Chapter 14

Evaluating Climate, Vegetation, and Soil Controls on Groundwater Recharge Using Unsaturated Flow Modeling

K. E. Keese[1], B. R. Scanlon[1], and R. C. Reedy[1]

Introduction

Quantification of recharge and understanding controls on recharge are important for water-resources assessment and for determining groundwater vulnerability to contamination. Some groundwater districts are considering restricting groundwater pumpage to the rate at which groundwater is being replenished through recharge. Areas with high recharge rates are inherently most susceptible to surface sources of contamination. A variety of approaches are available for estimating groundwater recharge, including physical, chemical, and modeling approaches based on surface water, unsaturated zone, and groundwater data (Scanlon and others, 2002b). Numerical modeling is a valuable tool for assessing recharge because it allows the influence of different factors, such as climate, vegetation, and soils, to be evaluated independently to determine the dominant controls on recharge. Numerical modeling also provides a predictive tool for recharge estimation. The ready availability of online data on meteorological parameters, vegetation coverage (McMahan and others, 1984), detailed soils data (STATSGO, SSURGO; USDA 1994, 1995), and pedotransfer functions to translate soils data to hydraulic parameters (Schaap and Leij, 1998) greatly enhances our ability to model recharge. Many previous studies have used numerical modeling to estimate the spatial and temporal variability in recharge (Rockhold and others, 1995; Fayer and others, 1996; Kearns and others, 1998; Salama and others, 1999). These studies provided valuable insights into controls on recharge.

Climate, Vegetation, and Soils of Texas

Long-term (1961–1990) average annual precipitation ranges from 224 mm/yr in west Texas to 1184 mm/yr in east Texas, based on evaluation of precipitation data for 10 meteorological stations throughout Texas (Figure 14-1). Annual precipitation at individual stations ranged from 110 mm (El Paso, 1969) to 1783 mm (Houston, 1973). Summer precipitation (Jun–Aug) is dominant throughout much of the state, particularly

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[1] Bureau of Economic Geology, Jackson School of Geosciences, Univ. of Texas at Austin

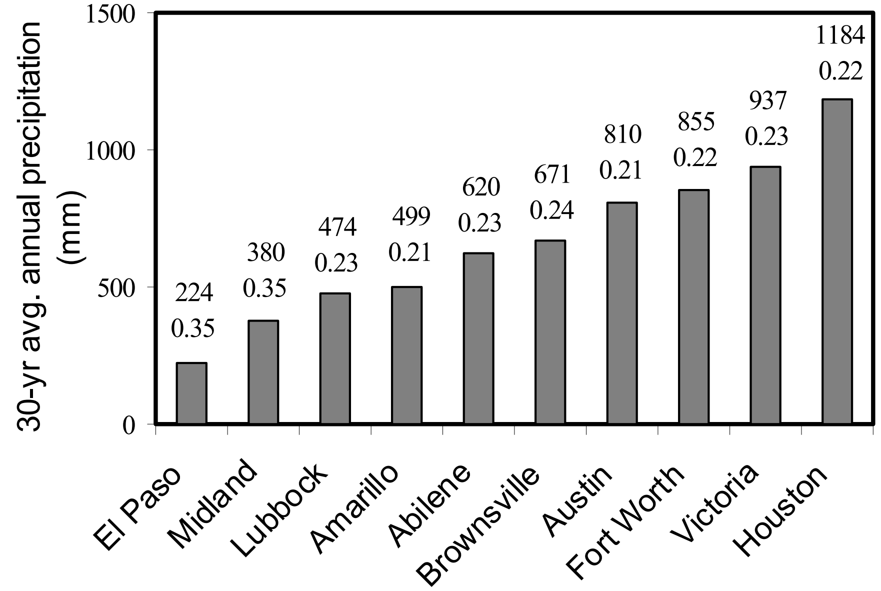

Figure 14-1: Long-term (1961-1990) average annual precipitation for 10 meteorological stations throughout Texas. Labels: precipitation (mm), coefficient of variation.

in the Trans Pecos (43 percent) and the High Plains (33 to 48 percent) regions (Figure 14-2). Spring precipitation is dominant in the Austin/Fort Worth region (29 to 33 percent), whereas fall precipitation is dominant in the Gulf Coast region (28 to 39 percent). Precipitation is fairly uniformly distributed in the more humid regions in east Texas. Winter precipitation is generally low throughout most of the state (8 to 16 percent), with the exception of the humid east (21 percent). Precipitation was generally low throughout much of the state in 1963–64, 1977, 1980, and 1988 and high in 1968, 1973–74, 1976, 1981, and 1986 (Figure 14-3). Variability in annual precipitation was greatest in semiarid regions in west Texas (coefficient of variation, CV: 0.35), whereas variability was fairly uniform throughout the rest of Texas (CV: 0.21–0.23) (Figure 14-1).

Vegetation in Texas is influenced by climate, soils, and topography. The vegetation types of Texas have been mapped using LANDSAT data and computer classification in the eastern two-thirds of the state and land resource mapping by Kier and others (1977) (McMahon and others, 1984). Vegetation ranges from shrubs and grasses in the Trans Pecos region, shrub/forest to forest/shrub in the Edwards Trinity Plateau, and forest and forest/shrub in east Texas (Figure 14-4). Cropland areas dominate much of the High Plains, Rolling Plains, Blackland Prairie, and Gulf Coast aquifers.

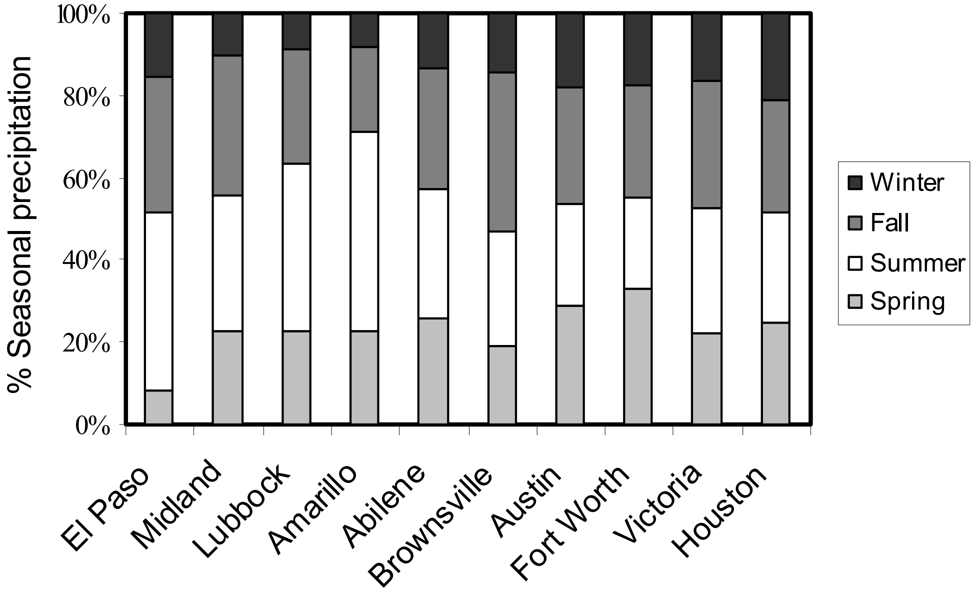

Figure 14-2: Normalized long-term (1961-1990) average seasonal distribution of precipitation.

