Assessing controls on diffuse groundwater recharge using unsaturated flow modeling

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[1] Understanding climate, vegetation, and soil controls on recharge is essential for estimating potential impacts of climate variability and land use/land cover change on recharge. Recharge controls were evaluated by simulating drainage in 5-m-thick profiles using a one-dimensional (1-D) unsaturated flow code (UNSAT-H), climate data, and vegetation and soil coverages from online sources. Soil hydraulic properties were estimated from STATSGO/SSURGO soils data using pedotransfer functions. Vegetation parameters were obtained from the literature. Long-term (1961–1990) simulations were conducted for 13 county-scale regions representing arid to humid climates and different vegetation and soil types, using data for Texas. Areally averaged recharge rates are most appropriate for water resources; therefore Geographic Information Systems were used to determine spatial weighting of recharge results from 1-D models for the combination of vegetation and soils in each region. Simulated 30-year mean annual recharge in bare sand is high (51–709 mm/yr) and represents 23–60% (arid–humid) of mean annual precipitation (MAP). Adding vegetation reduced recharge by factors of 2–30 (humid–arid), and soil textural variability reduced recharge by factors of 2–11 relative to recharge in bare sand. Vegetation and soil textural variability both resulted in a large range of recharge rates within each region; however, spatially weighted, long-term recharge rates were much less variable and were positively correlated with MAP ($r^2 = 0.85$ for vegetated sand; $r^2 = 0.62$ for variably textured soils). The most realistic simulations included vegetation and variably textured soils, which resulted in recharge rates from 0.2 to 118 mm/yr (0.1–10% of MAP). Mean annual precipitation explains 80% of the variation in recharge and can be used to map recharge.

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1. Introduction

[2] Understanding controls on the water cycle, such as climate, vegetation, and soils, is important in evaluating the potential impact of climate variability and land use/land cover (LU/LC) change on the water cycle. Land surface models are currently being used on regional scales to assess the relative importance of these influences on the water cycle [*Bonan*, 1997; *Pielke et al.*, 1998]. These models focus on evapotranspiration (ET) and feedback between the land surface and climate and have not been applied to estimating subsurface components of the water cycle. Recharge (addition of water to an aquifer) is a critical component of the water cycle for water resources and as a vector for nutrients and contaminants from the land surface to underlying aquifers. The need to control recharge at regional scales for environmental purposes, such as management of water resources and reduction in salinization, underscores the importance of understanding fundamental controls on recharge. Examples include removal of brush and riparian vegetation in semiarid regions of the southwestern United States to increase recharge and reforestation in areas of Australia to reduce recharge and associated salinity problems [*Allison et al.*, 1990; *Dugas et al.*, 1998; *Dawes et al.*, 2002; *Wilcox*, 2002].

[3] The basic controls on diffuse groundwater recharge include climate, vegetation, soils, and topography. Diffuse recharge refers to areally distributed recharge derived from precipitation or irrigation and should be distinguished from focused or concentrated recharge in topographic depressions, such as streams, lakes, and playas. Comparison of previous recharge estimates from various studies indicates that recharge is higher in humid versus arid regions; however, most studies focus on recharge in arid regions [*Lerner et al.*, 1990; *Robins*, 1998]. The presence of vegetation markedly reduces recharge in semiarid to arid basins [*Gee et al.*, 1994]. Vegetation type also significantly impacts recharge rates: recharge is higher in areas of annual crops and grasses than in areas of trees and shrubs [*Prych*, 1998]. Replacement of deep-rooted native eucalyptus trees with shallow-rooted crops in Australia increased recharge by about two orders of magnitude ($\leq$0.1 mm/yr for native mallee vegetation to 5–30 mm/yr for crop/pasture rotations) [*Allison et al.*, 1990]. Field and modeling studies have shown that recharge is greater in coarser versus finer textured soils [*Cook and Kilty*, 1992; *Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998]. The influence of topography on recharge is variable. Catchment-scale modeling studies indi-

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cate that subsurface lateral flow was negligible in some catchments and flow could be treated as 1-D [*Dawes et al.*, 1997; *Hatton*, 1998; *Zhang et al.*, 1999].

[4] Previous studies have evaluated controls on groundwater recharge using field studies or numerical modeling. *Kennett-Smith et al.* [1994] related variations in recharge to precipitation and clay content using a simple water balance model and field recharge estimates. *Sophocleous* [1992] used multiple regression analysis to link variations in field-based recharge estimates primarily to variations in precipitation and also to variations in soil water storage, water table depth, and spring precipitation rate for a 3,400-km^2 area in Kansas. *Petheram et al.* [2002] evaluated impacts of land use on recharge by reviewing previous recharge studies in Australia and correlated recharge to precipitation in areas of annual vegetation and sandy soils (r^2 = 0.6). However, comparison of recharge rates among the different studies was difficult because of the wide variety of techniques used that represented a range of space and timescales.

[5] Physical, chemical, and modeling approaches can be used to estimate recharge on the basis of surface water, unsaturated zone, and groundwater data [*Scanlon et al.*, 2002b]. Numerical modeling is the only tool that can predict recharge, and it is also extremely useful in isolating the relative importance of different controls on recharge, provided that the model properly accounts for physical and biological processes. Various types of codes can be used to simulate recharge, such as land-atmosphere, watershed, unsaturated zone, and groundwater codes. Although land-atmosphere codes simulate all the processes required to estimate recharge, including Richards' equation for simulating unsaturated flow and a variety of approaches for simulating evapotranspiration (ET) [*Cotton et al.*, 2003; *Dai et al.*, 2003], these codes have generally not been used to simulate recharge. Watershed codes have been used to estimate groundwater recharge [*Hatton*, 1998; *Zhang et al.*, 1999]; however, the large number of parameters required makes it difficult to obtain a unique solution. Unsaturated zone codes range from simple bucket codes [*Hatton*, 1998; *Hevesi et al.*, 2002; *Lewis and Walker*, 2002] to those based on Richards' equation [*Braud et al.*, 1995; *Fayer et al.*, 1996], as well as some that include plant growth modules [*Dawes and Hatton*, 1993; *Zhang et al.*, 1996]. Simulation studies of recharge using unsaturated zone codes range from bare ground [*Scanlon and Milly*, 1994; *Scott et al.*, 2000] to vegetated systems [*Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998]. One-dimensional unsaturated zone modeling has been used with GIS coverages of vegetation and soils to determine areally distributed recharge [*Fayer et al.*, 1996]. Sensitivity analyses to assess controls on recharge using unsaturated zone codes were fairly simplistic, ranging from monolithic to simple two-layered soil profiles, with or without vegetation and different vegetation types (shrubs/grasses) [*Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998]. Groundwater model calibration or inversion can also be used to estimate recharge rates; however, model inversion using hydraulic head data is limited only to estimating the ratio of recharge to hydraulic conductivity [*Sanford*, 2002]. Such recharge estimates are generally not considered highly reliable because hydraulic conductivity can vary over several orders of magnitude. More reliable recharge estimation requires information on water fluxes or ages in addition to hydraulic head to calibrate the model [*Sanford*, 2002].

