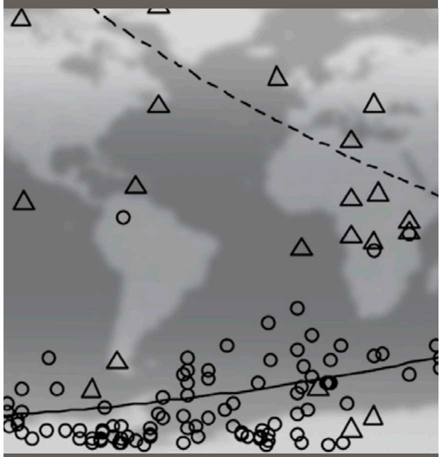
Review and Analysis

John H. Kim*
Robert B. Jackson

A Global Analysis of Groundwater Recharge for Vegetation, Climate, and Soils

Because groundwater is an essential resource for people and ecosystems, a better understanding is needed of the fundamental controls on recharge and its interactions with vegetation change. We analyzed >600 estimates of groundwater recharge to obtain the first global analysis of recharge and vegetation types. Globally, croplands had the highest proportion of water input (WI = precipitation + irrigation) that become recharge, followed by grasslands, woodlands, and scrublands (average proportional recharge: 0.11, 0.08, 0.06, and 0.05, respectively; $P < 0.0001$). A stepwise regression model revealed that WI had the strongest association with recharge overall, followed by vegetation type, potential evapotranspiration (PET), saturated hydraulic conductivity based on soil texture (K_s), and seasonality of rainfall (R^2 = 0.29, 0.16, 0.12, 0.06, and 0.01, respectively; $P < 0.0001$). Recharge increased with increasing WI, K_s, and seasonality of rainfall and decreased with increasing PET. Relative differences in recharge among vegetation types were larger in drier climates and clayey soils, indicating greater biological control on soil water fluxes under these conditions. To further test the relationship between recharge and vegetation, we compared global synthesis data to our parallel field estimates of recharge in paired grasslands, croplands, and woodlands across the Argentinean Pampas and the southwestern United States. Our field estimates of recharge were similar to, and followed the same pattern of, recharge under vegetation types in the synthesis data, suggesting that land-use changes will continue to alter recharge dynamics and vadose zone processes globally. The results of this study highlight the implications of land-use management for sustainable groundwater use and should also help test and improve recharge estimates in large-scale water balance and climate models.

Abbreviations: AI, aridity index; ET, evapotranspiration; PET, potential evapotranspiration; PWE, potential water excess; WI, water input.



Vegetation exerts a strong control over the hydrological cycle, including groundwater recharge, which provides water for many human and natural communities. Understanding the effect of vegetation on recharge globally within the relevant physical constraints such as climate and soil will help land-use decisions for sustainable groundwater management.

J.H. Kim, University Program in Ecology, Duke Univ., Durham, NC, 27708; and R.B. Jackson, Nicholas School of the Environment, Biology Dep., and Center on Global Change, Duke Univ., Durham, NC, 27708. *Corresponding author (john.kim@duke.edu).

Vadose Zone J.
doi:10.2136/vzj2011.0021RA
Received 5 Mar. 2011.

Open Access Article

Groundwater sustains the lives of one quarter of the human population (Ford and Williams, 1989; White et al., 1995) and is vital for industrial, agricultural, and recreational activities and for the health of other species and ecosystems (Postel and Carpenter, 1997; Jackson et al., 2001). Its importance is most apparent in arid and semiarid regions, where a paucity of surface waters often leads to greater groundwater exploitation. Given the increasing use and scarcity of groundwater in many locations, and its relatively slow replenishment, sustainable groundwater use and management are necessary to meet the needs of people and ecosystems (Shiklomanov, 1997; Shah et al., 2000; Vörösmarty et al., 2000).

The relationships between groundwater recharge and physical variables have long been of scientific and practical interest, traceable back to ancient Roman times (Dr. Nitish Priyadarshi, earthday.ning.com/profiles/blogs/1734264:BlogPost:24384 [verified 23 Oct. 2011]). Previous studies have identified climatic and geologic factors as major environmental controls on the rate of groundwater recharge. In general, recharge increases with the amount and intensity of rainfall, which influence how much water enters the soil and rocks (Lvovitch, 1970; Freeze and Cherry, 1979; Bredenkamp, 1988; Edmunds, 2001a; Jan et al., 2007; Stonestrom et al., 2007). In contrast, recharge typically decreases with increasing PET, an expression of the amount of energy available to evaporate water (Thornthwaite et al., 1957). Once in the soil, the movement of water is influenced by soil texture and structure, with sandier soils tending to have greater rates of recharge and more clayey soils having increased tortuosity and more limited water movement (Athavale et al., 1980; Kennett-Smith et al., 1994). Such general relationships are already important for use in some global models (e.g., Döll et al., 2003).

One aspect of recharge that is less well understood and rarely incorporated into global land-surface models is the effect of vegetation on recharge (Jackson et al., 2000; Gerten et al., 2004). Examples of key uncertainties include the primary effect of vegetation type compared with the physical climate and soil variables, as well as how changes in vegetation interact with climate and soils to alter recharge. Although considerable research has examined physical factors as controls of recharge, earlier work has rarely emphasized the effects of vegetation (but see Lull and Munns [1950] and also Petheram et al. [2002] for a review of Australian studies). Several studies have included vegetation in attempts to model groundwater recharge at various scales (i.e., Finch, 1998; Keese et al., 2005; Döll and Fiedler, 2008), although most have found or assumed the relationship to be of secondary importance compared with the effects of physical factors such as climate and soil on recharge.

Plants often mediate water fluxes between the soil and the atmosphere through the uptake of soil water by roots and through evapotranspiration (ET) from leaves, with plant traits such as rooting depth, leaf area, and phenology affecting the magnitude and duration of these fluxes (Skiles and Hanson, 1994; Neilson, 1995; Milly, 1997; Kergoat, 1998; Peel et al., 2001; Jackson et al., 2008). Pervasive land-use and land-cover changes from anthropogenic and natural forces could have large consequences for groundwater recharge and potentially for downstream effects such as salinization (Walker et al., 1999). Building on earlier studies of land use and recharge, including studies in Australia (Petheram et al., 2002) and in arid and semiarid regions (Scanlon et al., 2006), we examined the relative importance of vegetation in the relationship between recharge and physical factors.

We compiled a new global synthesis of groundwater recharge rates and data for different climates, soils, and vegetation types to understand how different vegetation types affect recharge. We hypothesized that vegetation would exert as strong an influence on recharge as climate and soils do. Moreover, we expected strong interactions among plant, climate, and soil factors that would create predictable patterns of recharge under different vegetation types. Among vegetation types, we emphasized croplands, grasslands, and forests because shifts among these common land covers represent most of the ongoing land-use changes today (Meyer and Turner, 1994; Klein Goldewijk and Battjes, 1997). To test the synthesis data and to compare recharge under paired vegetation types, we also collected new field data from paired land uses across precipitation gradients in central Argentina and the southwestern United States. We applied our findings to examine how land-use and land-cover changes may affect recharge across climatic and soil factors.

Conceptual Model of Recharge

A conceptual model of recharge suggests several important soil and climate factors that affect recharge:

$$R = \alpha P - \mathrm{ET} - \mathrm{d}S/\mathrm{d}t \qquad [1]$$

where R is recharge (mm yr^{-1}), P is precipitation and irrigation (mm yr^{-1}), dS/dt is any change in soil moisture storage (mm yr^{-1}), α is the proportion of P that becomes throughfall, and ET is an evapotranspiration term that is a function of soil water availability and the energy available for evaporation (mm yr^{-1}). Vegetation is likely to affect α through the interception of rainfall by leaves and branches and to affect ET through such factors as the coupling of vegetation to the atmosphere (e.g., through more leaves or taller vegetation stature) and to soil moisture (e.g., through deeper roots). The studies that we reviewed globally and our specific study sites were located in relatively level landscapes to minimize the effect of runoff, which is not considered in this conceptual framework.

Because available soil moisture can become either ET or R, the potential rate at which water moves through the soil matrix, and therefore out of the zone of root uptake, is another important determinant of recharge. When there is uniform matric potential, recharge is affected largely by the gravitational gradient and represented by simplified Darcy's law (Clapp and Horneberger, 1978):

$$R = K_s \left(\theta/\theta_s\right)^{2b+3} \qquad [2]$$

where K_s is the saturated hydraulic conductivity, θ is the soil moisture below the root zone (dependent on evaporation from the soil surface, root water uptake, and downward flux of water out of the root zone as determined by the water potential gradient), θ_s is soil moisture content at saturation, and b is an empirical parameter that varies with soil texture.

Because θ, θ_s, and K_s are not always reported in published studies, we estimated K_s in our regression model of recharge based on the soil texture information that the studies provided more frequently (see below). Furthermore, because ET depends on the available soil moisture, we used the energy available for evaporation or PET as a proxy for ET. Although our approach was statistical, we chose the predictors for the regression model based on this conceptual framework. The seasonal amplitude of rainfall and synchrony of rainfall with PET are both additional important considerations in the water balance because these factors affect the downward soil water flux bypassing root uptake (Milly, 1994; Potter et al., 2005). The predictors we chose for our model were precipitation, PET, K_s, and the seasonality of rainfall in addition to vegetation type.

Fig. 1. Locations of the study sites included in the global synthesis.

Methods

We examined studies of recharge and physical variables associated with land use or vegetation type, identified using literature searches involving the keywords "groundwater recharge," "deep drainage," or "residual flux," henceforth collectively referred to as *recharge* (Petheram et al., 2002; Scanlon et al., 2006). From tables, digitized graphs, and text, we recorded recharge estimates, precipitation during the study period or the reported long-term mean (P), PET, soil texture (clay and sand contents or textural classes), K_s, vegetation type, species present, and the amount of irrigation (I), when present. In studies where recharge estimates included data from multiple years and locations, such as those using permanent boreholes for the same vegetation and soil type, we used the mean of the estimates. Across the data set, 46% of the data points came from Oceania, 19% from North America, 15% from Asia, 10% from Africa, 6% from Europe, and 3% from South America (see Fig. 1).

Because we wanted to compare the effects of biological and physical variables on recharge, we excluded data from sites with significant sources or sinks for runoff, such as sinkholes, playas, and streams. Studies that estimated recharge for <1 yr were also excluded from our analysis. Due to the large number (>2500) of studies in the search, we sorted the results by relevance in the Web of Knowledge (Thomson Reuters, Philadelphia, PA) and included studies until fewer than two out of 10 additional studies yielded data on the following variables: recharge, vegetation type, precipitation, irrigation, and soil texture or K_s.

For the vegetation analyses, we divided plant types into five broad categories: cropland, grassland, woodland, scrubland, and no vegetation. Annual agricultural fields were classified as croplands; grasslands and pastures as grasslands; forests and woodlands as woodlands; scrublands, heathlands, shrublands, steppes, fynbos, and savannas as scrublands; and areas with sparse or no vegetation as "NoVeg."

Most studies did not provide data for PET or the seasonality of rainfall, and these variables were therefore obtained from the high spatial resolution (10′ by 10′) Climate Research Unit global data set (New et al., 2002; csi.cgiar.org/cru/index.asp [verified 24 Oct. 2011]), using locations of sites given in the studies. We calculated PET using the Penman–Monteith equation from the monthly climate data set. We defined two variables associated with the seasonality of rainfall (Milly, 1994; Potter et al., 2005): (i) the difference between the maximum and minimum mean monthly rainfall (amplitude); and (ii) the number of months between the maximum mean monthly temperature and precipitation (phase). Water input, the aridity index (AI), and potential water excess (PWE) were calculated as $P + I$, $(P + I)/\text{PET}$, and $P + I - \text{PET}$, respectively, to identify the climatic index with the strongest associations with recharge.

We estimated K_s using soil texture classes (Rawls et al., 1982). Where different soil horizons existed within the depth of soil examined, the estimated K_s for the top layer was used. To ensure that our estimates of PET and K_s were reasonable, we compared them with values of PET and K_s from the subset of studies where they were reported. Our estimates matched well with reported the PET and K_s values across the studies [$n = 220, 71$; $R^2 = 0.71, 0.70$; $P < 0.0001, 0.0001$, for PET and $\log(K_s)$, respectively].

Proportional recharge (P/WI) between each pair of vegetation and soil types was compared using a Kruskal–Wallis test. Proportional recharge was used for this analysis instead of recharge because it allowed comparisons after controlling for the effect of WI. A nonparametric test was used because the data were not normally distributed. Grouping the data into two soil texture categories was done for some analyses to more easily examine the effects of soil texture on recharge: "clays" were defined as soils whose estimated K_s was <0.25 m d^{-1} (silt loam and more clayey soils) and "sands" were texture classes with higher values of K_s.

We tested all climate variables (WI, AI, PET, PWE, and seasonality) and models (linear, logarithmic, exponential, and sigmoidal) to determine the best predictor of recharge. This approach was taken to choose a single best predictor variable to easily represent and compare the synthesis data with the new field data (see below). Due to the relatively low sample size (n < 50) and limited ranges in climatic variables (e.g., WI = 159–937 mm yr^{-1}) for scrublands and NoVeg, those two vegetation types were excluded from the curve-fitting and regression analyses (see below). All of the models tested were susceptible to the influence of relatively few data points at the most humid end of our data range (n = 5 for the perhumid region data); we therefore limited our curve-fitting and regression analyses to a data set without these extremely humid regions.

We tested for effects of WI, PET, vegetation type, K_s, seasonality of rainfall, and accompanying interactions on recharge using multiple regression analyses. Because of heteroscedasticity, we logarithmically transformed recharge and examined appropriate models to relate recharge to each of the predictor variables. The Breusch–Pagan test was used to test for homoscedasticity, and logarithmic transformation of recharge gave the most homoscedastic relationships with the predictor variables out of all the transformations of recharge values (untransformed, natural logarithm, and square root). We examined appropriate models (linear, exponential, and logarithmic) to relate recharge to the predictor variables individually and found that a logarithmic model explained the most statistical variation in the logarithmically transformed recharge using WI and PET and that a linear model maximized the fit of the logarithmically transformed recharge with K_s and the seasonality of rainfall (amplitude and phase). Thus, we logarithmically transformed WI and PET to linearize them with respect to the logarithmically transformed recharge for the multiple regression. We used WI and PET instead of PWE or AI for our multiple regressions to tease out the relative importance of WI and PET. Stepwise regression with whole effects was used to determine which main and interaction terms to retain in the model and to determine the relative importance of each term for recharge.

Finally, to test the reliability and predictive capability of our regression model, we used threefold cross-validation, in which a model based on a subset of the data is tested against the remainder of the data (Kohavi, 1995).

Site Description

In addition to the literature synthesis, we collected an extensive new field data set as an independent test of our global data set, using paired comparisons of adjacent vegetation types in Argentina and the United States. In Argentina, we located six sites in the Pampas on relatively level landscapes across a precipitation gradient that ranged from 382 to 1215 mm yr^{-1}. Where available, rainfed cropland and woody plant invasion (WPI) plots were paired with an adjacent or nearby (<1 km) natural grassland plot at each site. Cultivation and WPI plots correspond to cropland and woodland vegetation designations, respectively, in our literature synthesis (Tables 1 and 2).

We also selected five sites along a precipitation gradient (407–860 mm yr^{-1}) in the southern Great Plains of the United States. Land uses selected as paired plots were natural grasslands, rainfed croplands, and irrigated croplands. In both the U.S. and Argentina, most plots had >30 yr of relatively continuous land-use history (Table 1). Landowners or farm managers were surveyed for land-use history at each site, including cropping schemes (species and rotations) and fertilizer, pesticide, and irrigation inputs. Tree stand ages were verified with aerial photos or tree ring cores taken during our sampling campaign (2008–2010). Precipitation data were obtained from long-term (>30-yr) records maintained by weather stations onsite by the farm managers or from separate stations 1 to 30 km away (Instituto Nacional de Tecnología Agropecuaria, www.inta.gov.ar/index.asp [verified 23 Oct. 2011]; National Climatic Data Center, www.ncdc.noaa.gov/oa/ncdc.html [verified 23 Oct. 2011]).

In addition to our new field data, we also estimated additional recharge rates based on soil Cl^- data from five paired grassland and woody-encroached sites located across a precipitation gradient in the southwestern United States. Detailed descriptions for these sites are available in Jackson et al. (2002) and McCulley et al. (2004). We collectively refer to these and the southern Great Plains sites as our southwestern U.S. sites.

Soil Sampling

At the Argentinean sites, soil samples were taken by augering three to eight boreholes 6 to 9 m deep or to the depth of groundwater, as well as four to six shallow cores (30 cm deep), at each land-use plot. Augered samples were taken every 20 cm to the 1-m depth, then every 30 cm to the 4-m depth, then every 50 cm. The soil samples were homogenized and subsampled in the field and then frozen until analysis.

At our U.S. sites, we used a direct-push mechanical coring rig (Geoprobe Systems, Salina, KS) for five to eight cores per plot to a 8.5-m depth. At only one plot near San Angelo, TX, were soil samples not retrieved to 8.5 m because of indurated caliche found around the 5-m depth that blocked further coring. The soil cores were weighed in the field, subsampled for soil moisture and bulk density using intact cores and for elemental analysis using homogenized soil cores, then shipped to Duke University for analysis.

Table 1. Site information for our new field data in Argentina and the southwestern United States.

Site	Latitude, longitude	Precipitation	Soil†	Vegetation type‡	Time since change§
	degrees	mm/yr			yr
Nahuel Mapa	−34.8, −66.2	382	fine sand	G, W	80
Caldenadas	−33.8, −65.8	506	fine sand	G, W, C	60, 10
Dixonville	−34.7, −65.5	525	fine sand	G, W, C	60, 15
Parera	−35.1, −64.5	682	loam	G, W, C	100+, 80
San Claudio	−35.9, −61.2	1011	sandy loam	G, C	40
San Antonio	−34.2, −59.4	1219	loam	G, W, C	40, 60
Sevilleta	34.3, −106.7	277	Turney loam, sandy loams	G, W	50
Goodwell	36.6, −101.6	407	Gruver clay loam	G, C, C+I	60, 60
Tribune	38.5, −101.6	479	Richfield silt loam	G, C, C+I	30, 50
San Angelo	31.4, −101.3	514	Angelo clay loam	G, C, C+I	100, 40
Quanah	34.3, −99.8	679	Sagerton clay loam	G, C, C+I	100, 60
Vernon	33.9, −99.4	660	Tillman clay loam	G, W	40
Riesel	31.5, −96.9	840	Heiden clay	G, W, C	100+, 100+
Engeling	31.9, −95.9	1070	loamy fine sand	G, W	50

† Soil texture based on samples from the top 1 m of the soil profile.

‡ G, grassland; W, woodland; C, cropland; C+I, irrigated cropland.

§ Number of years since conversion of grassland to another land use. The numbers listed correspond to the order of land-use changes given in the previous column.

Table 2. Comparison of the proportion of water input that becomes recharge (R/WI) and potential water excess (PWE) among vegetation and soil types (mean ± standard error).

Parameter	R/WI	PWE	n
		mm/yr	
Vegetation type			
Crop	0.111 ± 0.007 a†	−677 ± 32 a	220
Grass	0.083 ± 0.009 b	−637 ± 41 a	138
Scrub	0.049 ± 0.011 c	−1116 ± 56 b	73
Wood	0.062 ± 0.009 c	−475 ± 46 c	109
No vegetation	0.178 ± 0.03 a‡	−1009 ± 77 b	39
Soil type			
Clays	0.073 ± 0.007 a	−606 ± 36 a	205
Sands	0.103 ± 0.006 b	−763 ± 26 b	374

† Different letters indicate a significant difference between each pair within the vegetation or soil type using a Kruskal–Wallis test for R/WI ($P < 0.0061$ for all significantly different comparisons except between cropland and no vegetation, see below) and Student's t-test for PWE ($P < 0.023$).

‡ Comparison of proportional recharge between cropland and no vegetation is marginally significant ($P < 0.07$).

In the laboratory, the soil samples were oven dried for gravimetric moisture content and analyzed for chemical constituents. Dried and homogenized soil samples were mixed with double deionized water at a 1:1 (w/w) ratio and shaken for 4 h. The mixture was centrifuged, the supernatant filtered, and the filtrate analyzed for anion contents (Cl^-, Br^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}) by ion chromatography (Dionex ICS-2000, Sunnyvale, CA). The Cl^- concentrations in the soil pore water were calculated by dividing the soil Cl^- contents (mg Cl kg^{-1} soil) by the gravimetric soil moisture. Soil texture was determined by the pipette method (Klute, 1986) and ranged from sand to clay (Table 1).

