwater can amount to almost 90% of the total stand ET during these months.

[42] As the wet season begins, the tree leaves senesce and grasses are again active. For any given year, the total grass transpiration occurring from October to February is highly dependent on the frequency and intensity of rain events during the wet season. Loss of moisture from the soil, or leakage, occurs, recharging the underlying, deep stores of water at rates between 30 and 100 mm per month. These numbers are uncertain, however, in wet years, when runoff may occur. Little or no runoff after rain events was observed during 2007 and 2008, the dry years.

[43] Year-to-year, this recharge, as compared to evapotranspiration, is highly variable and depends on precipitation. Uptake from groundwater, though, is more consistent. Figure 4 shows the ratio of ET that comes from groundwater uptake, denoted as G_w/ET, where $G_w = U - L$. During the wet months, variability is high and the ratio is typically negative, indicating leakage. As the summer dry months progress, the range decreases. In June, the proportion of ET from groundwater uptake is 40%–90%, while it is 75%–97% in August, when soil moisture resources are only rarely present. These ratios are consistent with literature reports on similar species, which have noted seasonally dependent uptake composing between 20% and 50% of total transpiration by *Juniperus ashei* and *Quercus fusiformis* trees [*McElrone et al.*, 2003 and *Jackson et al.*, 1999]; over 70% in an oak savanna dominated by *Quercus ilex ssp. rotundifolia* [*Paço et al.*,

2009]; 14%–70% in a semiarid shrubland system [*Scott et al.*, 2008a]; and 9% in old-growth coniferous forests [*Warren et al.*, 2007].

[44] While the proportion of ET from groundwater uptake is high during the summer months, the absolute amount of evapotranspiration is low, indicating that the trees still experience water stress. This may be a function of limited root transmission capacity and suggests an interesting hypothesis: a few deep roots may be providing for a low level of activity to sustain the plant during the summer, but the amount of carbon allocated to the roots is insufficient to build a deep root system extensive enough to prevent water stress. It follows that the primarily purpose of the deep roots may be to serve as a mechanism to avoid severe drought stress, serving as a buffer during years with below normal precipitation. The question then is: why not allocate more carbon resources to deep root development? It could be an issue of dimensioning returns. It may be that the trees rely on the presence of preexisting fractures in the hard rock matrix. If too many of these fractures are filled with roots, the permeability and porosity of the aquifer decreases, reducing overall water availability. A trade-off may exist between having sufficient extraction pathways and sufficient flow pathways; the current state may be an optimum for this system.