[6] Primary difficulties with modeling recharge are data requirements and model parameterization. The following online data sources have made recharge simulations much more feasible. Weather generators, such as GEM (Generation of weather Elements for Multiple applications), include databases of meteorological stations and can generate data for other regions [*Hanson et al.*, 1994; *Richardson*, 2000]. Geographic Information Systems (GIS) distributions of soils are provided by the State Soil Geographic (STATSGO) database (1:250,000 scale) and Soil Survey Geographic (SSURGO) database (1:24,000 scale). Pedotransfer functions are available to transfer soil texture information into water retention and hydraulic properties required for modeling [*Schaap et al.*, 2001]. Vegetation distribution and land use (National Land Cover Data) can be obtained from online sources [*McMahon et al.*, 1984; *Vogelmann et al.*, 2001]. Remote sensing also provides information on vegetation parameters at different resolutions (30 m; LandSat TM to 1.1 km; MODIS). Percent bare area can be estimated from fractional vegetation coverage using satellite data such as AVHRR or MODIS. Information on leaf area index is available from normalized difference vegetation index (NDVI) [*Myneni et al.*, 1997]. It is more difficult to obtain information on rooting depths; however, estimates can be obtained from the literature [e.g., *Canadell et al.*, 1996].

[7] The purpose of this study was to determine the relative importance of different controls on diffuse groundwater recharge using unsaturated, one-dimensional flow models of recharge for regions representing a range of climate (arid–humid), vegetation (shrubs, grasses, forests, crops), and soil (fine-coarse grained, monolithic and layered) conditions on the basis of data from Texas. This study focuses on long-term (30 year), areally averaged recharge rates that are appropriate for assessing water resources and evaluating aquifer vulnerability to nutrient loading. Unique aspects of the study are the (1) range of climate, vegetation, and soil conditions examined, (2) use of online and published data for input and parameterization of models, (3) combination of 1-D modeling and GIS coverages to develop areally averaged recharge estimates, (4) length of simulations (1961–1990), and (5) comparison with field-based estimates.

2. Materials and Methods

2.1. Study Area Description: Climate, Soils, and Vegetation

[8] The broad study area is the state of Texas ($\sim$700,000 km^2) (Figure 1). Thirteen study regions, representing a variety of climate, vegetation, and soil types were used in this study to simulate the water balance for a 30 year period (1961–1990). Simulated regions were also located to represent recharge areas of major porous media aquifers in the state (Figure 1 and Table 1). Each study region represents a one- or two-county area above an aquifer (1152–3042 km^2), with the exception of region 2 (entire outcrop of Cenozoic Pecos Alluvium Aquifer: 14,980 km^2). The topography of the regions is generally flat, with average slopes $\leq$0.5% in the High Plains and Gulf Coast regions and slightly higher slopes in the remaining regions ($\leq$1.3%) (Table 1). Long-term (1961–1990) mean annual precipita-

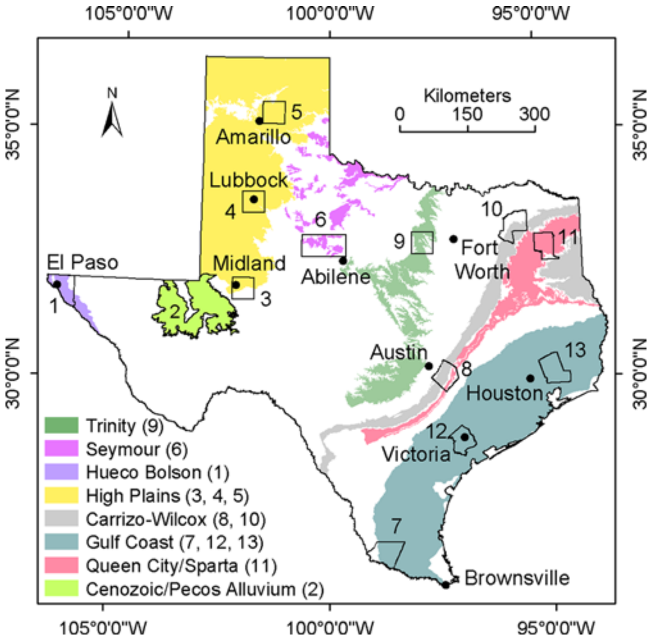

Figure 1. Modeled study regions (1–13), meteorological station locations (city name), and major porous media aquifer outcrop areas. Regions are numbered in order of increasing precipitation; refer to Table 1 for region names.

tion (MAP) ranges from 224 mm/yr in the west to 1,184 mm/yr in the east. Annual precipitation at individual meteorological stations ranged from 110 mm (region 1, El Paso, 1969) to 1783 mm (region 13, Houston, 1973). Summer precipitation (June–August) is dominant throughout much of the state, particularly in western (43%) and northern (33–48%) regions (Figure 2). Spring precipitation is dominant in central regions (29–33%), whereas fall precipitation is dominant in southeastern regions (28–39%). Precipitation is fairly uniformly distributed in the more humid regions in the east. Winter precipitation (December–February) is generally low throughout most of the state (8–16%), with the exception of the humid east (21%). The coefficient of variation (CV) in annual precipitation is greatest in semiarid regions in the west (0.35) and less throughout the rest of the area (CV: 0.21–0.24) (Figure 3 and Table 2). Vegetation ranges from predominantly shrubs and grasses in the west, shrub/forest to forest/shrub in the central area, and forest and forest/shrub in the east (Figure 4). Cropland areas dominate much of the northern and southeastern regions. Variations in clay content in the upper 1.5 to 2 m soil profile depths based on STATSGO data generally follow the distribution of underlying geologic units, e.g., high clay content in the central region of the Southern High Plains (region 5), corresponding to the underlying Blackwater Draw Formation, and high clay content in the northern and central parts of the Gulf Coast (regions 12 and 13), corresponding to the underlying Beaumont Formation (Figure 5).

2.2. Model Description

[9] Unsaturated flow modeling was used to simulate drainage below the root zone, which is equated to groundwater recharge and assumes that climate and land use/land cover remain constant over timescales required for water to move from the root zone to the water table. The UNSAT-H code (version 3.0 [*Fayer*, 2000]) was chosen because previous code comparison studies showed that water balance simulations based on UNSAT-H compare favorably with field data [*Scanlon et al.*, 2002a]. UNSAT-H is a 1-D, finite difference code that simulates nonisothermal liquid flow and vapor diffusion in response to meteorological forcing. The simulations focus on the water balance:

$$D = P - ET - R_0 - \Delta S \tag{1}$$

where D is deep drainage below the root zone, P is precipitation, ET is evapotranspiration, R_0 is surface runoff, and ΔS is change in water storage. UNSAT-H simulates subsurface water flow using Richards' equation:

$$\begin{aligned}\frac{\partial\theta}{\partial t} &= -\frac{\partial q}{\partial z} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial z}\right) - S(z,t)\\ &= \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial h}{\partial z} - K(\theta)\right) - S(z,t)\end{aligned} \tag{2}$$

where θ is volumetric water content, q is water flux, K is hydraulic conductivity, H is hydraulic head, h is matric potential head, and S is a sink term used to describe the removal of water by plants. UNSAT-H includes multiple analytical functions for water retention and unsaturated hydraulic conductivity.