Groundwater Recharge Calculations

Recharge rates at our sites were estimated by Cl^- mass balance from soil samples in the unsaturated zone (Allison and Hughes, 1983). Total atmospheric inputs of Cl^- were obtained from Piñeiro et al. (2007) and Santoni et al. (2010) for the Argentinean sites and from deposition networks in the United States (National Atmospheric Deposition Program, National Trends Network, nadp.sws.uiuc.edu/ntn/ [verified 23 Oct. 2011]; Clean Air Status and Trends Network, java.epa.gov/castnet/ [verified 23 Oct. 2011]). To estimate Cl^- deposition rates at our sites, we used the distance from the ocean (Junge and Werby, 1958; Keywood et al., 1997), which correlated well with Cl^- deposition for our Argentine and U.S. study regions (Supplementary Fig. 1; $P < 0.001$, 0.001; $n = 12, 6$; $R^2 = 0.99, 0.99$ for U.S. and Argentine sites, respectively). Dry deposition at U.S. sites was estimated based on the relationship between the dryfall/wetfall ratio in precipitation across the study region (Supplementary Fig. 2; $P < 0.001$, $n = 9$, $R^2 = 0.82$). Anthropogenic inputs of Cl^- due to cultivation were calculated by multiplying the Cl^- contents of the fertilizer, pesticide, and irrigation samples obtained at the sites with the average application rates revealed in the surveys (Table 2). Assuming steady-state conditions, the recharge rate was calculated using the following mass balance equation:

$$Q_{in}Cl_{in} = Q_{out}Cl_{out} \quad [3]$$

where Q_{in} is the average volume of rain and irrigation water entering the root zone per ground area per year ($mm^3\ mm^{-2}\ yr^{-1}$), Cl_{in} is the average atmospheric and anthropogenic Cl^- input expressed as the concentration in precipitation ($mg\ mm^{-3}$), Q_{out} is the volume of water exiting the root zone per ground area per year ($mm^3\ mm^{-2}\ yr^{-1}$), and Cl_{out} is the concentration of Cl^- in the soil water exiting the root zone ($mg\ mm^{-3}$). Assuming no dispersion and diffusion of Cl^- and assuming Cl_{out} to be the average Cl^- concentration of the soil pore water below the root zone, Q_{out} is the groundwater recharge rate ($mm\ yr^{-1}$). The approximate root zone was taken to be the top 2.1 m, below which we found a linear relationship between cumulative Cl^- and cumulative soil moisture content, except for some cultivated plots where we assumed the root zone to be the top 1 m (Phillips 1994). At the Tribune, Vernon, and Riesel sites, where we did not observe complete leaching of the original Cl^- peak with cultivation, we also used the Cl^- displacement method to calculate recharge rates based on the migration of the original grassland Cl^- and changes in water profiles (Walker et al., 1991). Calculations for the Cl^- tracer displacement (CTD) method were

$$Q_{CTD} = \theta \frac{z_1 - z_2}{t_1 - t_2} \qquad [4]$$

where Q_{CTD} is the recharge rate ($mm\ yr^{-1}$), z_1 and z_2 are the depths (mm) of the Cl^- fronts corresponding to land uses at years t_1 (new, rainfed cultivation) and t_2 (old, grassland), and θ is the average soil moisture content of this depth interval. A value of 8.5 m was used as z_1 for profiles without a clear Cl^- peak, providing a lower bound estimate for recharge.

We compared results from our global data set and independent field data to estimate the influence of vegetation shifts on recharge for different climatic and soil conditions globally. We calculated the absolute and relative changes in recharge with land-use changes. For the field data, the relative change (Δ) was defined as

$$\Delta = \frac{\text{recharge}_{veg1} - \text{recharge}_{veg2}}{\text{recharge}_{veg2}} \qquad [5]$$

where recharge_{veg1} and recharge_{veg2} are recharge estimates under two different vegetation types. Grassland was the original vegetation at our field sites, and grassland recharge values were used for recharge_{veg2}.

For the global synthesis data, we used recharge predicted from the best-fit curves to calculate the absolute and relative differences in recharge among vegetation types.

Results

Vegetation and soil types had strong effects on the proportional recharge (R/WI) globally ($\chi^2 = 73.7$ and 13.9, respectively; $P < 0.0002$). On average, proportional recharge was 0.18, 0.11, 0.08, 0.06, and 0.05 under NoVeg, croplands, grasslands, woodlands, and scrublands, respectively ($P < 0.0005$ for all pairwise comparisons except scrublands to woodlands and grasslands to croplands; Table 2). Sandy soils had 50% more proportional recharge as clayey soils, on average.

Potential water excess fitted to an exponential model was the best single predictor of recharge across the data set (Fig. 2). Recharge increased with PWE for croplands, grasslands, and woodlands in both sands and clays (average $R^2 = 0.52$, $P < 0.0001$ for all vegetation–soil types; Fig. 2). Differences among vegetation types were

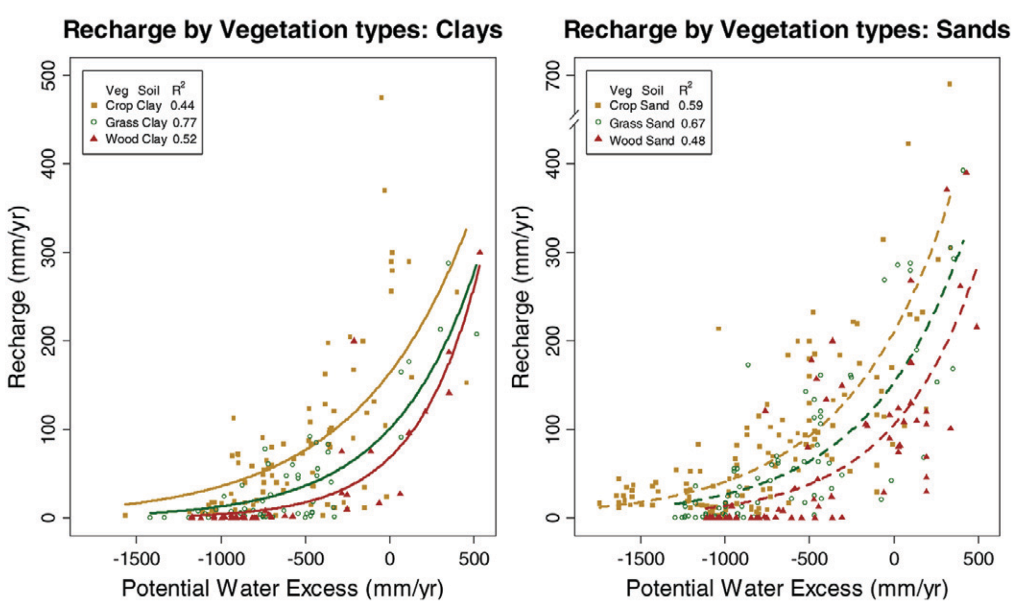


Fig. 2. Recharge and potential water excess fitted to an exponential model for three vegetation types and two soil types.

Table 3. Results from stepwise and least squares multiple regressions of logarithmically transformed recharge. Factors in the stepwise regression were selected using the Bayesian information criterion (Schwarz, 1978).

Terms†	Parameter estimates‡	Stepwise		*F* test	
		Seq. SS§	R^2	*F* ratio	*P*
Intercept	2.87 ± 1.88				
log(WI)	2.71 ± 0.159	626	0.29	292	<0.0001
Veg	1.19 ± 0.0762, 0.419 ± 0.0857, −1.61 ± 0.0896	336	0.45	193	<0.0001
log(PET)	−2.61 ± 0.190	260	0.57	189	<0.0001
K_s	0.0002336 ± 0.0000258	134	0.63	82	<0.0001
Veg × log(WI)	−1.01 ± 0.157, −0.510 ± 0.178, 1.52 ± 0.188)	119	0.69	37	<0.0001
Veg × log(PET)	0.993 ± 0.219, 0.172 ± 0.242, −1.17 ± 0.237	43	0.71	16	<0.0001
K_s × phase	−0.0000597 ± 0.0000131	17	0.72	21	<0.0001
log(PET) × K_s	0.000304 ± 0.000071	22	0.73	18	<0.0001
Amplitude	0.00408 ± 0.00105	12	0.73	15	0.0001
Veg × K_s	10^{-5}(−11.6 ± 3.38, 8.17 ± 3.58, −3.39 ± 3.79)	18	0.74	6	0.0020
log(WI) × phase	−0.188 ± 0.0668	10	0.75	8	0.0051
Phase	0.0577 ± 0.0282	6	0.75	4	0.0413

† WI, water inputs; Veg, vegetation type; PET, potential evapotranspiration; K_s, saturated hydraulic conductivity; phase, number of months between maximum mean monthly precipitation and temperature; amplitude, difference between maximum and minimum mean monthly precipitation. Interaction terms involving continuous variables are centered around their means for computational purposes, e.g., Veg × [log(WI) – 6.39]. Average values for the interaction terms were 6.39, 7.11, 1912, and 3.19 for log(WI), log(PET), K_s, and phase, respectively.

‡ Parameter estimates are given for the three vegetation types (cropland, grassland, and woodland, respectively) ± standard errors.

§ Sequential sum of squares.

evident in the fitted curves. For example, at a PWE of −250 mm yr^{-1} in clays, the predicted recharge under croplands, grasslands, and woodlands were 112, 61, and 35 mm yr^{-1}, respectively (n = 220, 138, and 109, respectively).

Water inputs in the multiple regression explained 29% of the statistical variation in recharge across the data set ($P < 0.0001$; Table 3). Other significant variables in the order of decreasing importance were vegetation type (16%, $P < 0.0001$), PET (12%, $P < 0.0001$), and K_s (6%, $P < 0.0001$), with amplitude and phase (seasonality) of rainfall contributing a statistically significant but minor 1% of the variation ($P < 0.0001$; Table 3). Recharge increased with increasing WI, K_s, and seasonality of rainfall and decreased with increasing PET. Overall, recharge was greatest under croplands, about two and 15 times greater than under grasslands and woodlands, respectively ($P < 0.0001$; Table 3, Veg term).

The interaction terms of vegetation type with climate or soil variables collectively explained an additional 8% of the variation in recharge (Table 3; Fig. 3). Of all the vegetation types, cropland recharge increased the most with WI, but grassland recharge increased the most with increasing K_s and decreasing PET. In contrast, woodland recharge was the least sensitive to K_s and PET, indicating that recharge under different vegetation types responded differently to climate and soil factors. These responses accentuated the differences in recharge among vegetation types in humid regions and in sandy soils (Fig. 3a, 3b, and 3c). The cross-validation analysis of the regression model and the data set produced comparable results, giving confidence in the model's reliability (Supplementary Fig. 3).

Our new field data set from central Argentina and the southwestern United States independently confirmed the strong differences in recharge for croplands, grasslands, and woodlands that the global synthesis revealed. Croplands had significantly lower average soil pore water Cl^- concentrations below the root zone, while woodland plots had significantly higher soil pore water Cl^- compared with their grassland pairs (Table 4; Supplementary Fig. 4; signed Wilcoxon test; $P < 0.0020$ and 0.0039 for grassland–cropland and grassland–woodland comparisons, respectively). This result indicated that the greatest recharge occurred under croplands, intermediate recharge occurred under grasslands, and the lowest recharge occurred under woodlands. This strong biological control over soil water fluxes is in close agreement with our global review (Fig. 4; Table 4). Crop cultivation using groundwater as an irrigation source resulted in a very high net discharge of groundwater (Table 4).

Our field data set also confirmed the interactive effect of vegetation and climate on recharge that the global synthesis revealed. For our global synthesis, absolute differences in recharge among vegetation types using PWE as the best-fit predictor variable were small in arid climates and grew with increasing PWE and were larger in sandy soils than in clays between grassland and woodland (Fig. 3 and 4). Relative differences were largest in arid climates and in clays (Supplementary Fig. 5), however, suggesting

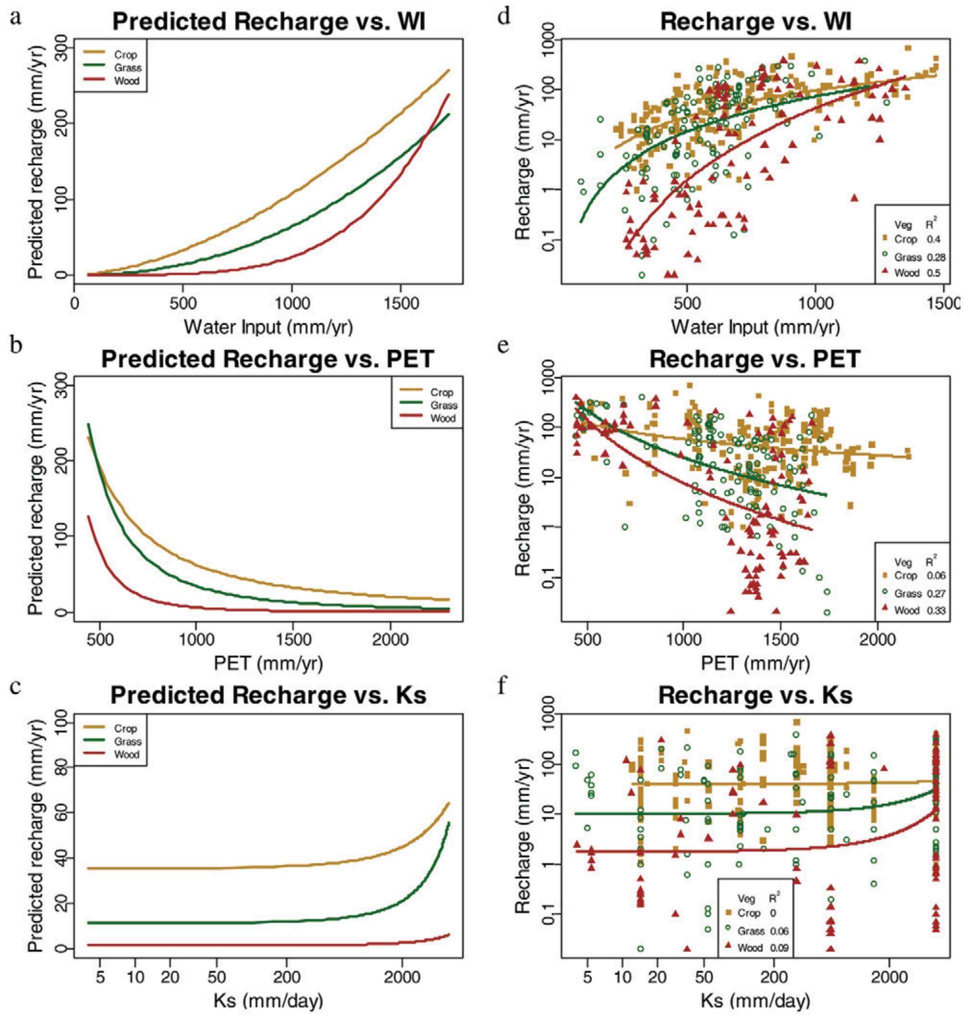


Fig. 3. (a, b, c) Predicted recharge from interaction of vegetation type and physical variables of (a) water input (WI), (b) potential evapotranspiration (PET), and (c) saturated hydraulic conductivity (K_s) in the multiple regression analysis, and (d, e, f) logarithmically transformed recharge fitted to the (d) WI, (e) PET, and (f) K_s in the data set. Recharge values were predicted from the multiple regression model holding all other terms constant around their means. Logarithmically transformed recharge was fitted without data at the very highest values of WI due to insufficient data across vegetation types. Note the different *y* axis scales.

that proportionately greater hydrologic effects of land use change may occur in more arid regions and in clayey soils. Similarly to the global synthesis, our new field estimates of recharge gains or losses due to land-use conversions of natural grasslands increased in magnitude with PWE (Fig. 4), revealing interactions between land use and the abiotic environment in determining recharge. As in the global synthesis, our field-based estimates of relative changes in recharge showed an increasing importance of vegetation effects toward lower precipitation and higher clay content areas, suggesting that while land-use changes have the potential to change recharge by large amounts in humid regions and coarse-textured soils, vadose zone processes may be particularly sensitive to land-use changes in relatively arid areas and fine-textured soils (Fig. 4; Supplementary Fig. 5).

Discussion

Although the role of vegetation in global terrestrial water fluxes is well recognized (Hutjes et al., 1998; Kucharik et al., 2000; Arora, 2002; Jackson et al., 2005), this synthesis is, to our knowledge, the first attempt to quantify the relative importance of vegetation on recharge rates globally. Vegetation was the second most powerful predictor of recharge after WI, explaining about 1.3 and three times as much variation in recharge as PET and K_s, respectively, indicating that vegetation type is often more important for determining recharge than most physical variables (Table 3). As a result, vegetation should be one of the key components of analyses or models addressing scales sufficiently large to include multiple vegetation types.

The treatment of vegetation parameters in global land-surface models are sometimes cursory and are rarely process based with regard to recharge (Gerten et al., 2004). Our global synthesis should help

Table 4. Chloride inputs and soil Cl^- values used for the groundwater recharge calculations.

Site	Vegetation type	Natural Cl^- inputs†	Irrigation	Anthropogenic Cl^- inputs‡	Soil water Cl^-§	Recharge rate¶
		mg/L	mm/yr	——— mg/L ———		mm/yr
Nahuel Mapa	grassland	0.435			34.5	4.81
	woodland				142.6	1.16
Caldenadas	grassland	0.284			19.5	7.38
	woodland				62.6	2.30
	rainfed cropland			–	11.7	12.3
Dixonville	grassland	0.357			9.2	20.5
	woodland				17.1	11.4
	rainfed cropland			–	6.5	28.8
Parera	grassland	0.338			7.75	29.7
	woodland				9.7	23.8
	rainfed cropland			–	4.0	57.6
San Claudio	grassland	0.290			13.5	21.0
	rainfed cropland			–	7.5	41.0
San Antonio	grassland	0.308			12.1	30.1
	woodland				16.3	22.4
	rainfed cropland			–	4.6	79.0
Sevilleta	grassland	0.244			1875	0.037
	woodland				4429	0.012
Goodwell	grassland	0.109			564	0.078
	rainfed cropland			0.001	38.8	1.45
	irrigated cropland		432	16.5	247	59.6
Tribune	grassland	0.089			255	0.317
	rainfed cropland			–	30.3	1.55 (4.76)
	irrigated cropland		584	5.3	47.4	146
San Angelo	grassland	0.194			266	0.47
	rainfed cropland			–	45.6	3.17
	irrigated cropland		254	112	709	60.0
Quanah	grassland	0.149			278	0.41
	rainfed cropland			–	70	3.24 (6.36)
	irrigated cropland		610	243	1071	279
Vernon	grassland	0.161			1925	0.06
	woodland				3900	0.03
Riesel	grassland	0.297			137	2.4
	rainfed cropland			–	37	7.2 (9.0)
	woodland				330	0.76
Engeling	grassland	0.302			11.7	28.8
	woodland				23.1	14.0

† Expressed as milligrams per liter of precipitation.

‡ Cl^- inputs from fertilizers, pesticides, and irrigation, expressed as milligrams per liter total water input (precipitation + irrigation). Most of the 30+ agricultural chemicals analyzed were not significant sources of Cl^-. – denotes negligible Cl^- inputs (<0.001 mg/L) from fertilizer and pesticide applications.

§ Average Cl^- concentration in the soil pore water below the root zone (>2.1 m)

¶ Average recharge rates based on Cl^- mass balance, with those based on the Cl^- tracer displacement method in parentheses.

parameterize such models and could contribute as inputs or could be used for independent testing of global water balance or climate models. For example, studies modeling the reciprocal effects of groundwater on climate (e.g., Niu et al., 2007) may benefit from better constrained estimates of recharge under different vegetation types.

Changes in recharge with land-use changes in our field data followed the patterns of recharge observed under different vegetation and soil types across our global synthesis (Fig. 4; Supplementary Fig. 5). Overall, agreement between the field and synthesis results suggests that vegetation is responsible for a large portion of the variation in recharge and that distinct patterns of recharge among vegetation types are typically clear and reproducible when covarying site factors such as soil properties are controlled for. Agricultural conversion of grasslands or woodlands would therefore probably bring about greater recharge, whereas woody plant invasion or afforestation into grasslands or croplands would probably reduce recharge. These hydrologic changes may be especially severe for land-use changes to and from woodlands because the capacity of woody plants to limit recharge leads to large differences in recharge between woodland and the other vegetation types (Fig. 2; Table 3). Loss of renewable water yield to planted or invading woody plants could be detrimental to groundwater-dependent communities, both human and natural, across long time scales. In contrast, cultivation generally increases recharge but may pose a risk of salinization or degradation of groundwater quality in some regions through associated leaching of salts through the vadose zone (Smettem, 1998; Boumans et al., 2005; Jobbágy and Jackson, 2007; Scanlon et al., 2007a). Such disruptions to the hydrologic cycle should be recognized in land management and policy decisions.