[45] Using the stand water balance data is not without difficulties. First, and foremost, its sensitivity to "leakage events" prevents the calculation of the true uptake rate; only the net flux to and from groundwater can be calculated: $G_w = U - L$. For 4 months of the year, when it is not raining, this value closely estimates uptake. Uptake could be occurring outside of this time span, but it would not be detected by this method. Second, the tower latent heat flux and the soil moisture measurements are subject to error: 1% for the calibrated
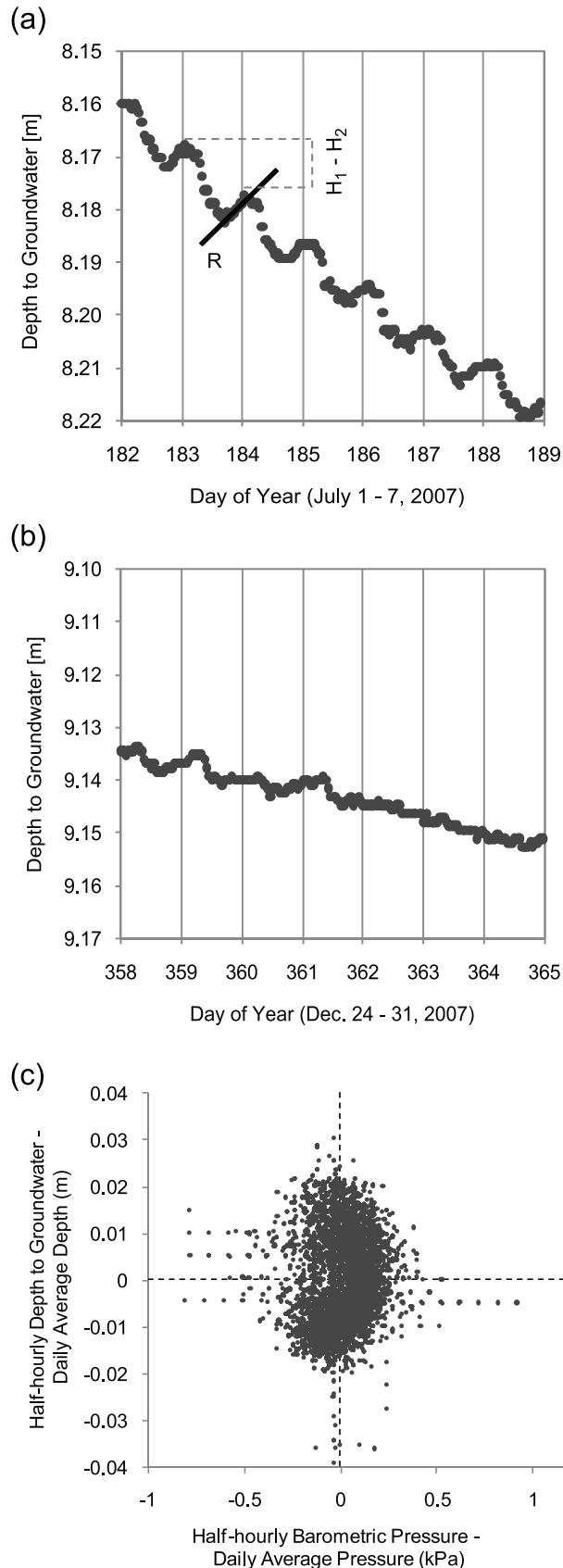
Delta T probes themselves [*Delta T Devices*, 1999] and between 5% and 25% for the eddy-covariance system [*Foken*, 2008; *Wilson et al.*, 2002]. These error values are reflected on the monthly stand water balance charts (Figure 4), but it should be noted that unquantified errors, such as those potentially caused by a lack of sample representativeness, are not included.

[46] With the soil moisture probes, there is the added difficulty of capturing spatial representativeness. To account for horizontal variability, an average of the tower probe and all of the sap flow station probes was used. Finding a representative soil moisture value that described the changes with depth was more complicated. A root weighted averaging method was used [*Miller et al.*, 2007], but given that there were only three depths measured, there is considerable uncertainty in the soil moisture portion of the tower water balance. While the Moisture Point probes provide a more integrated view of the soil profile, they can only capture weekly changes in soil moisture, leading to a lack of temporal resolution.

3.2. Groundwater Uptake From Diurnal Fluctuations

[47] While the stand level water balance allows for an analysis of multiple years using existing data, more direct measures are necessary to capture the patterns of year-round uptake. In this regard, the analysis of the groundwater data is very useful. Diurnal fluctuations in the depth to the groundwater table were observed during the oak active season (Figure 5a) and disappeared after the senescence of the oaks was complete (Figure 5b). The pattern of the daily fluctuations strongly supported oak groundwater uptake; the depth to the water table increased during the daylight hours, when the trees were transpiring, and decreased during the nighttime, indicating recharge of the aquifer. The patterns were similar to those that have been noted in other arid or riparian ecosystems [*Bauer et al.*, 2004; *Loheide*, 2008; *Vincke and Thiry*, 2008; *White*, 1932].

[48] To examine the possibility that these fluctuations were due to changes in atmospheric variables, we tested for correlations between the groundwater depth and pressure, as measured by the nearby meteorological equipment. Figure 5c plots the half-hourly fluctuations of groundwater depth and pressure about their daily mean values. No correlations were apparent, even when potential time lag effects were taken into account.

Figure 5. Diurnal groundwater fluctuations. Change in groundwater table fluctuations during (a) oak active season and (b) senescent season. Fluctuations are largest during the summer months when uptake is occurring and lowest during the winter months when recharge and uptake are both low. Groundwater fluctuations are a more direct measurement of uptake than the water balance, which is sensitive to individual precipitation/leakage events. In addition to the fluctuations, the relatively rapid decline of the water table in the summer months (0.007 mm d^{-1}) supports groundwater uptake by plants. After transpiration has ceased, the decline is reduced to 0.002 mm d^{-1}, which likely represents the baseline groundwater flow under a regional gradient. (c) Changes in barometric pressure and groundwater levels do not appear to be correlated. Their half-hourly fluctuations about the daily average are shown above, for 2008.