Table 1. General Characteristics of Modeled Regions[a]

Region Number	Region	MAP, mm/yr	PET, mm/yr	P/PET	HZ	Region Area, km^2	Topographic Slope Mean, %	Slope SD, %	Mean Sand, %	Mean Silt, %	Mean Clay, %
1	El Paso	224	2087	0.11	A	2079	0.73	1.36	69	20	11
2	CPA	380	2169	0.18	A	14980	0.38	0.42	60	21	19
3	Midland	380	2169	0.18	A	1388	0.25	0.27	56	20	24
4	Lubbock	474	2034	0.23	SA	2313	0.46	0.72	43	26	31
5	Carson	497	2096	0.24	SA	2363	0.54	0.88	29	35	35
6	Fisher/Jones	620	2132	0.29	SA	1577	0.45	0.42	52	21	26
7	Starr	671	1788	0.38	SA	2474	0.55	0.61	64	13	24
8	Bastrop	810	1732	0.47	SA	1197	1.01	1.04	49	21	30
9	Parker	855	1819	0.47	SA	1464	1.31	1.17	48	23	28
10	Hopkins/Rains	855	1819	0.47	SA	1152	0.52	0.49	41	28	31
11	Upshur/Gregg	855	1819	0.47	SA	1972	1.05	1.20	51	23	26
12	Victoria	933	1651	0.57	SH	2303	0.22	0.31	41	23	36
13	Liberty	1184	1362	0.87	H	3042	0.17	0.31	27	33	40

[a]CPA, Cenozoic Pecos Alluvium aquifer; MAP, 30 year mean annual precipitation; PET, 30 year mean annual potential evapotranspiration; HZ, humidity zone [*United Nations Environment Programme*, 1992], A, arid; SA, semiarid; SH, subhumid; H, humid.

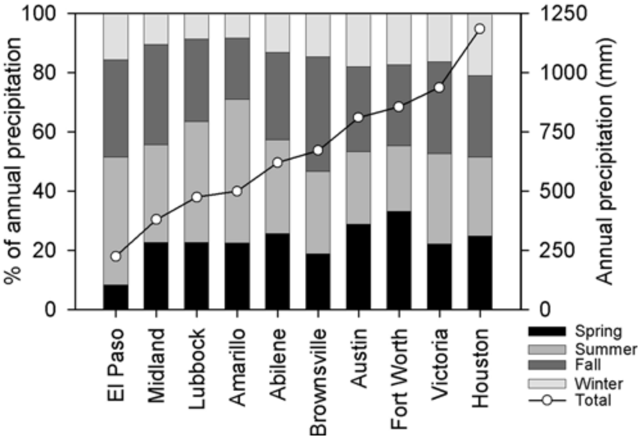

Figure 2. Mean (30 year) annual precipitation and seasonal distribution of mean annual precipitation for the 10 meteorological stations used in the simulations: spring (March–May), summer (June–August), fall (September–November), and winter (December–February).

[10] The upper atmospheric boundary condition is simulated as a system-dependent boundary condition that changes from a prescribed head to a prescribed flux, depending on climate and subsurface conditions. If the applied flux (precipitation or evapotranspiration) is $\leq$ the potential flux and the matric potential head at the surface is between 0 and a prespecified dry value (h_{dry}), then the potential flux, which is controlled by external conditions, applies. Runoff is simulated implicitly by UNSAT-H. If the precipitation rate exceeds the infiltration capacity of the soil, excess water runs off (infiltration excess or Hortonian runoff). If the matric potential head at the surface reaches 0, the soil becomes saturated, a constant head boundary condition applies (h = 0), and excess water runs off (saturation excess or Dunne runoff). If the soil surface becomes too dry ($h \leq h_{dry}$), a constant head boundary condition applies ($h = h_{dry}$) and evaporation or evapotranspiration is controlled by the rate at which water can be transmitted to the surface. Ponding is not simulated with this code. Plant water uptake is simulated according to the approach proposed by *Feddes et al.* [1978] that partitions PET into potential evaporation (PE) and potential transpiration (PT) using an empirical equation developed by *Ritchie and Burnett* [1971], which distributes PT over the root zone on the basis of depth variations in root density and reduces this PT to actual transpiration on the basis of matric potential head [*Fayer*, 2000].

2.3. Model Application

[11] The water balance for a 30 year period (1961–1990) was simulated for 13 study regions. Input data requirements for the model include meteorologic forcing, vegetation parameters, hydraulic parameters for different soil types, and initial conditions. To assess the relative importance of different controls on groundwater recharge, four different scenarios were used: (1) nonvegetated, monolithic sand, (2) nonvegetated, texturally variable soil, (3) vegetated, monolithic sand, and (4) vegetated, texturally variable soil. The simplest simulations of nonvegetated, monolithic sand were used to provide an upper bound on recharge rates. Complex, texturally variable soil profiles were simulated without vegetation to evaluate the impact of soil textural variability on recharge. Vegetation was added to the monolithic and texturally variable soil profiles to determine its impact on simulated recharge. The most realistic scenario is represented by vegetated, texturally variable soils.

[12] A soil-profile depth of 5 m was chosen for the simulations because it is deeper than root zone depths of the vegetation used. In addition, soil textural information is available only for the upper 2 m from STATSGO and SSURGO, and texture in the 2 to 5 m zone was assumed equal to that of the lowest data available. Sensitivity of simulated recharge to profile depth was evaluated. In monolithic profiles, nodal spacing ranged from 2 mm at the top and base of the profile and increased by a factor of ~1.2 with depth to a maximum value of 230 mm within the profile. In layered soil profiles, nodal spacing was also reduced near textural interfaces to a value of ~20 mm. Initial conditions were set arbitrarily at a matric potential head of −3 m for higher precipitation regions (6–13) and −10 m for all other regions. The impact of initial conditions on simulation results was evaluated by reinitializing simulations multiple times with the final conditions of each run; however, rerunning simulations once was found to be sufficient for minimizing the impact of initial conditions.

[13] Meteorological data for 10 stations were obtained from the database in the GEM code [*Hanson et al.*, 1994]. Some station data were used to simulate recharge in more than one region (Midland station, regions 2 and 3; Fort Worth station, regions 9–11). The 1961–1990 period was chosen because of availability of solar radiation for potential evapotranspiration calculations from the National Solar Radiation Data Base (National Renewable Energy Laboratory, Golden, Colorado; 1992). Meteorologic input to the model included daily precipitation, daily average dew point temperature, wind speed and cloud cover, total daily solar radiation, and minimum and maximum daily temperatures. Daily precipitation was applied at a prespecified default intensity of 10 mm/hr, and ET is not simulated during this time. Previous code comparisons showed that the approach used in codes to simulate precipitation and evapotranspiration when daily precipitation is used as input can have a large impact on simulated recharge and that the UNSAT-H approach adequately simulates measured data [*Scanlon et*

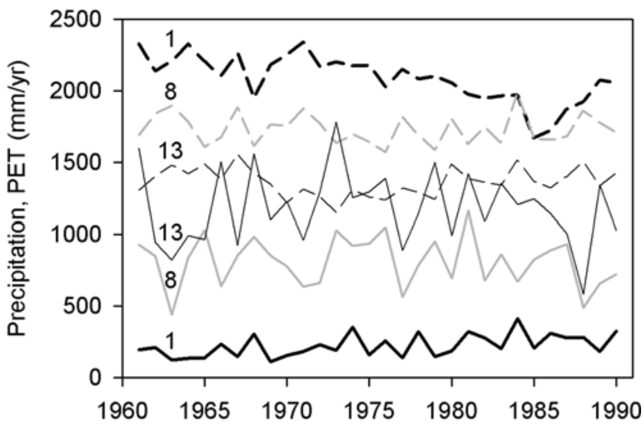

Figure 3. Total annual precipitation (solid lines) and PET (dashed lines) for stations that represent a range of precipitation and PET (1, El Paso; 8, Austin; 13, Houston).