The effect of vegetation on recharge was further evident along the entire climate gradient and across soil types (Fig. 2). In our synthesis, we observed large absolute differences in recharge among vegetation types in mesic regions (high WI, low PET) and in sands (high K_s) but larger relative differences in arid climates and in clays (Fig. 4; Supplementary Fig. 5). Relative differences between grasslands and the other vegetation types in clay soils, for example, were as much as −70

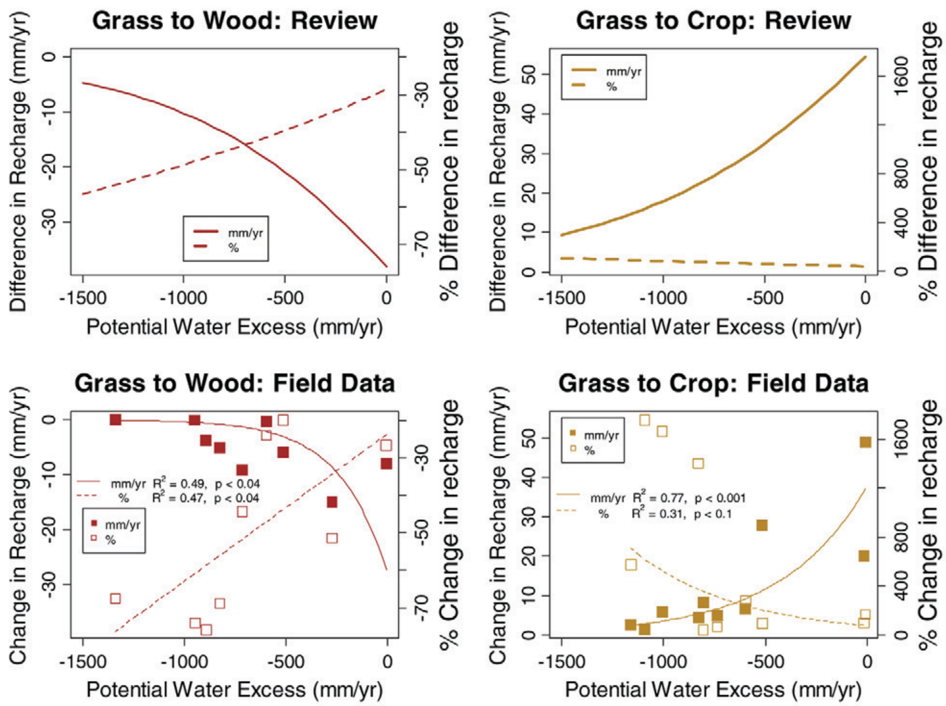


Fig. 4. Absolute and relative differences and changes in recharge between grassland, cropland, and woody vegetation from synthesis and field data. Solid lines and filled symbols denote absolute differences in recharge; dashed lines and open symbols denote relative differences. Fitted lines for the field data (bottom panels) were chosen from linear regressions on logarithmically transformed or untransformed differences in recharge.

and 250% (woodlands and croplands, respectively) in arid climates compared with only −20 and 60% in humid areas (Supplementary Fig. 5). Although the large absolute differences in recharge among vegetation types in humid climates highlight the importance of land-use changes on water yields in these climates, large relative differences in drier climates forecast proportionately important hydrologic changes in arid regions, as observed previously for stream flow (Farley et al., 2005). Mirroring the synthesis data, the observed 70% reduction in grassland recharge with woody plant invasion and >500% gain in recharge with cultivation of arid grasslands with clayey soils in our field data indicate that near-complete loss of groundwater recharge or flushing of accumulated vadose zone solutes may be possible with land-use changes (Fig. 4; Supplementary Fig. 5). The different responses of recharge among vegetation types to climate and soils warrant careful consideration of these interactions to avoid adverse hydrologic consequences of land-use changes.

Vegetation type explained a similar amount of variation in recharge as important physical variables did, and its interactions with physical variables contributed additional explanatory power. Recharge was correlated with high K_s (Table 3), but we observed this effect primarily in grasslands, which have relatively shallow root systems (2.5 m; Canadell et al., 1996). The analogous increases in woodland recharge were less pronounced. Woody plants grow deeper roots in areas with sandy soils (high K_s), in part to capture water throughout the soil profile (Schenk and Jackson, 2002, 2005); these deep woody roots may limit recharge despite higher K_s. In croplands, with the shallowest expected rooting depth (generally <2 m), recharge was generally higher than for other vegetation types but did not vary substantially with K_s. This result may be due to particular management practices in croplands, such as tillage increasing deep drainage and weakening the overall positive effect of K_s on recharge under croplands (Daniel 1999; Scanlon et al., 2008). Interactions between vegetation and physical variables such as K_s and PET collectively explained >8% of the statistical variation in recharge and helped identify potential mechanisms responsible for differences in recharge among vegetation types.

Irrigation is often used to enhance crop productivity and to meet increasing food demands given decreasing available productive land area (Kendall and Pimentel, 1994), but it also causes a large net discharge of groundwater, as we observed at our southwestern U.S. sites. Assuming that rainfed croplands represent the upper limits for recharge and irrigation uses groundwater, we consider the difficult issues of irrigation and sustainable groundwater use from a land management perspective. We observed from our global synthesis that, despite being the land use with the highest recharge, rainfed cultivation allowed only marginal recharge compared with the net discharge (irrigation − recharge) of irrigated cultivation (Fig. 5). Across a gradient of water availability, the area of rainfed cultivation needed to sustainably supply groundwater for 1 ha of irrigated agriculture decreases from 70 ha in arid climates to 0.5 ha in humid climates (Fig. 5), providing first-order approximation of the irrigated/rainfed cropland ratio necessary for sustainable

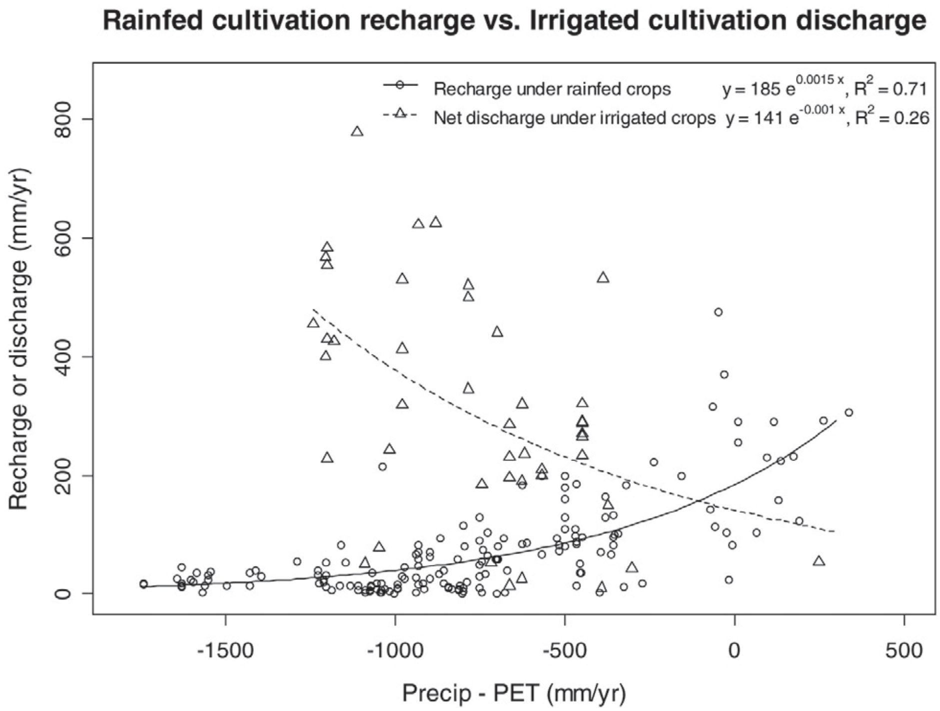


Fig. 5. Recharge under rainfed cropland (R_r) and net discharge (D = irrigation minus recharge) under irrigated cropland across water availability (precipitation − potential evapotranspiration [PET]). Net discharge under irrigated crops is up to two orders of magnitude greater than recharge. The ratio of D/R_r represents the land area of rainfed cultivation needed to provide a unit area of irrigated cultivation.

groundwater management. It points to challenges associated with providing enough groundwater for irrigated crops, especially in more arid regions where the lack of rainwater results in both larger irrigation needs and lower recharge rates under rainfed cultivation.

For the range of PWE and the recharge values analyzed, the exponential model gave the best overall fit but should not be extrapolated beyond the ranges presented in this study. For instance, with inclusion of the very limited data from perhumid regions, the sigmoidal model gave the best overall fit (data not shown), indicating that the increase in recharge with PWE may taper off in very humid regions due to the increasing importance of runoff on the water balance (Milly, 1997). Moreover, irrigation reported at most of the sites were often estimates without long-term monitoring, introducing uncertainty in our observed relationship between recharge and WI. The average uncertainty associated with irrigation from studies that reported ranges of irrigation was about 190 mm yr^{-1}. Although the effect of this uncertainty on the estimated parameters of our multiple regression were not statistically significant (data not shown), the large explanatory power of WI in our model highlights the importance of obtaining the best possible irrigation and precipitation data for recharge predictions.

In conclusion, vegetation and its interactions with other factors have a strong effect on groundwater recharge, explaining ∼24% of the global variation in recharge—more than other variables except WI. An average of 11% of WI becomes recharge under croplands, whereas only 8 and 6% do under grasslands and woodlands, respectively. Vegetation types had predictable effects on groundwater recharge, and the differences in recharge among vegetation types also varied predictably across the climate and soil variables. Independent field estimates of recharge under paired land-use plots confirmed our global synthesis results and provided a direct test of the relationships between vegetation and recharge. Significant gains and losses in recharge are possible with conversion to crops and to forests, respectively, and absolute changes in water yield accompanying land-use changes are likely to be larger in humid or sandy areas. Proportionately large relative hydrologic consequences result from land-use changes in arid or clayey regions, however, as observed previously for stream flow (Farley et al., 2005). Quantifying and predicting changes to water yield from land-use changes are necessary steps for sustainable and holistic management of water resources; our results highlight the importance of land-use change for the vadose zone and groundwater resources.

Acknowledgments

This work was supported by the National Science Foundation (DEB no. 0717191, IOS no. 0920355, and GRFP no. 2006044266). We wish to thank members of the Jackson lab for helpful comments on the manuscript, Nancy Scott and Chin-ling Chen for their assistance with the database, and Ricardo Andres, Matt Cleary, Laura Beth Konopinski, and others for their outstanding help in the lab and the field. We also thank many landowners and personnel at the following research centers who provided access to the sites and logistical support: Grupo Estudios Ambientales in San Luis, Argentina; Institute for Agricultural Plant Physiology and Ecology at Universidad de Buenos Aires (UBA); Estancia San Claudio maintained by UBA; Western Kansas Agricultural Research Center in Tribune; Oklahoma Panhandle Research and Extension Center in Goodwell; Texas AgriLife research and extension centers at Vernon and San Angelo; and USDA-ARS Grassland Soil and Water Research Laboratory in Temple, TX.

References

Abdalla, O.A.E. 2008. Groundwater discharge mechanism in semi-arid regions and the role of evapotranspiration. Hydrol. Processes 22:2993–3009. doi:10.1002/hyp.6872

Ahmed, I., and R. Umar. 2008. Hydrogeological framework and water balance studies in parts of Krishni–Yamuna interstream area, western Uttar Pradesh, India. Environ. Geol. 53:1723–1730. doi:10.1007/s00254-007-0778-7

Allen, A.J. 1981. Groundwater resources of the Swan Coastal Plain, near Perth, Western Australia. p. 29–47. In B.R. Whelan (ed.) Groundwater resources of the Swan Coastal Plain, Proc. Symp., Perth. 21–22 May 1981. CSIRO Div. of Land Manage., Wembley, Perth, WA, Australia.

Allison, G.B, P.G. Cook, S.R. Barnett, G.R. Walker, I.D. Jolly, and M.W. Hughes. 1990. Land clearance and river salinisation in the western Murray Basin, Australia. J. Hydrol. 119:1–20. doi:10.1016/0022-1694(90)90030-2

Allison, G.B., and M.W. Hughes. 1972. Comparison of recharge to groundwater under pasture and forest using environmental tritium. J. Hydrol. 17:81–95. doi:10.1016/0022-1694(72)90067-4

Allison, G.B., and M.W. Hughes. 1978. The use of environmental tritium and chloride to estimate total local recharge to an unconfined aquifer. Aust. J. Soil Res. 16:181–195. doi:10.1071/SR9780181

Allison, G.B., and M.W. Hughes. 1983. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. J. Hydrol. 60:157–173. doi:10.1016/0022-1694(83)90019-7

Allison, G.B., W.J. Stone, and M.W. Hughes. 1985. Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride. J. Hydrol. 76:1–25. doi:10.1016/0022-1694(85)90088-5

Al-Sagaby, A., and M.A. Moallim. 2001. Isotope based assessment of groundwater renewal and related anthropogenic effects in water scarce areas: Sand dunes study in Qasim area, Saudi Arabia. p. 221–230. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Amro, H., S. Kilani, J. Jawawdeh, I. Abd El- Din, and M. Rayan. 2001. Isotope based assessment of groundwater recharge and pollution in water scarce areas: A case study in Jordan. p. 171–220. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Anderson, G.C., I.R.P. Fillery, P.J. Dolling, and S. Asseng. 1998. Nitrogen and water flows under pasture–wheat and lupin–wheat rotations in deep sands in Western Australia: 1. Nitrogen fixation in legumes, net N mineralisation, and utilisation of soil-derived nitrogen. Aust. J. Agric. Res. 49:329–344. doi:10.1071/A97141

Andrews, R.J., J.W. Lloyd, and D.N. Lerner. 1997. Modelling of nitrate leaching from arable land into unsaturated soil and chalk: 2. Model confirmation and application to agricultural and sewage sludge management. J. Hydrol. 200:198–221. doi:10.1016/S0022-1694(97)00008-5

Anuraga, T.S., L. Ruiz, M.S. Mohan Kumar, M. Sekhar, and A. Leijnse. 2006. Estimating groundwater recharge using land use and soil data: A case study in South India. Agric. Water Manage. 84:65–76. doi:10.1016/j.agwat.2006.01.017

Arora, V. 2002. Modeling vegetation as a dynamic component in soil–vegetation–atmosphere transfer schemes and hydrological models. Rev. Geophys. 40:26. doi:10.1029/2001RG000103

Athavale, R.N., C.S. Murti, and R. Chand. 1980. Estimation of recharge to the phreatic aquifers of the Lower Maner Basin, India, by using the tritium injection method. J. Hydrol. 45:185–202. doi:10.1016/0022-1694(80)90019-0

Babiker, I.S., M.A.A. Mohamed, T. Hiyama, and K. Kato. 2005. A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. Sci. Total Environ. 345:127–140. doi:10.1016/j.scitotenv.2004.11.005

Beekman, H.E., E.T. Selaolo, and G.-J. Nijsten. 1996. Groundwater recharge at the fringe of the Kalahari: the Letlhakeng–Botlhapatou area. Botswana J. Earth Sci 3:19–23.

Bekele, E.B., R.B. Salama, and D.P. Commander. 2006. Impact of change in vegetation cover on groundwater recharge to a phreatic aquifer in Western Australia: Assessment of several recharge estimation techniques. Aust. J. Earth Sci. 53:905–917. doi:10.1080/08120090600686827

Bellot, J., J.R. Sanchez, E. Chirino, N. Hernandez, F. Abdelli, and J.M. Martinez. 1999. Effect of different vegetation type cover on the soil water balance in semi-arid areas of South Eastern Spain. Phys. Chem. Earth B 24:353–357. doi:10.1016/S1464-1909(99)00013-1

Bent, G.C. 2001. Effects of forest-management activities on runoff components and ground-water recharge to Quabbin Reservoir, central Massachusetts. For. Ecol. Manage. 143:115–129. doi:10.1016/S0378-1127(00)00511-9

Beverly, C., M. Bari, B. Christy, M. Hocking, and K. Smettem. 2005. Predicted salinity impacts from land use change: Comparison between rapid assessment approaches and a detailed modelling framework. Aust. J. Exp. Agric. 45:1453–1469. doi:10.1071/EA04192

Bird, P.R., T.T. Jackson, G.A. Kearney, G.R. Saul, R.A. Waller, and G. Whipp. 2004. The effect of improved pastures and grazing management on soil water storage on a basaltic plains site in south-west Victoria. Aust. J. Exp. Agric. 44:559–569. doi:10.1071/EA03019

Boumans, L.J.M., D. Fraters, and G. Van Drecht. 2005. Nitrate leaching in agriculture to upper groundwater in the sandy regions of the Netherlands during the 1992–1995 period. Environ. Monit. Assess. 102:225–241. doi:10.1007/s10661-005-6023-5

Bredenkamp, D.B. 1988. Quantitative estimation of ground-water recharge in dolomite. p. 449–460. In I. Simmers (ed.) Proc. NATO Adv. Res. Worksh. on Estimation of Natural Recharge of Groundwater (with special reference to arid and semi-arid regions, Antalya (Side), Turkey. 8–15 Mar. 1987. D. Reidel Publ. Co., Dordrecht, the Netherlands.

Bredenkamp, D.B., and M.A.C. Vandoolaeghe. 1982. Die Ontginbare Grondwater Potensiaal van die Atlantisgebied. DWAF Rep. GH 3227. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa.

Butler, M.J., and B.T. Verhagen. 2001. Isotope studies of a thick unsaturated zone in a semi-arid area of southern Africa. p. 45–70. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Calder, I.R., I. Reid, T.R. Nisbet, and J.C. Green. 2003. Impact of lowland forests in England on water resources: Application of the Hydrological Land Use Change (HYLUC) model. Water Resour. Res. 39:1319. doi:10.1029/2003WR002042

Canadell, J., R.B. Jackson, J.B. Ehleringer, H.A. Mooney, O.E. Sala, and E.-D. Schulze. 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108:583–595. doi:10.1007/BF00329030

Carbon, B.A, F.J. Roberts, P. Farrington, and J.D. Beresford. 1982. Deep drainage and water use of forests and pastures grown on deep sands in a Mediterranean environment. J. Hydrol. 55:53–63. doi:10.1016/0022-1694(82)90120-2

Carlson, D.H., T.L. Thurow, R.W. Knight, and R.K. Heitschmidt. 1988. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. p. 51–69. In Water yield improvement from rangeland watersheds. Texas Water Dev. Board, Austin.

Cherkauer, D.S., and S.A. Ansari. 2005. Estimating ground water recharge from topography, hydrogeology, and land cover. Ground Water 43:102–112. doi:10.1111/j.1745-6584.2005.tb02289.x

Cho, J., V.A. Barone, and S. Mostaghimi. 2009. Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed. Agric. Water Manage. 96:1–11. doi:10.1016/j.agwat.2008.07.005

Clapp, R.B., and G.M. Hornberger. 1978. Empirical equations for some soil hydraulic properties. Water Resour. Res. 14:601–604. doi:10.1029/WR014i004p00601

Colville, J., and J. Holmes. 1972. Water table fluctuations under forest and pasture in a karstic region of southern Australia. J. Hydrol. 17:61–80. doi:10.1016/0022-1694(72)90066-2

Conrad, J., J. Nel, and J. Wentzel. 2005. The challenges and implications of assessing groundwater recharge: A case study on northern Sandveld, Western Cape, South Africa. Water SA 30:75–81.

Cook, P.G. 1992. The spatial and temporal variability of groundwater recharge. Flinders Univ., Bedford Park, SA, Australia.

Cook, P.G., W.M. Edmunds, and C.B. Gaye. 1992a. Estimating paleorecharge and paleoclimate from unsaturated zone profiles. Water Resour. Res. 28:2721–2731. doi:10.1029/92WR01298

Cook, P.G., T.J. Hatton, D. Pidsley, A.L. Herczeg, A. Held, A. O'Grady, and D. Eamus. 1998. Water balance of a tropical woodland ecosystem, northern Australia: A combination of micro-meteorological, soil physical and groundwater chemical approaches. J. Hydrol. 210:161–177. doi:10.1016/S0022-1694(98)00181-4

Cook, P.G., I.D. Jolly, M.W. Hughes, T.A. Beech, and C.T. Fiebiger. 1992b. Recharge studies in the western Murray Basin: 5. Results of drilling programs at Maggea, Melevale, Pfeiffers and Boolgun. Publ. 92/8. CSIRO Div. of Water Resour., Canberra, ACT, Australia.

Cook, P.G., I.D. Jolly, F.W. Leaney, G.R. Walker, G.L. Allan, L.K. Fifield, and G.B. Allison. 1994. Unsaturated zone tritium and chlorine 36 profiles from southern Australia: Their use as tracers of soil water movement. Water Resour. Res. 30:1709–1719. doi:10.1029/94WR00161

Cook, P.G., and S. Kilty. 1992. A helicopter-borne electromagnetic survey to delineate groundwater recharge rates. Water Resour. Res. 28:2953–2961. doi:10.1029/92WR01560

Cook, P.G., F.W. Leaney, and M. Miles. 2004. Groundwater recharge in the north-east Mallee region, South Australia. CSIRO Tech. Rep. 25/04. CSIRO Land and Water, Glen Osmond, SA, Australia.

Cook, P.G., G.R. Walker, and I.D. Jolly. 1989. Spatial variability of groundwater recharge in a semiarid region. J. Hydrol. 111:195–212. doi:10.1016/0022-1694(89)90260-6

Crosbie, R.S., J.D. Hughes, J. Friend, and B.J. Baldwin. 2007. Monitoring the hydrological impact of land use change in a small agricultural catchment affected by dryland salinity in central NSW, Australia. Agric. Water Manage. 88:43–53. doi:10.1016/j.agwat.2006.08.009

Dams, J., S.T. Woldeamlak, and O. Batelaan. 2008. Predicting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. Hydrol. Earth Syst. Sci. 12:1369–1385. doi:10.5194/hess-12-1369-2008

Daniel, J.A. 1999. Influence of wheat tillage practices on shallow groundwater recharge. J. Soil Water Conserv. 54:560–564.

Datta, P.S., B.I. Desai, and S.K. Gupta. 1980. Hydrological investigations in Sabarmati Basin: 1. Groundwater recharge estimation using tritium tagging method. Proc. Indian Natl. Sci. Acad. A 46:84–98.