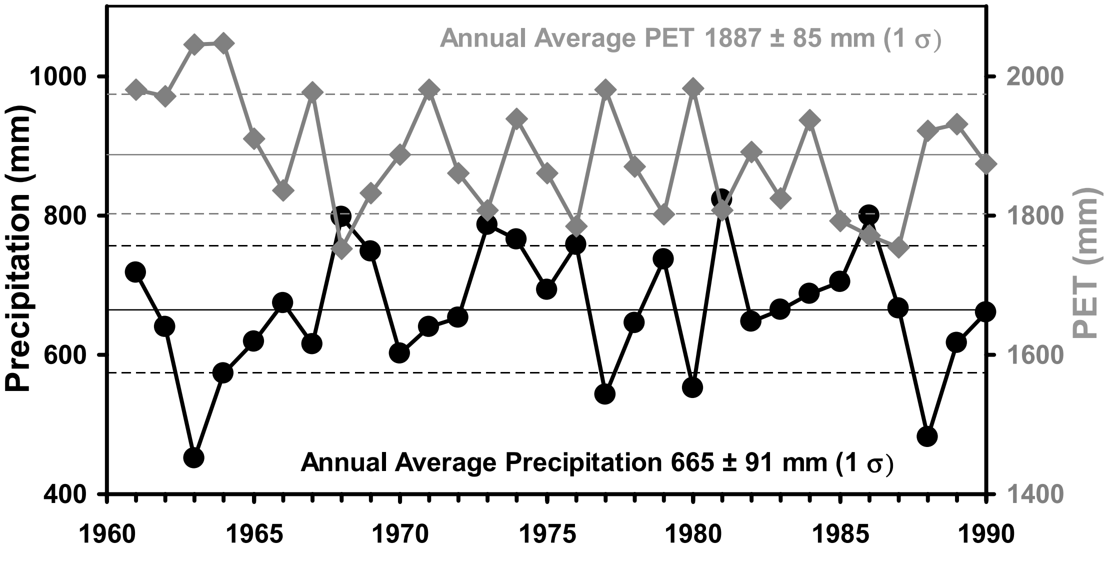

Figure 14-3: Long-term (1961-1990) average annual precipitation and PET for the stations listed in Table 1. The solid horizontal lines represent the 30-yr average, dashed horizontal lines represent standard deviation (± 1σ).

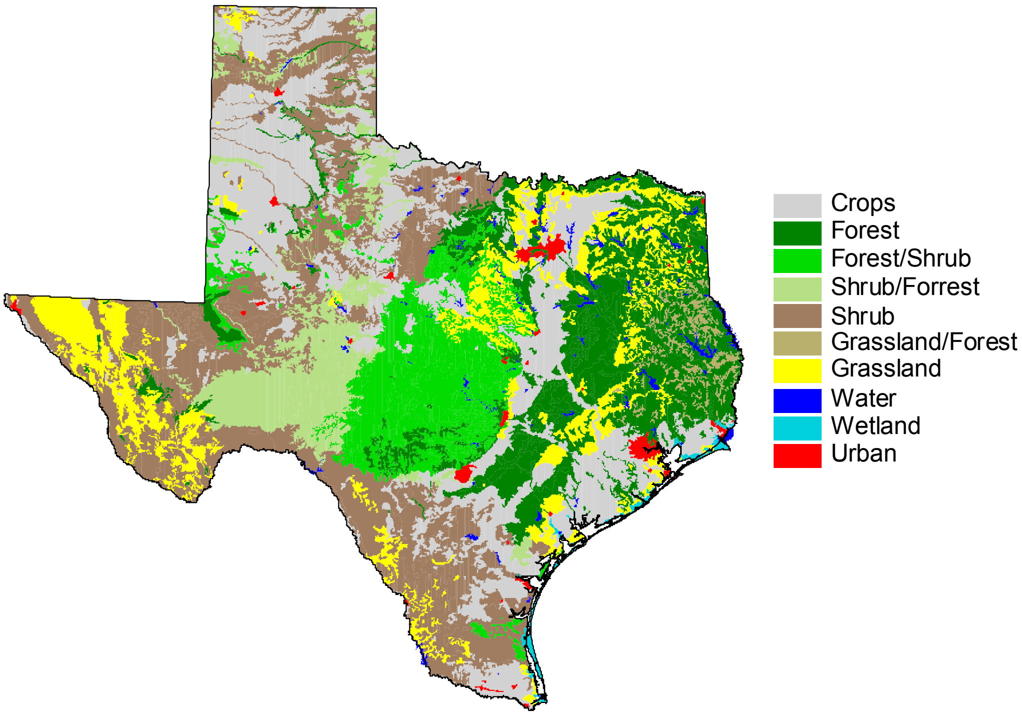

Figure 14- 4: Distribution of dominant vegetation types in Texas.

The distribution of different soils in Texas is similar to the distribution of various geologic units. The average clay content in the shallow subsurface (down to 1.5 to 2.0 m depths), according to STATSGO data, shows some general trends: low clay content in west Texas (Trans Pecos and Cenozoic Pecos Alluvium regions), high clay content in the central High Plains (generally corresponding to the Blackwater Draw Fm.) decreasing in the southern High Plains, generally high clay content in central Texas, low clay content in east Texas, high clay content in the central and northern portions of the Gulf Coast (generally corresponding to the Beaumont Fm.), and low clay content in the southwestern Gulf Coast (Figure 14-5).

Methods

Unsaturated flow modeling is used to simulate drainage below the root zone, which is equated to groundwater recharge. The code UNSAT-H (Version 3.0; Fayer, 2000) is a one-dimensional, finite-difference code that was used for the simulations. The simulations focus on the water balance:

$$D = P - ET - R_0 - \Delta S \qquad (1)$$

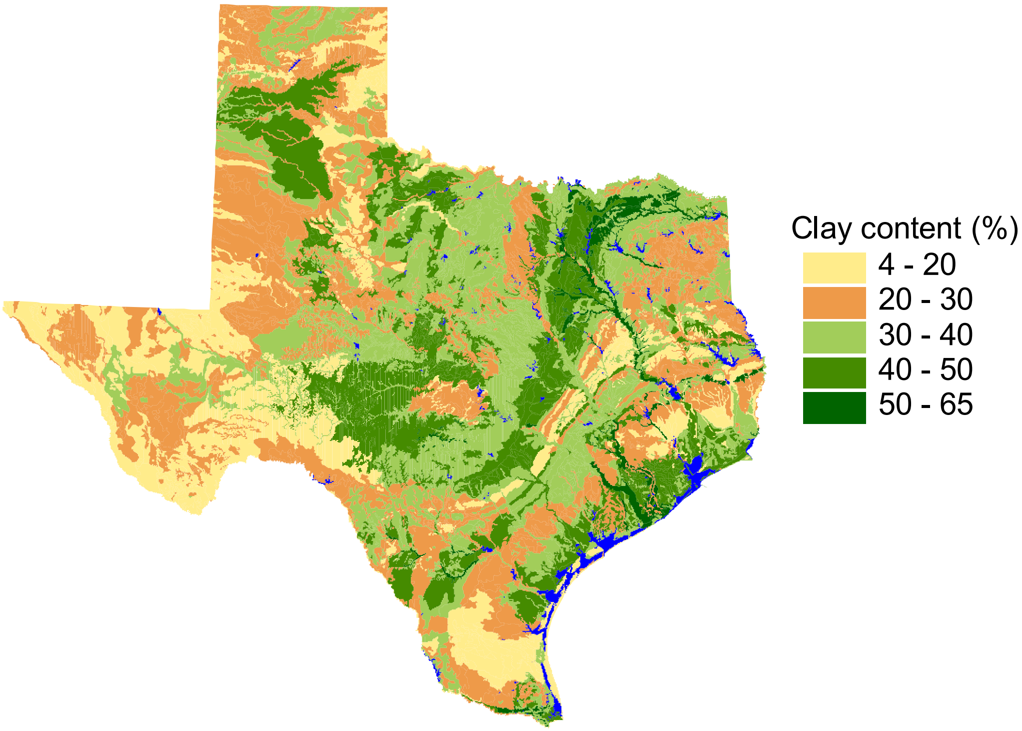

Figure 14-5: Average soil profile clay content derived from STATSGO database. Water covered areas shown in blue.

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. Precipitation and irrigation are input parameters for the simulations; all soil parameters in the water balance are simulated. A soil-profile depth of 5 m was chosen for the simulations becauseroot-zone depths are generally less than this value. Deep drainage at the base of the 5-m profile is equated with groundwater recharge. UNSAT-H was used to simulate the water balance for a 30-yr period (1961–1990). Average annual drainage for this period was calculated from the simulations and was equated to the long-term recharge rate. Input data requirements for the model include meteorologic forcing, vegetation parameters, lower boundary condition, initial conditions, and hydraulic parameters for the different soil types.