Table 2. Daily Uptake from Groundwater Fluctuations for 7 Days in July 2007

DOY	ET_g	ET	ET_g/ET (%)
182	0.26	0.97	27
183	0.60	0.78	77
184	0.58	0.76	76
185	0.45	0.75	60
186	0.37	0.71	51
187	0.41	0.96	43
188	0.50	0.65	76
Total	3.16	5.59	57

[49] Using the minimum residual sum of squares method described in section 2.2.1, the value of S_y^* was estimated to be 0.056, with a residual standard deviation of 0.31 mm d^{-1}. This value is consistent with the high end of literature estimates for fractured crystalline rocks; several authors reported total porosity values from 0 to 0.10 [*Domenico and Schwartz*, 1998; *Freeze and Cherry*, 1979] and specific yields of 0.02 to 0.05 [*Singhal and Gupta*, 1999]. In other rocks with significant secondary porosity, such as shale and limestone, specific yield was found to be between 0.005 and 0.05 [*Driscoll*, 1986]. All subsequent calculations of ET_g use this specific yield value of 0.056.

[50] To see how fluctuations in the groundwater level translate into uptake rates, equation (2) was applied to data from 7 days in July 2007 (Figure 5). Using this method, we found that groundwater uptake (ET_g) was between 0.26 and 0.60 mm d^{-1}, for a total of 3.16 mm. The eddy-covariance system measured daily stand evapotranspiration at 0.65–1.0 mm d^{-1}, for a total of 5.59 mm. These numbers indicated that over this 1 week period, approximately 57% of transpired water came from deep sources (Table 2). Day-to-day variability in this uptake was somewhat high; the ET_g rate and the ET_g/ET ratio had standard deviations of 0.07 mm d^{-1} and 12%. Changes in this ratio were positively correlated with changes in vapor pressure deficit and net radiation, suggesting that plant physiological processes, such as stomatal control, are at work here. This link may be fruitful to explore in the future, given additional data sets.

[51] Examining these daily uptake rates during 2007 and 2008 (Figure 6a), we saw similar day-to-day variability. However, compared to the stand evapotranspiration rates, groundwater uptake was steadier throughout the growing season, at about 0.25–0.4 mm d^{-1}. This trend suggests that there is a baseline uptake level which fluctuates slightly based on atmospheric conditions. It is also not as susceptible to precipitation events, the problem noted with the stand scale water balance. As shown on Figure 6, the tower-derived estimate of water uptake frequently became negative in the wet months. This problem did not plague the fluctuation derived values, shown in blue, with the exception of several days in January of 2008 when large rain events occurred. These events caused the summed flux for the month to also be negative (Figure 6).

[52] Looking at the monthly sums in Figure 6b, we found that groundwater uptake occurs for a wider span of the year than suggested by the water balance data. This uptake started in April, rather than May, and continued until the beginning of December. Rates from April through July of 2008 ranged from 18 to 25 mm month^{-1} and dropped slightly in August