Deans, J.D., W.M. Edmunds, D.K. Lindley, C.B. Gaye, B. Dreyfus, J.J. Nizinski, M. Neyra, K. Ingleby, and R.C. Munro. 2005. Nitrogen in interstitial waters in the Sahel: Natural baseline, pollutant or resource? Plant Soil 271:47–62. doi:10.1007/s11104-004-1994-5

De Vries, J.J., E.T. Selaolo, and H.E. Beekman. 2000. Groundwater recharge in the Kalahari, with reference to paleo-hydrologic conditions. J. Hydrol. 238:110–123. doi:10.1016/S0022-1694(00)00325-5

Di, H.J., and K.C. Cameron. 2002. Nitrate leaching and pasture production from different nitrogen sources on a shallow stoney soil under flood-irrigated dairy pasture. Aust. J. Soil Res. 40:317–334. doi:10.1071/SR01015

Döll, P., and K. Fiedler. 2008. Global-scale modeling of groundwater recharge. Hydrol. Earth Syst. Sci. 12:863–885. doi:10.5194/hess-12-863-2008

Döll, P., F. Kaspar, and B. Lehner. 2003. A global hydrological model for deriving water availability indicators: Model tuning and validation. J. Hydrol. 270:105–134. doi:10.1016/S0022-1694(02)00283-4

Dolling, P.J., S. Asseng, M.J. Robertson, and M.A. Ewing. 2007. Water excess under simulated lucerne–wheat phased systems in Western Australia. Aust. J. Agric. Res. 58:826–838. doi:10.1071/AR06048

Dripps, W.R., and K.R. Bradbury. 2007. A simple daily soil–water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas. Hydrogeol. J. 15:433–444. doi:10.1007/s10040-007-0160-6

Duffková, R. 2002. The effect of rainfall and extensive use of grasslands on water regime. Rostl. Vyroba 48:89–95.

Dunin, F.X., J. Williams, K. Verburg, and B.A. Keating. 1999. Can agricultural management emulate natural ecosystems in recharge control in south eastern Australia? Agrofor. Syst. 45:343–364. doi:10.1023/A:1006271805222

Dyck, M.F., and R.G. Kachanoski, and E. de Jong. 2003. Long-term movement of a chloride tracer under transient, semi-arid conditions. Soil Sci. Soc. Am. J. 67:471–477. doi:10.2136/sssaj2003.0471

Edmunds, W.M. (ed.). 2001a. Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Edmunds, W.M. 2001b. Investigation of the unsaturated zone in semi-arid regions using isotopic and chemical methods and applications to water resource problems. p. 7–22. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Edmunds, W., E. Fellman, I. Goni, and C. Prudhomme. 2002. Spatial and temporal distribution of groundwater recharge in northern Nigeria. Hydrogeol. J. 10:205–215. doi:10.1007/s10040-001-0179-z

Edmunds, W.M., and C.B. Gaye. 1994. Estimating the spatial variability of groundwater recharge in the Sahel using chloride. J. Hydrol. 156:47–59. doi:10.1016/0022-1694(94)90070-1

Facchi, A., C. Gandolfi, B. Ortuani, and D. Maggi. 2005. Simulation supported scenario analysis for water resources planning: A case study in northern Italy. Water Sci. Technol. 51:11–18.

Farley, K.A., E.G. Jobbágy, and R.B. Jackson. 2005. Effects of afforestation on water yield: A global synthesis with implications for policy. Global Change Biol. 11:1565–1576. doi:10.1111/j.1365-2486.2005.01011.x

Favreau, G., B. Cappelaere, S. Massuel, M. Leblanc, M. Boucher, N. Boulain, and C. Leduc. 2009. Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review. Water Resour. Res. 45:W00A16. doi:10.1029/2007WR006785

Favreau, G., C. Leduc, C. Marlin, M. Dray, J.-D. Taupin, M. Massault, C.G. La Salle, and M. Babic. 2002. Estimate of recharge of a rising water table in semiarid Niger from 3H and 14C modeling. Ground Water 40:144–151. doi:10.1111/j.1745-6584.2002.tb02499.x

Fayer, M.J., G.W. Gee, M.L. Rockhold, M.D. Freshley, and T.B. Walters. 1996. Estimating recharge rates for a groundwater model using a GIS. J. Environ. Qual. 25: 510–518.

Fillery, I.R.P., and R.E. Poulter. 2006. Use of long-season annual legumes and herbaceous perennials in pastures to manage deep drainage in acidic sandy soils in Western Australia. Aust. J. Agric. Res. 57:297–308. doi:10.1071/AR04278

Finch, J.W. 1998. Estimating direct groundwater recharge using a simple water balance model: Sensitivity to land surface parameters. J. Hydrol. 211:112–125. doi:10.1016/S0022-1694(98)00225-X

Fisher, L.H., and R.W. Healy. 2008. Water movement within the unsaturated zone in four agricultural areas of the United States. J. Environ. Qual. 37:1051–1063. doi:10.2134/jeq2006.0561

Ford, D.C., and P.W. Williams. 1989. Karst geomorphology and hydrology. Unwin Hyman, London.

Fouty, S.C. 1989. Chloride mass-balance as a method for determining long-term ground-water recharge rates and geomorphic surface stability in arid and semi-arid regions: Whisky Flat and Beatty, Nevada. M.S. thesis. Univ. of Arizona., Tucson.

Freeze, A.R., and J.A. Cherry. 1979. Groundwater. Prentice Hall, Upper Saddle River, NJ.

Gates, J.B., W.M. Edmunds, J. Ma, and B.R. Scanlon. 2008. Estimating groundwater recharge in a cold desert environment in northern China using chloride. Hydrogeol. J. 16:893–910. doi:10.1007/s10040-007-0264-z

Gaye, C.B., and W.M. Edmunds. 1996. Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. Environ. Geol. 27:246–251. doi:10.1007/BF00770438

Gee, G.W., D.G. Felmy, J.C. Ritter, M.D. Campbell, J.L. Downs, M.J. Fayer, R.R. Kirkham, and S.O. Link. 1993. Field Lysimeter Test Facility status report IV: FY 1993. Pac. Northw. Natl. Lab., Richland, WA.

Gee, G.W., P.J. Wierenga, B.J. Andraski, M.H. Young, M. Fayer, and M.L. Rockhold. 1994. Variations in water balance and recharge potential at three western desert sites. Soil Sci. Soc. Am. J. 58:63–72.

George, R.J., and P.W.C. Frantom. 1988. Preliminary groundwater and salinity investigations in the eastern wheatbelt: 2. Merredin catchment. Resour. Manage. Tech. Rep. 89. Western Australia Dep. of Agriculture, South Perth, WA, Australia.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch. 2004. Terrestrial vegetation and water balance: Hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286:249–270. doi:10.1016/j.jhydrol.2003.09.029

Gieske, A. 1992. Dynamics of groundwater recharge: A case study in semi-arid eastern Botswana. Drukkerij Febodruk BV, Enschede, the Netherlands.

Gieske, A., E.T. Selaolo, and H.E. Beekman. 1995. Tracer interpretation of moisture transport in a Kalahari sand profile. p. 373–382. In E.M. Adar and C. Leibundgut (ed.) Application of tracers in arid zone hydrology: Proc. Symp., Vienna. 22–26 Aug. 1994. IAHS Publ. 232. Int. Assoc. Hydrol. Sci., Wallingford, UK.

Goni, I.B., and W.M. Edmunds. 2001. The use of unsaturated zone solutes and deuterium profiles in the study of groundwater recharge in the semi-arid zone of Nigeria. p. 85–100. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Goodrich, D.C., D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S.N. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. p. 77–99. In F.M. Phillips et al. (ed.) Recharge and vadose zone processes: Alluvial basins of the southwestern United States. Water Sci. Appl. 9. Am. Geophys. Union, Washington, DC.

Green, C.T., L.H. Fisher, and B.A. Bekins. 2008. Nitrogen fluxes through unsaturated zones in five agricultural settings across the United States. J. Environ. Qual. 37:1073–1085. doi:10.2134/jeq2007.0010

Gregory, P.J., D. Tennant, A.P. Hamblin, and J. Eastham. 1992. Components of the water balance on duplex soils in Western Australia. Aust. J. Exp. Agric. 32:845–855. doi:10.1071/EA9920845

Gupta, S.K., and P. Sharma. 1984. Soil moisture transport through the unsaturated zone: Tritium tagging studies in Sabarmati Basin, Western India. Hydrol. Sci. J. 29:177–189. doi:10.1080/02626668409490932

Hadas, Am., Av. Hadas, B. Sagiv, and N. Haruvy. 1999. Agricultural practices, soil fertility management modes and resultant nitrogen leaching rates under semi-arid conditions. Agric. Water Manage. 42:81–95. doi:10.1016/S0378-3774(99)00026-8

Halm, D., Th. Gaiser, and K. Starh. 2002. Seepage and groundwater recharge in sandy soils of the semi-arid region of Picos, northeast Brazil. Neues Jahrb. Geol. Palaontol. Abh. 225:85–101.

Hatton, T.J., and R.A. Nulsen. 1999. Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. Agrofor. Syst. 45:203–214. doi:10.1023/A:1006215620243

Heilweil, V.M., D.K. Solomon, and P.M. Gardner. 2006. Borehole environmental tracers for evaluating net infiltration and recharge through desert bedrock. Vadose Zone J. 5:98–120. doi:10.2136/vzj2005.0002

Heng, L.K,, R.E. White, K.R. Helyar, R. Fisher, and D. Chen. 2001. Seasonal differences in the soil water balance under perennial and annual pastures on an acid Sodosol in southeastern Australia. Eur. J. Soil Sci. 52:227–236. doi:10.1046/j.1365-2389.2001.00386.x

Holmes, J.W., and J.S. Colville. 1968. On the water balance of grassland and forest. p. 39–46. In Proc. Trans. Congr. Int. Soil Sci. Soc., 9th, Adelaide, SA, Australia. Vol. 1. Angus and Robertson, Sydney.

Holmes, J.W., and J.S. Colville. 1970a. Grassland hydrology in a karstic region of southern Australia. J. Hydrol. 10:38–58. doi:10.1016/0022-1694(70)90053-3

Holmes, J.W., and J.S. Colville. 1970b. Forest hydrology in a karstic region of southern Australia. J. Hydrol. 10:59–74. doi:10.1016/0022-1694(70)90054-5

Holmstead, G.L., R.W. Knight, and M.A. Hussey. 1988. Water-use and water yield of three C4 bunchgrasses in the South Texas plains. p. 73–¬91. In Water yield improvement from rangeland watersheds. Texas Water Dev. Board, Austin.

Houston, J.F.T. 1982. Rainfall and recharge to a dolomite aquifer in a semi-arid climate at Kabwe, Zambia. J. Hydrol. 59:173–187. doi:10.1016/0022-1694(82)90010-5

Howard, K.W.F., and J. Karundu. 1992. Constraints on the exploitation of basement aquifers in East Africa: Water balance implications and the role of the regolith. J. Hydrol. 139:183–196. doi:10.1016/0022-1694(92)90201-6

Huang, M., and J. Gallichand. 2006. Use of the SHAW model to assess soil water recovery after apple trees in the gully region of the Loess Plateau, China. Agric. Water Manage. 85:67–76. doi:10.1016/j.agwat.2006.03.009

Hughes, M.W., P.G. Cook, I.D. Jolly, T.A. Beech, and C.T. Fiebiger. 1988. Recharge studies in the western Murray Basin: 1. Results of a drilling program at Borrika. Tech. Mem. 88/10. CSIRO Div. of Water Resour., Canberra, ACT, Australia.

Hume, I.H. 1997. Episodic deep drainage under crops and shrubs in the mallee zone. p. 19–26. In S. Wilson and T. Lawry (ed.). Proc. Dryland Forum, North Adelaide, SA, Australia. 28–30 Oct. 1997. Murray–Darling Basin Commission, Canberra, ACT, Australia.

Hussein, M.F. 2001. Water flow and solute transport using environmental isotopes and modeling. p. 231–271. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Hutjes, R.W.A., P. Kabat, S.W. Running, W.J. Shuttleworth, C. Field, B. Bass, et al. 1998. Biospheric aspects of the hydrological cycle. J. Hydrol. 212–213:1–21. doi:10.1016/S0022-1694(98)00255-8

Jackson, D., and K.R. Rushton. 1987. Assessment of recharge components for a chalk aquifer unit. J. Hydrol. 92:1–15. doi:10.1016/0022-1694(87)90086-2

Jackson, R.B., J.L. Banner, E.G. Jobbágy, W.T. Pockman, and D.H. Wall. 2002. Ecosystem carbon loss with woody plant invasion of grasslands. Nature 418:623–626. doi:10.1038/nature00910

Jackson, R.B., S.R. Carpenter, C.N. Dahm, D.M. McKnight, R.J. Naiman, S.L. Postel, and S.W. Running. 2001. Water in a changing world. Ecol. Appl. 11:1027–1045. doi:10.1890/1051-0761(2001)011[1027:WIACW]2.0.CO;2

Jackson, R.B., E.G. Jobbágy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray. 2005. Trading water for carbon with biological carbon sequestration. Science 310:1944. doi:10.1126/science.1119282

Jackson, R.B., J.T. Randerson, J.G. Canadell, R.G. Anderson, R. Avissar, D.D. Baldocchi, et al. 2008. Protecting climate with forests. Environ. Res. Lett. 3:044006. doi:10.1088/1748-9326/3/4/044006

Jackson, R.B., H.J. Schenk, E.G. Jobbágy, J. Canadell, G.D. Colello, R.E. Dickinson, et al. 2000. Belowground consequences of vegetation change and their treatment in models. Ecol. Appl. 10:470–483. doi:10.1890/1051-0761(2000)010[0470:BCOVCA]2.0.CO;2

Jan, C.-D., T.-H. Chen, and W.-C. Lo. 2007. Effect of rainfall intensity and distribution on groundwater level fluctuations. J. Hydrol. 332:348–360. doi:10.1016/j.jhydrol.2006.07.010

Jipp, P.H., D.C. Nepstad, D.K. Cassell, and C. Reis de Carvalho. 1998. Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. Clim. Change 39:395–412. doi:10.1023/A:1005308930871

Jobbágy, E.G., and R.B. Jackson. 2007. Groundwater and soil chemical changes under phreatophytic tree plantations. J. Geophys. Res. 112:G02013. doi:10.1029/2006JG000246

Johnston, C.D. 1987a. Distribution of environmental chloride in relation to subsurface hydrology. J. Hydrol. 94:67–88. doi:10.1016/0022-1694(87)90033-3

Johnston, C.D. 1987b. Preferred water flow and localised recharge in a variable regolith. J. Hydrol. 94:129–142. doi:10.1016/0022-1694(87)90036-9

Jolly, I.D., P.G. Cook, G.B Allison, and M.W. Hughes. 1989. Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. J. Hydrol. 111:391–396. doi:10.1016/0022-1694(89)90270-9

Jolly, J.L. 1992. The geohydrology of the Graafwater Government Subterranean Water Control Area. DWAF Rep. GH 3778. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa.

Joshi, B. 1997. Estimation of diffuse vadose zone soil-water flux in a semi-arid region. Ph.D. diss. Univ. of Saskatchewan, Saskatoon, SK, Canada.

Julien, P.A., R.W. Knight, and C.L. Fischer. 1988. Water yields from mesquite and grass lysimeters on the Carrizo–Wilcox Sands aquifer in southwest Texas. p. 92–115. In Water yield improvement from rangeland watersheds. Texas Water Dev. Board, Austin.

Junge, C.E., and R.T. Werby. 1958. Concentration of chloride, sodium, potassium, calcium, and sulfate in rain water over the United States. J. Meteorol. 15:417–425.

Keese, K.E., B.R. Scanlon, and R.C. Reedy. 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour. Res. 41:W06010. doi:10.1029/2004WR003841

Kendall, H.W., and D. Pimentel. 1994. Constraints on the expansion of the global food supply. Ambio 23:198–205.

Kendy, E., P. Gérard-Marchant, M.T. Walter, Y. Zhang, C. Liu, and T.S. Steenhuis. 2003. A soil water balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Processes 17:2011–2031. doi:10.1002/hyp.1240

Kendy, E., Y. Zhang, C. Liu, J. Wang, and T.S. Steenhuis. 2004. Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000. Hydrol. Processes 18:2289–2302. doi:10.1002/hyp.5529

Kennett-Smith, A., P.G. Cook, and G.R. Walker. 1994. Factors affecting groundwater recharge following clearing in the south western Murray Basin. J. Hydrol. 154:85–105. doi:10.1016/0022-1694(94)90213-5

Kennett-Smith, A.K., G.R. Budd, P.G. Cook, and G.R. Walker. 1990. The effect of lucerne on the recharge to cleared mallee lands. Rep. 27. Ctr. for Groundwater Stud., Glen Osmond, SA, Australia.

Kennett-Smith, A.K., G.R. Budd, and G.R. Walker. 1992a. Groundwater recharge beneath woodlands cleared for grazing, south western New South Wales. CSIRO Div. of Water Resour., Canberra, ACT, Australia.

Kennett-Smith, A.K., P.G. Cook, and R. Thorne. 1992b. Comparison of recharge under native vegetation and dryland agriculture, in the Big Desert region of Victoria. Ctr. for Groundwater Stud., Glen Osmond, SA, Australia.

Kennett-Smith, A.K., R. Thorne, and G.R. Walker. 1993. Comparison of recharge under native vegetation and dryland agriculture near Goroke, Victoria. Ctr. for Groundwater Stud. Glen Osmond, SA, Australia.

Kergoat, L. 1998. A model for hydrological equilibrium of leaf area index on a global scale. J. Hydrol. 212–213:268–286. doi:10.1016/S0022-1694(98)00211-X

Keywood, M.D., A.R. Chivas, L.K. Fifield, R.G. Cresswell, and G.P. Ayers. 1997. The accession of chloride to the western half of the Australian continent. Aust. J. Soil Res. 35:1177–1190. doi:10.1071/S97001

Kienzle, S.W., and R.E. Schulze. 1992. A simulation model to assess the effect of afforestation on ground-water resources in deep sandy soils. Water SA 18:265–272.

Klein Goldewijk, C.G.M., and J.J. Battjes. 1997. A hundred year (1890–1990) database for integrated environmental assessments (HYDE, version 1.1). Rep. 28-02-1997. PBL Netherlands Environ. Assess. Agency, Bilthoven.

Klute, A. (ed.) 1986. Methods of soil analysis. Part 1. Physical and mineralogical methods. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Knoche, D., A. Embacher, and J. Katzur. 2002. Water and element fluxes of red oak ecosystems during stand development on post-mining sites (Lusatian lignite district). Water Air Soil Pollut. 141:219–231. doi:10.1023/A:1021350321058

Kohavi, R. 1995. A study of cross-validation and bootstrap for accuracy estimation and model selection. p. 1137–1145. In Int. Joint Conf. on Artificial Intelligence, 14th, Montreal, QB, Canada. 20–25 Aug. 1995. Morgan Kaufmann Publ, San Francisco.

Krajenbrink, G.J.W., D. Ronen, W. Van Duijvenbooden, M. Magaritz, and D. Wever. 1988. Monitoring of recharge water quality under woodland. J. Hydrol. 98:83–102. doi:10.1016/0022-1694(88)90207-7

Kucharik, C.J., J.A. Foley, C. Delire, V.A. Fisher, M.T. Coe, J.D. Lenters, C. Young-Molling, N. Ramankutty, J.M. Norman, and S.T. Gower. 2000. Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure. Global Biogeochem. Cycles 14:795–825. doi:10.1029/1999GB001138

Külls, C. 2000. Groundwater of the north-western Kalahari, Namibia: Estimation of recharge and quantification of the flow systems. Julius-Maximilians-Universität Würzburg, Würzburg, Germany.

Ladekarl, U.L., K.R. Rasmussen, S. Christensen, K.H. Jensen, and B. Hansen. 2005. Groundwater recharge and evapotranspiration for two natural ecosystems covered with oak and heather. J. Hydrol. 300:76–99. doi:10.1016/j.jhydrol.2004.05.003

Larsen, F., R. Owen, T. Dahlen, P. Mangeya, and G. Barmen. 2002. A preliminary analysis of the groundwater recharge to the Karoo formations, mid-Zambezi basin, Zimbabwe. Phys. Chem. Earth 27:765–772. doi:10.1016/S1474-7065(02)00064-5

Leaney, F.W., and G.B. Allison. 1986. Carbon-14 and stable isotope data for an area in the Murray Basin: Its use in estimating recharge. J. Hydrol. 88:129–145. doi:10.1016/0022-1694(86)90201-5

Leaney, F.W., and A.L. Herczeg. 1995. Regional recharge to a karst aquifer estimated from chemical and isotopic composition of diffuse and localised recharge, South Australia. J. Hydrol. 164:363–387. doi:10.1016/0022-1694(94)02488-W

Leaney, F.W.J., and A.L. Herczeg. 1999. The origin of fresh groundwater in the SW Murray Basin and its potential for salinisation. Tech. Rep. 7/99. CSIRO Land and Water, Adelaide, SA, Australia.