Data from 10 meteorological stations were used to simulate recharge in 13 study areas, which represent the major porous media aquifers in the state (Figure 14-6, Table 14-1). Each study area represents an aquifer outcrop area or recharge area within a single or multi-county area exclusive of urbanized regions. The 1961-1990 period was chosen because of availability of solar radiation for the meteorological stations for this time. Many solar radiation monitoring stations were discontinued in 1990. The upper boundary condition included meteorological forcing obtained from the database in the GEM code (Hanson and others, 1994). Meteorological input requirements included values of daily

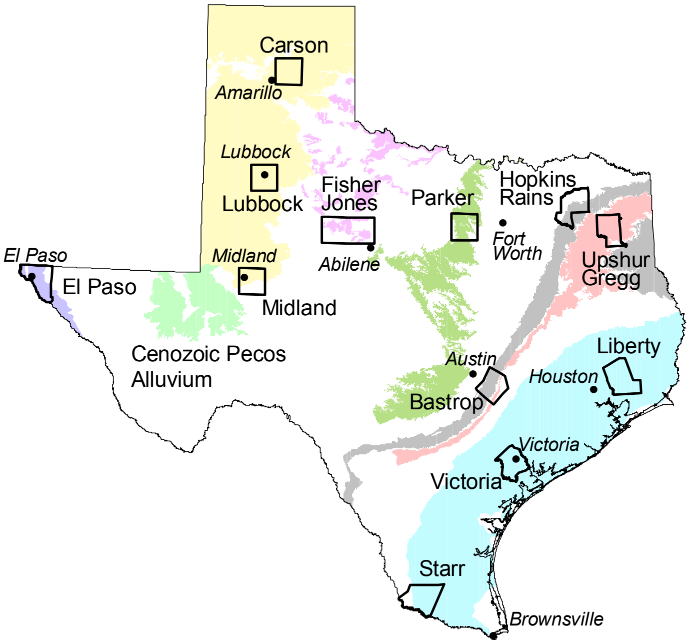

Figure 14-6: Modeled study areas (normal font) and meteorological station locations (italic font). The entire Cenozoic Pecos Alluvium Aquifer was simulated whereas all other study areas included 1- to 2-county areas.

Table 14-1: Study areas, corresponding meteorological stations, and associated aquifer outcrops listed in order of increasing precipitation.

Study Area	*Meteorological Station*	*Aquifer Outcrop*
El Paso County	El Paso	Hueco Bolson
Midland County	Midland	Ogallala
Cenozoic Pecos Alluvium	Midland	Cenezoic Pecos Alluvium
Lubbock County	Lubbock	Ogallala
Carson County	Amarillo	Ogallala
Fisher/Jones Counties	Abilene	Seymour
Starr County	Brownsville	Gulf Coast
Bastrop County	Austin	Carrizo-Wilcox
Parker County	Fort Worth	Carrizo-Wilcox
Hopkins/Rains Counties	Fort Worth	Trinity
Upshur/Gregg Counties	Fort Worth	Trinity
Victoria County	Victoria	Gulf Coast
Liberty County	Houston	Gulf Coast

Table 14-2: Monolithic profile hydraulic and retention parameters.

Texture	K_s (mm/day)	θ_s	θ_r	α (1/m)	n
Sand	5870	0.38	0	0.0503	1.7736
Silt loam	430	0.47	0	0.0266	1.1689

K_s: saturated hydraulic conductivity, θ_s: saturated water content, θ_r: residual water content, α and n: van Genuchten function parameters.

average precipitation, dew point temperature, wind speed, solar radiation, and minimum and maximum air temperature.

The lower boundary condition for the simulations was specified as a unit gradient that allows water to drain when it reaches the boundary. Matric-potential head initial conditions were arbitrarily set at –3 m in humid counties (Fisher-Jones, Parker, Hopkins-Rains, Upshur-Gregg, Liberty, Bastrop, and Victoria) and –10 m for all other counties. The impact of initial conditions on simulation results was evaluated by rerunning the simulations multiple times; however, rerunning simulations once was found to be sufficient for minimizing the impact of initial conditions.

Simulations for evaluating the impact of climate on drainage or recharge were based on monolithic sand or silt-loam soil profiles. Hydraulic properties for the sand were obtained from the UNSODA database (UNSODA 4650, Leij and others, 1996), and those for the silt loam were based on data from Scanlon and others (2002c) (Table 14-2). Information for layered soil profiles was obtained from STATSGO and SSURGO databases (USDA, 1994; 1995). Geographic Information System software was used to create study-area polygon files for the selected counties, or aquifer in the case of the Cenozoic Pecos Alluvium aquifer. These polygon files were then used to clip the study areas out of the original soil map polygon files. Areas for each of the resulting soil map polygons within a study area were calculated and totaled over each unique mapped unit. The resulting master list of mapped soil unit areas was sorted, and the dominant units that represented at least 80 percent of the study area were selected for modeling analysis.

Soil layer physical characteristics for most of the study areas were obtained from the SSURGO version 2 database (USDA, 1994). The Cenozoic Pecos Alluvium aquifer had limited SSURGO data available for analysis; therefore, data for the entire (multicounty) outcrop area were obtained from the STATSGO database (USDA, 1995). Pedotransfer functions were used to determine soil hydraulic properties. Rosetta software uses neural network programming (Schaap and others, 2001) and a database of measured texture, water retention, and saturated hydraulic conductivity samples to provide estimates of the van Genuchten water retention functions and saturated hydraulic conductivity for input to unsaturated flow models. Only texture and bulk density information was available from the STATSGO database for input to the Rosetta program. 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.

Vegetation parameters required for UNSATH include root length density function, percent bare area, time of seeding and harvesting crops, and time series of rooting depth and leaf area index (LAI). Distribution of different vegetation types for each of the modeled areas was obtained from a map of dominant vegetation associations in Texas (Kier and others, 1977; McMahan and others, 1984) (Figure 14-4). Vegetation parameter values were obtained from the literature. A value of 0.3 was used for albedo (Tindall and others, 1999).

The vegetation map, available as a GIS polygon file, was intersected with the study area soil unit polygon files. This analysis resulted in a large number of soil unit/vegetation type combinations, and exhaustive simulations were not performed for each combination. Rather, drainage results for the layered nonvegetated models within a given study area were examined. Soil profiles having similar magnitude drainage values were grouped together, and a representative profile from each group was selected for simulation with the various vegetation types that intersected all of the soil units in that group. Similar to the nonvegetated modeling procedure, the resulting polygon areas were totaled for each group/vegetation type combination, and the dominant combinations that summed to 80 percent of the area were modeled.

A soil profile depth of 5 m was used in the simulations. In monolithic profiles, nodal spacing was 2 mm at the land surface and was increased by a factor of ~1.2, to a maximum value of 230 mm, and then reduced by a factor of 1.2, to a value of 2 mm at the base of the profile. In layered profiles, nodal spacing was also reduced near textural interfaces to a value of 20 mm by gradually increasing and decreasing nodal spacing away from these interfaces.

Results and Discussion

The relative importance of climate, soil texture, and vegetation in controlling recharge was evaluated by conducting simulations using different combinations of these parameters. The simplest simulations consisted of nonvegetated, monolithic sand and silt loam profiles for evaluating the impact of climate. Complex layered soil profiles were simulated without vegetation to evaluate the impact of soil texture on recharge. Vegetation was added to the monolithic and layered profiles to determine its impact on simulated recharge. The most realistic scenario is represented by vegetated layered soil profiles.

The simulated recharge results were represented by a single recharge value for each location. For the monolithic profile simulations, models were developed for each of the meteorological stations resulting in 10 representative recharge values. For the layered soils profiles simulations, models were developed for each soil profile and the results were areally weighted to produce 13 recharge values representative of each of the study areas. Each of the representative recharge values was plotted versus precipitation and models were fit to the results for each of the four modeling scenarios (for example, non-vegetated monolithic and layered soil profiles, and vegetated monolithic and layered soil profiles) (Figure 14-7). Power law models were used as they resulted in higher correlation coefficients and lower residual standard deviations than linear models (Table 14-3). Finally, the power law model relationships were used to generate continuous statewide recharge rate maps for each of the modeling scenarios. Though shown for the entire state, the results should only be applied to the outcrop areas of the porous media aquifers shown.