to 12 mm. Groundwater uptake continued to occur until mid-December, much longer than previously assumed. This late-season uptake may have been due to the activity of individuals that were still transpiring after the majority of trees have lost their leaves or due to groundwater use by the evergreen grey pines at the site. As with the eddy-covariance data, these measurements are subject to some uncertainty. Two errors influence the uptake rates from the fluctuation method: uncertainty in both the specific yield parameter and in the pressure transducer measurements themselves. We estimated specific yield to be 0.056, with a residual standard
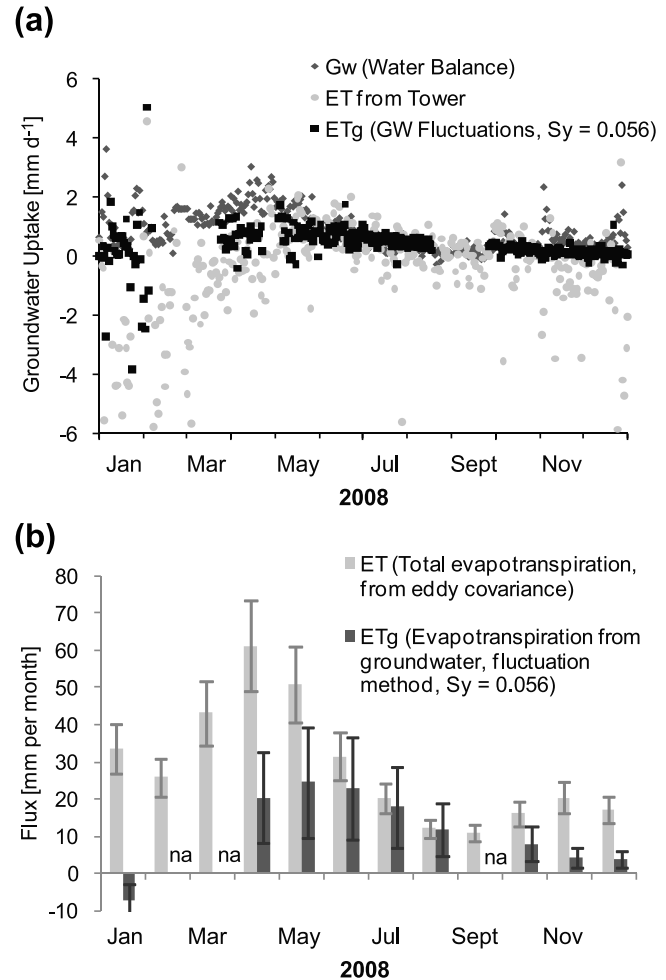

Figure 6. Daily and monthly groundwater uptake from fluctuation method. (a) Groundwater uptake occurs longer than previously suspected, continuing into December when only a small fraction of trees are still active. (b) Its measurement is subject to error due to estimation of the specific yield. Neither method is error free, however. The water balance method produces occasionally erroneous values in G_w at the daily scale. Large peaks in rainy season groundwater uptake are typically balanced out by equally large negative values the following day. This effect is likely due to the soil moisture wetting fronts associated with precipitation events, and the inability of the method to adequately account for them. This is one of the major drawbacks to the water balance method that is eliminated by the groundwater fluctuation method.
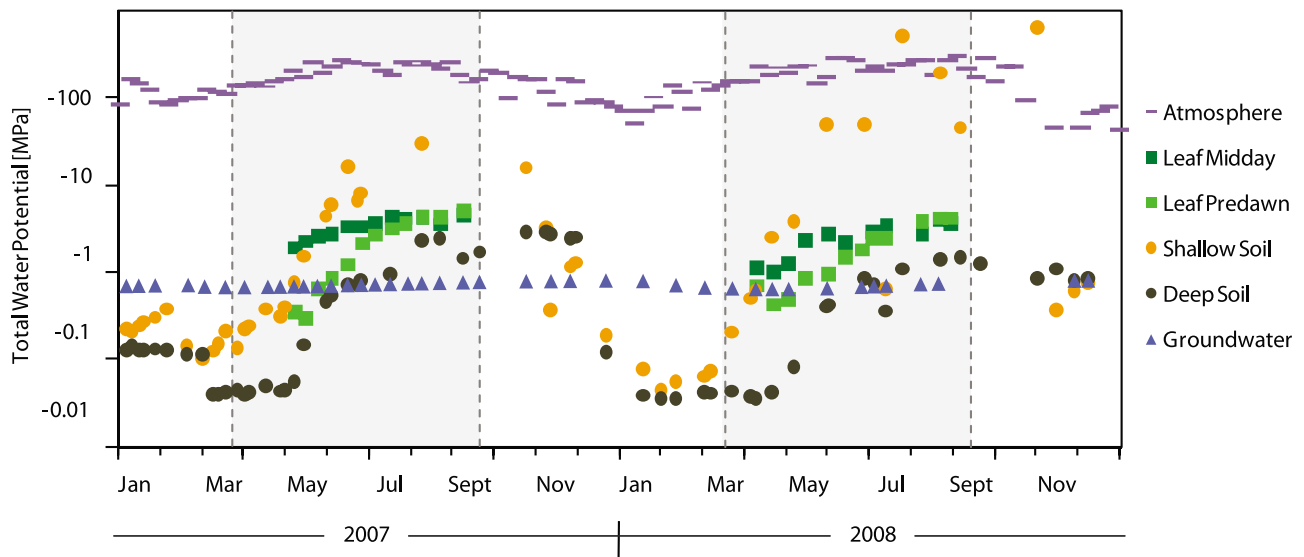
Figure 7. Water potential across the GSPA continuum. Total adjusted water potential measured in the leaves, soil, and at the groundwater table. All measurements are adjusted to account for the frictional and gravitational resistance associated with moving sap water upward through the xylem (approximately 0.09 MPa per meter). The gray bars indicate the portion of the year when the majority of the blue oaks are active. Surface soil measurements were collected at a depth of 5–10 cm, while deep soil measurements occurred near the soil-rock interface, 50–60 cm below the surface.

deviation of 0.3 mm d^{-1}, an uncertainty of around 60%, as shown in Figure 6b.