Leduc, C., G. Favreau, and P. Schroeter. 2001. Long-term rise in a Sahelian water-table: The continental terminal in south-west Niger. J. Hydrol. 243:43–54. doi:10.1016/S0022-1694(00)00403-0

Li, S.-G., C.-T. Lai, G. Lee, S. Shimoda, T. Yokoyama, A. Higuchi, and T. Oikawa. 2005. Evapotranspiration from a wet temperate grassland and its sensitivity to microenvironmental variables. Hydrol. Processes 19:517–532. doi:10.1002/hyp.5673

Lin, R., and K. Wei. 2001. Environmental isotope profiles of the soil water in loess unsaturated zone in semi-arid areas of China. p. 101–118. In W.M. Edmunds (ed.) Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Loh, I.C., and R.A. Stokes. 1981. Predicting stream salinity changes in southwestern Australia. Agric. Water Manage. 4:227–254. doi:10.1016/0378-3774(81)90052-4

Lull, H.W., and E.N. Munns. 1950. Effect of land use practices on ground water. J. Soil Water Conserv. 5:169–179.

Lvovitch, M.I. 1970. World water balance (general report). p. 401–415. In Proc. Symp. World Water Balance, Reading, UK. July 1970. IAHS Publ. 93. Int. Assoc. Hydrol. Sci., Wallingford, UK.

Maréchal, J.C., B. Dewandel, S. Ahmed, L. Galeazzi, and F.K. Zaidi. 2006. Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. J. Hydrol. 329:281–293. doi:10.1016/j.jhydrol.2006.02.022

Maréchal, J.C., M.R.R. Varma, J. Riotte, J.'M. Vouillamoz, M.S. Mohan Kumar, L. Ruiz, M. Sekhar, and J.-J. Braun. 2009. Indirect and direct recharges in a tropical forested watershed: Mule Hole, India. J. Hydrol. 364:272–284. doi:10.1016/j.jhydrol.2008.11.006

McCulley, R.L., E.G. Jobbágy, W.T. Pockman, and R.B. Jackson. 2004. Nutrient uptake as a contributing explanation for deep rooting in arid and semi-arid ecosystems. Oecologia 141:620–628. doi:10.1007/s00442-004-1687-z

McDowall, M.M., D.J.M. Hall, D.A. Johnson, J. Bowyer, and P. Spicer. 2003. Kikuyu and annual pasture: A characterisation of a productive and sustainable beef production system on the south coast of Western Australia. Aust. J. Exp. Agric. 43:769–783. doi:10.1071/EA02230

McMahon, P.B., K.F. Dennehy, B.W. Bruce, J.K. Böhlke, R.L. Michel, J.J. Gurdak, and D.B. Hurlbut. 2006. Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States. Water Resour. Res. 42:W03413. doi:10.1029/2005WR004417

McMahon, P.B., K.F. Dennehy, R.L. Michel, M.A. Sophocleous, K.M. Ellett, and D.B. Hurlbut. 2003. Water movement through thick unsaturated zones overlying the central High Plains aquifer, southwestern Kansas, 2000–2001. Water Resour. Invest. Rep. 03-4177. USGS, Reston, VA.

Meyer, W.B., and B.L. Turner. 1994. Changes in land use and land cover: A global perspective. Cambridge Univ. Press, Cambridge, UK.

Mileham, L., R. Taylor, J. Thompson, M. Todd, and C. Tindimugaya. 2008. Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa. J. Hydrol. 359:46–58. doi:10.1016/j.jhydrol.2008.06.007

Milly, P.C.D. 1994. Climate, soil water storage, and the average annual water balance. Water Resour. Res. 30:2143–2156. doi:10.1029/94WR00586

Milly, P.C.D. 1997. Sensitivity of greenhouse summer dryness to changes in plant rooting characteristics. Geophys. Res. Lett. 24:269–271. doi:10.1029/96GL03968

Milroy, S.P., S. Asseng, and M.L. Poole. 2008. Systems analysis of wheat production on low water-holding soils in a Mediterranean-type environment: II. Drainage and nitrate leaching. Field Crops Res. 107:211–220. doi:10.1016/j.fcr.2008.02.008

Monirul Islam, M., and P. Kanungoe. 2005. Natural recharge to sustainable yield from the Barind aquifer: A tool in preparing effective management plan of groundwater resources. Water Sci. Technol. 52:251–258.

Müller, J., and A. Bolte. 2009. The use of lysimeters in forest hydrology research in north-east Germany. Landbauforschung (vTI Agric. For. Res.) 59:1–10.

Navada, S.V., A.R. Nair,. 2001. Application of isotopes and chemistry in unsaturated zone in arid areas of Rajasthan, India. p. 119–130. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Neilson, R.P. 1995. A model for predicting continental-scale vegetation distribution and water balance. Ecol. Appl. 5:362–385. doi:10.2307/1942028

New, M., D. Lister, M. Hulme, and I. Makin. 2002. A high-resolution data set of surface climate over global land areas. Clim. Res. 21:1–25. doi:10.3354/cr021001

Newman, B.D., A.R. Campbell, and B.P. Wilcox. 1997. Tracer-based studies of soil water movement in semi-arid forests of New Mexico. J. Hydrol. 196:251–270. doi:10.1016/S0022-1694(96)03320-3

Nichols, D.S., and E.S. Verry. 2001. Stream flow and ground water recharge from small forested watersheds in north central Minnesota. J. Hydrol. 245:89–103. doi:10.1016/S0022-1694(01)00337-7

Niu, G.-Y., Z.-L. Yang, R.E. Dickinson, L.E. Gulden, and H. Su. 2007. Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data. J. Geophys. Res. 112:D07103. doi:10.1029/2006JD007522

O'Connell, M.G., G.J. O'Leary, and D.J. Connor. 2003. Drainage and change in soil water storage below the root-zone under long fallow and continuous cropping sequences in the Victorian Mallee. Aust. J. Agric. Res. 54:663–675. doi:10.1071/AR02079

Ojeda, C.G. 2001. Aquifer recharge estimation at the Mesilla Bolson and Guaymas aquifer systems, Mexico. p. 23–44. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Pakrou, N., and P.J. Dillon. 2000. Comparison of type and depth of lysimeter for measuring the leaching losses of nitrogen under urine patches. Soil Use Manage. 16:108–116. doi:10.1111/j.1475-2743.2000.tb00185.x

Paydar, Z., and J. Gallant. 2008. A catchment framework for one dimensional models: Introducing FLUSH and its application. Hydrol. Processes 22:2094–2104. doi:10.1002/hyp.6809

Peck, A.J., and D.H. Hurle. 1973. Chloride balance of some farmed and forested catchments in southwestern Australia. Water Resour. Res. 9:648–657. doi:10.1029/WR009i003p00648

Peck, A.J., C.D. Johnston, and D.R. Williamson. 1981. Analyses of solute distributions in deeply weathered soils. Agric. Water Manage. 4:83–102. doi:10.1016/0378-3774(81)90045-7

Peel, M.C., T.A. McMahon, B.L. Finlayson, and F.G.R. Watson. 2001. Identification and explanation of continental differences in the variability of annual runoff. J. Hydrol. 250:224–240. doi:10.1016/S0022-1694(01)00438-3

Petheram, C., G. Walker, R Grayson, T. Thierfelder, and L. Zhang. 2002. Towards a framework for predicting impacts of land-use on recharge: 1. A review of recharge studies in Australia. Aust. J. Soil Res. 40:397–417. doi:10.1071/SR00057

Phillips, F.M. 1994. Environmental tracers for water-movement in desert soils of the American Southwest. Soil Sci. Soc. Am. J. 58:15–24. doi:10.2136/sssaj1994.03615995005800010003x

Piñeiro, G., E.G. Jobbágy, R.B. Jackson, C.S. Santoni, S.I. Portella, and C. di Bella. 2007. RP-RainNet: The Rio de la Plata atmospheric deposition network: Set up and preliminary results. Abstr. B33A-07. In AGU Spring Meeting, Joint Assembly, Acapulco, Mexico. 22–25 May 2007. Am. Geophys. Union, Washington, DC.

Postel, S., and S. Carpenter. 1997. Freshwater ecosystem services. p. 95–214. In G.C. Daily (ed.) Nature's services: Societal dependence on natural ecosystems. Island Press, Washington, DC.

Potter, N.J., L. Zhang, P.C.D. Milly, T.A. McMahon, and A.J. Jakeman. 2005. Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments. Water Resour. Res. 41:W06007. doi:10.1029/2004WR003697

Pracilio, G., S. Asseng, S.E. Cook, G. Hodgson, M.T.F. Wong, M.L. Adams, and T.J. Hatton. 2003. Estimating spatially variable deep drainage across a central-eastern wheatbelt catchment, Western Australia. Aust. J. Agric. Res. 54:789–802. doi:10.1071/AR02084

Prych, E.A. 1998. Using chloride and chlorine-36 as soil-water tracers to estimate deep percolation at selected locations on the U.S. Department of Energy Hanford Site, Washington. Water-Supply Pap. 2481. USGS, Denver, CO.

Radford, B.J., D.M. Silburn, and B.A. Forster. 2009. Soil chloride and deep drainage responses to land clearing for cropping at seven sites in central Queensland, northern Australia. J. Hydrol. 379:20–29. doi:10.1016/j.jhydrol.2009.09.040

Ragab, R., J. Finch, and R. Harding. 1997. Estimation of groundwater recharge to chalk and sandstone aquifers using simple soil models. J. Hydrol. 190:19–41. doi:10.1016/S0022-1694(96)03067-3

Rangarajan, R., N.C Mondal, V.S. Singh, and S.V. Singh. 2009. Estimation of natural recharge and its relation with aquifer parameters in and around Tuticorin town, Tamil Nadu, India. Curr. Sci. 97:217–226.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil-water properties. Trans. ASAE 25:1316–1320 & 1328.

Renard, K.G., L.J. Lane, J.R. Simanton, W.E. Emmerich, J.J. Stone, M.A. Weltz, D.C. Goodrich, and D.S. Yakowitz. 1993. Agricultural impacts in an arid environment: Walnut Gulch studies. Hydrol. Sci. Technol. 9:145–190.

Renger, M., O. Strebel, G. Wessolek, and W.H.M. Duynisveld. 1986. Evapotranspiration and groundwater recharge: A case study for different climate, crop patterns, soil properties and groundwater depth conditions. Z. Pflanzenernaehr. Bodenkd. 149:371–381. doi:10.1002/jpln.19861490403

Renger, M., and G. Wessolek. 1990. Auswirkungen von Grundwasserabsenkungen und Nutzungsänderungen auf die Grundwasserneubildung. Mitt. Inst. Wasserwesen 386:295–305.

Richardson, S.B., and K.A. Narayan. 1995. The effectiveness of management options for dryland salinity control at Wanilla, South Australia. Agric. Water Manage. 29:63–83. doi:10.1016/0378-3774(95)01183-8

Ridley, A.M., R.E. White, R.J. Simpson, and L. Callinan. 1997. Water use and drainage under phalaris, cocksfoot, and annual ryegrass pastures. Aust. J. Agric. Res. 48:1011–1024. doi:10.1071/A96157

Roberts, J., and P. Rosier. 2006. The effect of broadleaved woodland on chalk groundwater resources. Q. J. Eng. Geol. Hydrogeol. 39:197. doi:10.1144/1470-9236/04-076

Rodvang, S.J., D.M. Mikalson, and M.C. Ryan. 2004. Changes in ground water quality in an irrigated area of southern Alberta. J. Environ. Qual. 33:476–487.

Sami, K., and D.A. Hughes. 1996. A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and an integrated surface–subsurface model. J. Hydrol. 179:111–136. doi:10.1016/0022-1694(95)02843-9

Santoni, C.S., E.G. Jobbágy, and S. Contreras. 2010. Vadose zone transport in dry forests of central Argentina: Role of land use. Water Resour. Res. 46:W10541. doi:10.1029/2009WR008784

Scanlon, B.R. 1991. Evaluation of moisture flux from chloride data in desert soils. J. Hydrol. 128:137–156. doi:10.1016/0022-1694(91)90135-5

Scanlon, B.R., and R.S. Goldsmith. 1997. Field study of spatial variability in unsaturated flow beneath and adjacent to playas. Water Resour. Res. 33:2239–2252. doi:10.1029/97WR01332

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007a. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour. Res. 43:W03437. doi:10.1029/2006WR005486

Scanlon, B.R., K.E. Keese, A.L. Flint, L.E. Flint, C.B. Gaye, W.M. Edmunds, and I. Simmers. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol. Processes 20:3335–3370. doi:10.1002/hyp.6335

Scanlon, B.R., R.P. Langford, and R.S. Goldsmith. 1999. Relationship between geomorphic settings and unsaturated flow in an arid setting. Water Resour. Res. 35:983–999. doi:10.1029/98WR02769

Scanlon, B.R., R.C. Reedy, R.L. Baumhardt, and G. Strassberg. 2008. Impact of deep plowing on groundwater recharge in a semiarid region: Case study, High Plains, Texas. Water Resour. Res. 44:W00A10. doi:10.1029/2008WR006991

Scanlon, B.R., R.C. Reedy, D.A. Stonestrom, D.E. Prudic, and K.F. Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern us. Global Change Biol. 11:1577–1593. doi:10.1111/j.1365-2486.2005.01026.x

Scanlon, B.R., R.C. Reedy, and J.A. Tachovsky. 2007b. Semiarid unsaturated zone chloride profiles: Archives of past land use change impacts on water resources in the southern High Plains, United States. Water Resour. Res. 43:W06423. doi:10.1029/2006WR005769

Schenk, H.J., and R.B. Jackson. 2002. The global biogeography of roots. Ecol Monogr. 72:311–328.

Schenk, H.J., and R.B. Jackson. 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. Geoderma 126:129–140.

Schwarz, G. 1978. Estimating the dimension of a model. Ann. Stat. 6:461–464. doi:10.1214/aos/1176344136

Selaolo, E.T. 1998. Tracer studies and groundwater recharge assessment in the eastern fringe of the Botswana Kalahari: The Letlhakeng–Botlhapatlou area. Vrije Universiteit, Amsterdam.

Selaolo, E.T., H.E. Beekman, A.S.M. Gleske, and J.J. de Vries. 2003. Multiple tracer profiling in Botswana: GRES findings. p. 33–50. In Y. Xu and H.E. Beekman (ed.) Groundwater recharge estimation in southern Africa. UNESCO, Paris.

Shah, T., D. Molden, R. Sakthivadivel, and D. Seckler. 2000. The global groundwater situation: Overview of opportunities and challenges. IWMI Books, Rep. H025885. Int. Water Manage. Inst., Colombo, Sri Lanka.

Sharda, V.N., R.S. Kurothe, D.R. Sena, V.C. Pande, and S.P. Tiwari. 2006. Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. J. Hydrol. 329:224–243. doi:10.1016/j.jhydrol.2006.02.015

Sharma, P., and S.K. Gupta. 1987. Isotopic investigation of soil water movement: A case study in the Thar Desert, Western Rajasthan. Hydrol. Sci. J. 32:469–483. doi:10.1080/02626668709491206

Shiklomanov, I.A. 1997. Comprehensive assessment of the freshwater resources of the world. World Meteorol. Organ., Stockholm, Sweden.

Silburn, D.M., B.A. Cowie, and C.M. Thornton. 2009. The Brigalow Catchment Study revisited: Effects of land development on deep drainage determined from non-steady chloride profiles. J. Hydrol. 373:487–498. doi:10.1016/j.jhydrol.2009.05.012

Singh, J., W.W. Wapakala, and P.K. Chebosi. 1984. Estimating groundwater recharge based on the infiltration characteristics of layered soil. P. 37–45. In Challenges in African hydrology and water resources. IAHS Publ. 144. Int. Assoc. Hydrol. Sci., Wallingford, UK.

Skiles, J.W., and J.D. Hanson. 1994. Responses of arid and semiarid watersheds to increasing carbon dioxide and climate change as shown by simulation studies. Clim. Change 26:377–397. doi:10.1007/BF01094403

Sloots, R.R., and M.M. Wijnen. 1990. Groundwater recharge to a fractured aquifer in S-E Botswana. Results of a survey of the Molepolole-East wellfield. Vrije Univ., Amsterdam.

Smettem, K.R.J. 1998. Deep drainage and nitrate losses under native vegetation and agricultural systems in the Mediterranean climate region of Australia. CSIRO Land and Water Resour. Res. and Dev., Canberra, ACT, Australia.

Smith, C.J., F.X. Dunin, S.J. Zegelin, and R. Poss. 1998. Nitrate leaching from a riverine clay soil under cereal rotation. Aust. J. Agric. Res. 49:379–390. doi:10.1071/A97076

Snow, V.O., W.J. Bond, B.J. Myers, S. Theiveyanathan, C.J. Smith, and R.G. Benyon. 1999. Modelling the water balance of effluent-irrigated trees. Agric. Water Manage. 39:47–67. doi:10.1016/S0378-3774(98)00086-9

Sophocleous, M. 2005. Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. Hydrogeol. J. 13:351–365. doi:10.1007/s10040-004-0385-6

Sophocleous, M., and J.A. McAllister. 1987. Basinwide water balance modeling with emphasis on spatial distribution of groundwater recharge. J. Am. Water Resour. Assoc. 23:997–1010. doi:10.1111/j.1752-1688.1987.tb00849.x

Stone, W.A., J.M. Thorp, O.P. Gifford, and D.J. Hoitink. 1983. Climatological summary for the Hanford area. Rep. PNL-4622. Pac. Northw. Natl. Lab., Richland, WA.

Stonestrom, D.A., J. Constantz, T.P.A. Ferré, and S.A. Leake (ed.). 2007. Ground-water recharge in the arid and semiarid southwestern United States. Prof. Pap. 1703. USGS, Denver, CO.

Stonestrom, D.A., D.E. Prudic, R.J. Laczniak, K.C. Akstin, R.A. Boyd, and K.K. Henkelman. 2003. Estimates of deep percolation beneath native vegetation, irrigated fields, and the Amargosa-River channel, Amargosa Desert, Nye County, Nevada. Open-File Rep. 03-104. USGS, Denver, CO.

Sukhija, B.S., D.V. Reddy, P. Nagabhushanam, and R. Chand. 1988. Validity of the environmental chloride method for recharge evaluation of coastal aquifers, India. J. Hydrol. 99:349–366. doi:10.1016/0022-1694(88)90058-3

Sumioka, S., and H.H. Bauer. 2004. Estimating ground-water recharge from precipitation on Whidbey and Camano islands, Island County, Washington, water years 1998 and 1999. Water-Resour. Invest. Rep. 03-4101. USGS, Tacoma, WA.

Sun, H., and P.S. Cornish. 2005. Estimating shallow groundwater recharge in the headwaters of the Liverpool Plains using SWAT. Hydrol. Processes 19:795–807. doi:10.1002/hyp.5617

Talsma, T., and E.A. Gardner. 1986. Groundwater recharge and discharge response to rainfall on a hillslope. Aust. J. Soil Res. 24:343–356. doi:10.1071/SR9860343

Taylor, R.G., and K.W.F. Howard. 1996. Groundwater recharge in the Victoria Nile basin of East Africa: Support for the soil moisture balance approach using stable isotope tracers and flow modelling. J. Hydrol. 180:31–53. doi:10.1016/0022-1694(95)02899-4

Thorburn, P.J., B.A. Cowie, and P.A. Lawrence. 1991. Effect of land development on groundwater recharge determined from non-steady chloride profiles. J. Hydrol. 124:43–58. doi:10.1016/0022-1694(91)90005-3

Thornthwaite, C.W., J.R. Mather, D.B. Carter, . 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publ. Climatol. 10(3). Drexel Inst. of Technol., Lab. of Climatol., Centerton, NJ.

Thorpe, P.M. 1987. Tritium as an indicator of groundwater recharge to the Gnangara Groundwater Mound on the Swan Coastal Plain, Perth, Western Australia. p. 41–55. In M.L. Sharma (ed.) Proc. Symp. on Ground Water Recharge, Mandurah, WA, Australia. 6–9 July 1987. A.A. Balkema, Rotterdam, the Netherlands.

Timmerman, L.R.A. 1985. Possibilities for the development of groundwater from the cenozoic sediments in the Lower Berg River region. Rep. GH3374. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa.

Timmerman, L.R.A. 1986. Sandveld region: Possibilities for the development of a groundwater supply scheme from a primary aquifer northwest of Graafwater. Rep. GH3471. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa.

Tomasella, J., M.G. Hodnett, L.A. Cuartas, A.D. Nobre, M.J. Waterloo, and S.M. Oliveira. 2008. The water balance of an Amazonian micro-catchment: The effect of interannual variability of rainfall on hydrological behaviour. Hydrol. Processes 22:2133–2147. doi:10.1002/hyp.6813

Unkovich, M., K. Blott, A. Knight, I. Mock, A. Rab, and M. Portelli. 2003. Water use, competition, and crop production in low rainfall, alley farming systems of south-eastern Australia. Aust. J. Agric. Res. 54:751–762. doi:10.1071/AR03049

Vandoolaeghe, M.A.C., and E. Bertram. 1982. Atlantis grondwatersisteem: Herevaluasie van versekerde lewering. Tech. Rep. GH 3222. Div. of Geohydrology, Directorate of Water Affairs, Dep. of Environment Affairs, Cape Town, South Africa.

van Lanen, H.A.J., and R. Dijksma. 1999. Water flow and nitrate transport to a groundwater-fed stream in the Belgian–Dutch chalk region. Hydrol. Processes 13:295–307. doi:10.1002/(SICI)1099-1085(19990228)13:33.0.CO;2-O

Vegter, J.R. 1995. An explanation of a set of national groundwater maps. Rep. TT 74/95. Water Res. Commiss., Pretoria, South Africa.