Table 2. Simulation Results for the Four Basic Scenarios[a]

	MAP		Nonvegetated Sand					Nonvegetated Texturally Variable Soils					Vegetated Sand			Vegetated Texturally Variable Soils				
			Recharge					Recharge					Recharge			Recharge				
Region	Total	CV	Total	CV	R/P	AE	PET/AE	Total	R/P	AE	R_O	ΔS	Total	R/P	AET	Total	R/P	AET	R_O	ΔS
1	224	0.35	51	0.22	23	173	12.1	19	9	205	0	0.0	2	1	222	0.2	0.1	224	0	−0.7
2	380	0.35	137	0.20	36	243	8.9	80	21	286	14	0.0	34	9	346	11.1	2.9	356	14	−0.7
3	380	0.35	137	0.20	36	243	8.9	56	15	316	7	−0.1	11	3	369	1.5	0.4	375	4	−0.6
4	474	0.23	180	0.24	38	294	6.9	19	4	366	90	−0.4	33	7	441	0.8	0.2	390	85	−0.9
5	497	0.21	174	0.16	35	323	6.5	16	3	286	195	−1.0	29	6	468	0.4	0.1	312	186	−1.4
6	620	0.23	269	0.19	43	351	6.1	88	14	364	168	−0.4	80	13	540	5.6	0.9	435	180	−0.8
7	671	0.24	338	0.19	50	334	5.4	191	29	454	25	0.0	115	17	556	33.8	5.0	610	27	−0.1
8	810	0.21	406	0.20	50	403	4.3	98	12	586	125	0.0	95	12	715	10.1	1.3	619	181	−0.8
9	855	0.22	432	0.18	51	423	4.3	193	23	587	74	0.0	106	12	749	29.0	3.4	727	99	−0.4
10	855	0.22	432	0.18	51	423	4.3	146	17	663	46	0.0	83	10	772	4.7	0.6	792	59	−0.4
11	855	0.22	432	0.18	51	423	4.3	193	23	639	24	0.0	111	13	744	35.1	4.1	795	25	−0.2
12	933	0.23	507	0.22	54	427	3.9	91	10	423	419	−0.2	285	31	648	25.7	2.8	520	388	−0.3
13	1184	0.22	709	0.18	60	475	2.9	230	19	619	335	−0.2	369	31	815	117.7	9.9	748	319	−0.2

[a]Runoff and change in storage is 0 for nonvegetated and vegetated monolithic sand profiles. All ratios are expressed as percent. Units are mm/yr. MAP, measured 30 year mean annual precipitation; CV, coefficient of variation; R, simulated 30 year mean annual recharge; R/P, recharge to precipitation ratio; AE, actual evaporation; AET, actual evapotranspiration; ΔS, change in water storage; R_O, runoff.

al., 2002a]. A modified Penman-Monteith equation was used to calculate PET [*Doorenbos and Pruitt*, 1977]. Parameter h_{dry} was set to −100 m. A unit gradient lower boundary condition was used that corresponds to free drainage or gravitational flow and is most appropriate for simulating unimpeded recharge.

[14] Distribution of vegetation types for each of the modeled regions was obtained from a GIS coverage of vegetation in Texas [*McMahon et al.*, 1984] (Figures 4 and 6). Crop vegetation types were derived from the percentage of area harvested over the simulation period (USDA National Agricultural Statistics Service). Vegetation parameters required for UNSAT-H include percent bare area, planting and harvesting dates for crops, time series of leaf area index (LAI) and rooting depth (RD), and root length density (RLD). These parameters were obtained mostly from the literature (see auxiliary material).[1] Additional information was obtained from discussions with ecologists and crop specialists. Time series for LAI and root growth were specified on particular days of the year and linearly interpolated. Root growth was simulated for crops only; other plant types were perennial. The RLD function is based on the assumption that normalized total root biomass is related directly to RLD (ρ_{rL}) and can be related to depth below the surface (z) by

$$\rho_{rL} = a\exp(-bz) + c \tag{3}$$

where a, b, and c are coefficients that optimize fit to normalized biomass data. Some vegetation classes contain more than one vegetation type. For example, forests are classified as 75% trees and 25% grasses. Recharge estimates for these regions were obtained by simulating different vegetation types separately and areally weighting results. The 1-D modeling approach used in this study does not account for effects of neighboring plant root systems and may overestimate recharge in areas where deeper rooted vegetation extends into areas with shallower rooted vegetation. Recharge would be overestimated most in areas where the difference in rooting depths is greatest. However, this error is considered relatively minor considering that information on the distribution of different vegetation types is only approximate. Dominant vegetation types that represented ∼70–80% of the area of each region were simulated.

[15] Soil profiles for the simulations ranged from monolithic sand to texturally variable profiles. Hydraulic properties for the sand were obtained from the UNSODA database (UNSODA 4650: K_s: 5.87 m/day; θ_s: 0.38; θ_r: 0; α: 5.03 1/m; n: 1.7736 [*Leij et al.*, 1996]). SSURGO version 2 data [*U.S. Department of Agriculture* (*USDA*), 1994] were used to provide information for texturally variable soil profiles for all regions but were unavailable for region 2, where STATSGO data [*USDA*, 1995] were used for the entire (multicounty) outcrop area of the aquifer. Pedotransfer functions were used to determine soil hydraulic properties. Rosetta software uses neural network programming and a database of measured texture, water retention, and saturated hydraulic conductivity to provide estimates of van

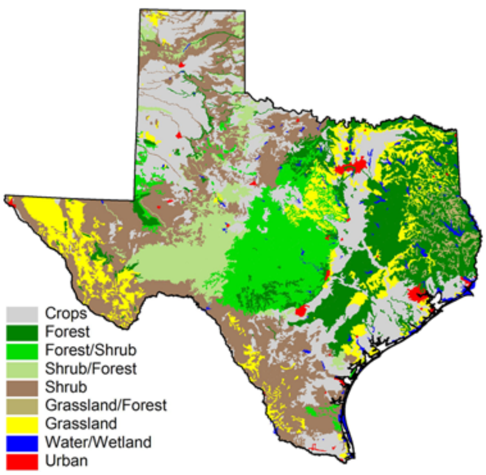

Figure 4. Dominant vegetation associations in Texas [*McMahon et al.*, 1984].

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/wr/2004WR003841.

