TEMPORAL VARIABILITY OF DIFFUSE GROUNDWATER RECHARGE IN NEW MEXICO

By

Anne K. Kearns
Graduate Research Assistant
Department of Earth and Environmental Science
New Mexico Tech

and

Jan M.H. Hendrickx
Associate Professor of Hydrology
Department of Earth and Environmental Science
New Mexico Tech

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ABSTRACT

The high level of dependence upon groundwater in the American Southwest has led to the rapid depletion of those resources. Future population and economic pressures will force further increases in the extraction of groundwater, perhaps at the expense of the economic well-being of the region. Recent studies support the probability of diffuse precipitation recharge but none have quantified it on a long-term basis. The objective of this study was to verify the possibility of significant quantities of diffuse precipitation recharge.

One hundred years of actual precipitation data from near Las Cruces, NM were used as input to a one-dimensional numerical model to explore this concept. Four soil textures (two sandy loams, a loamy fine sand, and a clay) were simulated in soil profiles, some two, some six meters deep, both barren and vegetated. Barren loamy fine sand showed continuous recharge throughout the evaluated time period. This decreased to five major periods of possibly substantial recharge when vegetation was simulated. Barren and vegetated sandy loam soils both displayed recharge during these five periods. Sandy loam and even clay soils showed localized recharge under ponded conditions as if enhanced by surface runoff.

Climate conditions supporting the initiation of recharge include both single, very large rainfall events and gradual soil moisture content increases. Recharge periods ended if two consecutive years had below average rainfall. El Niño conditions didn't correlate well with the five recharge periods, but Eastern Pacific cyclones were responsible for the two single, largest rainfall events, both of which initiated major recharge periods and may be responsible for the perpetuation of other periods as well.

Keywords: diffuse areal recharge, vadose zone, unsaturated flow

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Water availability is a major factor affecting economic development in the arid regions of the western United States. Overpumping of aquifers has caused a rapid decline in groundwater levels in many areas and this problem has serious implications for future water supplies. Governmental agencies and cities which monitor groundwater rely on estimates of groundwater recharge in order to make responsible decisions concerning the allocation of groundwater resources. The ability to make accurate recharge predictions could be critical to the long term economic and environmental health of this region.

Groundwater recharge in arid regions takes place by indirect focused recharge beneath ephemeral stream channels, by direct precipitation recharge through the vadose zone (e.g. Simmers 1997; Stephens 1995), and by infiltration through fractured bedrock in mountain front areas. Since in arid and semi-arid climates potential evaporation frequently exceeds precipitation amounts by an order of magnitude, many practitioners have assumed that precipitation recharge through desert vadose zones is generally negligible but possibly can occur during heavy winter precipitation events (Cable 1980; Evans *et al.* 1981; Mann 1976; Mercer *et al.* 1983). Other researchers hold this viewpoint on the basis of region-wide observations such as high concentrations of conservative solutes, such as chloride, in the root zone (but lower concentrations below the root zone), enrichment of stable isotopes in the near-surface zone (but less enrichment deeper), and generally upward water potential gradients in the top 5 to 10 meters (e.g. Phillips 1995). However, lysimeter and field measurements in the southwestern United States (e.g. Gee *et al.* 1994; Stephens 1994) clearly demonstrate that some precipitation recharge does occur, and the concept has gained more acceptance.

Two different precipitation recharge mechanisms can be recognized: (i) direct or diffuse recharge resulting from widespread infiltration of rainwater at the point of impact; (ii) localized recharge where some horizontal flow occurs into local depressions that are not connected to any draining water courses. Localized recharge is considered to be as significant as direct recharge in arid and semi-arid lands (Gee & Hillel 1988; Hendrickx & Walker 1997; Lerner *et al.* 1990; Stephens 1994). Field determined precipitation recharge fluxes in southern New Mexico and west Texas vary more than three orders of magnitude from 0.01 (Scanlon 1992) to 37 mm/year (Stephens and Knowlton 1986; Stephens 1995). This large variability of recharge rates is in all likelihood caused by differences in soil, vegetation, and precipitation distribution in time. Several studies have been conducted worldwide to investigate the effects of soil and vegetation on precipitation recharge (e.g. Hendrickx & Walker 1997; Lerner *et al.* 1990), but very few studies have addressed the temporal variability of precipitation recharge. A notable exception is the simulation study by Rockhold *et al.* (1995), who calculated precipitation recharge at the Hanford site (Washington) for three soil types (loamy fine sand, silty loam, and sand over silty loam) and four soil covers (sagebrush, cheat grass, bunch grass, and bare soil) during the period 1963-1993. Average annual precipitation for the 30 year simulation period was 160 mm, ranging from a low of 76 mm in 1976 to a high of 281 mm in 1983. The average, minimum and maximum recharge rates for the 30-year simulation period for a bare sand soil are 22, 11, and 68 mm/year while sagebrush on silt loam produces, respectively, 1, 0.5, and 4 mm/year. Although a bare soil always results in more recharge, the absolute differences in recharge between a bare and vegetated soil become less when the soil texture becomes finer. The study demonstrates a large temporal variability of recharge rates and makes a strong case for longer-term recharge studies.

Although precipitation recharge is now an accepted idea, a number of questions are still unresolved. For example, how frequently does precipitation recharge occur? Does it happen continuously in minute amounts, or episodically in response to major storm events? What climatic and soil conditions preclude these episodes? Is sand, due to it's coarse texture and higher hydraulic conductivity, the only soil type in which to expect aquifer recharge to occur? Do heavy winter rainfall patterns correlate with all the large recharge events, or can heavy summer thunderstorms initiate major recharge events as well? Can a single large precipitation event trigger a major recharge period, or is a large cluster of rainfall events required before recharge can occur? How well do years influenced by the El Niño Southern Oscillation (ENSO) condition correlate with precipitation recharge? How much water is contributed by this type of recharge? Up to now this potential supply of groundwater has been neglected in arid regions. Is the volume enough to warrant consideration by water resource managers or should it continue to be ignored? The natural temporal variability of a data set from near Las Cruces, New Mexico showing actual daily rainfall for one hundred years has been used in this study to evaluate groundwater recharge in that area on a long term basis. The goal is not to generate a more accurate value for the average yearly recharge rate but, by use of a numerical model, to detect and quantify episodic patterns if they exist and to answer these questions for southern New Mexico.

METHODS

Numerical Model

The numerical model, SWAP (Soil-Water-Air-Plant), previously known as SWATRE, was chosen for this study because of its ability to model transient water flow in unsaturated soil conditions with or without vegetation. It is a dynamic, one-dimensional, finite-difference model developed by Feddes, *et al.* (1974) for use in water-limited agricultural situations to account for field water use and to estimate crop yield. Belmans (1983) modified SWAP to introduce a computationally less intensive solution for soil water uptake by roots.

The governing soil water equation of SWAP is the Richards equation modified to include a sink term for water uptake by roots:

$$\frac{\partial h}{\partial t}=\frac{1}{C(h)}\frac{\partial}{\partial z}[K(h)(\frac{\partial h}{\partial z}+1)]-\frac{S(h)}{C(h)} \qquad \textbf{(1)}$$

where h = soil water pressure [cm], t = time [day], C = differential moisture capacity [cm^{-1}], z = vertical coordinate with origin at the soil surface, directed positive upwards [cm], K = hydraulic conductivity [cm day^{-1}], and S = water uptake by roots [cm^3 cm^{-3}day^{-1}].

The sink term, $S(h)$, was defined by Feddes, *et al.* (1978) as:

$$S(h)=\alpha(h)S_{\max} \qquad \textbf{(2)}$$

where $\alpha(h)$ = the sink term variable, a function of the soil water pressure, $S_{\max}$ = the maximum root extraction rate [cm^3 cm^{-3}day^{-1}], defined as:

$$S_{\max} = \frac{T^*}{|z_r|} \quad (3)$$

where T^* = potential transpiration rate [cm day^{-1}], and z_r = bottom of the root zone [cm].

The dynamic nature of this model enables numerous variables to be incorporated. The upper boundary condition is determined by daily input values for precipitation and potential evapotranspiration rates. Water use by vegetation requires input of effective rooting depths throughout the year, soil coverage, and leaf area index. The lower boundary condition used in this study is free drainage, i.e. the flux calculated for the conditions of a unit gradient. This flux is the recharge. An IBM SP1 computer was used to run the simulations. Graphical analysis was done on a PC using MS Excel.

Meteorologic Data

The weather data used are from the northern Chihuahuan desert and were recorded at the Jornada research facility on the New Mexico State University College ranch, 32 miles northeast of Las Cruces in Dona Aña County, NM. Compiled by Malm (1994), these weather data span the years 1892-1991 and include daily precipitation values and daily maximum and minimum temperatures.

Potential evapotranspiration (PET) is a critical upper boundary condition in the simulation of water content redistribution in arid soils. Although 100 years of high and low temperatures were recorded along with the rainfall data no attempt was made to utilize the temperature data to generate PET estimates because temperature methods fail to produce reliable PET estimates in arid environments (Stephens *et al.* 1995). Instead, values as calculated with the Penman method at the Leyendecker Weather Station near Las Cruces were used. This weather station, administered by New Mexico State University, Las Cruces, is located forty three miles south of the Jornada research facility. Daily PET values from 1983-1994 were averaged on a julian day basis and used as the daily PET input into the model for the entire 100 year period. This is not an ideal situation. Averaged values for PET overestimate actual PET in the time periods surrounding precipitation events. Averaging can't reflect the cooler temperatures and cloudy conditions which precede and follow an actual thunderstorm and which dampen evapotranspiration rates. Consequently, underestimation of recharge is expected from such a method. A comparison made between daily mean PET values generated in this manner and the unaveraged PET values show a good fit for the 11 year period (Figure 1). Convective thunderstorms which provide the Southwest with over half its rainfall are localized in their occurrences. Although the rainfall data show much variability (Figure 2), the PET data show a clear trend. Use of the averaged data was considered justified on the basis of the strength of the comparison between the actual and the daily mean PET. The present study was pursued with the understanding that any recharge calculated by the model would represent a conservative estimate.

Soils Data

Two sets of soil physical data have been used. The first set consists of homogeneous soil profiles, two meters in depth, representing three different soil parent materials commonly found in New Mexico: loamy fine sand, sandy loam, and clay. Since few New Mexico soils have been hydraulically characterized, soil physical properties (i.e. van Genuchten parameters) (van Genuchten 1980) for this first set of soils were selected from the Staring series (Wösten 1987) (Table 1) which includes soil physical parameters for a wide variety of soils. These soils are referred to in the present study as "loamy fine sand", "sandy loam I", and "clay". A profile of two meters is rather shallow and allows determination of only the potential recharge, but large computer processing times did not permit the use of a deeper profile at this stage of the study. Kemp *et al.* (1997) compiled soil physical parameters for several soils along a transect at the Jornada research facility from soil physical parameters measured by Wierenga *et al.* (1989). Among them is a sandy loam soil with van Genuchten parameter values similar to the previously mentioned loamy fine sand. This sandy loam was chosen to simulate a homogeneous soil six meters deep, and is called "sandy loam II" in this study.