Monolithic Sand and Silt Loam Profiles Simulations

Recharge estimated using monolithic sand profiles without vegetation provide an upper bound on recharge rates because vegetation and layering in soils would generally reduce recharge. These simulations were used to assess the impact of climate alone on recharge. Recharge ranged from 54 mm/yr in west Texas to 720 mm/yr in east Texas (Table 14-4), representing 24 to 61 percent of long-term (30-yr) average annual precipitation in these regions. Simulated recharge increased eastward across Texas, following the precipitation gradient (Figures 14-1 and 14-8). Lack of runoff in the simulated results was attributed to the high saturated hydraulic conductivity of the sand (5.87 m/d) relative to applied precipitation intensity.

Simulated annual recharge increased with precipitation (R = 0.99; Figure 14-8). Simulated recharge was more highly correlated with winter (R = 0.97) and fall (R = 0.97) precipitation than with spring (R = 0.93) or summer (R = 0.76) precipitation. Although the relative amount of precipitation in winter is low, recharge is high because evaporation is low during the winter (Figures 14-2, and 14-9). Runoff estimates from previous statewide water balance simulations ranged from 0 in west Texas to 415 mm/yr in east Texas (Reed and others, 1997); therefore, these simulated recharge values are expected to overestimate actual recharge, particularly in east Texas, where much of the water runs off. Variability in annual recharge is similar throughout the state and is similar to variability in precipitation (Table 14-4). Potential ET is much greater than simulated actual ET; the PET/AET ratio decreased from 11.6 in the west (El Paso) to 2.8 in the east (Houston).

The negative correlation between PET and AET is attributed to AET being controlled by water availability throughout much of the state, as opposed to energy availability, as represented by PET.

Simulated recharge for a monolithic silt loam soil was less than that of the monolithic sand profile by as much as a factor of 1.7. Simulated recharge ranged from 32 mm/yr in west Texas to 594 mm/yr in east Texas (Table 14- 4), which represented 14 to 50 percent of long-term average annual precipitation in these regions. No runoff was simulated for the silt loam profile probably because precipitation intensity was less than saturated hydraulic conductivity (0.43 m/d).

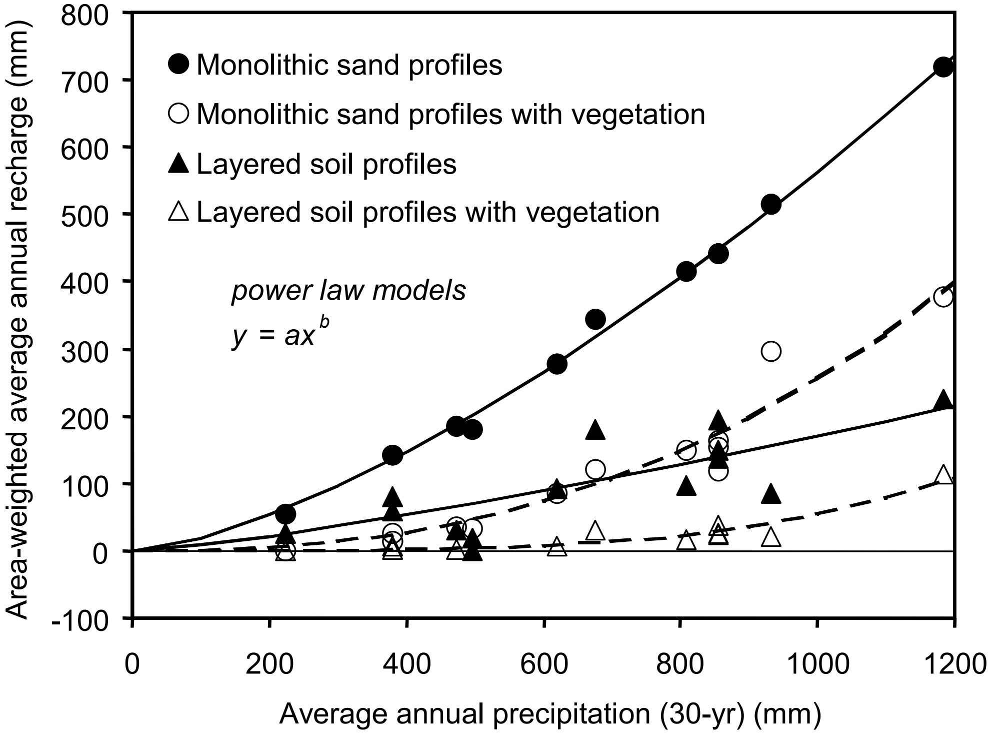

Figure 14-7: Relationships between precipitation and simulated area weighted average annual recharge. Solid lines are power law models fit to the results for profiles without vegetation. Dashed lines are models fit to the results for profiles with vegetation.

Table 14-3: Power law ($y = ax^b$) model coefficients and residual statistics for estimating recharge (*y, mm/yr*) from precipitation (*x, mm/yr*). The power law models are shown in Figure 7.

Model	*Modeling Scenario*	*Coefficients*		*R*	*Residual*	
		a	*b*		□	$\|y_r\|$
Power Law ($y = ax^b$)	Monolithic sand	2.266×10^{-02}	1.465	0.998	8.1	7.9
	Monolithic sand with vegetation	9.855×10^{-06}	2.471	0.962	23.5	30.2
	Layered soil	2.560×10^{-02}	1.275	0.788	26.7	18.9
	Layered soil with vegetation	6.830×10^{-11}	3.964	0.949	6.7	6.4
Linear ($y = ax + b$)	Monolithic sand	6.854×10^{-01}	-129.5	0.994	9.7	16.8
	Monolithic sand with vegetation	3.823×10^{-01}	-135.9	0.928	25.3	31.5
	Layered soil	1.927×10^{-01}	-23.5	0.786	25.3	32.1
	Layered soil with vegetation	8.847×10^{-02}	-37.4	0.793	11.9	13.7

R: correlation coefficient, □*:* standard deviation, $|y_r|$*:* average absolute deviation

Table 14-4: Simulated average annual recharge and actual evapotranspiration (*AET*) for monolithic sand and silt loam profiles with measured 30-yr average annual precipitation, calculated potential evapotranspiration (*PET*), and the ratio of *PET* to *AET*.

Units: mm/yr	*P*		*PET*	*Sand*					*Silt Loam*		
				Recharge			*AET*	$\frac{PET}{AET}$	*Recharge*		*AET*
	Total	*CV*	*Total*	*Total*	*CV*	*R/P (%)*			*Total*	*R/P (%)*	
El Paso	224	0.35	2087	54	0.22	24	180	11.6	32	14	200
Midland	380	0.35	2169	142	0.20	37	250	8.7	143	38	242
Lubbock	474	0.23	2034	186	0.24	39	302	6.8	127	27	356
Amarillo	499	0.21	2096	180	0.16	36	331	6.3	119	24	388
Abilene	620	0.23	2132	277	0.19	45	358	6.0	198	32	433
Brownsville	671	0.24	1788	345	0.19	51	340	5.3	261	39	420
Austin	810	0.21	1732	416	0.20	51	411	4.2	315	39	505
Fort Worth	855	0.22	1819	442	0.18	52	430	4.2	335	39	531
Victoria	937	0.23	1651	516	0.22	55	434	3.8	406	43	538
Houston	1184	0.22	1362	720	0.18	61	482	2.8	594	50	600

P: precipitation, *PET*: potential evapotranspiration, *AET*: simulated actual evapotranspiration, *CV*: coefficient of variation, *R/P*: ratio of recharge to precipitation.