[53] Investigating the late-fall, early-winter transpiration issue, we noted that at the site, tree senescence typically occurs at the end of September. The fluctuation method indicated, however, that uptake was still occurring in early December 2008. What explains this discrepancy? The date for senescence is typically selected when a certain percentage of trees have lost their leaves for the winter. However, through careful observation in 2008, we noted that leaf fall for select, individual trees can be much later. The evergreen grey pines, which are within the tower's footprint [*Kim et al.*, 2006], may have been responsible for some groundwater uptake, but it is impossible to differentiate the two using these methods.

3.3. Evidence of Uptake in Water Potential

[54] Water potential measurements can help determine if uptake is possible or even favorable from a "thermodynamic" perspective. For all of the oak active season, the midday leaf water potential was sufficiently negative to induce ground-water uptake (Figure 7). For instance, in July of 2007, the adjusted groundwater potential was around −0.8 MPa, while soil moisture potentials were at −1 and −12 MPa. During the day, the driving potential at the leaf surface was −3.4 MPa. This potential should be sufficient to extract and transport both groundwater and deep soil water to the leaf, although it takes less energy to use the groundwater (−0.8 MPa versus −1 MPa). Shallow soil moisture cannot be extracted, as more suction is required than what was present at the leaf surface (−12 MPa required versus −3.4 MPa present).

[55] Further, groundwater uptake was energetically favored over uptake from the shallow surface soil (<10 cm) during the entire dry season, from late March to late November, and over uptake from deep soil (40–50 cm) during the summer

months, from late June to late November. These dates roughly corresponded to the time when the water balance data indicated a transition in source water, early June, and through the time when they indicated the end of uptake, early December.

[56] Water potential differences also provided an alternate hypothesis for the uptake seen in the water balance after senescence; hydraulic redistribution may have occurred. During redistribution, the deep roots of a plant passively uptake groundwater and rerelease it through shallow roots into dry surface soil layers. *Hultine et al.* [2004] noted such behavior in another woody phreatophytic species, *Prosopis velutina* Woot., "despite the absence of crown transpiration during the dormant season." A negative potential gradient between the saturated and unsaturated zones can induce this effect. On the basis of the water potential data (Figure 7), such a gradient was present at the site until early December 2007 and then again until late November or early December 2008, making this hypothesis plausible.

[57] Regardless of the favorable energetics, uptake is only possible if a sufficient number of roots are present at the depth required; the necessary plant hydraulic architecture must be present in order to take advantage of groundwater resources. Deep penetration of woody plant roots into fractured rock has been documented and is plausible at this site. In one study in Southern California [*Hellmers et al.*, 1955], canyon live oaks (*Quercus chrysolepis* Liebm.) and California scrub oaks (*Quercus dumosa* Nutt.) were directly observed to penetrate up to 7.3 and 8.5 m deep, respectively, into cracks and fractures in unweathered rock. Using triti-ated water as a tracer, the previously cited *Lewis and Burgy* [1964] study documented groundwater uptake by blue oaks, indicating that the trees could penetrate through up to 20.4 m of fractured, metamorphic rock; very similar circumstances to those present at the Tonzi Ranch site.

[58] The largest errors associated with this method relate to the conversion of soil moisture to water potential, since it is extremely difficult to measure such negative (<-10 MPa) soil matric pressure in situ. The water retention curve discussed earlier was used to estimate the potential from the volumetric water content. These values correlate well ($r^2 = 0.96$), but do have some uncertainty. Predawn and midday leaf water potentials can be measured to a 0.1 MPa resolution, but these are subject to sample variability. A standard deviation of around 0.42 MPa in the nighttime and 0.27 MPa in the daytime was common.