Vegetation Data

Although SWAP was created as an agricultural model, customizing the parameter options designed for crop production enables the simulation of natural vegetation. To simplify the

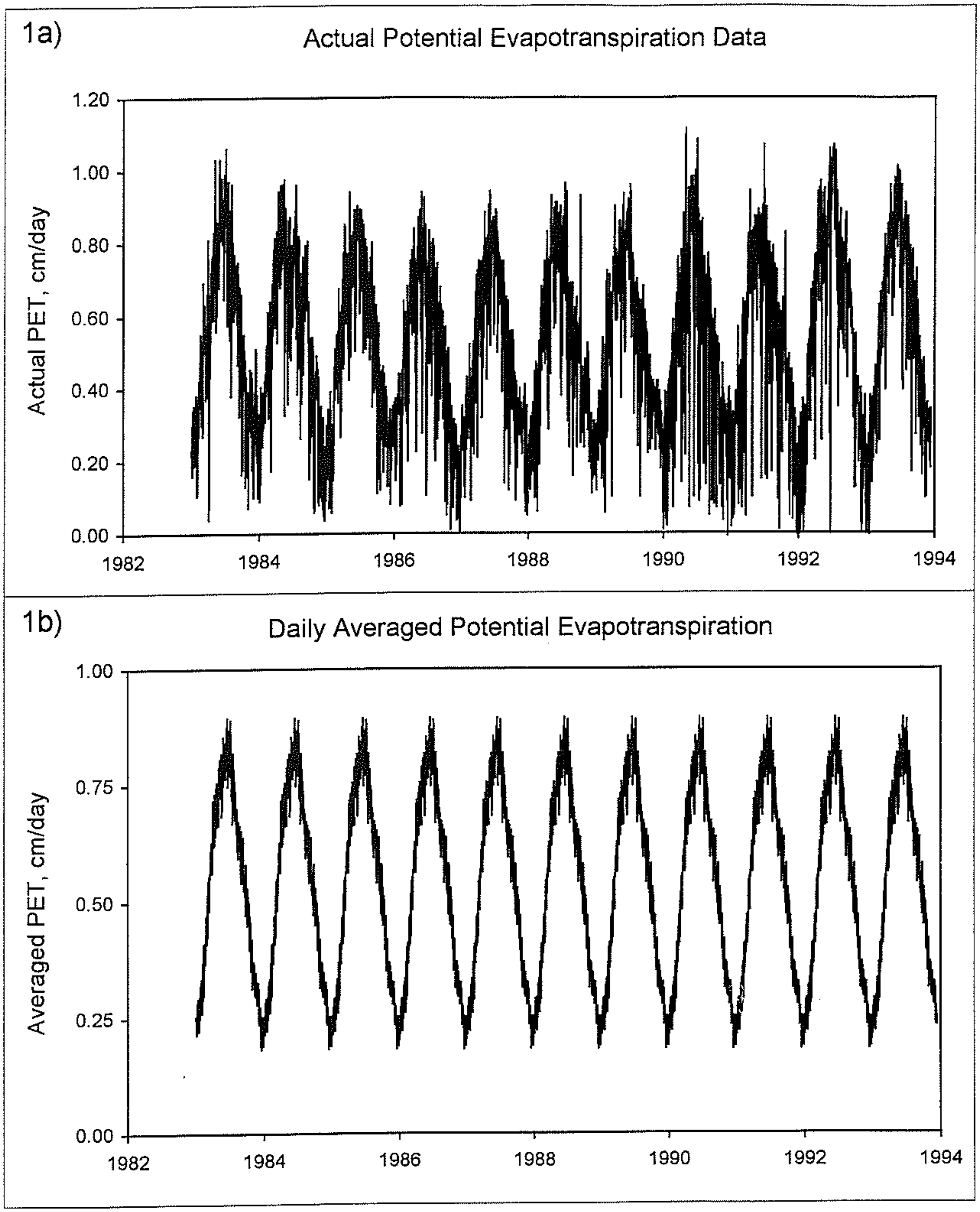


Figure 1. Comparison between 'averaged' and 'actual' daily potential evapotranspiration (PET) rates during the years 1983-1994. The 'actual' values came from actual PET values which were measured hourly at the Leyendecker weather station then averaged on a daily basis. These '24-hour averaged' values were finally averaged on a julian day basis, then used repeatedly as the PET input for the 100-year simulations.

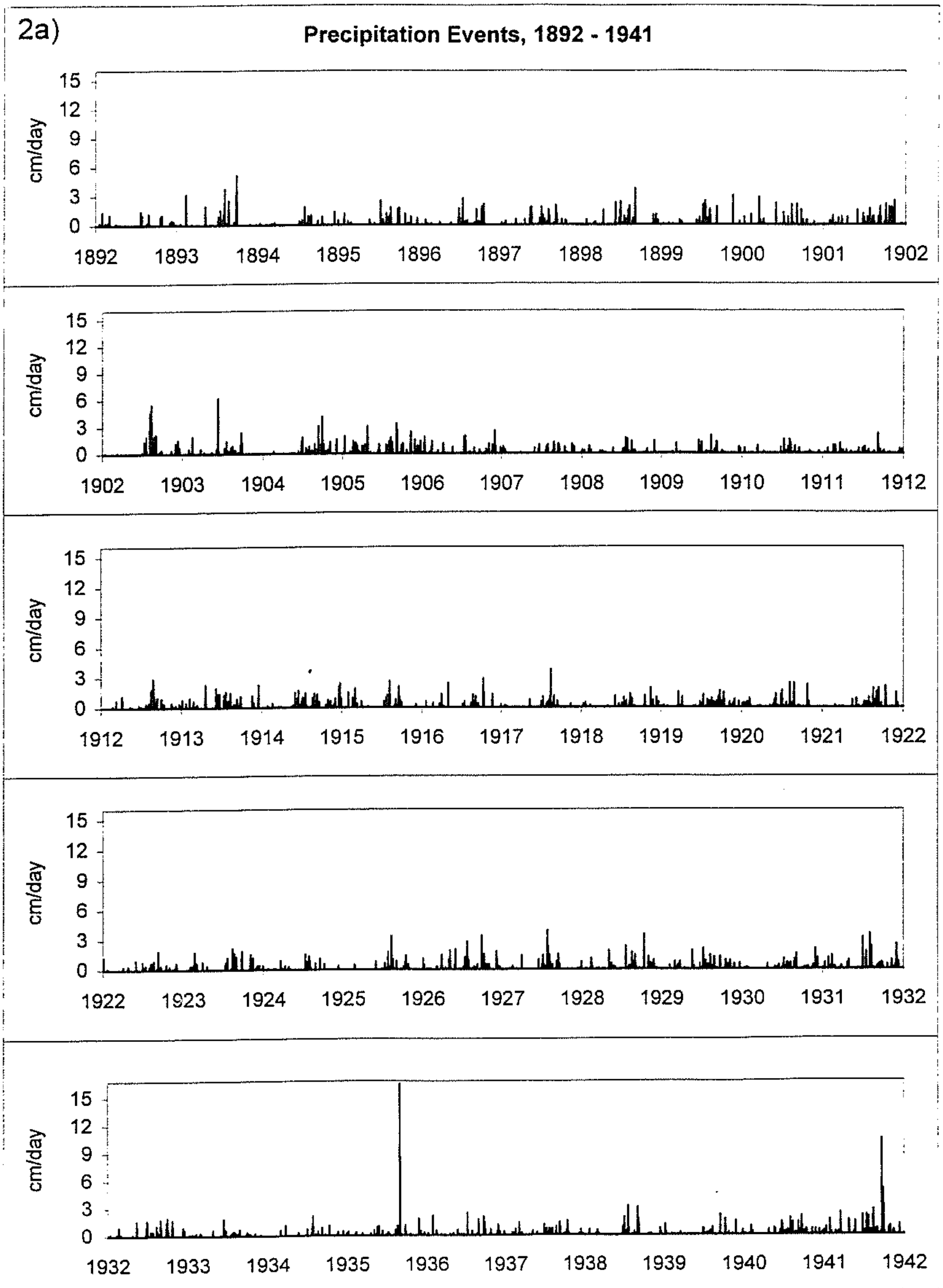


Figure 2a. Precipitation events 1892-1941.

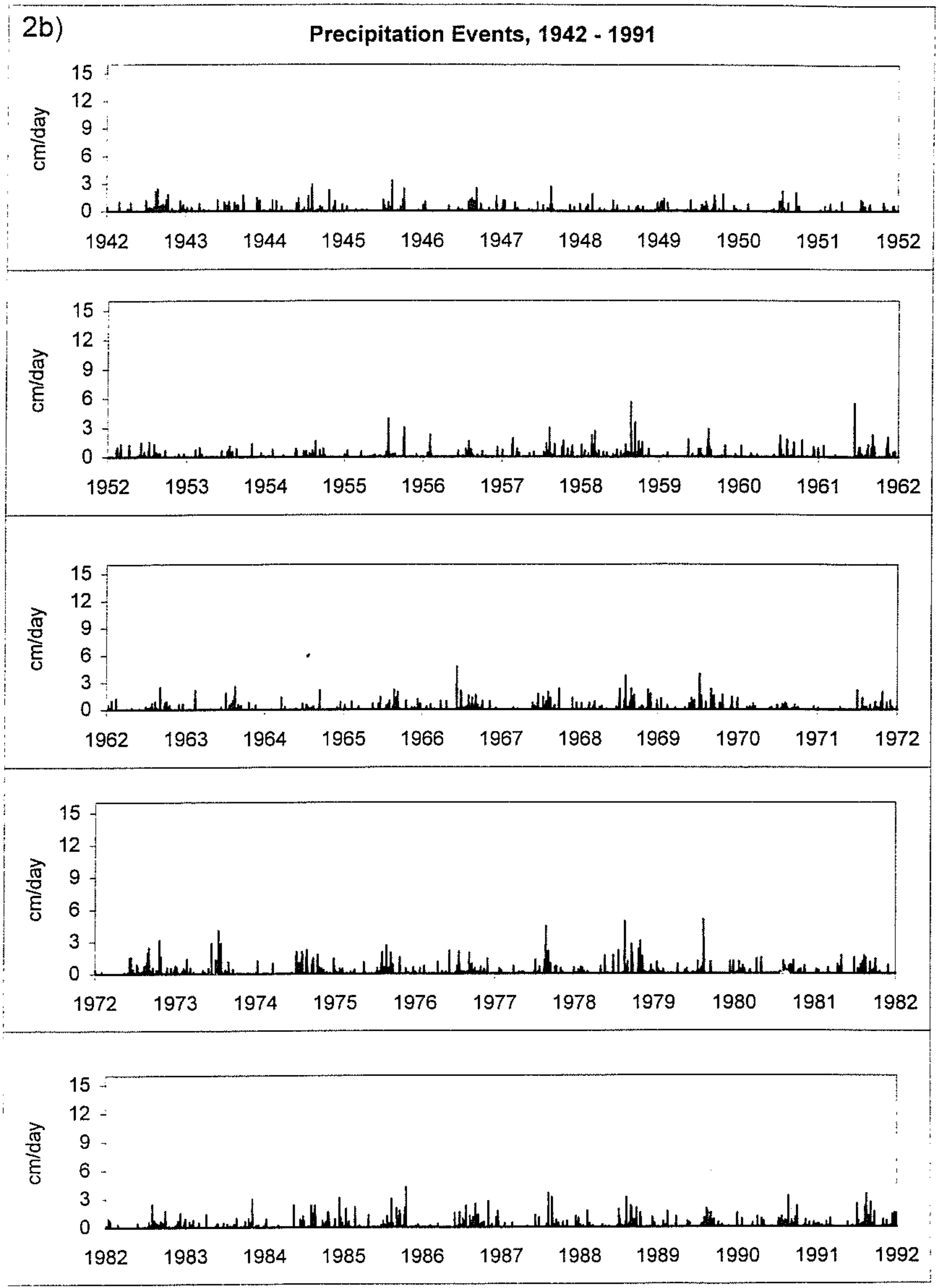


Figure 2b. Precipitation events, 1942-1991.

Table 1. Van Genuchten Parameters Used for the Soil Physical Characteristics of the Four Study Soils

Soil type	θ_r $\left[\frac{m^3}{m^3}\right]$	θ_s $\left[\frac{m^3}{m^3}\right]$	K_s $\left[\frac{cm}{d}\right]$	α_d $\left[cm^{-1}\right]$	L	n
Loamy Fine Sand	0	.38	63.9	.0182	.911	1.870
Sandy Loam I	0	.36	53.1	.0216	-.520	1.54
Clay	0	.42	61.0	.042	-3.706	1.125
Sandy Loam II †	.017	.355	411.0	.00064	.5	2.346

θ_r = Residual soil water content, θ_r = saturated soil water content, K_s = saturated hydraulic conductivity, α_d = fitting parameter reflecting the drying curve, L = fitting parameter, n = fitting parameter.