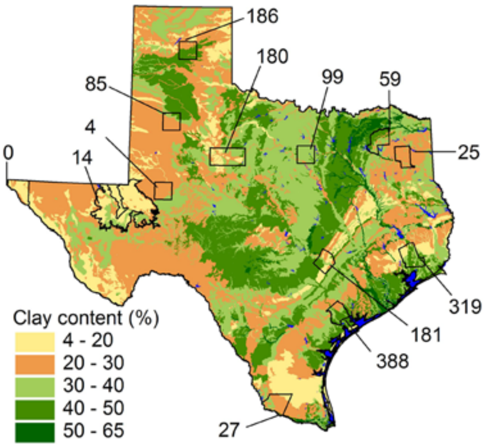

Figure 5. Average soil profile clay content derived from STATSGO database. Water-covered areas are shown in blue. Simulated runoff using vegetated, texturally variable soils are shown for each region.

Genuchten water retention parameters and saturated hydraulic conductivity for input to unsaturated flow models [*Schaap et al.*, 2001]. Only texture and bulk density information was available from the STATSGO database for input to Rosetta. Soil layer texture, bulk density, and volumetric water content at −3 and −150 m head were available from the SSURGO version 2 database for input to Rosetta. Simulations were run for soil profiles that represented ~80% of the area of each simulated region, which corresponded to 6−29 profiles for different regions. Examination of recharge results for all profiles for a region showed that recharge rates could be categorized into distinct groups, resulting in a more manageable 3−7 representative profiles for each region.

[16] Simulated recharge results are represented by a single temporal (30 year) and spatial average recharge value for each region, using GIS coverages to determine the area represented by each vegetation type, soil type, or combination of vegetation and soil types to spatially weight 1-D results. A total of 460 simulations were conducted for the final analysis. For monolithic profile simulations, models were developed for each of the 10 meteorological stations, resulting in 10 representative recharge values. For vegetated and texturally variable soil profile simulations, 13 recharge values representative of each of the study regions

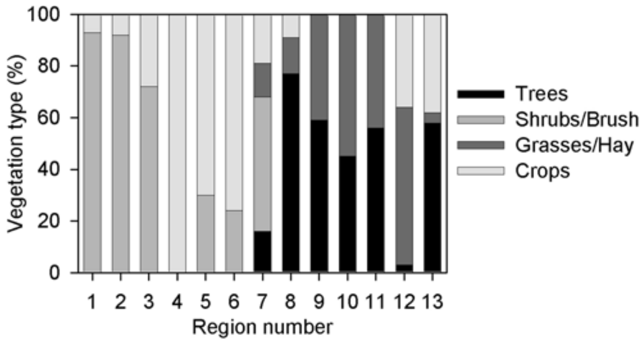

Figure 6. Percentages of vegetation types found in each region.

were determined. Recharge rates for each region (30 year, spatially weighted average) were plotted versus long-term (30 year) MAP, and equations were fit to the results for each of the four modeling scenarios (i.e., nonvegetated monolithic and texturally variable soil profiles and vegetated monolithic and texturally variable soil profiles). Power law equations were used because they resulted in higher correlation coefficients and lower residual standard deviations than linear or log linear equations. Finally, the power law equation representing the vegetated, texturally variable soils scenario was used to generate a continuous statewide recharge rate map based on the distribution of MAP. Although shown for the entire state, results should be applied only to outcrop areas of the porous media aquifers shown.

[17] Sensitivity of recharge to climate, vegetation, and soils was evaluated in the four different scenarios considered, isolating the impact of each of these parameters. Additional sensitivity analyses were conducted to evaluate variations in vegetation parameters, initial conditions, PET, and depth of soil profile. Vegetation parameters evaluated included percent bare area, leaf area index, root depth, and root length density. Each parameter was increased and decreased by 50 percent, with the exception of percent bare area, which is 0 for the base case and was increased to 25 and 50%, and profile depth, which was increased from 5 to 10 m in the sensitivity analysis. Sensitivity analyses were conducted using data from region 6.

3. Results and Discussion

[18] Simulation results are represented for the four basic scenarios to assess relative importance of climate, vegetation, and soils in controlling recharge. Final mass balance errors were <5% of final recharge rates and <0.5 mm/yr.

3.1. Nonvegetated, Monolithic Sand Simulations

[19] Simulated mean (30 year) annual recharge for bare sand is high and ranges from 51 mm/yr in the arid west to 709 mm/yr in the more humid east, representing 23 (arid) to

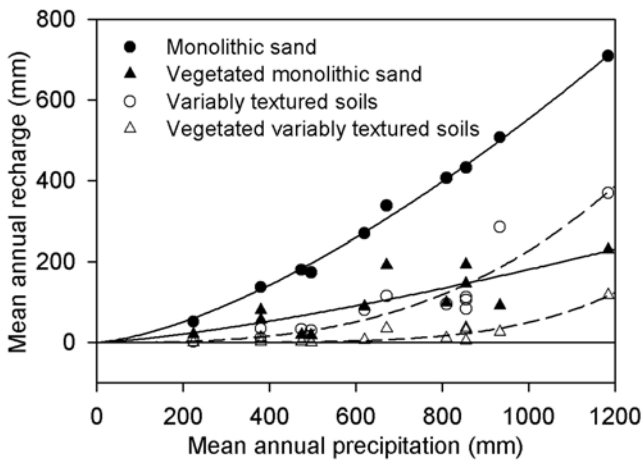

Figure 7. Relationships between long-term (30 year) MAP and simulated mean annual areally weighted recharge. Power law equations were fit to the results for monolithic sand profiles (solid lines) and variably textured soil profiles (dashed lines).

Table 3. Power Law Equation Coefficients and Residual Statistics for Estimating Long-Term (30 Year) Mean Annual Recharge From Precipitation[a]

Modeling Scenario	Coefficients a	Coefficients b	r^2	Residual σ	Residual $\|y_r\|$
Nonvegetated, monolithic sand	1.956×10^{-02}	1.484	0.996	8.5	8.5
Vegetated, monolithic sand	6.131×10^{-07}	2.855	0.854	28.6	28.4
Nonvegetated, layered soil profiles	1.661×10^{-02}	1.345	0.624	28.2	34.3
Vegetated, layered soil profiles	3.242×10^{-09}	3.407	0.805	9.2	10.2

[a]Recharge rates estimated from the power law equation for vegetated, texturally variable soils are shown in Figure 10. The power law model is $y = ax^b$, where y is mean annual recharge (mm/yr) and x is precipitation (mm/yr). Here r^2, coefficient of determination; σ, standard deviation; $|y_r|$, average absolute deviation.

60% (humid) of MAP (Table 2). Variations in mean annual recharge can be explained entirely by variations in MAP, using the power law relationship. Recharge increases with precipitation (r^2 = 1.0; Figure 7 and Tables 2 and 3). These recharge estimates provide an upper bound on actual recharge rates because vegetation and soil textural variability were not included. In addition, simulated runoff from the 1-D model is zero, whereas runoff estimates based on a statewide water balance range from 0 mm/yr in the west to 415 mm/yr in the east [*Reed et al.*, 1997]. Lack of simulated runoff was attributed to the high saturated hydraulic conductivity of the sand (0.24 m/hr) relative to the prespecified precipitation intensity (0.01 m/hr).