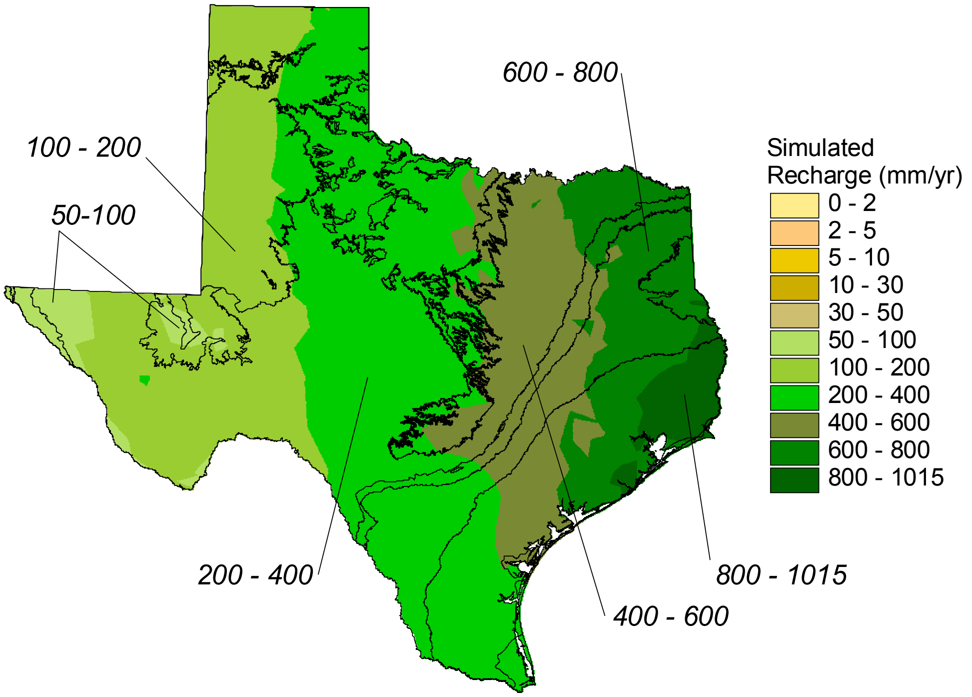

Figure 14-8: Predicted recharge using the power law relationship between precipitation and simulated recharge for the monolithic sand profile modeling results.

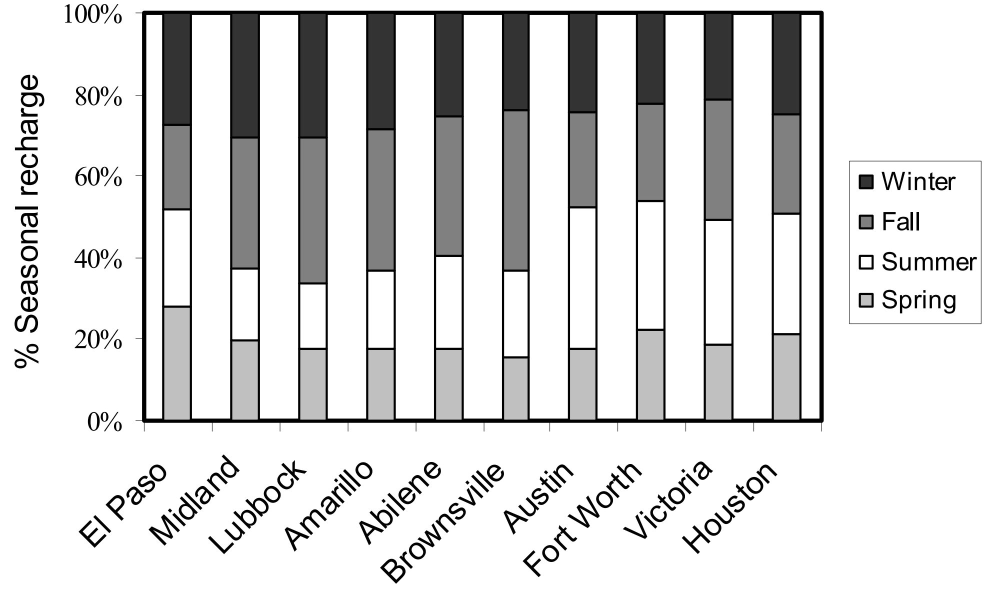

Figure 14-9: Normalized long-term (1961-1990) average seasonal distribution of simulated recharge.

Layered Soil Profiles Simulations

Soil profiles in most regions are generally layered; therefore, simulations using layered profiles are more realistic than those based on monolithic profiles. Layering of soil profiles should generally reduce recharge relative to monolithic sand profiles because of hydraulic conductivity reductions in coarse over fine layers and capillary barrier effects in fine over coarse layers. The number of soil profiles representing ~80 percent of the study areas ranged from 6 to 29. Profiles with similar drainage results were grouped into categories, which resulted in 3 to 7 representative profiles for each study area. Simulated recharge for different groups in a single study area varied over 1 to 2 orders of magnitude, indicating high local variability in simulated recharge. Simulated recharge for each group of soil profiles was area weighted, resulting in an average recharge rate for each of the 13 study areas (Table 14-5). Recharge ranged from 18 mm/yr in central Texas to 226 mm/yr in east Texas and correlated with precipitation (R = 0.79; Figures 14-7 and 14-10). Areally averaged recharge rates ranged from 4 to 26 percent of the long-term average precipitation for each study area. Recharge rates for different study areas were reduced in the layered profiles relative to those for monolithic sand by factors ranging from 2 to 10.

Simulated runoff in the various sites generally reflects differences in climate and texture in the state. Simulated runoff was low in El Paso County (0.1 mm/yr) and the Cenozoic Pecos Alluvium (15 mm/yr) where soils have low clay content and are fairly coarse grained (Figure 14-5, Table 14-5). Higher runoff was simulated in the central portion of the High Plains in Carson County (259 mm/yr) where soils are fine grained corresponding to the Blackwater Draw Fm. Simulated runoff decreased to the south in the High Plains as soils become coarser grained (Lubbock, 59 mm/yr; Midland, 8 mm/yr). Simulated runoff in central Texas was moderately high and variable (Fisher/Jones Counties, 169 mm/yr; Parker County, 146 mm/yr; Bastrop County, 147 mm/yr). Simulated runoff was moderately low in east Texas (Hopkins/Rains Counties, 49 mm/yr; Upshur/Gregg, 26 mm/yr). Variability in simulated runoff in the Gulf Coast sites is related to soil texture; low runoff occurs in the southern Gulf Coast (Starr County, 30 mm/yr), where soils are coarse grained, and higher runoff occurs in the central (Victoria County, 431 mm/yr) and northern (Liberty County, 316 mm/yr) Gulf Coast, where the soils are finer grained corresponding to the Beaumont Fm.

Table 14-5: Simulated average annual recharge and actual evaporation for layered soil profiles without vegetation with measured 30-yr average annual precipitation and the ratio of recharge to precipitation.

Units: mm/yr *Study Area*	*P*	*R*	*R/P (%)*	*RO*	*AE*
El Paso County	224	27	12	0.1	190
Midland County	380	59	16	8	329
Cenozoic Pecos Alluvium	380	81	21	15	276
Lubbock County	474	31	7	59	288
Carson County	497	18	4	259	241
Fisher/Jones Counties	619	93	15	169	380
Starr County	676	179	26	30	466
Bastrop County	809	96	12	147	625
Parker County	855	150	18	146	606
Hopkins/Rains Counties	855	138	16	49	672
Upshur/Gregg Counties	855	195	23	26	653
Victoria County	932	84	9	431	439
Liberty County	1184	226	19	316	687

P: precipitation, *R*: simulated recharge, *R/P*: ratio of simulated recharge to precipitation, *RO*: simulated runoff, *AE*: simulated actual evaporation