[59] The procedure to adjust the water potential for the frictional resistance encountered is also subject to uncertainty. In this analysis, a constant value of K_s was estimated, based on the literature. In reality, this parameter would not be constant, and xylem friction would vary depending on location in the stem, the vessel diameter, and the time of year. Typically, the combined frictional and gravitational gradient along a stem is between 0.02 and 0.2 MPa m^{-1}. However, the conclusions of the study are not overly sensitive to the value selected. Using the lower value, we found that groundwater uptake was not only possible, it was energetically favorable for most of the growing season. Using the higher value, we observed that deep soil moisture and groundwater were more competitive from an energy perspective. While more negative matric potentials make soil moisture more difficult to extract, higher friction makes groundwater more difficult to transport. In this scenario, groundwater uptake may not occur during the early part of the growing season in spring 2008. For future applications, we recommend that an effective stem hydraulic conductivity be measured along with leaf water potential.

4. Conclusions

[60] Woody vegetation in the California oak savanna uses a significant amount of groundwater during the late spring and early summer months, as soil moisture reserves are depleted. Direct measurements of water table fluctuations provide the most reliable method for determining its quantity; in this study, these indicated uptake rates between 15 and 23 mm per month for late April to July and between 3 and 13 mm per month from August to early December. During the dry summer, these rates occasionally accounted for almost all of the evapotranspiration measured by the tower, but typically ET$_g$ was around 70%–90% of ET. This conclusion was also supported by the stand water balances, which revealed similar groundwater uptake patterns in the dry season with total June, July, and August ET$_g$/ET ratios around 80%. These estimation techniques suffer from a variety of problems, primarily that they are sensitive to precipitation and leakage events and that they demand extremely accurate equipment.

[61] Although they represent indirect evidence, water potential measurements strongly support these conclusions. Not only did they show that uptake is possible, they showed that it is often energetically favorable over soil moisture extraction, supplying an independent confirmation of the direct measurements. Provided that they have sufficiently deep rooting systems and that the cohesive theory of sap ascent is correct, oak trees at the site should be using groundwater for over half the year.

[62] On the basis of these lines of evidence, we can conclude that the blue oaks are indeed obligate phreatophytes. The ecosystem meets three of the six criterion suggested by *Eamus et al.* [2006a] for determining groundwater dependence: sufficient rooting depths, fixing carbon during dry periods (no drought deciduous behavior), and daily changes in groundwater level. Additionally, a large percentage of water transpired in the summer comes from deep, long-term stores rather than shallow, ephemeral sources. Early circumstantial evidence suggests that as the water table declines in the dry season, certain trees begin to senesce while others continue to be active. Exploring this possibility may also provide clues as to how tree rooting extents change with diameter, species, or stand location and how adaptable vegetation is to both short and long term changes in groundwater availability.

[63] Groundwater use by the blue oak species has implications for ecosystem survival under a changing hydroclimate. Given access to groundwater, a longer dry season or increased average time between precipitation events would not be as severe a threat to the oak ecoregions of California. Nonetheless, these changes could limit carbon fixation even further, as groundwater seems to provide for sustenance, but not growth. Long-term, lower carbon uptake rates could inhibit reproductive processes, while more frequent droughts could reduce seedling establishment, since groundwater is not available to them. The combination could lead to the eventual conversion of the stand to pasture, as older trees die and new seedlings do not take their place.

[64] Considerations of recharge make the situation more complex, as the effect of these potential changes on the groundwater levels are largely unknown. The site is located very near the area where Sierra Nevada snowmelt recharges the Central Valley aquifer. Despite its location, it sits on low-porosity metamorphic rock rather than the highly porous alluvial deposits less than 50 km away. As such, the trees access what should be considered "local" groundwater, and it is very unlikely that the two groundwater systems are hydrologically connected. In one respect, this makes the system less susceptible to anthropogenic influence, namely pumping in the Central Valley. On the other hand, recharge then depends on local precipitation or run-on, primarily in the wet season.

[65] Overall, groundwater uptake serves to buffer seasonal fluctuations in precipitation. In this capacity, it can be viewed as a critical survival strategy for woody vegetation, on both an annual and perhaps long-term basis. This study examined a California oak savanna for this behavior and confirmed that blue oaks were obligate phreatophytes, quantified their rate of groundwater uptake, and demonstrated several field methods for identifying groundwater dependent ecosystems.

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