† = From Kemp et al. (1997). The α-value of this soil is unrealistically low.

modeling of soil-water uptake by natural vegetation, a homogeneous root system was simulated. Generic perennial grass, one of the most common and dominant plant types found in the northern Chihuahuan Desert (Gile *et al.* 1981) provided the prototype for this purpose. Although creosote may be considered the most representative of Chihuahuan Desert vegetation, it has a slow growth rate compared to other desert shrubs (Odening *et al.* 1974). Kemp *et al.* (1997) found the highest transpiration rate on their plot with the highest percent cover. Creosote communities had a lower percent soil coverage (30% peak cover) than areas with a mixed vegetation community (70% peak cover). Perennial grasses had the largest share of total soil cover in that study (Kemp *et al.* 1997). It is assumed here that simulating perennial grass with a high cover provides a conservative influence on the subsequent recharge estimate.

Simulation of plant growth by SWAP requires the input of three vegetation coefficients generated from leaf area index values (LAI) together with the percent of soil covered by vegetation (SC). The coefficients a, b, and c, which are required by the model, are generated by solving the polynomial equation:

$$LAI = a*SC + b*SC^2 + c*SC^3$$

This was accomplished by standard polynomial regression on vegetation data compiled from the transect study by Kemp *et al.* (1997), utilizing data from 1986, the year with their most complete data set. Fractional soil cover data for grass, forbs, annuals, subshrubs, and creosote were read from a graph showing fractional plant coverage throughout the year. Leaf area index coefficients were generated for seven days in the year (julian days 50, 100, 150, 200, 250, 300, and 350) and were derived in the following manner. The fractional cover for each plant type present on that day was multiplied by the leaf area index specific to that particular plant type (Kemp *et al.* 1997). These products (one for each plant type) were then summed, resulting in a leaf area index coefficient specific to each day. This process was repeated until seven daily LAI coefficients had been generated. The total soil coverage for each of those same seven days was found by summing all the fractional values. A standard third order polynomial regression (Excel subroutine) was then performed on the values in this seven by two array, resulting in the three vegetation coefficients, a, b, and c.

Four more vegetation coefficients relate to the growth-limiting values for soil water pressure for the plant in question. The first is the matrix potential value (cm) below which the plant begins to extract moisture from the soil; any wetter and the plant would suffer from water-logging. The second is the matrix potential value (cm) below which the plant begins to optimally extract water from the soil; maximum transpiration and growth begin below this value. The third is the matrix potential value (cm) below which the plant no longer extracts water optimally from the soil; a soil drier than this limits the growth of the plant. The fourth is the matrix potential (cm) below which no further water extraction occurs: the wilting point. The four vegetation coefficients which relate to the limiting soil water potential were estimated according to the phenological data (Kemp 1983) and seasonal weather patterns. Although I estimated vegetation coefficients which I believe to be realistic, I did not do a sensitivity test on them.

The effective rooting depth value of 30 cm for perennial grass was found in Cannon (1911), but dates throughout the year for effective rooting depths were estimated from vegetation phenology data found in Kemp, 1983, together with seasonal weather patterns. The values used in this study for vegetation coefficients, soil coverage, and seasonal rooting patterns are shown in Table 2.

Localized Recharge

Surface runoff increases in low permeability soils and during high intensity rainstorms. Studies by Boers (1996) and Nieber *et al.* (1993) have shown that recharge estimates can significantly increase due to localized recharge where some horizontal flow occurs into local depressions. Ponding can occur when rainfall intensity is greater than the capacity of the soil to absorb water and is further enhanced in topographic low spots by the contributions of overland flow. Topographic variability in New Mexico is commonplace; irregular surface features ensure that overland flow and some ponding will occur in rainfall events of moderate to high intensities, as are common during summer storms. Visual observations during periods of high intensity rainfall confirm the occurrence of ponding in the Jornada (John Anderson, *per com.* 1997).

To determine if increased recharge occurs as a result of localized recharge under ponded surface water conditions on the sandy loam I and clay soils, higher levels of precipitation were introduced to mimic the influence of overland flow in creating ponded conditions. Overland

Table 2. Vegetation Parameters Used in the Study

Vegetation coefficients a, b, and c from polynomial regression:

a = 0.3668
b = -0.1718
c = 0.0254

$r^2 = 0.8867$

Soil coverage throughout the year for the vegetation:

Julian day	Fractional coverage
1	0
50	0.02
100	0.11
150	0.21
200	0.3
250	0.49
300	0.26
350	0.04

Rooting patterns thoughout the growing season:

Julian day	Rooting depth, cm
1	0
140	10
200	30
270	30
300	10
301	0
365	0

Growth-limiting values for matrix potential (cm):

-80	No water extraction
-100	Water logging
-600	Optimal transpiration
-900	Reduced transpiration
-15000	Wilting point

flow includes the scenario in which lower precipitation rates fill shallow depressions while higher precipitation rates may cause shallow depressions to overflow into deeper depressions. If the actual precipitation for a day was between 1.0 cm and 6.0 cm, its value was doubled in this introduced precipitation scheme. On the three days (June 11, 1905, August 30, 1935, and September 21, 1941) when precipitation was greater than 6.0 cm, the value was tripled. These increases were necessary in order for the rainfall intensity to exceed the infiltration capacity of the soil, thus making it possible for the model to simulate ponded conditions. The maximum depth of ponding was limited to 10 cm. No change was made for days whose original precipitation values were below 1.0 cm to ensure that the enlarged rainfall events would be separated by relatively dry periods.

The simulation of precipitation recharge through desert vadose zones may be complicated by occurrence of vapor flow in dry soils. Hendrickx and Walker (1997), however, reviewed work by Campbell (1995), Fayer and Gee (1992), Feddes and Bastiaanssen (1992), Hanks and Ashcroft (1986), Milly (1984a,b; 1996), Scanlon and Milly (1994), and Scanlon (1994) and concluded that for years with substantial recharge under conditions of deep groundwater tables the effects of vapor flow likely will be smaller than other inherent uncertainties in the values of unsaturated hydraulic conductivities, root distributions, and weather data. Since the objective of this study is the detection of major recharge events, if any, during a one-hundred year period in southern New Mexico, neglecting vapor fluxes is warranted. In this study, comparisons will be made between the recharge fluxes simulated here with those measured in lysimeters and field studies as an additional validation of the model results.

RESULTS

Precipitation

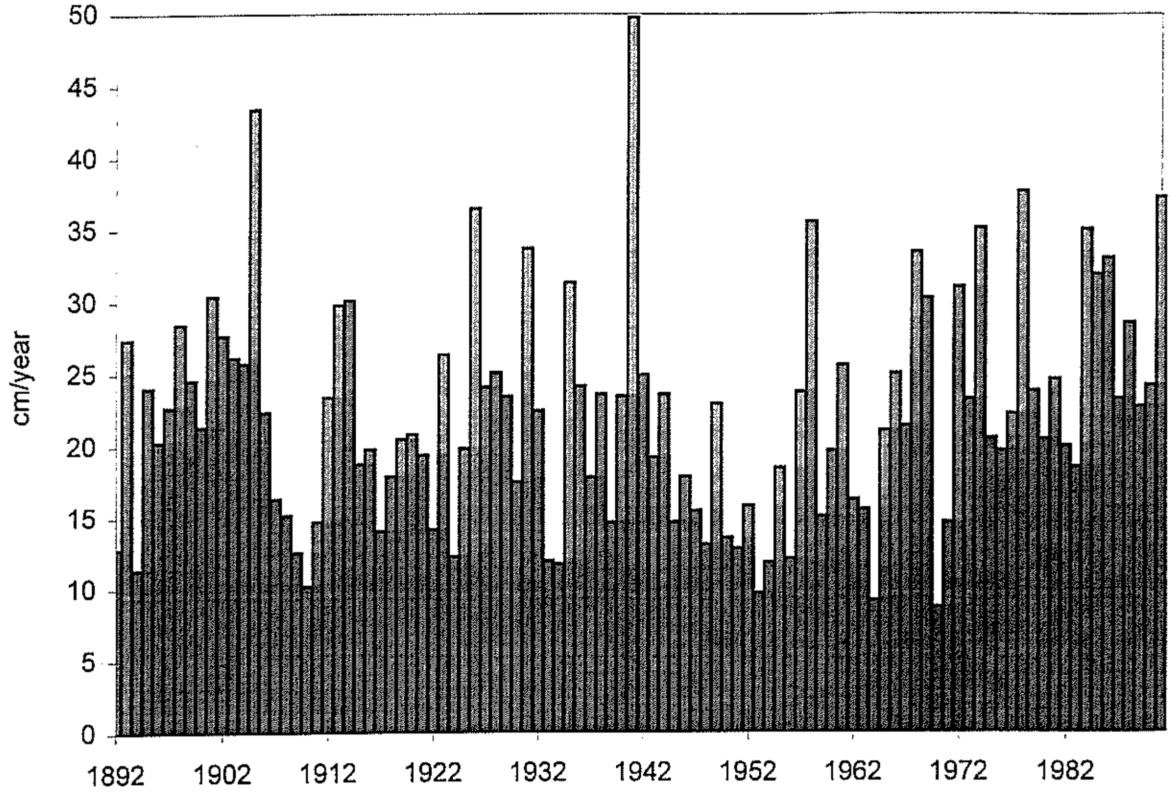
The precipitation data in Figure 2 show the temporal variability of rainfall in the Las Cruces area. The mean annual rainfall during the 100 years is 20.3 cm per year, with a range from 8.7 to 49.8 cm per year. Most striking are the two largest rainfall events of this century;

16.5 cm which fell on August 30, 1935, and 10.4 cm which fell on September 21, 1941. The tick marks on the x-axes of Figure 2 are located at the beginning of each year, enabling one to visually estimate in what time of year clusters of precipitation events occur. Winters with large precipitation clusters are easily determined, e.g. 1905 and 1958. The months from October through June produce, on average, 48% of the annual precipitation in the Chihuahuan desert (National Weather Service data), but rainfall variability can be quite large, both within and between years (Figure 3a). A Kolgomorov-Schmirnof test performed on the yearly precipitation values confirmed a log-normal distribution to that data set (K-S statistic = 7.4E-2; probability = 6.4) (Press, *et al.*, 1992) (Figure 3b).

Averaging Daily Potential Evapotranspiration

In order to test the validity of the assumption that using averaged PET data would cause an underestimation of recharge rates, the actual PET data from the Leyendecker weather station were further analyzed. Figure 4 presents the comparison of calculated recharge rates in loamy fine sand using averaged and actual PET values. To bring the soil profile into a realistic initial condition, soil water transport was simulated first using the Jornada rainfall with the julian averaged Las Cruces PET during the years 1973 through 1982. From 1983 through 1996 the Las Cruces precipitation and PET data were utilized, with the actual daily PET data in one simulation and the julian-averaged PET data in the other. It is clear from Figure 4 that the julian averaged PET rates caused an underprediction of recharge compared to the actual daily PET data, by a factor of 1.7 during periods of low recharge, and by as much as a factor of 3.4 during periods of high recharge. Stothoff (1997), studying infiltration in the desert near Yucca Mountain, Nevada, found that time-averaging of the meteorological data over a 24 hour period as opposed to using unaveraged hourly data caused an underprediction of infiltration by as much as a factor of 3. It is assumed here that time averaging on a julian day basis also will result in a conservative influence on recharge estimates. Three meteorological averaging processes, by necessity, were used in this study in order for the input data units to match. The historic weather data was compiled on a daily basis, rather than hourly, setting the unit standard for the study. The PET data, though collected hourly, was averaged on a daily basis, then again on a julian-day basis. Using three