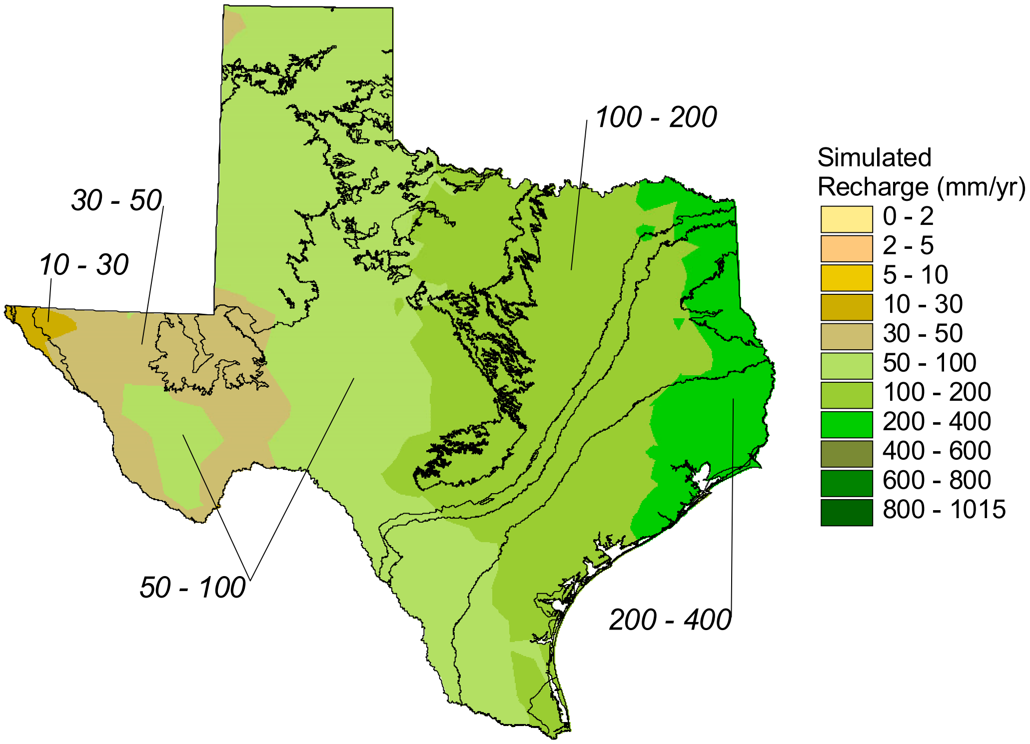

Figure 14-10: Predicted recharge using the power law relationship between precipitation and simulated recharge for the layered soil profile modeling results.

Monolithic Sand Profiles with Vegetation Simulations

To assess the impact of vegetation without the influence of soil layering, simulations of recharge were conducted in vegetated monolithic sand profiles (Table 14-6). Recharge for areas with more than one vegetation type, such as trees with grasses, was estimated by simulating the different vegetation types separately and combining the results. Average recharge rates were calculated for each study area by areally weighting recharge for each vegetation type. Vegetation greatly reduced simulated recharge for each study area relative to that for the nonvegetated, monolithic sand profile by factors ranging from 2 to 10, with the exception of El Paso, where recharge was reduced from 54 mm/yr to 0 mm/yr. Simulated average annual recharge for vegetated, monolithic sand profiles was much lower than that for the nonvegetated, monolithic sand profiles (Figure 14-7). Reduction in recharge results from increased ET; no runoff was simulated in these sandy profiles. Relative amounts of evaporation and transpiration also varied with vegetation type. Transpiration was much greater than evaporation for trees. The relative proportion of evaporation and transpiration for grasses, crops, and brush is related to soil texture. Generally, transpiration is higher than evaporation in coarser grained soils.

Table 14- 6: Simulation results for monolithic sand profiles with vegetation. All runoff was zero.

Units: mm/yr *Study Area*	*P*	*R*	*R/P (%)*	*ET*
El Paso County	224	0	0	236
Midland County	380	14	4	387
Cenozoic Pecos Alluvium	380	27	7	469
Lubbock County	474	36	8	459
Carson County	497	33	7	490
Fisher/Jones Counties	619	86	14	557
Starr County	676	120	18	573
Bastrop County	809	150	19	704
Parker County	855	153	18	726
Hopkins/Rains Counties	855	164	19	716
Upshur/Gregg Counties	855	118	14	763
Victoria County	932	296	32	662
Liberty County	1184	377	32	629

P: precipitation, *R*: simulated recharge, *R/P*: ratio of simulated recharge to precipitation, *ET*: simulated evapotranspiration.

Simulations indicate that the presence or absence of vegetation has a large impact on simulated recharge; however, the type of vegetation also greatly affects simulated recharge, as shown by the range in simulated recharge by 1 to 2 orders of magnitude for different vegetation types within a study area. Shrubs were effective in reducing recharge because of a longer growing season and greater root zone depth relative to crops. Different crop types also varied in their effectiveness in reducing recharge: sorghum resulted in more recharge relative to cotton (factor of 3 difference in Lubbock), which is attributed to the shallower root zone depth in sorghum (1.5 m) relative to that in cotton (2.1 m). Differences in recharge rates between trees and grasses could be attributed to differences in rooting depth: ≤1 m for grasses and ≤4.3 m for trees. Simulated recharge for vegetated sand profiles for each study area range up to 32 percent of precipitation and decrease across the state from west to east (Figure 14- 11).

Layered Soil Profiles with Vegetation Simulations

The layered profile with vegetation is the most realistic representation of actual conditions and should provide the most reliable recharge estimates for the different regions. Soil profiles with similar recharge rates were grouped into categories. Vegetation associated with these soil profiles was estimated using GIS overlay analysis. Recharge rates range from a minimum of 0.2 mm/yr in west Texas (El Paso County) to a maximum of 114 mm/yr in east Texas (Liberty County) (Table 14-7; Figure 14-12). Simulated recharge was generally low in semiarid regions (0.2 to 7 mm/yr) and higher in more humid regions (16 to 114 mm/yr). The relationship between average annual recharge and precipitation seems to be better described by a power law model (R = 0.90) than by a linear model (R=0.79) (Figure 14-12). Simulated average recharge rates for the 30-yr period represented 0.1 to 9.6 percent of the applied precipitation. Addition of vegetation greatly reduced simulated recharge relative to the layered profiles without vegetation

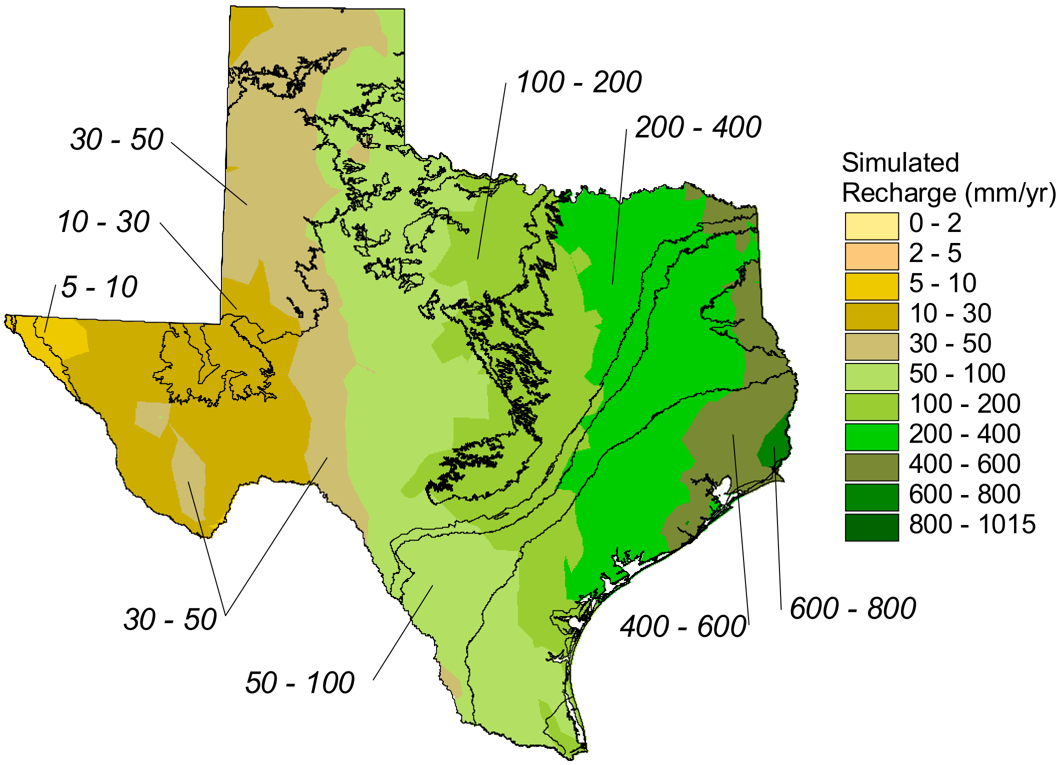

Figure 14-11: Predicted recharge using the power law relationship between precipitation and simulated recharge for monolithic sand profiles with vegetation modeling results.

Table 14-7: Simulation results for layered soil profiles with vegetation.