[20] Temporal variability in mean annual recharge is similar throughout the state (CV: 0.16–0.24) and is less than that of precipitation (Table 2). Lower correlations between mean annual recharge and summer precipitation (r^2 = 0.66) relative to precipitation during the other seasons (r^2 = 0.83–0.96 for spring, fall, and winter) were attributed to higher evaporation during summer (Figures 2 and 8). Potential ET is much greater than simulated actual E; the PET/AE ratio decreased from 12.1 in the west (region 1) to 2.9 in the east (region 13) (Table 2). In arid regions most infiltrated water is returned to the atmosphere through evaporation, as shown by the tracking of precipitation and evaporation in region 1 (Figure 9). The high correlation (r^2 = 0.83) between evaporation and precipitation in this region may be attributed to evaporation rarely being energy limited (high PET). Annual recharge is not directly correlated with annual precipitation (r^2 = 0.03) because there is a lag between elevated precipitation and recharge. In contrast, in more humid settings evaporation and precipitation are not as highly correlated (r^2 = 0.66, region 13), which may be related to energy limitations on ET (lower PET). There is little lag between high precipitation and recharge, as shown by the strong correlation between annual precipitation and recharge (r^2 = 0.90, region 13).

3.2. Nonvegetated, Texturally Variable Soil Simulations

[21] Simulated mean (30 year) annual, areally averaged recharge ranges from 16 mm/yr in the north to 230 mm/yr in the southeast for texturally variable soil profiles, representing 3 to 29% of MAP (Figure 7 and Table 2). These recharge rates are 2 to 11 times lower than those based on monolithic sand profiles, indicating the importance of soil textural variability in controlling recharge. The lower recharge rates may reflect finer textured soils, or they may be related to reductions in recharge caused by profile layering, both fine over coarse (capillary barrier effect) and coarse over fine layering. Reductions in recharge in the texturally variable soil simulations correspond to increased runoff, evaporation, or both. Approximately 60% of the variation in recharge can be explained by variations in precipitation using the power law relationship (r^2 = 0.62, Table 3). Multiple linear regression using log-log data shows that including clay content (profile average) with precipitation explains 80% of the variation in recharge. Recharge varies over 1 to 2 orders of magnitude locally, within each region, because of textural variability among soil profiles.

[22] Variations in simulated mean (30 year) annual runoff generally reflect differences in climate and texture among

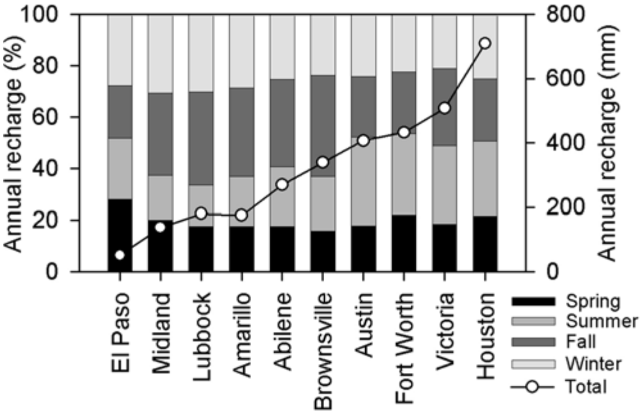

Figure 8. Seasonal distribution of simulated recharge for monolithic sand at each of the meteorological station locations.

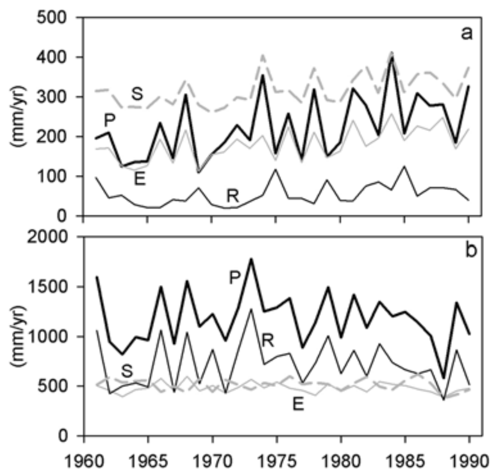

Figure 9. Mean annual water budget parameters for nonvegetated, monolithic sand simulations at (a) region 1 and (b) region 13. P, precipitation; E, evaporation; R, recharge; S, storage.

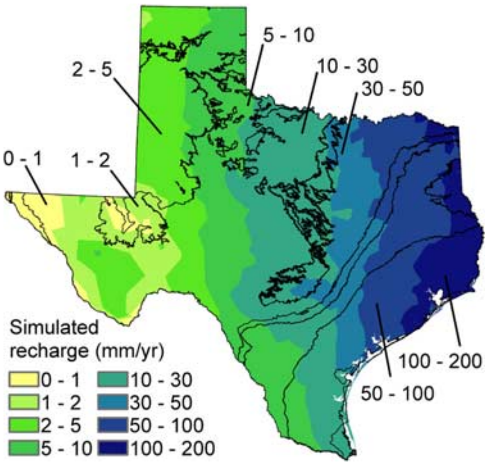

Figure 10. Predicted recharge using the relationship between precipitation and simulated recharge for vegetated, texturally variable soils.

regions. Simulated runoff is positively correlated with mean clay content ($r^2 = 0.57$) and negatively correlated with mean sand content ($r^2 = -0.49$). Sandy areas, particularly regions 1, 2, 3, and 7, have low runoff and generally correspond to areas of low or moderate precipitation. Most regions with clay-rich soils have higher runoff and generally overlie fine-grained geologic units. Simulated recharge rates in clay-rich soils may not accurately reflect actual recharge rates if preferential flow occurs in these settings because this process is not included in the simulations.

3.3. Vegetated, Monolithic Sand Simulations

[23] To assess the impact of vegetation without the influence of soil textural variability, simulations of recharge were conducted in vegetated, monolithic sands (Table 2). Vegetation markedly reduces simulated mean annual recharge (2–369 mm/yr; 1–31% of MAP) by factors of 2 to 30 relative to recharge for nonvegetated simulations. MAP explains 85% of the variance in simulated recharge using the power law relationship (Table 3 and Figure 7). Simulated runoff was 0 for nonvegetated and vegetated simulations. Vegetation type also affects simulated recharge, as seen in the 1 to 2 orders of magnitude range in simulated recharge for different vegetation types within a study region. In general, lower recharge rates in areas with trees relative to grasses can be attributed to greater rooting depth of trees ($\leq$4.3 m) relative to grasses (1 m). Shrubs are generally more effective than crops in reducing recharge because of greater rooting depth and longer growing season. Crops also differ in their recharge rates: e.g., factor of 4 lower recharge beneath cotton (maximum rooting depth 2.1 m) relative to sorghum (maximum rooting depth 1.5 m), in region 4.