3a) **Yearly Precipitation, 1892 - 1991**



3b) **Frequency of Yearly Precipitation Amounts**

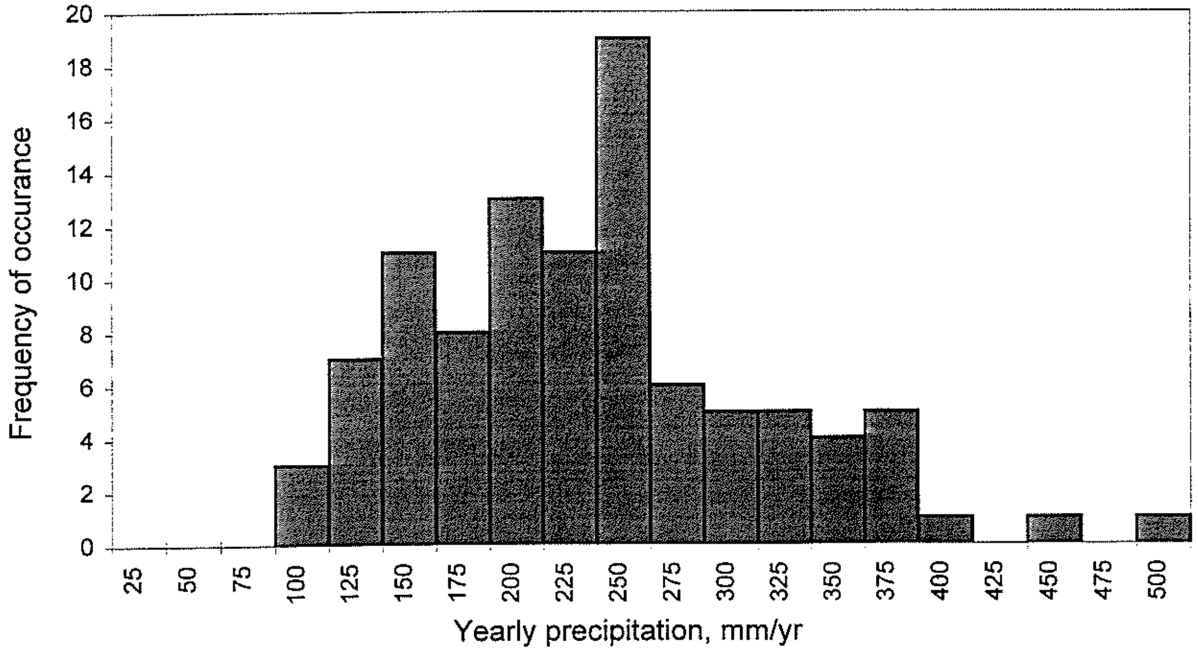


Figure 3. 100 years of yearly precipitation values and frequency diagram.

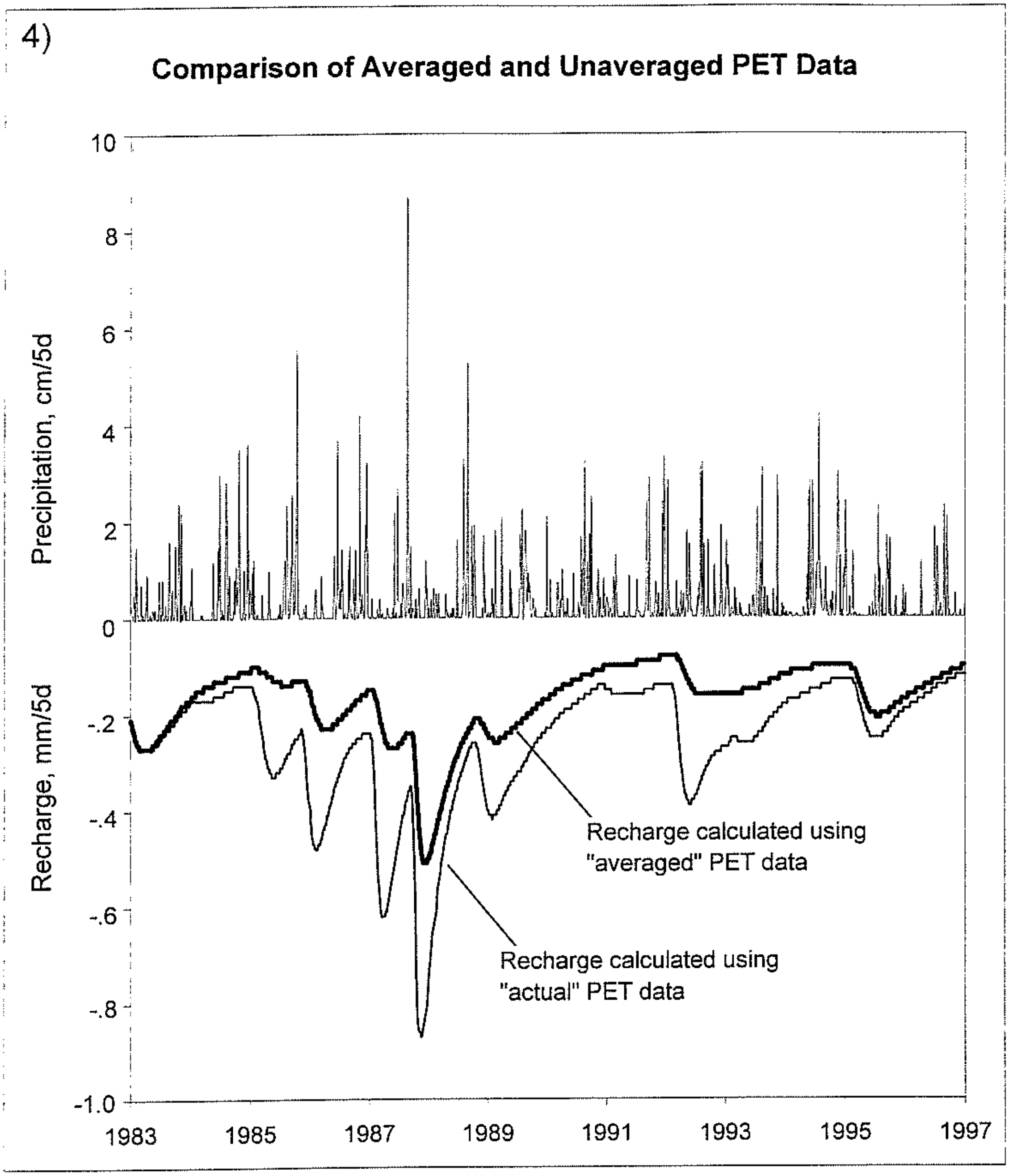


Figure 4. Comparison of calculated recharge in loamy fine sand using averaged and actual daily PET values. "Actual values were measured hourly then averaged on a 24-hour basis. "Averaged" values were created by averaging on a Julian-day basis the "actual" values from the available years, 1983-1995. Negative values indicate downward flux.

meteorological averaging processes, it is concluded, again ensures conservative recharge estimates.

Recharge estimates

Simulations with the three Staring series soils in their unvegetated state were run initially. The vegetated conditions were run next, followed by the six meter profile, barren and vegetated, using soil parameters from Kemp *et al.* (1997). Each soil type required an equilibration period of from three to six years for the effects of excess initial water in the soil profile to no longer be seen in the recharge values. Consequently, a maximum of 94 years could be fully evaluated.

This study showed soil texture to be the most important factor in the prediction of potential recharge. The loamy fine sand showed substantially more deep infiltration than either the sandy loam I, sandy loam II, or clay. This was expected because recharge can take place only under moist conditions, and coarse textured soils have a higher hydraulic conductivity under moist conditions than do fine textured soils. Likewise, less recharge is expected from clay than loam soils because clay has a finer texture than loam, and a subsequent lower hydraulic conductivity under moist conditions.

Throughout the 100 years, five major and several minor periods of recharge can be seen in the output from the loamy fine sand simulation (Figure 5). Unexpectedly, a small amount of precipitation recharge was calculated for the barren loamy fine sand even during severe droughts. Inclusion of grass in the simulation has a scaling-back effect on the recharge estimate: gone are all the minor periods of recharge and just the five major periods remain. Plotted recharge estimates for barren sandy loam I (Figure 6) are similar to those for vegetated loamy fine sand; the same five major periods are evident in the recharge estimate and no minor periods are represented. The inclusion of grass in the sandy loam I simulation scaled back the recharge estimate even further to just the largest two recharge periods seen in the previous scenarios. The clay simulation yielded almost no measurable recharge, but following the 1941 rainfall events a small flux was detected through the bottom of the clay profile for a short period. This is seen in the 1942 and 1943 outputs. Because so little recharge was calculated with barren clay, no clay-with-grass simulation was made. Simulations using the six meter deep sandy loam II gave results

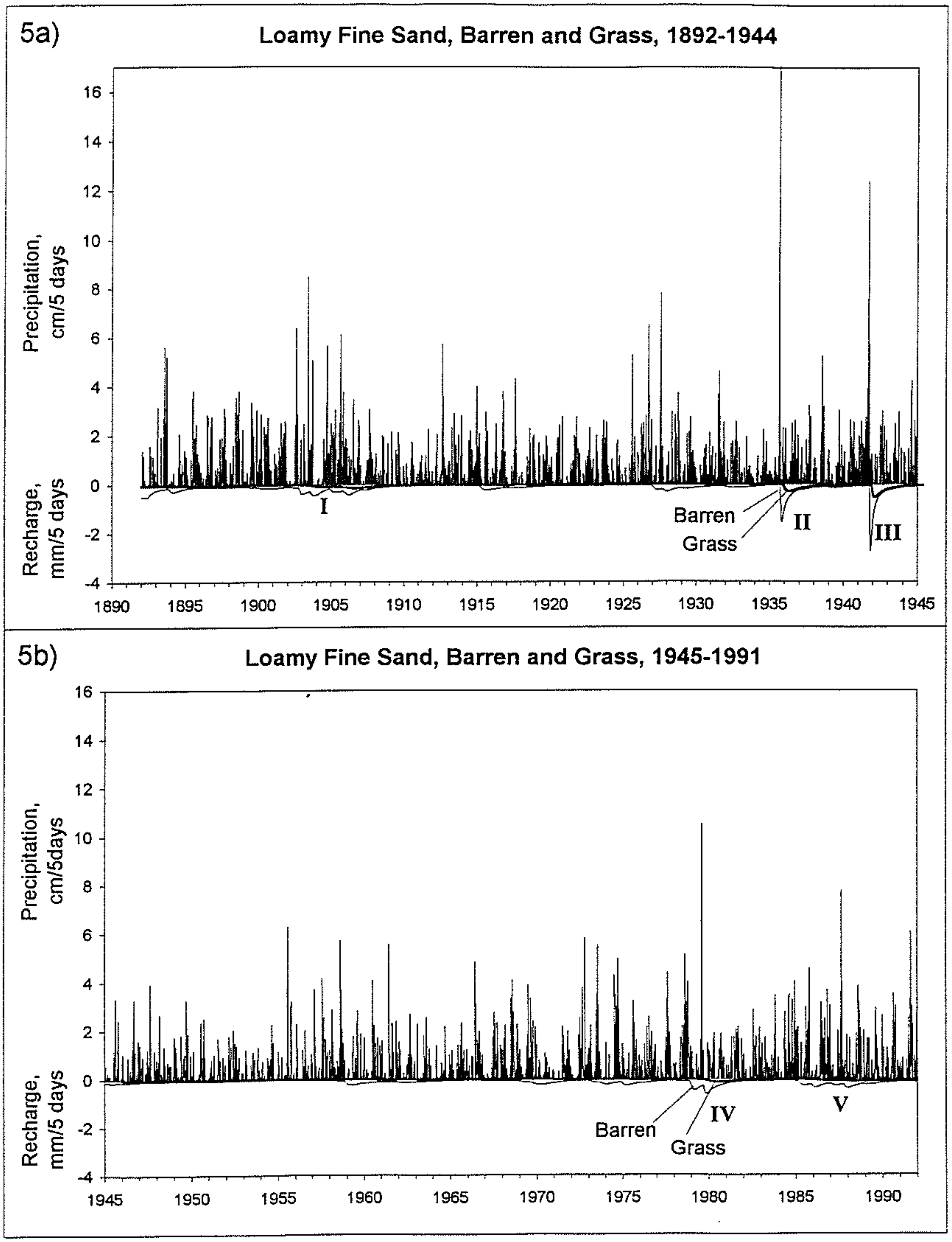


Figure 5. Recharge in barren and grassy loamy fine sand showing precipitaton events. Negative values indicate downward flux.