Units: mm/yr *Study Area*	*P*	*R*	*R/P* (%)	*RO*	*ET*
El Paso County	224	0.2	0.1	0	208
Midland County	380	2.0	0.5	5	393
Cenozoic Pecos Alluvium	380	7.0	1.8	13	365
Lubbock County	474	1.0	0.2	55	312
Carson County	497	0.5	0.0	244	273
Fisher/Jones Counties	619	7.0	1.1	179	459
Starr County	676	31.0	4.6	31	524
Bastrop County	809	16.0	2.0	192	634
Parker County	855	27.0	3.2	162	713
Hopkins/Rains Counties	855	24.0	2.8	59	789
Upshur/Gregg Counties	855	38.0	4.4	27	816
Victoria County	932	21.0	2.3	401	537
Liberty County	1184	114.0	9.6	325	750

P: precipitation, *R*: recharge, *R/P: ratio of* recharge to precipitation, *RO*: runoff, *E*: evaporation, *T*: transpiration

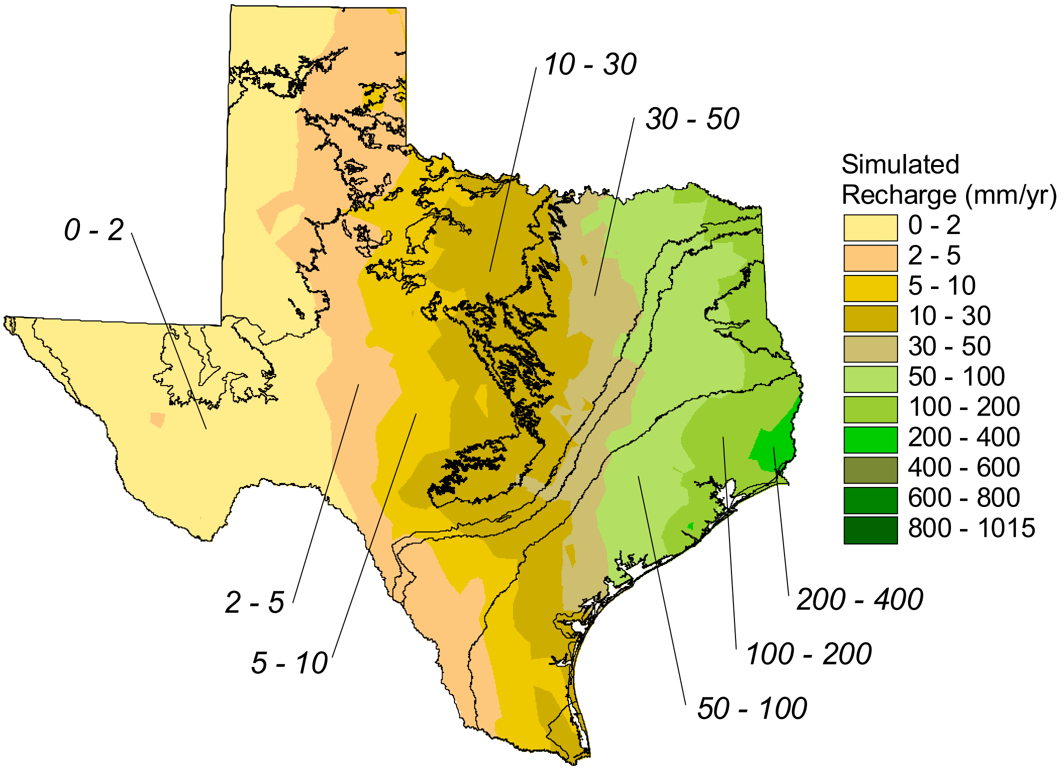

Figure 14-12: Predicted recharge using the power law relationship between precipitation and simulated recharge for the layered soil profiles with vegetation modeling results.

(Figure 14-7; Tables 14-5 and 14-7). Reduction factors ranged from 6 to 25 in the more humid settings (Gulf Coast, Carrizo Wilcox, Trinity aquifers) and ranged from 21 to 380 in the more arid settings (Ogallala, Seymour, Cenozoic Pecos Alluvium, and Hueco Bolson aquifers). Local variability in simulated recharge within a study area for different vegetation types for the same soil profile was generally within an order of magnitude.

Different vegetation types varied in their effectiveness in reducing recharge. Semiarid regions with shrubs resulted in negligible recharge (<1 mm/yr). Sorghum resulted in slightly higher recharge than cotton (factor of 2 in Lubbock), which is attributed to shallower rooting depth in sorghum (1.5 m) relative to cotton (2.1 m). Grasses resulted in much higher recharge than trees in more humid settings. For example, in Parker County in the Trinity aquifer, simulated recharge in grasses ranged from 1 to 197 mm/yr for different soil profiles, whereas simulated recharge for oak/mesquite/juniper and post-oak woodland forest was 0.

Sensitivity Analyses Based on Vegetation Parameters

Sensitivity of recharge to precipitation, vegetation, and soils was evaluated in the different simulated recharge scenarios, which isolated the impact of each of these parameters. Additional sensitivity analyses were conducted to evaluate the impact of varying vegetation parameters, such as percent bare area, leaf area index, root depth, and root length density on simulated recharge. These analyses were conducted on four soil profiles, representing the range of simulated recharge rates in Fisher/Jones Counties on the Seymour aquifer. The dominant vegetation type in the region is brush. Each parameter was reduced by 50 percent and increased by 150 percent, with the exception of percent bare area, which is 0 for the base case and was increased by 25 and 50 percent in the sensitivity analyses (Table 14-8; Figure 14-13).

Table 14-8: Sensitivity of recharge to variations in LAI, RD, RLD, and BA for four soil profiles. Each parameter was reduced by 50 percent and increased by 150 percent relative to the base case with the exception of percent bare area, which was zero for the base case and was increased to 25 percent and 50 percent. Factor refers to the ratio of annual recharge including the effect (e.g., LAI × 50 percent) to the base case annual recharge. Variable/constant indicates that a parameter changes or is held constant with time or depth during the simulated period.

Units: mm/yr	*Base Case Recharge*	*Effect*		*Effect*	
		Recharge	*Factor*	*Recharge*	*Factor*
		50% LAI		150% LAI	
Leaf Area Index (LAI) time variable	0.9	1.6	1.9	0.7	0.8
	4.0	9.0	2.3	2.8	0.7
	17.4	30.1	1.7	13.1	0.8
	26.9	42.9	1.6	21.0	0.8
		50% RD		150% RD	
Root Depth (RD) time constant	0.9	12.6	14.6	0.1	0.1
	4.0	17.4	4.4	1.0	0.2
	17.4	39.9	2.3	6.8	0.4
	26.9	55.3	2.1	13.3	0.5
		50% RLD		150% RLD	
Root Length Density (RLD) time constant depth variable	0.9	1.0	1.1	0.8	0.9
	4.0	4.2	1.1	3.7	0.9
	17.4	18.0	1.0	17.1	1.0
	26.9	30.2	1.1	25.7	1.0
		25% BA		50% BA	
Percent Bare Area (BA) time constant	0.9	1.4	1.6	7.9	9.2
	4.0	7.5	1.9	26.2	6.6
	17.4	27.4	1.6	51.6	3.0