Verhagen, B.T. 1994. Semiarid zone groundwater mineralization processes as revealed by environmental isotope studies. p. 245–266. In Int. Symp. on Application of Tracers in Arid Zone Hydrology, Vienna, Austria. 22–26 Aug. 1994. Int. Assoc. Hydrol. Sci., Wallingford, UK.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. Global water resources: Vulnerability from climate change acid population growth. Science 289:284–288. doi:10.1126/science.289.5477.284

Walker, G., M. Gilfedder, and J. Williams. 1999. Effectiveness of current farming systems in the control of dryland salinity. CSIRO Land and Water, Canberra, ACT, Australia.

Walker, G.R., R.M. Blom, and A.K. Kennett-Smith. 1992a. Preliminary results of recharge investigations in the upper south-east region of South Australia. Ctr. for Groundwater Stud., Adelaide, SA, Australia.

Walker, G.R., G.R. Budd, P. Pavelic, A.K. Kennett-Smith, and P.G. Cook. 1990a. Groundwater recharge beneath open woodlands in south western New South Wales. Ctr. for Groundwater Stud., Adelaide, SA, Australia.

Walker, G.R., P.J. Dillon, P. Pavelic, and A.K. Kennett-Smigh. 1992b. Preliminary results of recharge and discharge investigations at Cooke Plains, South Australia. Ctr. for Groundwater Stud., Adelaide, SA, Australia.

Walker, G.R., I.D. Jolly, and P.G. Cook. 1991. A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. J. Hydrol. 128:49–67. doi:10.1016/0022-1694(91)90131-Z

Walker, G.R., I.D. Jolly, M. Stadter, F. Leaney, W. Stone, P. Cook, R. Davie, and L. Fifield. 1990b. Estimation of diffuse recharge in the Naracoorte Ranges Region, South Australia: An evaluation of chlorine-36 for recharge studies. AWRAC Final Rep. P87/10. Aust. Water Res. Advisory Counc., Dep. of Primary Ind., Canberra, ACT, Australia.

Walvoord, M.A., and F.M. Phillips. 2004. Identifying areas of basin-floor recharge in the Trans-Pecos region and the link to vegetation. J. Hydrol. 292:59–74. doi:10.1016/j.jhydrol.2003.12.029

Wang, B., M. Jin, J.R. Nimmo, L. Yang, and W. Wang. 2008. Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers. J. Hydrol. 356:209–222. doi:10.1016/j.jhydrol.2008.04.011

Wang, X.-P., R. Berndtsson, X.-R. Li, and E.-S. Kang. 2004. Water balance change for a re-vegetated xerophyte shrub area. Hydrol. Sci. J. 49:283–295. doi:10.1623/hysj.49.2.283.34841

Wanke, H., A. Duenkeloh, and P. Udluft. 2008. Groundwater recharge assessment for the Kalahari catchment of north-eastern Namibia and north-western Botswana with a regional-scale water balance model. Water Resour. Manage. 22:1143–1158. doi:10.1007/s11269-007-9217-5

Ward, P.R., F.X. Dunin, S.F. Micin. 2002. Water use and root growth by annual and perennial pastures and subsequent crops in a phase rotation. Agric. Water Manage. 53:83–97. doi:10.1016/S0378-3774(01)00157-3

Watson, A.J., T.J.A. Davie, W.B. Bowden, and J.J. Payne. 2004. Drainage to groundwater under a closed-canopy radiata pine plantation on the Canterbury Plains, South Island, New Zealand. J. Hydrol. 43:111–123.

Weaver, T.B., N.R. Hulugalle, and H. Ghadiri. 2005. Comparing deep drainage estimated with transient and steady state assumptions in irrigated Vertisols. Irrig. Sci. 23:183–191. doi:10.1007/s00271-005-0106-5

Webb, R.M.T., M.E. Wieczorek, B.T. Nolan, T.C. Hancock, M.W. Sandstrom, J.E. Barbash, E.R. Bayless, R.W. Healy, and J. Linard. 2008. Variations in pesticide leaching related to land use, pesticide properties, and unsaturated zone thickness. J. Environ. Qual. 37:1145–1157. doi:10.2134/jeq2007.0245

Wechsung, F., V. Krysanova, M. Flechsig, and S. Schaphoff. 2000. May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg? Landsc. Urban Plan. 51:177–189. doi:10.1016/S0169-2046(00)00108-0

Wegehenkel, M., Y. Zhang, T. Zenker, and H. Diestel. 2008. The use of lysimeter data for the test of two soil-water balance models: A case study. J. Plant Nutr. Soil Sci. 171:762–776. doi:10.1002/jpln.200700244

Weltz, M.A., and W.H. Blackburn. 1995. Water budget for South Texas rangelands. J. Range Manage. 48:45–52. doi:10.2307/4002503

White, R.E. 1997. Soil water and nitrogen dynamics under perennial and annual pastures: Final report to the program coordinator and the corporations on the results of this project from 1 October 1993 to 30 September 1997. SGS140/417. Dep. of Agric. and Resour. Manage.m Univ. of Melbourne, Parkville, VIC, Australia.

White, R.E., B.P. Christy, A.M. Ridley, A.E. Okom, S.R. Murphy, W.H. Johnstone, et al. 2003. SGS water theme: Influence of soil, pasture type and management on water use in grazing systems across the high rainfall zone of southern Australia. Aust. J. Exp. Agric. 43:907–926. doi:10.1071/EA02239

White, W.B., D.C. Culver, J.S. Herman, T.C. Kane, and J.E. Mylroie. 1995. Karst lands. Am. Sci. 83:450–459.

Williamson, T.N., B.D. Newman, R.C. Graham, and P.J. Shouse. 2004. Regolith water in zero-order chaparral and perennial grass watersheds four decades after vegetation conversion. Vadose Zone J. 3:1007–1016.

Wright, T.A., R.W. Knight, and R.K. Heitschmidt. 1988. Water yield of North Texas native grasslands. p. 42–50. In Water yield improvement from rangeland watersheds. Texas Water Dev. Board, Austin.

Zeppel, M.J.B., I.A.M. Yunusa, and D. Eamus. 2006. Daily, seasonal and annual patterns of transpiration from a stand of remnant vegetation dominated by a coniferous Callitris species and a broad leaved eucalyptus species. Physiol. Plant. 127:413–422. doi:10.1111/j.1399-3054.2006.00674.x

Zhang, L., W.R. Dawes, T.J. Hatton,, I.H. Hume, M.G. O'Connell, D.C. Mitchell, P.L. Milthorp, and M. Yee. 1999. Estimating episodic recharge under different crop/pasture rotations in the Mallee region: 2. Recharge control by agronomic practices. Agric. Water Manage. 42:237–249. doi:10.1016/S0378-3774(99)00034-7

Zhu, C. 2000. Estimate of recharge from radiocarbon dating of groundwater and numerical flow and transport modeling. Water Resour. Res. 36:2607–2620. doi:10.1029/2000WR900172

Zouari, K., M.A. Maliki, M. Moumni, and J.F. Aranyossy. 2001. Chemical (Cl) and isotopic (18O, 2H, 3H) study of the unsaturated zone in the arid region of Nefta (South Tunisia). p. 71–84. In W.M. Edmunds (ed.) Isotope based assessment of groundwater renewal in water scarce regions. IAEA TECDOC 1246. Int. Atomic Energy Agency, Vienna.

Appendix

Table A1. Recharge estimates, site information, and values used for multiple regression analyses.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Abdalla (2008)	11.1, 32.6	sand	scrubland	0.9	400		1930	154.2	4	model
	11.1, 29.1	clay	scrubland	4	1025		1893	147.4	4	model
	16.1, 34.6	sand	scrubland	7.3	130		2102	72.9	2	model
Ahmed and Umar (2008)	29.4, 77.3	clay	cropland	205	668	550	1454	267.2	2	WTF
	29.4, 77.3	clay	cropland	280	668	800	1454	267.2	2	WTF
	29.4, 77.3	clay	cropland	300	668	800	1454	267.2	2	WTF
Allen (1981)	−31.8, 115.9	sand	scrubland	85	775		1661	155.5	4	WB
Allison and Hughes (1972)	−37.8, 140.8	sand	grassland	63	686		1132	86.3	5	T
	−37.8, 140.8	sand	woodland	13	686		1132	86.3	5	T
Allison and Hughes (1978)	−37.8, 140.8	sand	grassland	106	700		1132	86.3	5	T
	−37.8, 140.8	sand	grassland	114	700		1132	86.3	5	T
Allison and Hughes (1983)	−35.1, 142.1	sand	cropland	3.5	335		1379	15.5	5	T
	−35.1, 142.1	sand	woodland	0.07	335		1379	15.5	5	T
Allison et al. (1985)	−34.3, 139.6	sand	woodland	0.135	300		1374	14.8	3	T
Allison et al. (1990)	−36.3, 140.8	clay	cropland	2	500		1245	44	6	T
	−36.3, 140.8	clay	cropland	2	500		1245	44	6	T
	−34.3, 139.6	sand	cropland	13	300		1374	14.8	3	T
	−35.1, 140.3	sandy loam	cropland	25.2	370		1346	22	5	T
	−34.3, 139.6	sand	woodland	0.05	300		1374	14.8	3	T
	−35.1, 140.1	sand	woodland	0.05	340		1335	23.1	5	T
	−35.1, 141.9	sand	woodland	0.06	340		1373	15.7	5	T
	−35.1, 140.3	sand	woodland	0.07	370		1346	22	5	T
	−34.4, 140.1	sandy loam	woodland	0.07	270		1361	15.2	6	WB
	−35.1, 140.3	sand	woodland	0.64	370		1346	22	5	WB
	−34.4, 140.1	sand	woodland	1.3	270		1361	15.2	6	T
Al-Sagaby and Moallim (2001)	25.8, 42.9	sand	no vegetation	1.8	133		2283	41	4	T
Amro et al. (2001)	29.8, 35.3	sand	no vegetation	0.03	65		1768	10	5	T
	32.1, 36.1	sandy silt	no vegetation	0.2	67		1504	51.6	5	T
	32.1, 36.1	sandy silt	no vegetation	1.5	67		1504	51.6	5	T
	32.3, 35.9	sand	no vegetation	8	480		1447	77.3	5	T
	32.3, 35.9	sand	no vegetation	28	480		1447	77.3	5	T
Anderson et al. (1998)	−30.6, 116.1	loam	cropland	214	703		1740	75.2	4	WB

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Andrews et al. (1997)	52.3, 0.4	sand	cropland	83	474		481	20.1	4	WTF
	52.3, 0.3	clay loam	cropland	104	455		481	20.4	1	WTF
Anuraga et al. (2006)	13.1, 78.3	clay	cropland	84	902		1530	160	4	model
	12.9, 78.3	clay	cropland	90	902	410	1529	160.9	4	model
	13.1, 78.3	clay	cropland	124	902	150	1530	160	4	model
	13.1, 78.3	sandy loam	cropland	184	902		1530	160	4	model
	13.1, 78.3	sandy loam	cropland	220	902	410	1530	160	4	model
	13.1, 78.3	sandy loam	cropland	232	902	150	1530	160	4	model
Athavale et al. (1980)	16.9, 78.6	clay	cropland	67	1100		1669	177.3	4	T
	16.9, 78.6	clay	cropland	73	1150		1669	177.3	4	T
	16.9, 78.6	clay	cropland	80	970		1669	177.3	4	T
	16.9, 78.6	sandy clay loam	cropland	83	1310		1669	177.3	4	T
	16.9, 78.6	sandy loam	cropland	83	1150		1669	177.3	4	T
	16.9, 78.6	clay	cropland	96.8	1310		1669	177.3	4	T
	16.9, 78.6	sandy loam	cropland	98	1200		1669	177.3	4	T
	16.9, 78.6	sandy loam	cropland	133	1310		1669	177.3	4	T
	16.9, 78.6	sandy loam	cropland	222	1430		1669	177.3	4	T
Babiker et al. (2005)	35.4, 136.9	sand	cropland	860	1915		895	195.1	2	WB
Beekman et al. (1996)	−22.1, 26.3	sand	scrubland	12.5	500		1408	83.8	0	T
Bekele et al. (2006)	−29.8, 115.6	sand	cropland	14.7	440		1869	109.5	4	T
	−29.8, 115.6	sand	cropland	35.7	440		1869	109.5	4	WTF
	−29.8, 115.6	sand	grassland	16.2	440		1612	109.5	4	T
	−29.8, 115.6	sand	grassland	35.9	440		1612	109.5	4	T
	−29.8, 115.6	sand	scrubland	9	440		1869	109.5	4	T
Bellot et al. (1999)	38.3, −0.6	loam	grassland	61.5	454		1136	55	2	model
	38.3, −0.6	loam	no vegetation	125	454		1136	55	2	model
	38.3, −0.6	loam	scrubland	18.6	454		1136	55	2	model
	38.3, −0.6	loam	woodland	9.6	454		1136	55	2	model
Bent (2001)	42.4, −72.3	fine sandy loam	woodland	262	1248		855	22.5	4	model
	42.4, −72.3	fine sandy loam	woodland	371	1169		855	22.5	4	model
Beverly et al. (2005)	−37.3, 144.9	sand	grassland	113	651		1121	40.3	6	model

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				———— mm yr^{-1} ————				mm mo^{-1}	mo	
Bird et al. (2004)	−37.8, 142.1	clay loam	cropland	36	695		1149	57	6	WB
	−37.8, 142.1	clay loam	grassland	18	695		1149	57	6	WB
Bredenkamp and Vandoolaeghe (1982)	−33.6, 18.4	coarse sands	scrubland	73.5	350		1236	73.2	5	model
	−33.6, 18.4	coarse sands	scrubland	95	350		1236	73.2	5	WB
Butler and Verhagen (2001)	−27.1, 22.8	sand	grassland	1.8	337		1572	65.6	2	T
	−27.1, 22.8	sand	grassland	13	337		1572	65.6	2	T
Calder et al. (2003)	53.3, −1.1	sand	grassland	169	800		449	14.6	5	model
	53.3, −1.1	sand	scrubland	156	800		449	14.6	5	model
	53.3, −1.1	sand	woodland	30	643		449	14.6	5	T
	53.3, −1.1	sand	woodland	45.8	643		449	14.6	5	model
	53.3, −1.1	sand	woodland	69	643		449	14.6	5	WB
	53.3, −1.1	sand	woodland	106	643		449	14.6	5	model
	53.3, −1.1	sand	woodland	120	643		449	14.6	5	WB
Carbon et al. (1982)	−31.8, 115.9	coarse sands	grassland	173	800		1661	155.5	4	WB
	−31.8, 115.9	coarse sands	woodland	121	900		1661	155.5	4	WB, WTF, T
Carlson et al. (1988)	33.3, −99.3	clay loam	grassland	7	671		1610	70.9	2	lysimeter
	33.3, −99.3	clay loam	no vegetation	9.3	671		1610	70.9	2	lysimeter
	33.3, −99.3	clay loam	woodland	3.3	671		1610	70.9	2	lysimeter
Cherkauer and Ansari (2005)	43.3, −88.3	sand	cropland	123	1030		839	71.2	1	base flow
Cho et al. (2009)	37.3, −80.1	12 mm d^{-1}	woodland	27	1045		982	33.6	0	model
Colville and Holmes (1972)	−37.6, 140.8	sand	grassland	82	700		1151	86.9	5	WTF
	−37.6, 140.8	sand	woodland	44	700		1151	86.9	5	WTF
Conrad et al. (2005)	−32.4, 18.8	coarse sands	cropland	15	275		1440	58.7	4	T
	−32.4, 18.8	coarse sands	scrubland	2	200		1440	58.7	4	T
Cook (1992)	−35.1, 140.1	loamy sand	cropland	9.8	340		1335	23.1	5	T
Cook and Kilty (1992)	−35.1, 140.1	sand	cropland	9	340		1335	23.1	5	EMI
Cook et al. (1989)	−34.6, 142.8	sandy clay loam	cropland	7	312		1421	15.9	4	T
	−34.6, 143.6	sandy clay loam	cropland	8.3	322		1378	13.8	6	T
	−35.1, 140.1	sand	grassland	2.7	340		1335	23.1	5	EMI
	−35.1, 140.1	sand	grassland	17.4	340		1335	23.1	5	T
	−35.1, 140.1	sand	woodland	0.05	340		1335	23.1	5	T
Cook et al. (1992a)	−34.4, 140.1	sandy loam	cropland	3	270		1361	15.2	6	T
Cook et al. (1992b)	15.6, −16.3	sand	cropland	15	356		1853	130.1	2	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Cook et al. (1994)	−34.3, 139.6	sand	grassland	11	340		1374	14.8	3	T
	−35.1, 140.1	sand	grassland	13	340		1335	23.1	5	T
	−35.1, 140.1	sand	grassland	16	340		1335	23.1	5	T
	−35.1, 140.1	sand	woodland	0.1	260		1335	23.1	5	T
	−35.1, 140.1	sand	woodland	0.9	260		1335	23.1	5	T
Cook et al. (1998)	−12.6, 131.1	clay	woodland	200	1720		1931	372	2	T
Cook et al. (2004)	−34.3, 140.6	sand	grassland	2.7	260		1373	14	3	T
	−34.3, 140.6	sand	grassland	4.9	260		1373	14	3	model
	−34.3, 140.6	sands	woodland	0.1	260		1373	14	3	T
Crosbie et al. (2007)	−34.6, 148.8	clay	grassland	5.2	613		1153	25.3	3	WTF
	−34.6, 148.8	clay	grassland	48.4	613		1153	25.3	3	WTF
Dams et al. (2008)	51.3, 4.8	sand	cropland	292	839		577	26.9	4	model
Daniel (1999)	35.6, −98.1	loam	cropland	93.8	743		1424	101	2	WTF
	35.6, −98.1	loam	grassland	63.9	743		1424	101	2	WTF
Datta et al. (1980)	23.6, 73.3	sandy loam	cropland	34	852		1724	307.7	2	T
	23.1, 72.6	sandy loam	cropland	35.6	648		1718	276.1	2	T
	23.1, 72.6	sandy loam	cropland	58.5	1014		1718	276.1	2	T
	23.4, 72.4	sandy loam	cropland	70.9	1357		1754	256.5	2	T
	23.8, 73.1	sandy loam	cropland	87	1145		1758	301.1	2	T
	23.4, 72.4	sandy loam	cropland	144	1682		1754	256.5	2	T
	23.1, 73.1	sandy loam	cropland	184	1411		1731	325.6	2	T
De Vries et al. (2000)	−24.8, 25.3	sand	scrubland	0.9	325		1376	99.6	0	T
	−24.8, 25.3	sand	scrubland	1	350		1376	99.6	0	T
	−24.1, 25.3	sand	scrubland	3	420		1372	88.2	0	T
	−23.8, 25.1	sand	scrubland	5	450		1396	81.1	0	T
Deans et al. (2005)	15.6, −16.3	sand	cropland	15	356		1853	130.1	2	T
Di and Cameron (2002)	−43.8, 171.8	silt loam	cropland	370	650		681	21.9	5	
Dolling et al. (2007)	−29.9, 116.6	sand	cropland	30	335		1732	53.1	5	model
	−33.9, 117.1	sand	cropland	115	496		1295	77	5	model
Dripps and Bradbury (2007)	43.1, −89.6	silt loam	cropland	256	834		824	75.6	1	WB
	43.1, −89.6	silt loam	cropland	290	834		824	75.6	1	WB
	46.1, −89.8	clay	grassland	279	790		688	84.9	1	WTF
	46.1, −89.8	clay	grassland	287	790		688	84.9	1	WB
	46.1, −89.8	clay	woodland	130	790		688	84.9	1	WTF
	46.1, −89.8	clay	woodland	175	790		688	84.9	1	WB
	46.1, −89.8	clay	woodland	176	790		688	84.9	1	WTF
	46.1, −89.8	clay	woodland	268	790		688	84.9	1	WB