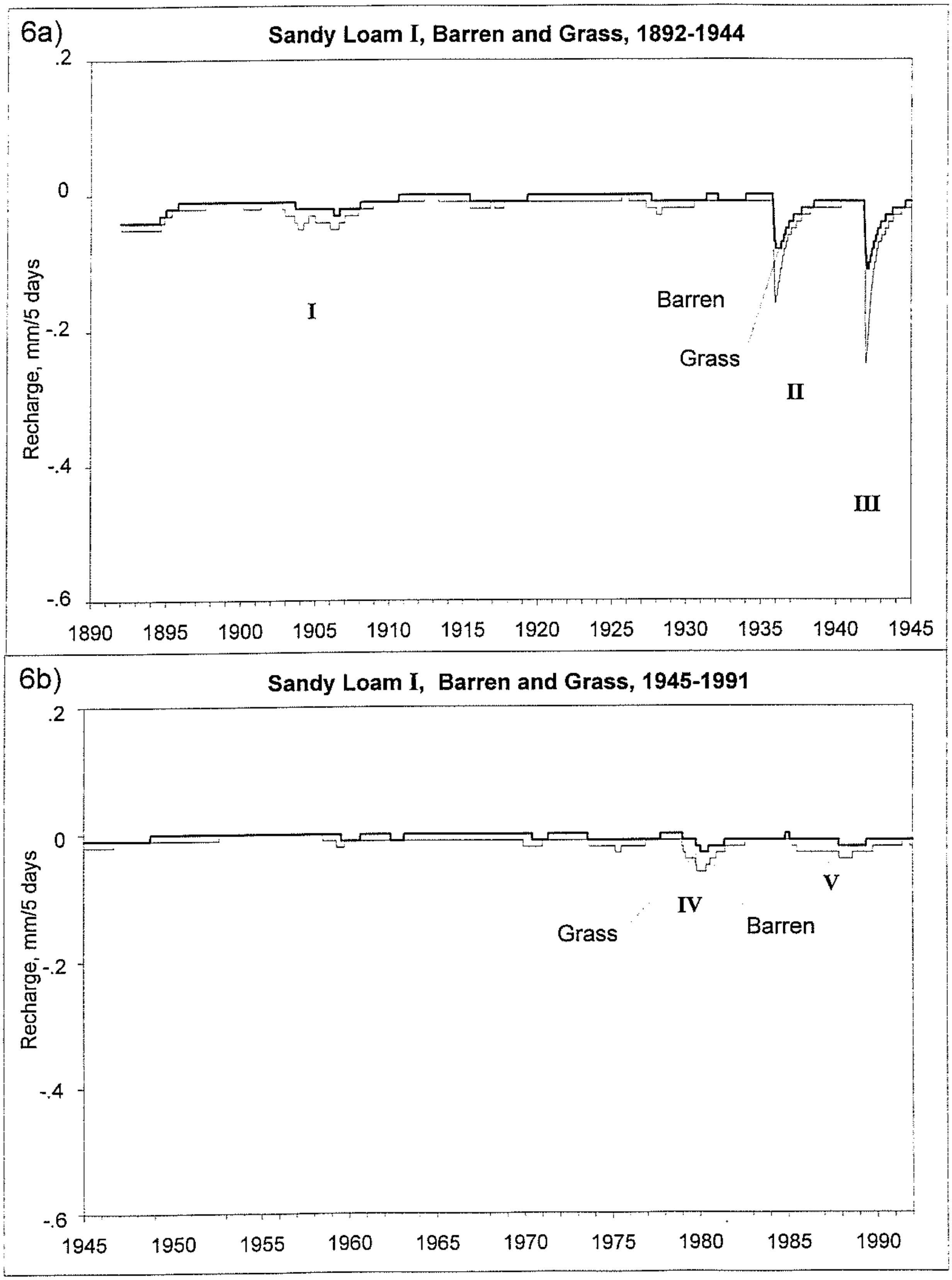


Figure 6. Recharge in barren and grassy sandy loam I. Negative values indicate downward flux.

similar to that of the grassy two meter deep Staring sandy loam I: the five major periods of diffuse recharge are seen, but the minor periods are not represented. Results from the simulations of sand and loam soils are plotted together in Figure 7a. Recharge estimates for the four sandy loam simulations (sandy loams I and II, barren and vegetated) plot so closely together that, for clarity, a separate enlarged graph was made for them (Figure 7b).

Recharge occurs during periods of increased soil water content. A sudden increase in water content of the profile (e.g. following a large rainfall event) is followed (after lengths of time varying according to soil/vegetation condition) by an increase in calculated flux through the bottom of the soil profile. Each of the five major recharge periods described in this study closely follows a soil water content increase. Each recharge period begins on the date the calculated flux starts to increase from a stable value. The periods end on the last date before the calculated flux returns to that same (prior stable) value. The base level recharge rate of this "stable value" varied for different soil textures. For the loamy fine sand the "stable value" also varied from one recharge period to another.

An inspection of Figure 7a reveals the barren loamy fine sand to show the earliest recharge response to heavy precipitation. Grass on loamy fine sand responds next, followed closely by the finer textured soils. Depending on the soil and condition simulated, a prolonged "tail" of recharge is sometimes calculated which increases the duration but lowers the overall calculated recharge rate for that period. Thus, each soil/vegetation condition has a different duration, flux rate, and cumulative total for a given recharge period. The mean duration is 4.0 years, with a range from 1.17 to 6.97 years. The loamy fine sand not only displays the largest cumulative total recharge, but also shows the longest duration and the highest flux rate. Table 3 shows the starting dates, duration, cumulative recharge (one-dimensional depth, cm), and flux rates (mm/month) for the five recharge periods.

Recharge estimates from the grassy sandy loam II simulation are very close to the estimates from the barren sandy loam II simulation (Figure 8). Throughout the evaluated period the total soil water content of the six meter profile, barren condition, was generally 1- 2 mm greater than for the six meter profile, vegetated condition (the difference ranged from 0 to 3 mm higher). For example, on September 17, 1946 the total amount of water in the barren sandy loam II profile

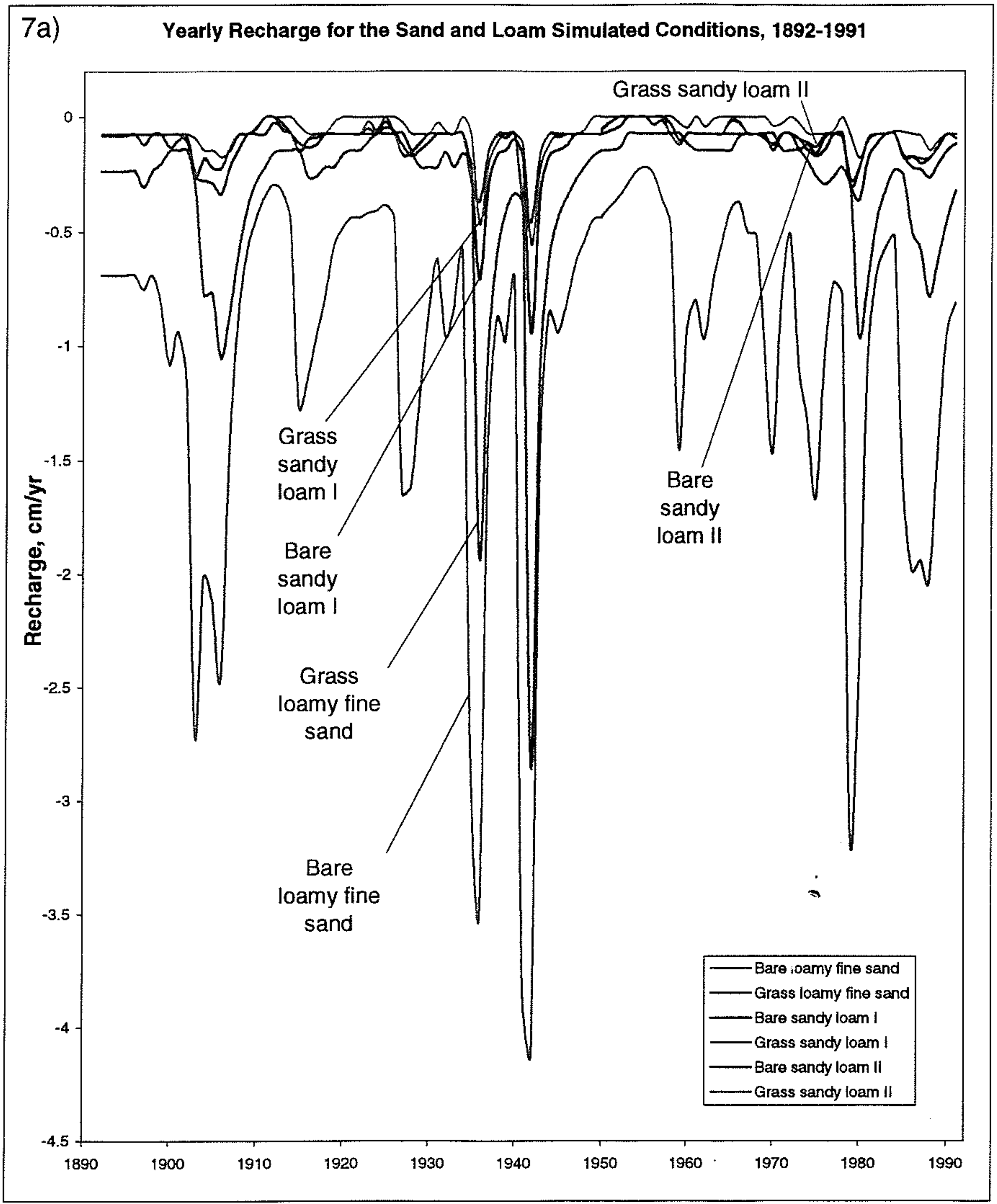
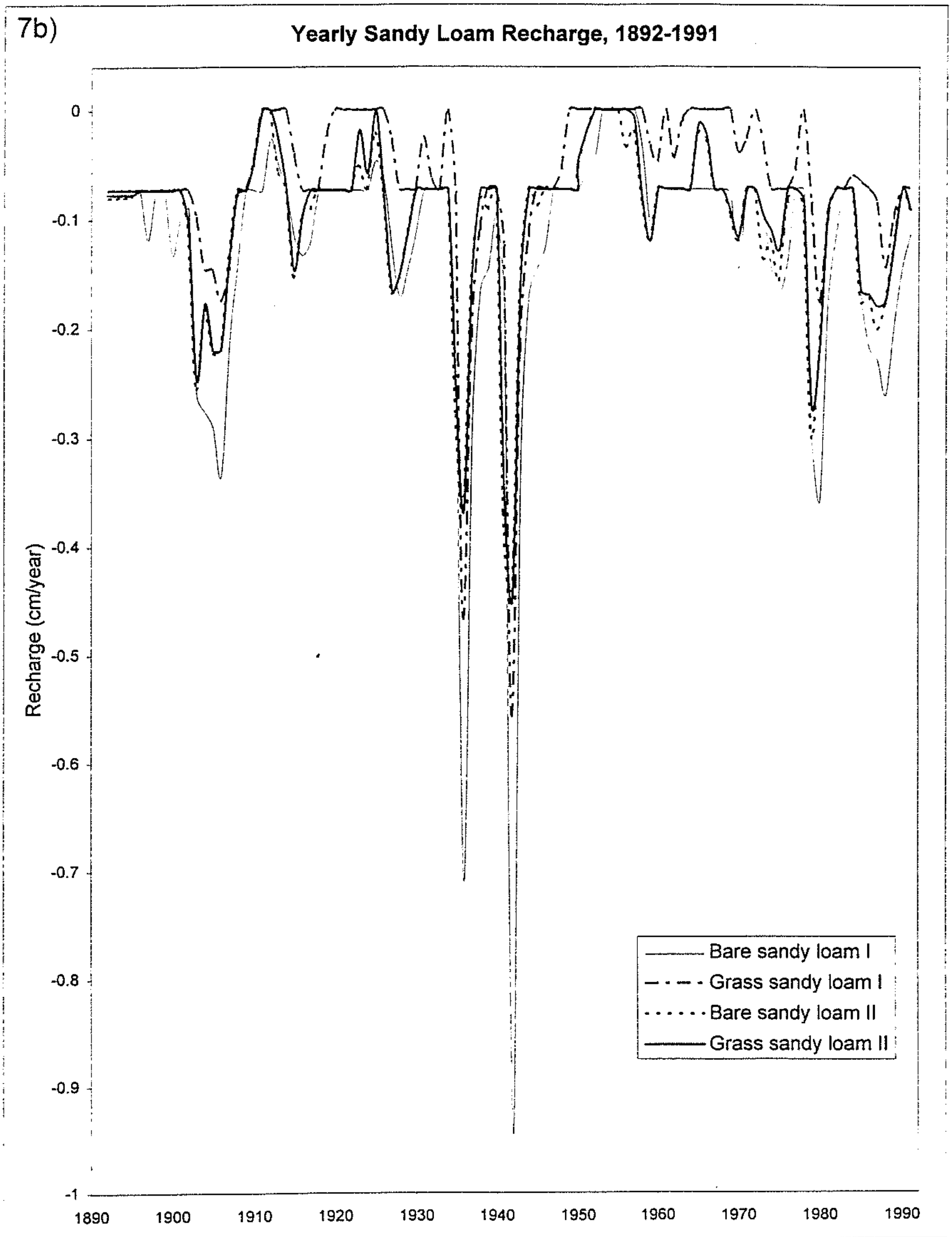
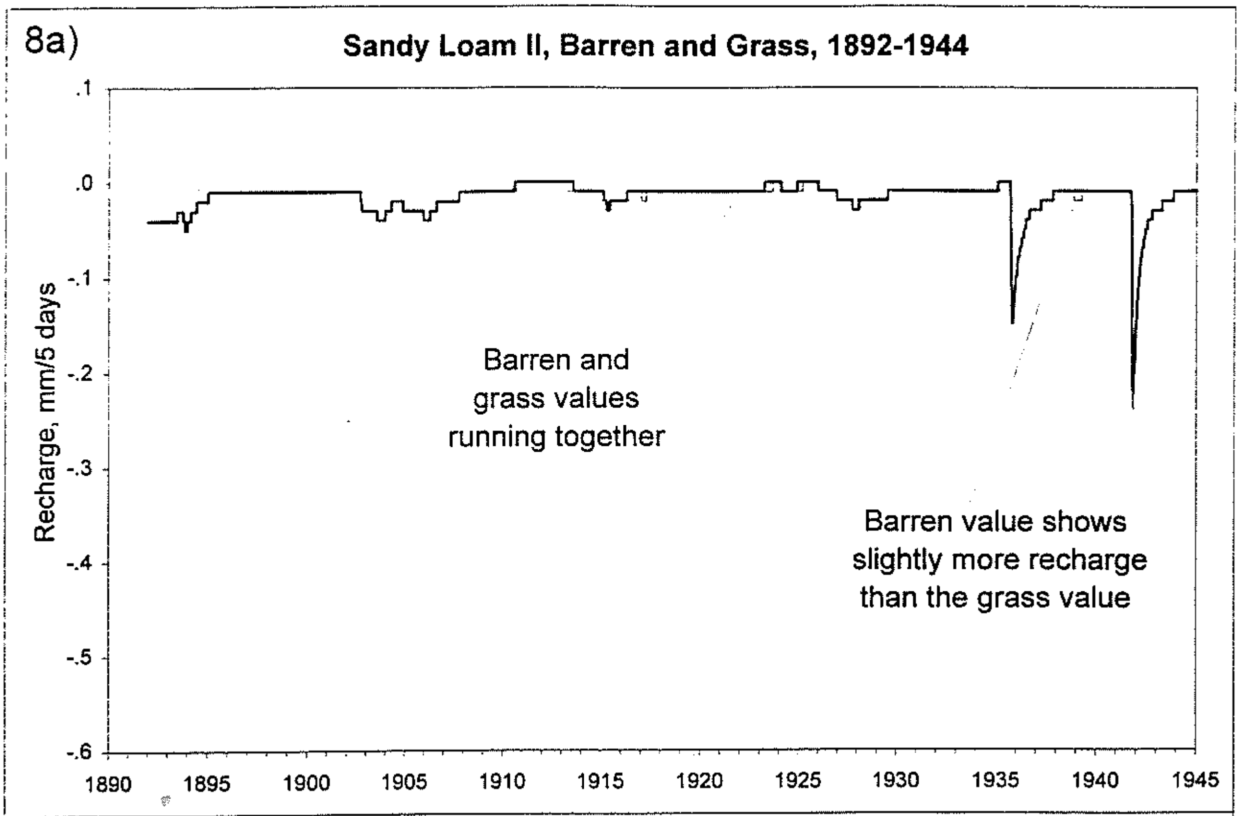