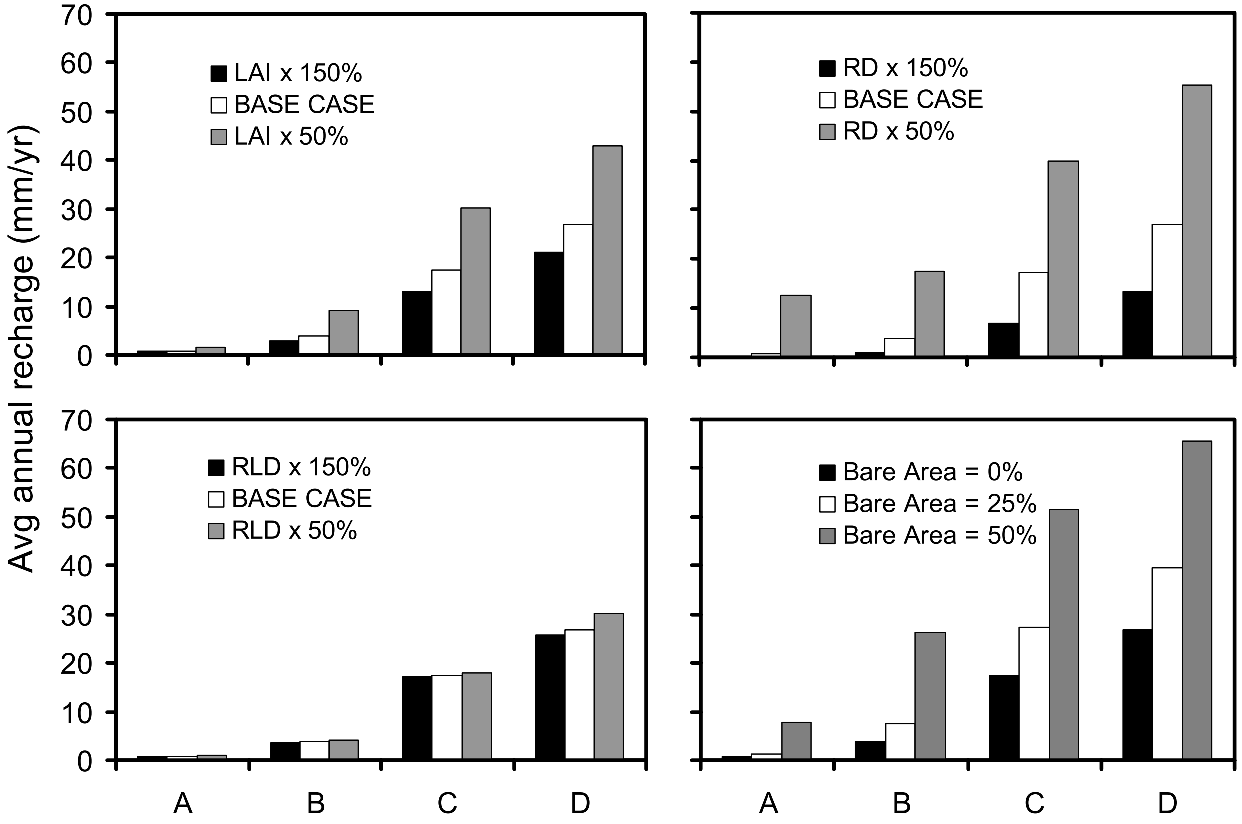

Figure 14-13: Recharge sensitivity analysis results. A, B, C, and D represent different soil profiles.

Simulated recharge was most sensitive to variations in root depth. Decreasing root depth by 50 percent resulted in an average increase in recharge of a factor of 6, whereas increasing root depth by 150 percent decreased recharge by a factor of 0.3. The inverse relationship between root depth and simulated recharge is expected because decreasing root depth allows water to drain more readily below the root zone. Simulated recharge was fairly insensitive to variations in root length density. Varying percent bare area had a large impact on simulated recharge. Increasing percent bare area by 25 percent increased recharge by an average factor of 1.6, whereas increasing bare area by 50 percent increased recharge by an average factor of 5. Simulated recharge was more sensitive to decreasing LAI than increasing LAI. Decreasing LAI by 50 percent resulted in an average doubling of recharge, whereas increasing LAI resulted in an average decrease in recharge by a factor of 0.8. These sensitivity analyses indicate that accurate estimates of root depth and percent bare area are critical for reliable simulation of recharge. Percent bare area can be estimated from fractional vegetation coverage using satellite data such as AVHRR or MODIS. However, accurate estimates of rooting depth are difficult to obtain. Few techniques are available for estimating rooting depth. The traditional approach, requiring manual measurement of roots in soils, is labor intensive and time consuming.

Minirhizotrons can be installed in the subsurface to estimate root distribution using cameras; however, some have suggested that these instruments induce root growth, further suggesting that the measurements may be an artifact of the instrumentation.

Comparison of Recharge Estimates Based on Modeling with those Based on Other Techniques

Modeled recharge rates were compared with those based on groundwater availability modeling (GAM). Recharge estimates are available for GAM models of the High Plains and the Carrizo Wilcox aquifers. GAM recharge estimates for the High Plains are not directly comparable to recharge estimates based on unsaturated flow modeling in this study. Recharge in the GAM models represent areally averaged recharge that includes playa and interplaya settings, whereas this study focused on interplaya recharge. As indicated in the introductory section, playa recharge is about an order of magnitude higher than interplaya recharge in many areas (Wood and Sanford, 1995; Scanlon and Goldsmith, 1997). GAM recharge rates in the Central High Plains aquifer ranged from 4 to 38 mm/yr and increased from west to east, reflecting sandy soils to the east near the escarpment (Dutton and others, 2000). Simulated recharge based on unsaturated zone modeling in this study for Carson County in natural interplaya settings is 0.5 mm/yr and is similar to that in previous field studies conducted in that region (Scanlon and Goldsmith, 1997; Scanlon and others, 1997). GAM recharge rates for the Southern High Plains ranged from 0.2 to 2.2 mm/yr during predevelopment (Blandford and others, 2003). Post development recharge rates ranged from 0 to 50 mm/yr. GAM recharge estimates for Lubbock County (0–50 mm/yr) are higher than those estimated from unsaturated zone modeling in this study (6 mm/yr) because the GAM recharge rates include playa recharge.

Recharge rates in the Carrizo Wilcox GAM model are consistent with recharge estimates in this study and show an increase in recharge rates from the southwest (0 mm/yr) to the northeast (as much as 64 mm/yr) (Deeds and others, 2003; Fryar and others, 2003). Recharge rates in the Central Carrizo Wilcox GAM model were based on field studies using chloride data, and an average value of 25 mm/yr was used for Bastrop County (Dutton and others, 2003). Field studies focused on the high permeability Simsboro Formation, and estimated recharge rates ranged from 20 to 36 mm/yr. The average recharge rate in the GAM for Bastrop County (25 mm/yr) is slightly higher than the areally averaged simulated recharge rate in this study (16 mm/yr). The discrepancy between the two estimates can be attributed to the bias toward high permeability units in the GAM estimate (Simsboro Formation) versus the inclusion of low- and high-permeability zones in the areally averaged estimate in this study. GAM recharge rates in the northern section of the Carrizo Wilcox aquifer were compared with estimates in this study for Hopkins/Rains and Upshur/Gregg Counties (Fryar and others, 2003). GAM recharge estimates for Hopkins/Rains Counties (0–12.5 mm/yr; small areas 12.5–25.4 mm/yr) are slightly lower than the areally averaged recharge rates from this study of 24 mm/yr. The GAM recharge estimate for Upshur/Gregg Counties (25–50 mm/yr) is similar to the areally averaged estimate from this study of 28 mm/yr. Recharge was also estimated for these counties using median groundwater chloride concentration and chloride mass balance approach. This approach resulted in an estimated recharge rate of 45 mm/yr, which is also consistent with GAM model estimates and the unsaturated zone modeling estimate.

Recharge estimates based on unsaturated zone modeling in this study are generally consistent with those used in the groundwater availability models, and discrepancies can be explained by inclusion or exclusion of different types of recharge (for example, playa recharge in the High Plains) and focusing on different zones (for example, Simsboro unit in the Carrizo Wilcox aquifer).

Conclusions

The main conclusions of this study are as follows:

- High simulated recharge in monolithic sand profiles indicates that climate is not a limiting factor for recharge.
- Long-term (30-yr), simulated recharge using bare, sandy soil was highly correlated with precipitation throughout the state (R = 0.99) and increased with precipitation from 54 mm/yr in west Texas to 720 mm/yr in east Texas.
- Presence and type of vegetation greatly reduced simulated recharge in the sandy profiles.
- Layered soil profiles based on SSURGO soils data and pedotransfer functions generally resulted in much lower simulated recharge rates relative to monolithic soil profiles.
- Layered soil profiles combined with vegetation resulted in reasonable, areally averaged recharge rates for the 13 sites simulated in the state.
- Simulated recharge in vegetated layered systems was positively correlated with precipitation.

Modeling analysis proved useful in estimating areally averaged recharge rates for different settings within the state and indicates that long-term (30-yr) precipitation may be used as a predictor of recharge rates in a reconnaissance mode. However, field data are required for detailed estimation of recharge.

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