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				———— mm yr^{-1}			————	mm mo^{-1}	mo	
Duffková (2002)	49.3, 14.8	sandy loam	grassland	20.6	528		599	52.5	1	lysimeter
Dunin et al. (1999)	−35.4, 147.6	850 mm d^{-1}	cropland	15	611		1079	38.7	5	WB
	−35.4, 147.6	850 mm d^{-1}	cropland	84	611		1079	38.7	5	WB
	−35.4, 147.6	850 mm d^{-1}	cropland	89	611		1079	38.7	5	WB
	−35.4, 147.6	sandy clay loam	cropland	185	611		1079	38.7	5	WB
	−35.4, 147.6	sandy clay loam	grassland	25	611		1079	38.7	5	WB
	−35.4, 147.6	850 mm d^{-1}	grassland	2	611		1079	38.7	5	WB
Dyck et al. (2003)	51.9, −107.3	silty loam	cropland	3	321		719	48.7	0	T
Edmunds (2001b)	34.8, 32.9	sand	grassland	52.5	420		1364	104.1	4	T
	34.8, 32.9	sand	grassland	55.5	420		1364	104.1	4	T
Edmunds and Gaye (1994)	15.9, −16.3	clay	cropland	2.69	290		1858	107.3	1	T
	15.8, −16.3	sand	cropland	14.9	290		1853	118.4	2	T
Edmunds et al. (2002)	13.1, 10.1	sand	no vegetation	35.3	314		2286	168.4	3	T
Facchi et al. (2005)	45.1, 9.6	coarse sands	grassland	491	800	512	678	55.9	3	model
Favreau et al. (2009)	13.6, 2.8	sand	cropland	25	557		2160	171.6	3	WTF
	13.6, 2.8	sand	scrubland	2	557		2160	171.6	3	model
Favreau et al. (2002)	13.4, 2.8	sand	cropland	35	567		2152	175.1	3	WTF
	13.4, 2.8	sand	scrubland	3	567		2152	175.1	3	T
Fayer et al. (1996)	46.6, −119.4	loamy sand	grassland	1.2	159		1083	18.5	5	T
	46.6, −119.4	sandy loam	grassland	5.1	159		1083	18.5	5	T
	46.6, −119.4	sandy loam	grassland	25.4	159		1083	18.5	5	WB
	46.6, −119.4	coarse sands	no vegetation	55.4	159		1083	18.5	5	lysimeter
	46.6, −119.4	gravel	no vegetation	86.7	184		1083	18.5	5	lysimeter
	46.6, −119.4	gravel	no vegetation	300	480		1083	18.5	5	lysimeter
	46.6, −119.4	loamy sand	scrubland	0.02	159		1083	18.5	5	T
	46.6, −119.4	silt loam	scrubland	0.05	159		1083	18.5	5	T
	46.6, −119.4	loamy sand	scrubland	2	159		1083	18.5	5	T
	46.6, −119.4	silt loam	scrubland	2.75	159		1083	18.5	5	T
Fillery and Poulter (2006)	−30.8, 116.6	loamy sand	cropland	53	495		1643	62.7	5	WB
Finch (1998)	51.6, −1.1	sandy clay loam	cropland	290	587		473	25.3	5	WB
	51.6, −1.1	sandy clay loam	grassland	176	587		473	25.3	5	WB
	51.6, −1.1	sandy clay loam	woodland	96	587		473	25.3	5	WB

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Fisher and Healy (2008)	46.3, −119.9	silty clay	cropland	119	187	744	1068	22.5	5	lysimeter, WB
	39.3, −76.1	fine sandy loam	cropland	315	981		1045	27.6	1	lysimeter, WB
	37.3, −120.8	sand	cropland	423	270	1200	1384	48.4	6	lysimeter, WB
	39.8, −85.8	silty clay loam	cropland	475	906		955	68.4	0	lysimeter, WB
Fouty (1989)	36.9, −116.8	loamy sand	scrubland	0.23	104		1754	12.2	5	T
Gates et al. (2008)	39.9, 101.9	sand	grassland	1.5	84		1010	17.5	1	T
Gaye and Edmunds (1996)	15.8, −16.4	sand	cropland	24	290		1843	118.3	2	T
	15.8, −16.4	sand	cropland	31.5	290		1843	118.3	2	T
Gee et al. (1994)	32.6, −106.4	loamy fine sand	no vegetation	87	338		1704	50.8	1	lysimeter, WB
Gee et al. (1993)	46.6, −119.4	sand	no vegetation	71.1	172		1083	18.5	5	lysimeter, WB
	46.6, −119.4	sand	no vegetation	300	480		1083	18.5	5	lysimeter, WB
George and Frantom (1988)	−31.6, 118.3	sandy clay	woodland	0.1	328		1501	42	5	T
	−31.6, 118.3	sandy clay	woodland	1.5	328		1501	42	5	T
Gieske (1992)	−24.4, 25.6	sand	scrubland	10	492		1357	94.1	0	T
Gieske et al. (1995)	−24.3, 25.3	sand	scrubland	9	425		1372	91.6	0	T
	−24.3, 25.3	sand	scrubland	15	425		1372	91.6	0	T
Goni and Edmunds (2001)	13.6, 13.4	fine sands	scrubland	7	389		2300	132.7	3	T
	12.1, 12.8	fine sands	scrubland	22.5	389		2184	191.2	3	T
Goodrich et al. (2004)	31.8, −110.8	silty clay	scrubland	3	324		1499	99.9	0	T
Green et al. (2008)	41.6, −96.6	silt loam	cropland	159	720	203	1024	94.4	1	WTF
	41.6, −96.6	loamy sand	grassland	48	720		1024	94.4	1	WTF
Gregory et al. (1992)	−32.1, 117.1	sandy loam	cropland	6.5	380		1469	69.5	5	WB
Gupta and Sharma (1984)	22.9, 76.6	sand	cropland	67	750		1690	348.9	3	T
	22.9, 76.6	sand	cropland	81	894		1690	348.9	3	T
	22.9, 76.6	sand	cropland	94	821		1690	348.9	3	T
Hadas et al. (1999)	31.3, 34.6	360 mm d^{-1}	cropland	70	210	525	1452	57.6	5	WB, T
	31.9, 34.8	680 mm d^{-1}	cropland	73.7	567		1311	136.8	5	WB, T
	32.1, 34.8	330 mm d^{-1}	cropland	81.6	544	266	1290	141.1	4	WB, T
	32.3, 34.9	680 mm d^{-1}	cropland	95.9	588	150	1307	154.6	4	WB, T
Halm et al. (2002)	−7.1, −41.8	sand	Cropland	14.5	700		1835	163.6	5	WB
	−7.1, −41.8	sand	Scrubland	6.5	700		1835	163.6	5	WB

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Hatton and Nulsen (1999)	−35.4, 147.6	sandy clay loam	grassland	3	611		1079	38.7	5	model
	−35.4, 147.6	sandy clay loam	grassland	134	611		1079	38.7	5	model
	−35.4, 147.6	sandy clay loam	woodland	0	611		1079	38.7	5	model
Heilweil et al. (2006)	37.1, −113.3	loam	scrubland	0.3	210		1639	34.7	4	T
	37.1, −113.3	loam	scrubland	4	210		1639	34.7	4	T
	37.1, −113.3	loam	scrubland	6.8	210		1639	34.7	4	T
	37.1, −113.3	loam	scrubland	10	210		1639	34.7	4	T
Heng et al. (2001)	−35.4, 147.6	clay	grassland	47.6	650		1079	38.7	5	WB
Holmes and Colville (1968)	−37.8, 140.8	sand	grassland	120	700		1132	86.3	5	lysimeter
Holmes and Colville (1970a)	−37.8, 140.8	sand	grassland	63	600		1132	86.3	5	WB
Holmes and Colville (1970b)	−37.9, 140.9	sand	woodland	0	600		1147	84.2	5	WB
Holmstead et al. (1988)	29.1, −99.9	loam	grassland	0	273		1565	58.9	2	lysimeter
	29.1, −99.9	loam	grassland	1.2	736		1565	58.9	2	lysimeter
	29.1, −99.9	loam	no vegetation	10.7	273		1565	58.9	2	lysimeter
	29.1, −99.9	loam	no vegetation	29.9	736		1565	58.9	2	lysimeter
Houston (1982)	−14.4, 28.4	1800 mm d^{-1}	no vegetation	281	937		1448	240.3	3	base flow
	−14.4, 28.4	1800 mm d^{-1}	woodland	80	937		1448	240.3	3	base flow
Howard and Karundu (1992)	0.1, 30.8	loam	cropland	66	869		1235	105.4	4	WB
	0.1, 30.8	loam	grassland	33.5	869		1235	105.4	4	WB
	0.1, 30.8	loam	no vegetation	81	869		1235	105.4	4	WB
	0.1, 30.8	loam	woodland	0	869		1235	105.4	4	WB
Huang and Gallichand (2006)	35.3, 107.8	silty clay loam	cropland	18.3	545		818	109.9	0	model
Hughes et al. (1988)	−35.1, 140.1	sandy loam	cropland	16.5	340		1335	23.1	5	T
Hume (1997)	−35.8, 150.1	coarse sands	woodland	200	800		1163	63.8	1	
Hussein (2001)	31.1, 33.8	sand	no vegetation	18	300		1405	25.6	4	T
	31.1, 33.8	sand	no vegetation	24	300		1405	25.6	4	T
Jackson and Rushton (1987)	50.1, 10.1	boulder clay	cropland	24	521		540	38.5	1	WB
Jipp et al. (1998)	−2.9, −47.6	clay	grassland	287	1672		1321	323	4	WB
	−2.9, −47.6	clay	woodland	141	1672		1321	323	4	WB
	−2.9, −47.6	clay	woodland	187	1672		1321	323	4	WB
Johnston (1987a)	−33.4, 115.9	clay	woodland	28.1	1220		1504	178	5	T
	−33.4, 115.9	clay	woodland	75	1220		1504	178	5	T
Johnston (1987b)	−33.3, 116.4	clay	woodland	2.45	800		1423	138.9	5	T
	−33.4, 115.9	sand	woodland	26.5	1250		1504	178	5	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Jolly (1992)	−32.3, 18.4	coarse sands	scrubland	23.5	196		1398	40.7	4	WTF
Jolly et al. (1989)	−35.1, 140.3	sand	cropland	45	370		1346	22	5	T
	−35.1, 140.3	sand	woodland	0.8	370		1346	22	5	T
Joshi (1997)	52.1, −106.1	silt	cropland	12	371		699	51.3	0	T
	52.1, −106.1	silt	grassland	1	371		699	51.3	0	T
Julien et al. (1988)	33.3, −99.3	fine sandy loam	grassland	0	723		1610	70.9	2	lysimeter
	33.3, −99.3	fine sandy loam	grassland	0	811		1610	70.9	2	lysimeter
	33.3, −99.3	fine sandy loam	grassland	0	852		1610	70.9	2	lysimeter
	33.3, −99.3	fine sandy loam	no vegetation	10.8	837		1610	70.9	2	lysimeter
	33.3, −99.3	fine sandy loam	woodland	0	678		1610	70.9	2	lysimeter
Kendy et al. (2003)	37.9, 114.8	loam	cropland	66.3	367	81	1031	150.6	1	WB
	37.9, 114.8	loam	cropland	105	367	301	1031	150.6	1	WB
	37.9, 114.8	loam	cropland	140	367	371	1031	150.6	1	WB
	37.9, 114.8	loam	cropland	174	367	460	1031	150.6	1	WB
Kendy et al. (2004)	37.9, 114.8	loam	cropland	200	461		1031	150.6	1	WB
	37.9, 114.8	loam	cropland	690	461	900	1031	150.6	1	WB
	37.9, 114.8	loam	cropland	1300	461	1500	1031	150.6	1	WB
Kennett-Smith et al. (1990)	−34.3, 141.3	sandy clay loam	cropland	4	310		1387	11.5	3	T, WB
	−34.3, 141.3	loamy sand	cropland	7.5	310		1387	11.5	3	T, WB
	−34.6, 142.8	loamy sand	cropland	13.6	312		1421	15.9	4	T, WB
	−34.6, 143.6	sandy clay loam	cropland	18	322		1378	13.8	6	T, WB
Kennett-Smith et al. (1992a)	−37.6, 143.9	clay	cropland	3	430		1108	56.7	6	T, WB
Kennett-Smith et al. (1992b)	−33.4, 142.6	loamy sand	grassland	0.4	255		1493	9.4	3	T, WB
Kennett-Smith et al. (1993)	−35.8, 141.4	clay	grassland	3.5	530		1294	27.8	5	T, WB
Kennett-Smith et al. (1994)	−35.1, 141.9	sandy clay loam	cropland	9	340		1373	15.7	5	T
Kienzle and Schulze (1992)	−27.4, 32.6	sand	woodland	179	850		1337	103.2	0	WB
Knoche et al. (2002)	51.8, 13.6	sand	woodland	82	652		616	36.7	1	model
Krajenbrink et al. (1988)	52.3, 5.6	coarse sands	cropland	305	854		518	34.3	4	T
	52.3, 5.6	coarse sands	grassland	305	854		518	34.3	4	T
	52.3, 5.6	coarse sands	woodland	101	854		518	34.3	4	T
Külls (2000)	−24.3, 29.9	sand	scrubland	11.5	465		1341	98.6	1	T
Ladekarl et al. (2005)	56.4, 8.9	sand	scrubland	733	1077		450	49.4	3	T
	56.4, 9.4	sand	woodland	390	875		445	40.2	4	T
Larsen et al. (2002)	−19.9, 28.3	sand	scrubland	25	550		1528	126	2	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Leaney and Allison (1986)	−34.1, 139.9	sand	woodland	0.15	275		1394	13.9	3	T
	−34.1, 139.9	sand	woodland	0.25	275		1394	13.9	3	T
Leaney and Herczeg (1995)	−36.3, 140.8	clay	cropland	1.1	545		1245	44	6	T
	−36.3, 140.8	clay	cropland	10	545	450	1245	44	6	T
	−36.3, 140.8	sand	cropland	60	545		1245	44	6	T
	−36.3, 140.8	clay	woodland	0.5	545		1245	44	6	T
	−36.3, 140.8	sand	woodland	0.5	545		1245	44	6	T
Leaney and Herczeg (1999)	−35.3, 140.8	clay	grassland	12	375	640	1346	23.3	5	T
	−35.3, 140.9	clay	woodland	0.3	440		1345	21.5	5	T
	−36.6, 141.3	sand	woodland	1.5	450		1216	46.3	6	T
Leduc et al. (2001)	13.6, 2.6	sand	scrubland	3	565		2162	174.9	3	T
	13.6, 2.6	sand	scrubland	6	565		2162	174.9	3	T
	13.6, 2.6	sand	scrubland	20	565		2162	174.9	3	WTF
Li et al. (2005)	36.1, 140.1	loam	grassland	392	1194		781	130	2	WB
Lin and Wei (2001)	42.9, 118.9	silt loam	no vegetation	47	360		899	118.3	0	T
	37.8, 113.8	silt loam	no vegetation	68	550		931	146.8	0	T
	42.9, 118.9	silt loam	no vegetation	85	360		899	118.3	0	T
	37.8, 113.8	silt loam	no vegetation	288	550		931	146.8	0	T
Loh and Stokes (1981)	−32.9, 121.6	sand	cropland	15	390		1462	23.5	5	T
	−32.9, 117.6	sand	cropland	19	410		1331	61.4	5	WTF
	−31.8, 116.4	sand	cropland	30	590		1570	125.4	4	WTF
	−33.3, 116.4	sand	cropland	40	750		1423	138.9	5	WTF
	−33.3, 116.6	sand	cropland	55	650		1396	115.7	5	WTF
	−33.3, 116.4	sand	cropland	60	725		1423	138.9	5	WTF
	−33.4, 115.9	sand	cropland	100	1150		1504	178	5	WTF
	−31.8, 116.4	clay	grassland	24	590		1570	125.4	4	WTF
	−33.4, 115.9	sand	woodland	10	1250		1504	178	5	WTF
Maréchal et al. (2006)	17.4, 78.4	clay	cropland	114	613	165	1704	180.5	4	WTF
Maréchal et al. (2009)	11.8, 76.4	clay	woodland	75	1273		1386	501.9	3	WTF, T
McDowall et al. (2003)	−33.4, 121.9	sand	grassland	55.3	522		1448	43.8	5	WB
McMahon et al. (2003)	37.8, −100.8	sand	cropland	53	487	675	1419	68.4	0	T
	37.3, −101.8	loamy fine sand	grassland	5.1	453		1464	57.7	2	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
McMahon et al. (2006)	33.6, −102.8	loam	cropland	17	420	585	1627	57.6	1	T
	33.8, −102.8	loam	cropland	24.5	440	450	1622	58	1	T
	33.6, −102.8	loam	cropland	32	420	433	1627	57.6	1	T
	33.8, −102.8	sandy loam	cropland	39	420	593	1622	58	1	T
	33.8, −102.8	loamy sand	cropland	54	420	638	1622	58	1	T
	33.8, −102.8	sandy loam	cropland	102	420	330	1622	58	1	T
	33.8, −102.8	sandy loam	cropland	111	420	540	1622	58	1	T
	34.1, −102.8	loamy sand	grassland	0.2	420		1595	60	1	T
	37.3, −101.8	loamy sand	grassland	5	453		1464	57.7	2	T
	40.6, −101.8	sand	grassland	70	500		1191	75	2	T
Mileham et al. (2008)	−0.9, 30.1	sandy loam	cropland	104	1190		1126	99.5	4	WB
Milroy et al. (2008)	−29.6, 115.8	sand	cropland	25.1	324		1969	74.1	4	model
	−29.6, 115.8	sand	cropland	37.9	356		1900	74.1	4	model
	−29.6, 115.8	sand	cropland	40.6	387		1800	74.1	4	model
	−29.6, 115.8	sand	cropland	45	339		1969	74.1	4	model
	−29.6, 115.8	sand	cropland	54.3	409		1700	74.1	4	model
	−29.6, 115.8	sand	cropland	83.1	461		1622	74.1	4	model
Monirul Islam and Kanungoe (2005)	24.8, 88.6	clay	cropland	153	1442	207	1195	360.3	2	WB
Müller and Bolte (2009)	52.6, 13.4	sand	grassland	285	620		593	36.6	1	lysimeter
	52.6, 13.4	sand	woodland	74.4	620		593	36.6	1	lysimeter
	52.6, 13.4	sand	woodland	80.6	620		593	36.6	1	lysimeter
	52.6, 13.4	sand	woodland	124	620		593	36.6	1	lysimeter
Navada et al. (2001)	24.9, 71.1	fine sands	cropland	12	240		1872	106.4	2	T
	24.9, 71.1	fine sands	cropland	14.5	240		1872	106.4	2	T
	24.9, 71.1	fine sands	cropland	18	240		1872	106.4	2	T
	25.4, 71.1	fine sands	cropland	20	240		1836	81.3	2	T
Newman et al. (1997)	35.8, −106.3	loam	grassland	1	470		1444	48.8	1	T
	35.8, −106.3	fine sandy loam	woodland	0.45	510		1444	48.8	1	T
	35.8, −106.3	loam	woodland	0.8	470		1444	48.8	1	T
Nichols and Verry (2001)	47.6, −93.4	fine sandy loam	woodland	109	784		725	89.9	0	WB
O'Connell et al. (2003)	−35.1, 141.9	sandy loam	cropland	5.3	356		1373	15.7	5	lysimeter
Ojeda (2001)	28.4, −110.8	sand	scrubland	0.11	320		1737	92.5	1	T
	28.4, −110.8	sand	scrubland	0.16	320		1737	92.5	1	T
	31.6, −106.9	sand	scrubland	0.24	230		1780	39.4	0	T
Pakrou and Dillon (2000)	−37.8, 140.8	silt loam	cropland	129	750		1132	86.3	5	lysimeter
	−37.8, 140.8	silt loam	cropland	163	750		1132	86.3	5	lysimeter