Figure 7a. Yearly recharge values for the loamy fine sand and sandy loams I and II.


7b)

Yearly Sandy Loam Recharge, 1892-1991

Figure 7b. Enlargement of the yearly recharge levels for sandy loam.



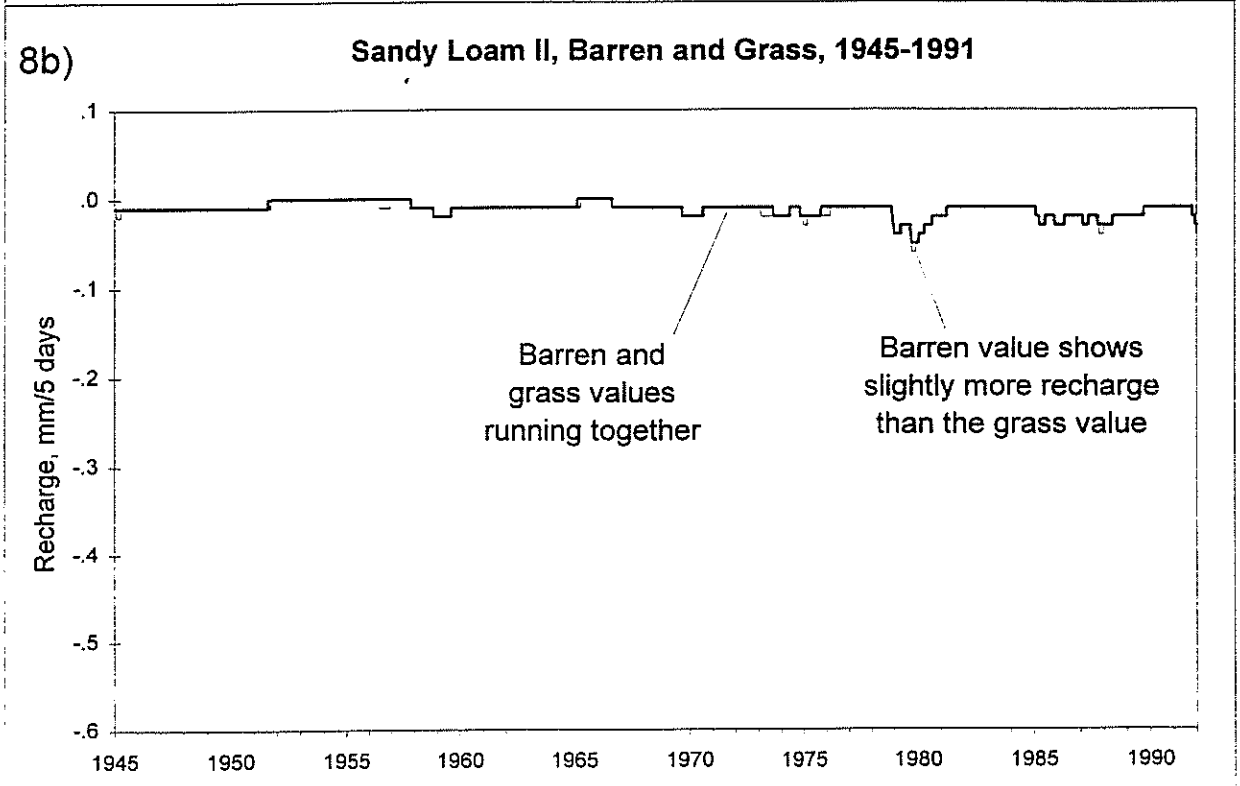


Figure 8. Recharge in 6m deep sandy loam II, barren and grass. Negative values indicate downward flux.

Table 3. Duration, Cumulative Recharge, and Rates for Five Periods

		Loamy fine sand (2m)		Sandy loam I (2m)		Sandy loam II (6m)		Clay (2m)
		Barren	Grass	Barren	Grass	Barren	Grass	Barren
I	Beginning date	9/27/02	8/28/03	10/22/02	9/7/03	10/17/02	10/22/02	–
	Duration (years)	5.64	6.36	6.12	4.34	3.89	3.85	0
	Cumulative recharge, cm	11.99	4.63	1.54	.67	.884	.86	0
	Recharge rate, mm/mo	1.77	.61	.21	.13	.19	.19	0
II	Beginning date	9/22/35	12/1/35	10/02/35	10/27/35	9/17/35	9/17/35	–
	Duration (years)	4.47	3.73	4.58	2.70	1.53	1.51	0
	Cumulative recharge, cm	9.49	4.24	1.55	.83	.69	.67	0
	Recharge rate, mm/mo	1.77	.95	.28	.26	.37	.37	0
III	Beginning date	10/7/41	11/26/41	11/21/41	11/16/41	10/02/41	10/07/41	6/09/42
	Duration (years)	4.69	4.90	4.82	2.73	3.54	2.08	1.17
	Cumulative recharge, cm	11.14	5.49	1.82	.93	1.06	.90	.09
	Recharge rate, mm/mo	1.98	.93	.31	.28	.25	.20	.01
IV	Beginning date	11/11/78	8/23/79	1/1/79	10/22/79	11/21/78	12/01/78	–
	Duration (years)	3.17	3.67	3.58	1.59	2.41	2.33	0
	Cumulative recharge, cm	6.87	2.40	.92	.27	.59	.55	0
	Recharge rate, mm/mo	1.8	.55	.22	.14	.20	.20	0
V	Beginning date	1/10/85	11/16/85	3/16/85	11/06/87	2/04/85	2/04/85	–
	Duration (years)	6.97	5.51	6.21	1.54	4.67	4.62	0
	Cumulative recharge, cm	10.76	3.13	1.27	.23	.84	.79	0
	Recharge rate, mm/mo	1.29	.47	.17	.12	.15	.14	0

was 17.3 cm while that of the grassy sandy loam II profile was 17.2 cm. This small difference appears to be insufficient to make a difference in calculated recharge. The closeness of these recharge estimates is at least partly due to a general decrease in difference between estimates derived from vegetated versus barren conditions as soil texture becomes finer. Rockhold *et al.* (1995) saw the same pattern in the recharge estimates from that study. It's possible that the unrealistic α-value of this soil may contribute to the closeness of the estimates as well. Whether some other undetermined hypothesis might account for the similarity was not pursued.

Conditions Surrounding the Five Periods of Recharge Seen in Barren Loamy Fine Sand

Period I: September 27, 1902 through May 20, 1908

The years from 1901 through 1906 all had above normal rainfall. During the third quarter of 1902 alone, 23.4 cm of rain fell at the recording site. The soil profile water content increased from 13.6 to 20.6 cm in 10 days. This initiated a significant flux of recharge in the barren loamy fine sand. Soil water content remained high enough to permit recharge during the summer rainy season of 1903. The moderate El Niño year, 1905, saw 43.4 cm of rain. During the 5.64 years from September 27, 1902 through May 20, 1908 a depth of 12.0 cm of recharge was simulated at the bottom of the unvegetated loamy fine sand profile, an average of 1.77 mm per month. This was the highest of all cumulative flux values found in this study.

The precipitation level fell to well below normal in 1907 and 1908. By May 20, 1908 the moisture content of the two meter deep soil profile had decreased from a high of 20.6 cm to 13.2 cm (mean = 16.1 cm) and simulated flux through the bottom of the profile ceased.

Period II: September 22, 1935 through March 11, 1940

Prior to the beginning of this period the calculated soil profile water content was only 11.1 cm. After the large 1935 rainfall event the water content of the soil profile jumped to 25.5 cm overnight, initiating a large flux of recharge in the barren loamy fine sand. The next five years saw yearly rainfall alternating between slightly above and slightly below average levels. By 1940 the water content of the soil profile had decreased from a high of 25.5 to 12.7 cm (mean = 15.1 cm). Though above average precipitation fell in 1940, this no longer sustained the calculated flux through the bottom of the profile, thus ending the recharge period. During the four and one half years following the large rainfall event 9.5 cm of recharge was calculated by SWAP for the unvegetated loamy fine sand, averaging 1.77 mm per month.