3.4. Vegetated, Texturally Variable Soil Simulations

[24] Texturally variable soils with vegetation are the most realistic representation of actual conditions and should provide the most reliable recharge estimates for the different regions. Simulated mean (30 year) annual, areally averaged recharge is lowest in the arid west (0.2 mm/yr) and highest in the humid east (118 mm/yr), representing 0.1 to 10% of MAP (Figure 7 and Table 2). Variability of MAP explains 80% of the variability in recharge among regions using the power law relationship ($r^2 = 0.81$, Table 3). The correlation between recharge and precipitation was used to map recharge throughout the entire study area (Figure 10).

[25] Vegetation markedly reduced recharge relative to that for nonvegetated, texturally variable soils. Reduction factors were greater in more arid regions in the west (7–78) relative to more humid regions in the east (2–31) and reflect the enhanced ability of vegetation to reduce recharge in more water-limited regions (Table 2). Local variability in simulated recharge within regions was generally within an order of magnitude and reflects variability due to differences in vegetation and soil texture.

[26] Simulated mean (30 year) annual runoff and runoff estimates based on measured stream gauge data (1961–1990) used to develop a statewide water balance [*Reed et al.*, 1997] are generally consistent in many regions considering that the 1-D modeling approach does not account for subsurface lateral flow and routing (Table 4). Discrepancies between the two estimates in other regions cannot readily be explained, with the exception of regions 4 and 5 in the Southern High Plains, where overestimation of runoff may be attributed to predominantly internal drainage to ephemeral lakes or playas and little runoff to gauged stream networks. Runoff is one of the most difficult parameters to simulate because it depends on accurate representation of rainfall intensity and hydraulic conductivity of surficial sediments that may be crusted, as shown by detailed comparisons of simulated and measured runoff at a controlled field experiment [*Scanlon et al.*, 2002a].

[27] Relative controls of different vegetation types in vegetated, texturally variable soil simulations are similar to those for vegetated monolithic sands: lower recharge in deep-rooted trees relative to shallow-rooted grasses, shrubs relative to crops, and cotton relative to sorghum. For example, in region 9, simulated recharge beneath trees is 0, whereas simulated recharge beneath grasses ranges from 1 to 156 mm/yr for different soils. Relative amounts of evaporation and transpiration vary with vegetation type and soil texture. Transpiration is much greater than evaporation for trees, irrespective of texture. Evaporation is higher than transpiration in finer textured soils than in coarser textured soils, irrespective of vegetation type, which is attributed to

Table 4. Comparison of Simulated Runoff (RO_{sim}) With Spatially Averaged Runoff Estimates (RO_{est}) Determined From *Reed et al.* 1997 for Each Region[a]

Region	RO_{sim}	RO_{est}	RO_{est} SD
1	0	4	5
2	14	0	4
3	4	0	1
4	85	6	1
5	186	3	8
6	179	15	4
7	27	3	7
8	180	118	37
9	99	55	41
10	59	268	53
11	25	232	22
12	387	148	26
13	314	328	22

[a]Units are in mm/yr. SD, standard deviation.

Table 5. Sensitivity of Recharge to Variations in Leaf Area Index (LAI), Root Depth (RD), Bare Area (% BA), Initial Conditions (IC), Potential Evapotranspiration (PET), and Profile Depth (PD) for Four Soil Profiles in Region 6[a]

		Effect	
	BC R	R	F
LAI variable			
50% LAI	0.7	1.3	1.8
50% LAI	3.2	7.2	2.2
50% LAI	15.6	27.6	1.8
50% LAI	23.5	38.0	1.6
150% LAI	0.7	0.6	0.8
150% LAI	3.2	2.4	0.7
150% LAI	15.6	12.1	0.8
150% LAI	23.5	18.8	0.8
RD constant			
50% RD	0.7	3.7	5.1
50% RD	3.2	14.8	4.6
50% RD	15.6	27.7	1.8
50% RD	23.5	43.2	1.8
150% RD	0.7	0.1	0.2
150% RD	3.2	0.7	0.2
150% RD	15.6	6.2	0.4
150% RD	23.5	11.5	0.5
Percent BA constant			
25% BA	0.7	1.2	1.6
25% BA	3.2	6.1	1.9
25% BA	15.6	25.0	1.6
25% BA	23.5	35.1	1.5
50% BA	0.7	5.9	8.1
50% BA	3.2	21.7	6.7
50% BA	15.6	47.3	3.0
50% BA	23.5	59.3	2.5
PET variable			
50% PET	0.7	27.9	38.2
50% PET	3.2	47.4	14.6
50% PET	15.6	77.6	5.0
50% PET	23.5	88.4	3.8
150% PET	0.7	0.3	0.4
150% PET	3.2	0.3	0.1
150% PET	15.6	4.5	0.3
150% PET	23.5	7.9	0.3
PD constant			
10 m PD	0.7	0.9	1.2
10 m PD	3.2	3.3	1.0
10 m PD	15.6	13.5	0.9
10 m PD	23.5	22.0	0.9

[a]In order of fine–coarse grained soil profiles. Factor (F) refers to the ratio of 30 year mean annual recharge (R), including the effect (e.g., LAI × 50%) to the base case (BCR) recharge rate. Variable/constant indicates that a parameter changes or is held constant with time during the simulated period. Units are in mm/yr.

finer textured soils retaining more water near the soil surface longer, allowing greater evaporation.

3.5. Sensitivity Analyses

[28] Sensitivity analyses were conducted for region 6 because it represents average climate and soil conditions in the study area. Sensitivity of simulated recharge to different vegetation parameters is variable (Table 5). Increasing percent bare area from 0 to 50% increases recharge up to a factor of 8. Simulated recharge is inversely related to root depth because decreasing root depth allows water to drain more readily below the root zone. Decreasing root depth increases recharge by factors of 2 to 5, whereas increasing root depth decreases recharge by factors of 0.2 to 0.5. Simulated recharge is more sensitive to decreasing LAI than increasing LAI. Decreasing LAI by 50% almost doubles recharge, while increasing LAI by 50% decreases recharge by 20%. Models were insensitive to variations in root-length density. Decreasing PET increases recharge by factors ranging from 4 in coarse-grained soils to 38 in fine-grained soils and was balanced by a reduction in ET, whereas increasing PET had the opposite effect.

[29] It is important to assess sensitivity of model output to variations in initial conditions, profile depth, and equilibration times to assess reliability of simulated recharge. The model is insensitive to variations in initial conditions. Increasing profile depth from 5 to 10 m decreases recharge in coarse-grained soils by a factor of 0.9 and increases recharge by a factor of 1.2 in fine-grained soil, which may be an artifact of drainage of initial water in the profile. Model equilibration times are greater for more arid settings and more clay-rich soils. Therefore final recharge estimates in these settings may represent an upper bound on actual recharge rates.

3.6. Comparison of Simulated Recharge Estimates With Those Based on Other Techniques

[30] Simulated recharge rates from this study were compared with those based on earlier studies (Table 6). Previous field and modeling investigations in the Chihuahuan Desert in west Texas indicate that there is no recharge in interdrainage settings [*Scanlon et al.*, 1999], which is generally consistent with the low (0.2 mm/yr) simulated recharge in this study (Table 2). Bulge-shaped chloride profiles and upward matric potential gradients indicate that this system has been drying out for the last 10,000 to 15,000 years since the Pleistocene [*Scanlon et al.*, 2003a].