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Paydar and Gallant (2008)	−35.8, 146.8	360 mm d^{-1}	cropland	93.8	546		1071	33.1	5	model
	−35.8, 146.8	360 mm d^{-1}	grassland	17.6	546		1071	33.1	5	model
Peck and Hurle (1973)	−32.4, 116.8	sand	grassland	24	490		1468	98.7	5	base flow
	−32.8, 116.8	sand	grassland	26	730		1434	95.5	5	base flow
	−33.1, 116.9	sand	grassland	37	500		1373	84.4	5	base flow
	−33.3, 116.6	sand	grassland	60	820		1396	115.7	5	base flow
	−31.8, 116.3	sand	grassland	61	880		1597	149.7	4	base flow
	−31.4, 116.1	sand	grassland	78	910		1647	125.7	4	base flow
	−32.4, 116.8	sand	woodland	0.82	490		1468	98.7	5	WB
	−33.1, 116.9	sand	woodland	1.2	500		1373	84.4	5	WB
	−33.3, 116.6	sand	woodland	1.7	820		1396	115.7	5	WB
	−32.8, 116.8	sand	woodland	1.9	730		1434	95.5	5	WB
	−31.8, 116.3	sand	woodland	3.9	880		1597	149.7	4	WB
	−31.4, 116.1	sand	woodland	8	910		1647	125.7	4	WB
	−31.6, 116.3	sand	woodland	13.4	660		1620	126.6	4	T
	−32.9, 116.3	sand	woodland	24.2	1100		1470	181.6	5	T
	−33.3, 116.3	sand	woodland	33.4	870		1456	162.2	5	T
	−32.8, 116.1	sand	woodland	106	1350		1517	229.1	5	T
	−32.3, 116.1	sand	woodland	134	1147		1546	217.7	4	T
	−32.3, 116.1	sand	woodland	157	1100		1559	217.7	4	T
Peck et al. (1981)	−33.4, 116.1	sand	woodland	0.69	1150		1457	169.7	5	T, model
	−33.4, 116.1	sand	woodland	8	800		1457	169.7	5	T, model
	−33.4, 116.1	sand	woodland	104	1300		1457	169.7	5	T, model
	−33.4, 116.1	sand	woodland	150	1150		1457	169.7	5	T, model
Pracilio et al. (2003)	−31.3, 117.6	loamy sand	cropland	12	336		1541	45	5	model
	−31.3, 117.6	loamy sand	cropland	32	336		1541	45	5	model
	−31.3, 117.6	sand	cropland	53	336		1541	45	5	model
Prych (1998)	46.6, −119.4	loam	grassland	1.2	160		1083	18.5	5	T
	46.6, −119.4	loam	grassland	5.1	160		1083	18.5	5	T
	46.6, −119.4	silt loam	scrubland	0.06	160		1083	18.5	5	T
	46.6, −119.4	loam	scrubland	0.15	160		1083	18.5	5	T
	46.6, −119.4	loam	scrubland	2.6	160		1083	18.5	5	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Radford et al. (2009)	−24.8, 150.1	clay	cropland	1.6	700		1502	72.1	1	T
	−23.9, 150.3	clay	cropland	2	659		1600	93.9	0	T
	−23.1, 148.1	clay	cropland	7.4	597		1638	93.8	1	T
	−24.3, 149.8	clay	cropland	8.9	632		1548	82.8	1	T
	−23.9, 148.4	clay	cropland	16.1	600		1596	94.7	1	T
	−22.9, 148.9	clay	cropland	18	580		1621	96.8	0	T
	−24.3, 150.4	clay	cropland	27.5	639		1579	88.2	1	T
	−22.9, 148.9	clay	woodland	0.2	580		1621	96.8	0	T
	−23.9, 148.4	clay	woodland	0.2	600		1596	94.7	1	T
	−23.9, 150.3	clay	woodland	0.2	659		1600	93.9	0	T
	−24.3, 149.8	cracking clay	woodland	0.3	632		1548	82.8	1	T
	−24.3, 149.8	cracking clay	woodland	0.3	638		1548	82.8	1	T
	−24.8, 150.1	cracking clay	woodland	0.3	700		1502	72.1	1	T
	−24.3, 150.4	clay	woodland	0.3	639		1579	88.2	1	T
	−23.1, 148.1	cracking clay	woodland	1.7	597		1638	93.8	1	T
Ragab et al. (1997)	52.3, −2.6	loamy sand	grassland	68	625		444	25.9	5	WB
	52.3, 0.3	4	grassland	91	550		481	20.4	1	WB
	50.8, −3.3	loamy sand	grassland	153	738		477	56	6	WB
	52.3, 0.3	4	grassland	165	550		481	20.4	1	lysimeter
	51.1, −1.3	silty clay loam	grassland	213	771		469	38.9	5	WB
Rangarajan et al. (2009)	8.8, 78.1	sandy loam	cropland	16.3	582		1514	186.6	5	T
	8.8, 78.1	sand	cropland	47.6	582		1514	186.6	5	T
	8.8, 78.1	sandy loam	cropland	60	582		1514	186.6	5	T
	8.8, 78.1	clay	cropland	70.2	582		1514	186.6	5	T
	8.8, 78.1	sand	cropland	82.3	582		1514	186.6	5	T
Renard et al. (1993)	31.8, −110.8	loam	scrubland	0.2	303		1499	99.9	0	model
Renger and Wessolek (1990)	53.1, 10.8	sand	cropland	230	615		519	32.5	0	
	51.4, 9.3	deposits of glacial till	cropland	232	687		516	34.9	1	
Renger et al. (1986)	52.3, 9.8	fine sands	cropland	225	655		518	34	1	WB, model
	52.3, 9.8	fine sands	grassland	190	655		518	34	1	WB, model
	52.3, 9.8	fine sands	woodland	110	655		518	34	1	WB, model
Richardson and Narayan (1995)	−34.4, 135.9	sand	cropland	40	550		1408	66.9	5	WTF, WB
	−34.4, 135.9	sand	grassland	10	550		1408	66.9	5	model

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				mm yr^{-1}				mm mo^{-1}	mo	
Ridley et al. (1997)	−36.1, 146.6	sandy clay loam	grassland	74.5	693		1056	42.2	5	WB
	−36.1, 146.6	sandy clay loam	grassland	83	693		1056	42.2	5	WB
	−36.1, 146.6	sandy clay loam	no vegetation	83	693		1056	42.2	5	WB
	−36.1, 146.6	sandy clay loam	no vegetation	142	693		1056	42.2	5	WB
	−36.1, 146.6	fine sandy clay loam	cropland	36.5	600		1056	42.2	5	WB
	−36.1, 146.6	fine sandy clay loam	cropland	51.5	600		1056	42.2	5	model
	−36.1, 146.6	fine sandy clay loam	grassland	5.5	600		1056	42.2	5	WB
	−36.1, 146.6	fine sandy clay loam	grassland	6.8	600		1056	42.2	5	model
Roberts and Rosier (2006)	51.1, −1.3	silty clay	grassland	207	986		469	38.9	5	WB
	51.1, −1.3	silty clay	woodland	300	1004		469	38.9	5	WB
Rodvang et al. (2004)	49.9, −112.8	fine sandy clay loam	cropland	11.6	400	300	851	50.4	1	T
	49.9, −112.8	coarse sands	cropland	29.7	400	350	851	50.4	1	T
	49.9, −112.8	fine sandy clay loam	cropland	34.7	400	300	851	50.4	1	WTF
	49.9, −112.8	coarse sands	cropland	59.7	400	350	851	50.4	1	WTF
	49.9, −112.8	coarse sands	cropland	117	400	350	851	50.4	1	T
	49.9, −112.8	coarse sands	cropland	170	400	440	851	50.4	1	T
	49.9, −112.8	coarse sands	grassland	42	400	440	851	50.4	1	T
Sami and Hughes (1996)	−32.8, 26.1	loam	grassland	5.2	460		1342	50.7	2	T
	−32.8, 26.1	loam	grassland	5.8	460		1342	50.7	2	model
Santoni et al. (2010)	−33.6, −65.8	sandy loam	cropland	5.3	518		1317	86	0	T
	−33.6, −65.8	sandy loam	cropland	6.9	502		1317	86	0	T
	−33.6, −65.8	sandy loam	cropland	7.9	502		1317	86	0	T
	−33.8, −65.8	sandy loam	cropland	9.6	542		1294	82.7	0	T
	−33.4, −65.9	sandy loam	cropland	10.4	538		1383	90	0	T
	−33.6, −65.8	sandy loam	cropland	10.8	518		1317	86	0	T
	−33.4, −65.9	sandy loam	cropland	13.2	538		1383	90	0	T
	−33.8, −65.8	sandy loam	cropland	128	542		1294	82.7	0	T
	−33.4, −66.6	sandy loam	woodland	0.02	447		1476	84.6	0	T
	−33.4, −65.9	sandy loam	woodland	0.04	538		1383	90	0	T
	−33.6, −65.8	sandy loam	woodland	0.05	502		1317	86	0	T
	−33.6, −65.8	sandy loam	woodland	0.14	518		1317	86	0	T
	−33.8, −65.8	sandy loam	woodland	0.33	542		1294	82.7	0	T
Scanlon (1991)	31.4, −105.8	silt loam	scrubland	0.07	280		1766	43.7	1	T

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Scanlon and Goldsmith (1997)	35.3, −101.8	silty clay loam	grassland	0.62	500		1571	71.5	1	T
Scanlon et al. (1999)	31.1, −105.3	clay	grassland	0.02	320		1737	48.4	1	T
	31.1, −105.3	clay loam	grassland	0.05	320		1737	48.4	1	T
Scanlon et al. (2005)	32.9, −102.1	sandy loam	cropland	19.5	457		1670	53.6	2	T
	32.9, −102.1	sand	cropland	24	457		1670	53.6	2	T
	32.9, −102.1	sand	grassland	2	457		1670	53.6	2	T
	36.8, −116.8	sand	scrubland	0.5	113		1870	11.3	5	T
Scanlon et al. (2007b)	32.8, −101.9	loamy sand	cropland	19	452		1677	53.3	2	T
	32.8, −101.9	loamy sand	cropland	31	449		1677	53.3	2	T
	32.8, −101.9	loamy sand	cropland	39	446		1677	53.3	2	T
	32.8, −101.9	loamy sand	grassland	0	426		1677	53.3	2	T
Selaolo (1998)	−24.1, 25.3	sand	scrubland	8	400		1372	88.2	0	T
Selaolo et al. (2003)	−23.6, 24.3	sand	scrubland	0.5	400		1433	78	0	T
	−23.6, 24.3	sand	scrubland	1.1	400		1433	78	0	T
	−23.6, 24.3	sand	scrubland	3.8	400		1433	78	0	T
	−24.1, 25.1	sand	scrubland	4	420		1384	86.1	0	T
	−24.1, 25.1	sand	scrubland	9.8	420		1384	86.1	0	T
	−25.3, 25.6	sand	scrubland	11	500		1394	102.2	0	T
	−25.3, 25.6	sand	scrubland	16	500		1394	102.2	0	T
Sharda et al. (2006)	23.1, 73.3	sandy clay loam	cropland	62.7	835		1734	322.4	2	T
	23.1, 73.3	sandy clay loam	cropland	71	835		1734	322.4	2	WTF
Sharma and Gupta (1987)	26.3, 73.1	sand	cropland	16.6	219		1963	122.8	2	T
	26.3, 73.1	sand	cropland	17.4	219		1963	122.8	2	T
	26.6, 72.8	sand	no vegetation	21.8	389		1907	108.6	1	T
	26.3, 73.1	sand	no vegetation	22.1	219		1963	122.8	2	T
	26.8, 71.3	sand	no vegetation	22.3	165		1770	65.2	2	T
	26.3, 73.1	sand	no vegetation	25.7	219		1963	122.8	2	T
	26.6, 72.8	sand	no vegetation	46.8	389		1907	108.6	1	T
Silburn et al. (2009)	−24.8, 149.8	cracking clay	cropland	19.8	720		1510	75.6	1	T
	−24.8, 149.8	cracking clay	grassland	0.16	720		1510	75.6	1	T
	−24.8, 149.8	cracking clay	no vegetation	32.4	720		1510	75.6	1	T
	−24.8, 149.8	cracking clay	woodland	0.17	720		1510	75.6	1	T
	−24.8, 149.8	clay	woodland	0.26	720		1510	75.6	1	T
Singh et al. (1984)	−0.1, 34.8	sandy clay loam	grassland	55	1278		1702	163.9	2	WB
Sloots and Wijnen (1990)	−24.4, 25.6	sand	scrubland	9	492		1357	94.1	0	
Smettem (1998)	−33.9, 121.8	sand	grassland	35	500		1410	85.5	5	WB

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Smith et al. (1998)	−35.4, 147.6	sandy clay loam	cropland	33.3	343		1079	38.7	5	WB, lysimeter
	−35.4, 147.6	sandy clay loam	cropland	97	628		1079	38.7	5	WB, lysimeter
Snow et al. (1999)	−35.4, 147.6	850 mm d^{-1}	woodland	216	674	896	1079	38.7	5	model
Sophocleous (2005)	34.3, −102.8	clay loam	cropland	7	408		1596	59.5	1	model
	38.9, −101.8	clay loam	cropland	15	465		1274	69.8	2	model
	40.6, −102.3	clay loam	cropland	29.5	448		1201	74.6	2	model
	40.6, −102.3	silt loam	cropland	49.5	448		1201	74.6	2	model
	38.1, −101.3	clay loam	cropland	91	623		1376	65.9	1	model
	47.9, −97.1	clay loam	cropland	102	464		809	67.1	1	model
	40.6, −98.1	clay loam	cropland	109	668		1138	95.5	2	model
	34.3, −102.8	clay loam	grassland	0	408		1596	59.5	1	model
	40.6, −102.3	clay loam	grassland	1	448		1201	74.6	2	model
	40.6, −102.3	silt loam	grassland	2	448		1201	74.6	2	model
	38.9, −101.8	clay loam	grassland	8	465		1274	69.8	2	model
	38.1, −101.3	clay loam	grassland	19	623		1376	65.9	1	model
	47.9, −97.1	clay loam	grassland	40	464		809	67.1	1	model
	40.6, −98.1	clay loam	grassland	92	668		1138	95.5	2	model
Sophocleous and McAllister (1987)	38.1, −98.8	silty clay loam	cropland	65	600		1330	87.9	1	WB
	38.1, −98.8	coarse sands	cropland	103	600		1330	87.9	1	WB
	38.1, −98.8	silty clay loam	grassland	1.6	600		1330	87.9	1	WB
	38.1, −98.8	coarse sands	grassland	42	600		1330	87.9	1	WB
Stone et al. (1983)	46.6, −119.4	sand	no vegetation	127	240		1083	18.5	5	
Stonestrom et al. (2003)	38.6, −116.1	sand	scrubland	0	113		1358	9.3	4	T
Sukhija et al. (1988)	11.9, 79.8	coarse sands	cropland	80	1200		1702	290.7	6	T
	11.9, 79.8	sand	cropland	110	1200		1702	290.7	6	T
	11.9, 79.8	coarse sands	cropland	130	1200		1702	290.7	6	T
	11.9, 79.8	sand	cropland	160	1200		1702	290.7	6	T
	11.9, 79.8	sand	cropland	180	1200		1702	290.7	6	T
	11.9, 79.8	coarse sands	cropland	200	1200		1702	290.7	6	T
Sumioka and Bauer (2004)	48.3, −122.6	sandy loam	woodland	89.8	618		643	69.1	4	T
	48.3, −122.6	coarse sands	woodland	116	618		643	69.1	4	WB
Sun and Cornish (2005)	−31.8, 150.6	180 mm d^{-1}	grassland	4.9	738		1226	65.3	0	model
Talsma and Gardner (1986)	−35.4, 148.8	10 mm d^{-1}	woodland	120	1230		1020	59.2	5	base flow, WTF
Taylor and Howard (1996)	2.6, 32.6	clay	cropland	200	1400		1558	174.6	6	T, model

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				——— mm yr^{-1} ———				mm mo^{-1}	mo	
Thorburn et al. (1991)	−24.8, 149.8	clay	cropland	17.6	650		1510	75.6	1	T
	−24.8, 149.8	clay	grassland	2.3	650		1510	75.6	1	T
	−24.8, 149.8	clay	woodland	0	650		1510	75.6	1	T
Thorpe (1989)	−31.8, 115.9	sand	scrubland	174	830		1661	155.5	4	T
Timmerman (1985)	−32.3, 18.4	coarse sands	scrubland	38.7	216		1398	40.7	4	
	−32.3, 18.4	coarse sands	scrubland	43.5	290		1398	40.7	4	
Timmerman (1986)	−32.1, 18.6	coarse sands	scrubland	20	250		1434	44.3	4	
Tomasella et al. (2008)	−3.1, −60.1	clay	woodland	438	2627		1299	260.8	5	base flow
Unkovich et al. (2003)	−35.1, 139.3	sand	cropland	1	300		1306	22.6	5	WB
	−35.1, 141.9	sandy loam	cropland	2.5	330		1373	15.7	5	WB
	−36.6, 143.9	silty clay loam	cropland	58.8	425		1241	23	6	WB
	−36.6, 143.9	silty clay loam	woodland	0.02	425		1241	23	6	WB
van Lanen and Dijksma (1999)	51.1, 5.8	sand	grassland	293	905		547	24.9	1	model
Vandoolaeghe and Bertram (1982)	−33.6, 18.4	coarse sands	scrubland	98.8	380		1236	73.2	5	WB
Vegter (1995)	−32.3, 18.4	coarse sands	scrubland	15.7	196		1398	40.7	4	
	−32.1, 18.4	coarse sands	scrubland	23.5	196		1398	39.4	4	
Verhagen (1994)	−22.1, 26.3	sand	scrubland	6	500		1408	83.8	0	T
	−23.8, 25.1	sand	scrubland	6	450		1396	81.1	0	T
	−23.8, 25.1	sand	scrubland	11.5	450		1396	81.1	0	T
Walker et al. (1990a)	−34.3, 141.3	sandy clay loam	grassland	4.7	295		1387	11.5	3	T
Walker et al. (1990b)	−36.8, 140.9	clay	grassland	1	520		1210	52.3	5	T
	−36.3, 140.8	clay	grassland	5	500		1245	44	6	T
	−36.9, 140.8	clay	grassland	8.5	580		1207	63.4	5	T
Walker et al. (1992a)	−35.1, 139.4	sand	grassland	60	580		1299	23.7	5	T
Walker et al. (1992b)	−35.4, 139.6	sand	cropland	25.5	380		1278	35	5	T
	−35.4, 139.6	sandy loam	grassland	13	380		1278	35	5	T
Walvoord and Phillips (2004)	31.4, −104.4	clay loam	grassland	0.1	365		1699	58.2	2	T
	31.4, −104.4	clay loam	scrubland	0	275		1699	58.2	2	T
	31.4, −104.4	clay loam	scrubland	0.05	365		1699	58.2	2	T
Wang et al. (2004)	37.4, 104.9	fine sand	no vegetation	48	191		879	54	1	WB, lysimeter

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				———— mm yr^{-1} ————				mm mo^{-1}	mo	
Wang et al. (2008)	37.8, 115.8	clay	cropland	15.3	423	251	1044	154.7	0	T
	37.9, 115.8	clay	cropland	131	667	281	1041	158.9	0	T
	38.1, 114.4	silty clay	cropland	168	626	178	1019	155.1	1	T
	37.4, 116.3	silty clay	cropland	198	650	63	1079	184	0	T
	38.3, 116.8	silt	cropland	256	670	787	1059	206.3	0	T
	37.8, 115.8	clay	grassland	0	544		1044	154.7	0	T
	37.4, 116.3	silty clay	grassland	84.6	643		1079	184	0	T
Wanke et al. (2008)	−22.6, 18.3	35 mm d^{-1}	grassland	7.6	409		1542	76	1	model
	−22.6, 18.3	43 mm d^{-1}	no vegetation	75.3	409		1542	76	1	model
	−22.6, 18.3	sand	scrubland	7	409		1542	76	1	model
Ward et al. (2002)	−33.8, 117.4	loamy sand	grassland	17	483		1286	65.8	5	WB
	−33.8, 117.4	loamy sand	grassland	45	483		1286	65.8	5	WB
Watson et al. (2004)	−43.6, 172.1	silt loam	woodland	17	625		686	28	5	lysimeter
Weaver et al. (2005)	−30.3, 149.3	clay	cropland	31.3	514	350	1495	63.3	0	T
	−30.3, 149.4	clay	cropland	56.5	460	300	1479	65.4	0	T
	−30.3, 149.6	clay	cropland	72.5	417	150	1466	71.9	0	T
	−30.3, 149.3	clay	cropland	87.3	514	500	1495	63.3	0	T
	−30.3, 149.3	clay	cropland	121	514	650	1495	63.3	0	T
Webb et al. (2008)	39.1, −75.4	silty loam	cropland	159	1150		1020	32.2	1	model
Wechsung et al. (2000)	52.6, 13.4	sand	cropland	114	534		593	36.6	1	model
	52.6, 13.4	sand	woodland	28.9	534		593	36.6	1	model
Wegehenkel et al. (2008)	52.4, 13.3	sand	grassland	269	545		601	38.2	1	lysimeter
Weltz and Blackburn (1995)	27.6, −98.3	fine sandy loam	grassland	22	887		1493	101.1	1	lysimeter
	27.6, −98.3	fine sandy loam	no vegetation	78	887		1493	101.1	1	lysimeter
	27.6, −98.3	fine sandy loam	woodland	0	887		1493	101.1	1	WB
White (1997)	−35.4, 147.6	sand	grassland	22	650		1079	38.7	5	WB
	−35.4, 147.6	sand	grassland	62	697		1079	38.7	5	WB
White et al. (2003)	−35.1, 147.4	sandy clay loam	grassland	44.5	593		1134	22.1	4	WB
	−30.6, 150.6	clay loam	grassland	47.5	662		1275	71.5	0	WB
	−37.4, 141.9	sandy loam	grassland	142	642		1160	57.8	6	WB
	−33.6, 149.1	sandy loam	grassland	159	885		1136	32.8	5	WB
	−34.9, 117.8	sand	grassland	161	758		1190	103	5	WB
	−37.1, 145.9	loamy sand	grassland	161	813		1066	84.7	6	WB
Williamson et al. (2004)	34.3, −117.8	sandy loam	grassland	55	678		1267	68.2	6	T
	34.3, −117.8	sandy loam	scrubland	39	678		1267	68.2	6	T
Wright et al. (1988)	33.3, −99.3	clay loam	grassland	0.13	679		1610	70.9	2	lysimeter

Table A1. Continued.

Reference	Lat., long.†	Soil texture or K_s	Vegetation	Recharge‡	Precipitation‡	Irrigation‡	PET§	Amplitude§	Phase§	Methods¶
				———— mm yr^{-1} ————				mm mo^{-1}	mo	
Zeppel et al. (2006)	−31.4, 150.8	sand	woodland	21	752		1226	55.9	0	WB
Zhang et al. (1999)	−33.4, 145.6	sandy clay	cropland	8.5	564		1400	14.7	3	model
	−35.1, 142.1	sandy clay loam	grassland	9.5	351		1379	15.5	5	model
Zhu (2000)	36.1, −111.3	fine sands	grassland	16	305		1545	19	1	T
	36.1, −111.3	fine sands	grassland	16	305		1545	19	1	T
Zouari et al. (2001)	34.9, 8.1	sand	grassland	0.9	94		1226	30.8	4	T

† Approximate latitude and longitude of the studies.

‡ Values as reported in the studies.

§ Estimated from the Climate Research Unit data set: PET, potential evapotranspiration; amplitude, difference between maximum and minimum mean monthly precipitation; phase, number of months between maximum mean monthly precipitation and temperature.

¶ T, natural and injected tracers such as Cl− and stable and radio isotopes of water; WTF, water table fluctuations; WB, water balance from monitoring of soil moisture or evapotranspiration; base flow, base flow of surface water bodies; model, simulations of soil water movement, water balance, geographic information systems, or spatially explicit models; EMI, electromagnetic induction.