Period III: October 7, 1941 through June 14, 1946

The years 1940-1941 were influenced by a very strong El Niño condition. The Jornada received a fairly wet winter, so the soil profile was relatively moist, 14.5 cm, when a series of storms began in late September. The 10.4 cm which fell on September 21st came in the middle of three rainy days, followed six days later by four days during which another 5.9 cm of rain fell. This caused the water content of the soil to jump to 26.7 cm over ten days. Average or near average precipitation fell during the next 3 years. This situation produced 11.14 cm of calculated recharge in the barren loamy fine sand during the ensuing 56 months, the highest rate of recharge in the century, an average of 1.98 mm per month. During this time the water content of the soil profile gradually decreased from a high of 26.7 cm to 12.8 cm, with a mean of 15.1 cm. Far below average rainfall was recorded in 1945 and below average in 1946, ending the period.

Period IV: November 11, 1978 through January 15, 1982

A gradual soil water content increase initiated this recharge period. Calculated recharge began when the two meter deep soil profile contained a relatively low 18.5 cm of water. From late June 1978 through mid-February 1979, 34.7 cm of precipitation fell, increasing the soil water content to a high of 22.5 cm. Average, to above average rain fell during 1979, 1980, and 1981, sustaining the soil water content at a level which allowed flux through the bottom of the profile. This situation produced a 6.87 cm flux of simulated recharge over a period of 38 months in the unvegetated loamy fine sand, 1.8 mm per month. The below average amount of rain which fell in 1982 caused the water content of the soil profile to fall to 13.1 cm at which time the recharge period ended. The mean soil water content during this period was 15.6 cm.

Period V: January 10, 1985 through December 31, 1991

The large recharge period which occurred in the late 1980s began with yearly rainfall well above normal in 1984, 1985, and 1986, but had no large, single precipitation event. The water content of the soil increased to 18.5 cm by mid-December 1984, which provided sufficient moisture for simulated recharge to begin. Normal, or somewhat above normal rainfall amounts fell during the next three years. By the end of the evaluated 100 years the model was still simulating flux from this situation. A total depth of 10.76 cm of recharge was calculated in just under seven years in the unvegetated loamy fine sand, a mean rate of 1.29 mm per month. During this time the water content of the soil profile increased to a high of 20.7 cm then gradually decreased to 12.7 cm, with a mean of 15.4 cm.

The yearly cumulative values for recharge for the seven soil conditions are displayed in Table 4.

Localized Recharge

Output from the simulations using increased precipitation levels showed resultant ponding on both the sandy loam I and clay soils. Ponded sandy loam I showed recharge to occur during all the major and minor periods seen in the barren loamy fine sand simulation (Figure 9) illustrating that deep infiltration through heavier soils can occur under ponded conditions. Ponded clay also showed recharge to be calculated (Figure 10) in all the major and minor periods seen in the barren loamy fine sand simulation, though not as much as was seen in the sandy loam I. Thus, it is shown that ponding as a result of overland flow can produce repeated episodes of calculated recharge in lower permeable soils.

In a recent study Baumhardt and Lascano (1993) showed that water can drain quickly in calcic soils under ponded conditions. They looked at hydraulic properties following artificial ponding and infiltration on the Btk2 calcic horizon of an Acuff soil in the Southern High Plains. Where periodic moisture is available in sufficient quantities, they postulate, rapid calcium dissolution can occur in soils with well developed calcic horizons leaving behind localized areas of soil with the texture of clay to sandy loam. Results from the present study predict potential recharge in both these soil textures. Ponded situations, whether from a playa lake, excess irrigation, or ponded runoff could provide the necessary conditions for the localized dissolution of the calcic horizon. Repeated episodes of this sort might lead to the formation of micropipes

Table 4. Yearly recharge totals (cm) for the simulated conditions.

Year	Loamy fine sand	Loamy fine sand	Sandy loam I	Sandy loam I	2m clay	Sandy loam II	Sandy loam II
	Bare	Grass	Bare	Grass		Bare	Grass
1892	0.69	0.24	0.07	0.07	0.00	0.08	0.08
1893	0.69	0.24	0.07	0.07	0.00	0.08	0.08
1894	0.69	0.24	0.07	0.07	0.00	0.08	0.08
1895	0.69	0.24	0.07	0.07	0.00	0.08	0.08
1896	0.69	0.24	0.07	0.07	0.00	0.07	0.07
1897	0.75	0.31	0.12	0.07	0.00	0.07	0.07
1898	0.69	0.24	0.07	0.07	0.00	0.07	0.07
1899	0.81	0.20	0.07	0.07	0.00	0.07	0.07
1900	1.08	0.15	0.13	0.07	0.00	0.07	0.07
1901	0.93	0.15	0.10	0.07	0.00	0.07	0.07
1902	1.16	0.15	0.09	0.07	0.00	0.11	0.11
1903	2.71	0.33	0.26	0.10	0.00	0.26	0.25
1904	2.01	0.78	0.28	0.15	0.00	0.18	0.18
1905	2.11	0.77	0.29	0.15	0.00	0.22	0.22
1906	2.46	1.05	0.34	0.18	0.00	0.22	0.22
1907	1.46	0.86	0.21	0.15	0.00	0.13	0.13
1908	0.88	0.60	0.14	0.08	0.00	0.07	0.07
1909	0.58	0.40	0.07	0.07	0.00	0.07	0.07
1910	0.44	0.28	0.07	0.05	0.00	0.05	0.05
1911	0.34	0.22	0.07	0.00	0.00	0.00	0.00
1912	0.29	0.16	0.03	0.00	0.00	0.00	0.00
1913	0.33	0.15	0.05	0.00	0.00	0.06	0.03
1914	0.46	0.15	0.07	0.00	0.00	0.07	0.07
1915	1.27	0.15	0.12	0.04	0.00	0.15	0.15
1916	1.15	0.26	0.13	0.07	0.00	0.10	0.10
1917	0.96	0.26	0.12	0.07	0.00	0.09	0.07
1918	0.79	0.22	0.07	0.07	0.00	0.07	0.07
1919	0.56	0.22	0.07	0.02	0.00	0.07	0.07
1920	0.49	0.17	0.07	0.00	0.00	0.07	0.07
1921	0.44	0.15	0.07	0.00	0.00	0.07	0.07
1922	0.44	0.15	0.07	0.00	0.00	0.07	0.07
1923	0.42	0.11	0.07	0.00	0.00	0.05	0.02
1924	0.41	0.07	0.07	0.00	0.00	0.07	0.06
1925	0.38	0.07	0.05	0.00	0.00	0.02	0.00
1926	0.44	0.07	0.06	0.00	0.00	0.08	0.08
1927	1.65	0.07	0.13	0.03	0.00	0.17	0.17
1928	1.62	0.15	0.17	0.07	0.00	0.16	0.15
1929	1.24	0.22	0.15	0.07	0.00	0.12	0.11
1930	0.87	0.22	0.11	0.07	0.00	0.07	0.07
1931	0.62	0.22	0.07	0.03	0.00	0.07	0.07
1932	0.96	0.15	0.07	0.06	0.00	0.07	0.07
1933	0.84	0.22	0.07	0.07	0.00	0.07	0.07
1934	0.59	0.16	0.07	0.00	0.00	0.07	0.07
1935	2.83	0.20	0.24	0.08	0.00	0.28	0.26
1936	3.51	1.92	0.71	0.47	0.00	0.37	0.37
1937	1.43	1.03	0.30	0.21	0.00	0.15	0.15
1938	0.88	0.60	0.17	0.11	0.00	0.08	0.07
1939	0.98	0.41	0.15	0.07	0.00	0.09	0.07

Year	Loamy fine sand	Loamy fine sand	Sandy loam I	Sandy loam I	2m clay	Sandy loam II	Sandy loam II
	Bare	Grass	Bare	Grass		Bare	Grass
1940	0.71	0.33	0.10	0.07	0.00	0.07	0.07
1941	3.82	0.38	0.18	0.12	0.00	0.39	0.36
1942	4.12	2.85	0.95	0.56	0.04	0.45	0.45
1943	1.46	1.13	0.33	0.22	0.04	0.16	0.16
1944	0.86	0.62	0.17	0.12	0.00	0.07	0.07
1945	0.94	0.45	0.15	0.07	0.00	0.09	0.07
1946	0.82	0.35	0.13	0.07	0.00	0.07	0.07
1947	0.64	0.28	0.07	0.07	0.00	0.07	0.07
1948	0.54	0.22	0.07	0.06	0.00	0.07	0.07
1949	0.45	0.17	0.07	0.00	0.00	0.07	0.07
1950	0.44	0.15	0.07	0.00	0.00	0.07	0.07
1950	0.43	0.15	0.07	0.00	0.00	0.05	0.05
1952	0.35	0.14	0.05	0.00	0.00	0.00	0.00
1953	0.29	0.07	0.00	0.00	0.00	0.00	0.00
1954	0.24	0.07	0.00	0.00	0.00	0.00	0.00
1955	0.22	0.07	0.00	0.00	0.00	0.00	0.00
1956	0.25	0.07	0.00	0.00	0.00	0.04	0.00
1957	0.36	0.07	0.00	0.00	0.00	0.02	0.01
1958	0.49	0.07	0.04	0.00	0.00	0.09	0.08
1959	1.45	0.07	0.11	0.03	0.00	0.12	0.12
1960	0.93	0.12	0.07	0.05	0.00	0.07	0.07
1961	0.80	0.15	0.07	0.00	0.00	0.07	0.07
1962	0.97	0.15	0.07	0.05	0.00	0.07	0.07
1963	0.73	0.15	0.07	0.01	0.00	0.07	0.07
1964	0.55	0.15	0.07	0.00	0.00	0.07	0.07
1965	0.41	0.15	0.07	0.00	0.00	0.02	0.01
1966	0.37	0.08	0.07	0.00	0.00	0.03	0.02
1967	0.50	0.07	0.07	0.00	0.00	0.07	0.07
1968	0.52	0.07	0.07	0.00	0.00	0.07	0.07
1969	0.99	0.07	0.08	0.00	0.00	0.10	0.09
1970	1.47	0.07	0.15	0.04	0.00	0.12	0.12
1971	0.80	0.14	0.08	0.03	0.00	0.07	0.07
1972	0.51	0.15	0.07	0.00	0.00	0.07	0.07
1973	1.08	0.15	0.10	0.03	0.00	0.14	0.10
1974	1.33	0.19	0.15	0.07	0.00	0.12	0.11
1975	1.67	0.26	0.17	0.07	0.00	0.16	0.13
1976	1.05	0.29	0.14	0.07	0.00	0.09	0.07
1977	0.72	0.26	0.07	0.06	0.00	0.07	0.07
1978	0.77	0.22	0.07	0.00	0.00	0.09	0.08
1979	3.15	0.32	0.30	0.09	0.00	0.30	0.27
1980	2.46	0.95	0.36	0.18	0.00	0.22	0.22
1981	1.06	0.72	0.18	0.10	0.00	0.09	0.09
1982	0.68	0.45	0.12	0.07	0.00	0.07	0.07
1983	0.57	0.32	0.07	0.07	0.00	0.07	0.07
1984	0.52	0.23	0.07	0.06	0.00	0.07	0.07
1985	1.59	0.26	0.17	0.07	0.00	0.18	0.17
1986	1.99	0.50	0.22	0.07	0.00	0.17	0.17
1987	1.94	0.58	0.23	0.09	0.00	0.20	0.18
1988	2.04	0.78	0.26	0.15	0.00	0.18	0.18
1989	1.46	0.62	0.20	0.10	0.00	0.13	0.13
1990	0.94	0.45	0.15	0.07	0.00	0.07	0.07
1991	0.81	0.32	0.12	0.07	0.00	0.09	0.09