[31] In the Southern High Plains, it is difficult to compare simulated recharge rates from this study, which represent diffuse recharge in interdrainage settings, with previous recharge estimates from groundwater data because most recharge in this region is focused beneath playas. Therefore simulated recharge at regions in the Southern High Plains (4 and 5) (0.4–0.8 mm/yr) is less than recharge estimates based on the chloride mass balance (CMB) approach applied to groundwater (11 mm/yr [*Wood and Sanford*, 1995]), as expected. Field studies indicate that there is no recharge in natural ecosystems in interplaya settings, as shown by chloride bulges and upward matric potential gradients [*Wood and Sanford*, 1995; *Scanlon and*

Table 6. Comparison of Simulated Recharge Estimates (R_{sim}) With Recharge Estimated Using Other Techniques (R_{est})[a]

Region	R_{sim}, mm/yr	R_{est}, mm/yr	Method	Source[b]
1	0.2	0	WP; UZ CMB	1
4, 5	0.4–0.8	11	GW CMB	2
3, 4	0.8–1.5	4–28	UZ CMB	3
6	5.6	5–30	UZ CMB	3
8	10.1	5–20	UZ/GW CMB	4
11	35.1	43–71	GW CMB	5

[a]Estimation methods include: WP, water potential; UZ CMB, unsaturated zone chloride mass balance approach; GW CMB, groundwater chloride mass balance approach.

[b]Sources are as follows: 1, *Scanlon et al.* [1999]; 2, *Wood and Sanford* [1995]; 3, *Scanlon et al.* [2003b]; 4, *Dutton et al.* [2003]; 5, R. C. Reedy (Bureau of Economic Geology, University of Texas at Austin, unpublished data, 2002).

Goldsmith, 1997; *Dennehy et al.*, 2005]. Recharge estimates based on chloride profiles from nonirrigated cultivated settings in the south part of the Southern High Plains range from 4 to 28 mm/yr [*Scanlon et al.*, 2003b]. Simulated recharge rates at regions 3 and 4 (1.5 and 0.8 mm/yr) fall within the range of values for natural and cultivated regions and may underestimate actual recharge because the effect of cultivation on hydraulic properties of surficial sediments was not included in the simulations.

[32] Simulated recharge in region 6 (5.6 mm/yr) is within the lower range of field-based estimates, using the CMB approach applied to the unsaturated zone (UZ) in natural and nonirrigated cultivated regions (5–30 mm/yr) [*Scanlon et al.*, 2003b]. Higher values from the field studies may be attributed to restriction of field regions to a large sand dune setting, whereas the spatially averaged value from this modeling study also includes finer grained soils found in other regions.

[33] Simulated recharge at region 8 (10.1 mm/yr) is within the range of field-based recharge estimates based on the chloride mass balance (CMB) approach applied to the unsaturated zone and groundwater (5–20 mm/yr [*Dutton et al.*, 2003]). Recharge estimates based on the CMB approach applied to groundwater for region 11 range from 43 to 71 mm/yr and are slightly higher than that simulated (35.1 mm/yr). The discrepancy may be attributed to bias toward high-permeability units in field-based estimates.

[34] Although the number of comparisons between simulated and field-based recharge estimates is limited, simulated recharge rates in this study are generally consistent with those based on previous field studies, and discrepancies can generally be explained by inclusion or exclusion of different types of recharge (e.g., focused versus diffuse recharge in the Southern High Plains) and concentrating on different zones (e.g., high-permeability versus low-permeability units).

3.7. Recommendations for Future Studies

[35] This study represents a relatively simple approach to estimating recharge using a 1-D unsaturated flow model and data found online and in the literature. Future simulations should consider using actual precipitation intensity where data are available and develop input to simulate recharge in irrigated regions. The most fundamental conceptual aspect of unsaturated flow modeling that should be addressed is simulation of vegetation dynamics. Current simulations prescribe vegetation input that precludes vegetation response to variability in soil moisture and precipitation. Two-way coupling between vegetation growth and soil moisture variability related to climate should provide more realistic simulations of recharge, particularly in semiarid–arid regions. In addition, representation of the continuum of roots and various rooting depths associated with vegetation communities is essential for reliable recharge estimation.

3.8. Implications for Water Resources

[36] Reliable recharge estimates are critical for evaluation of and optimal management of water resources. Long-term average recharge rates are beneficial to groundwater managers because management plans are developed generally for decadal timescales. The relationship between precipitation and recharge developed in this study for vegetated, texturally variable soils was used to map spatial variability of recharge for the groundwater model of the Carrizo-Wilcox aquifer in Texas [*Kelley et al.*, 2004]. Scaling factors were developed for the groundwater model that varied these recharge rates with topography and subsurface geology with high recharge in upland areas and above more permeable geologic units, similar to the B value discussed by *Hatton* [1998].

[37] Understanding of climatic and vegetation controls on groundwater recharge shown by simulations in this study can be used to assess potential impacts of climate variability and land use/land cover change on groundwater availability by using space as a proxy for time. The effect of vegetation types on simulated recharge can be used to provide preliminary estimates of potential impacts of removing invasive woody species in many areas of Texas. The state is currently investing millions of dollars in this program to increase water availability [*Wilcox*, 2002].

4. Conclusions

[38] 1. Unsaturated zone modeling using online data is a useful approach for simulating diffuse recharge in porous media systems from point to regional scales where input data are available.

[39] 2. Climate, vegetation, and soils each exert controls on groundwater recharge. (1) High simulated long-term (30 year) mean annual recharge (51–709 mm/yr) in nonvegetated sandy profiles represents 23 to 60% (arid–humid) of MAP and provides an upper bound on actual recharge. (2) Soil textural variability controls recharge, as shown by the large reduction by factors of 2 to 11 in simulated recharge for nonvegetated, texturally variable soils relative to those in monolithic sands. (3) Presence and type of vegetation control recharge, as shown by the reduction in recharge in vegetated relative to that in nonvegetated monolithic sand (factors of 2–30, humid–arid) and vegetated relative to that in nonvegetated, texturally variable soil (factors of 2–80, humid–arid). Relative reductions in recharge due to vegetation were greater in semiarid–arid relative to more humid regions and reflect the enhanced ability of vegetation to reduce recharge in more water-limited regions.

[40] 3. The most realistic long-term (30 year) recharge estimates based on vegetated, texturally variable soils range from 0.2 to 118 mm/yr, representing 0.1 to 10% (arid–humid) of long-term MAP.

[41] 4. Approximately 80% of the variability in simulated recharge can be explained by variability in MAP in vegetated, layered soil profiles using the power law relationship. MAP can be used as a predictor of mean annual recharge.

[42] 5. Simulated long-term, spatially averaged recharge rates generally compare favorably with recharge estimates based on previous field studies.

[43] 6. Simulated long-term (30 year), spatially averaged runoff is generally within the range of estimates based on gauge data in statewide water balance modeling for most regions. Discrepancies in the Southern High Plains can be explained by internal drainage to playas.

[44] 7. Unsaturated zone modeling provides a valuable tool for isolating controls on groundwater recharge. Understanding these controls can be used to assess potential

impacts of climate variability and land use/land cover change on groundwater recharge.

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