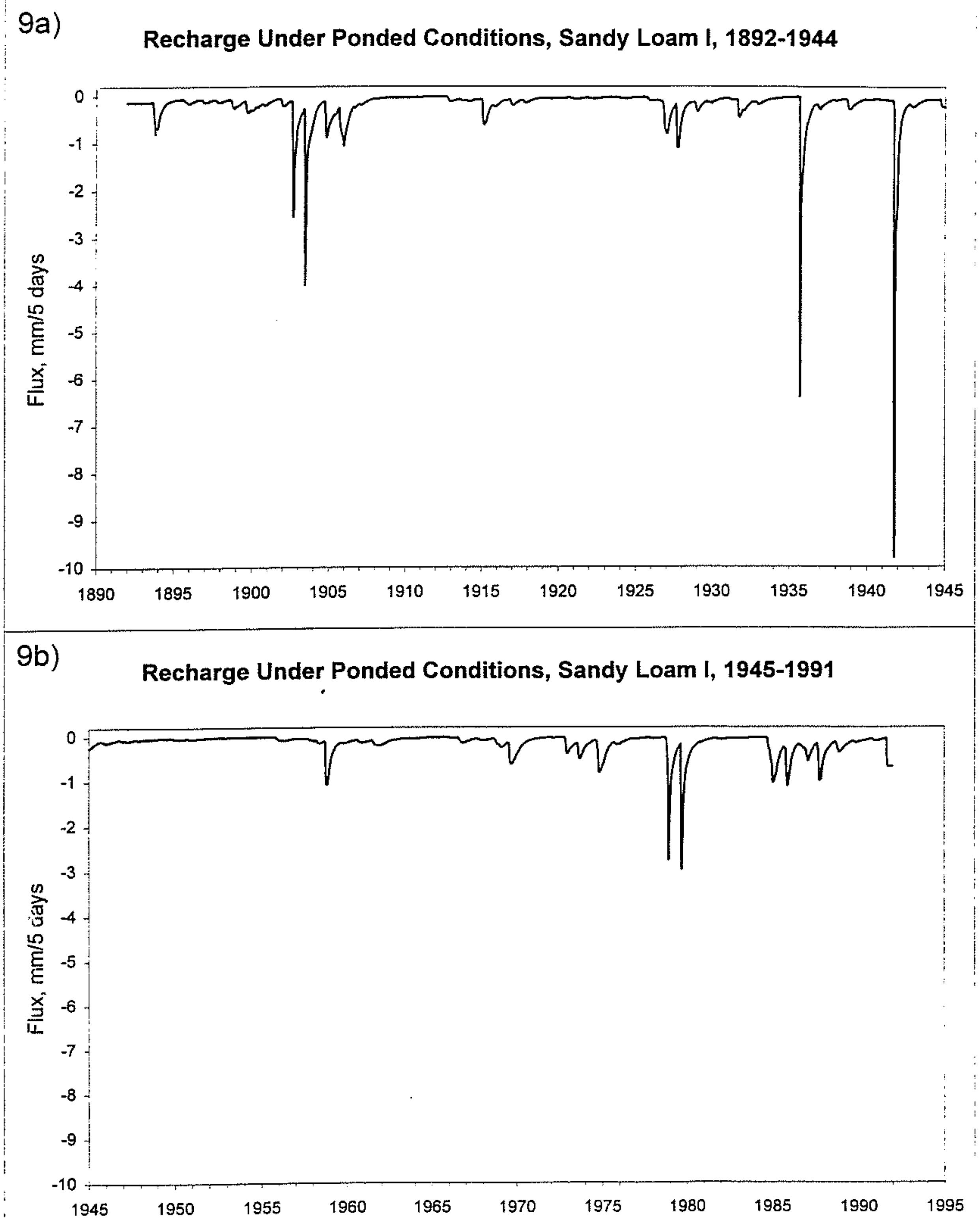


Figure 9. Recharge under ponded conditions for barren sandy loam I. Enhanced precipitation rates were used as input for this simulation in order to produce more rainfall than could be infiltrated into the soil. Negative values indicate downward flux.

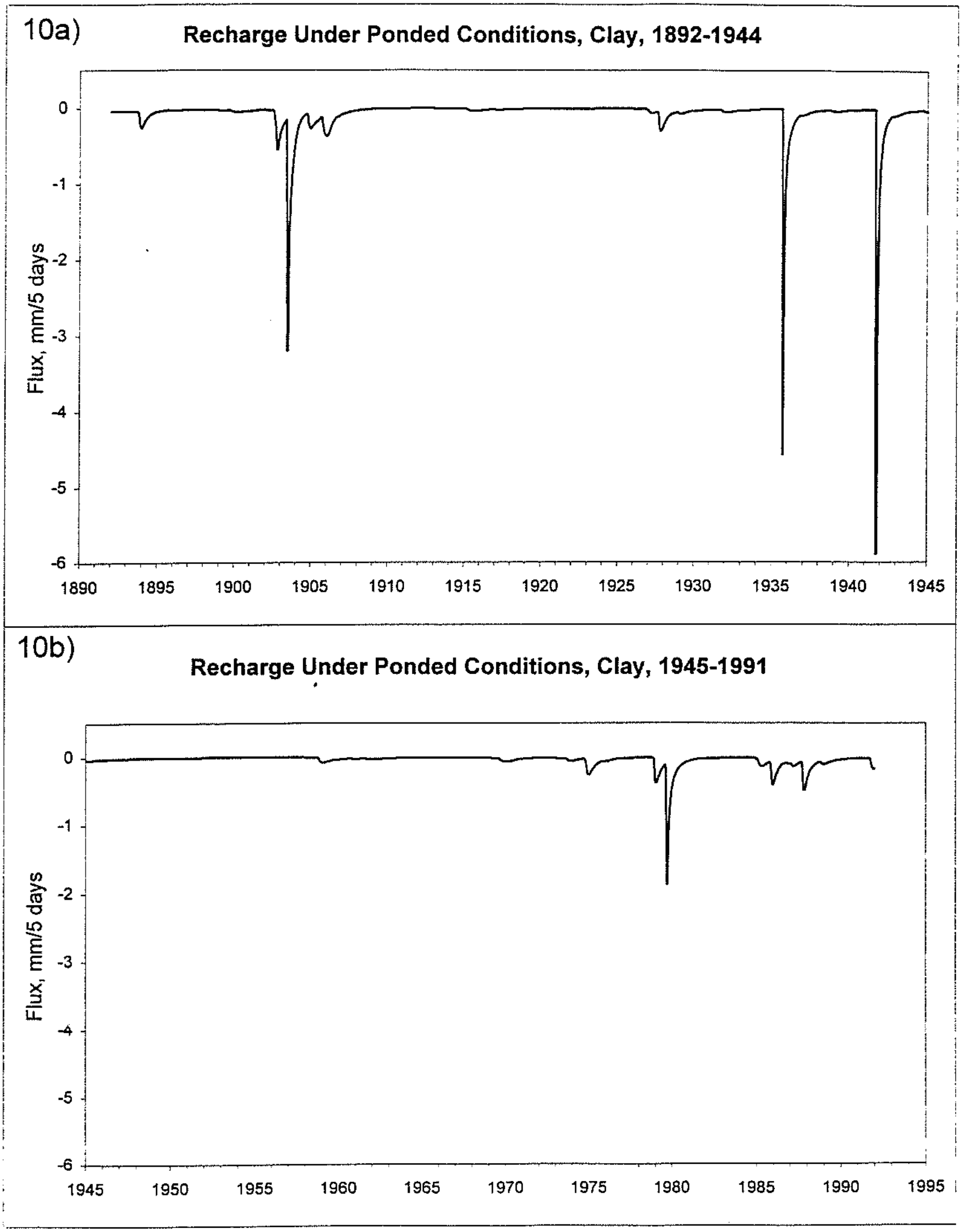


Figure 10. Recharge under ponded conditions for clay. Enhanced precipitation rates were used as input for this simulation in order to produce more rainfall than could be infiltrated into the soil. Negative values indicate downward flux.

such as described by Osterkamp and Wood (1987).

El Niño effects

The American Southwest receives more than half its precipitation from summer convection thunderstorms mostly spawned from moisture transported from the Gulf of Mexico. Winter precipitation is generated by frontal systems originating in the Pacific Ocean. The recent very strong El Niño Southern Oscillation (ENSO) condition throughout the Pacific basin brought a wetter than normal winter, speculations regarding groundwater recharge, and questions regarding El Niños of the past. According to Quinn *et al.*, (1987), the period from 1892 to 1991 saw nine ENSO periods of strong to very strong intensity and fifteen El Niños of moderate, or near moderate, intensity.

The strength of El Niños are rated according to the degree of barometric pressure decrease and surface temperature increase at selected meteorological stations across the tropical and sub-tropical Pacific Ocean. No guarantee exists that even a strong El Niño will produce heavy winter rains in a particular location in the southwestern region of North America. Looking only at strong to very strong ENSO conditions which straddle two years (in order to include an ENSO-influenced winter) we see a wide range of yearly precipitation values (Table 5). For example, the very strong El Niño of 1982-1983 failed to generate even normal rainfall in the Jornada area during either of those years. Of the other six strong to very strong El Niños which straddle two years during the period of evaluation, four ENSO periods (1925-1926, 1940-1941, 1957-1958, and 1972-1973) yielded yearly precipitation values greater than eight standard deviations above the 100 year mean precipitation value. Two more ENSO periods (1899-1900 and 1911-1912), are associated with years of approximately normal precipitation. Three moderate-strength El Niños (1915, 1923, and 1931) generated winters with abundant rain in the Las Cruces area, but many more did not. Two non-El Niño winters (1905 and 1985) produced substantial precipitation as well. Molles and Dahm (1990), however, showed spring stream flow levels to correlate more accurately with the presence of ENSO conditions than local precipitation does, possibly due to basin-scale effects. Their study showed a strong correlation between the long term hydrograph of the Gila River (290 km from the Jornada) and ENSO conditions. Results from the present

Table 5. El Nino data correlated with yearly rainfall

	Year	Yearly rainfall		
	1892	12.83		
	1893	27.41	*	
	1894	11.36		
	1895	24.05	*	
	1896	20.29		m
	1897	22.71	*	m
	1898	28.47	*	
	1899	24.56	*	s
	1900	21.34		s
	1901	30.38	**	
	1902	27.69	*	m
▨	1903	26.14	*	
▨	1904	25.73	*	
▨	1905	43.41	**	m
▨	1906	22.35	*	
	1907	16.31		m
	1908	15.16		
	1909	12.55		
	1910	10.21		
	1911	14.73		s
	1912	23.36	*	s
	1913	29.80	**	
	1914	30.10	**	m
	1915	18.72		
	1916	19.76		
	1917	14.04		s
	1918	17.86		m
	1919	20.45		m
	1920	20.78		
	1921	19.35		
	1922	14.18		
	1923	26.31	*	m
	1924	12.27		
	1925	19.81		s
	1926	36.45	**	s
	1927	24.05	*	
	1928	25.04	*	
	1929	23.42	*	
	1930	17.47		m
	1931	33.68	**	m
	1932	22.43	*	s
	1933	11.96		
	1934	11.73		
	1935	31.29	**	
	1936	24.13	*	
▨	1937	17.81		
▨	1938	23.55	*	
▨	1939	14.66		m
	1940	23.42	*	s
	1941	49.78	**	s
▨	1942	24.89	*	
▨	1943	19.18		m
▨	1944	23.55	*	
▨	1945	14.66		
	1946	17.83		
	1947	15.44		
	1948	13.10		
	1949	22.88	*	
	1950	13.56		
	1951	12.83		m
	1952	15.83		
	1953	9.68		m
	1954	11.84		
	1955	18.44		
	1956	12.14		
	1957	23.67	*	s
	1958	35.58	**	s
	1959	15.09		
	1960	19.63		
	1961	25.55	*	
	1962	16.23		
	1963	15.52		
	1964	9.19		
	1965	21.06		m
	1966	24.99	*	
	1967	21.39		
	1968	33.45	**	
	1969	30.25	**	
	1970	8.74		
	1971	14.65		
	1972	31.01	**	s
	1973	23.22	*	s
	1974	35.13	**	
	1975	20.52		
	1976	19.66		m
	1977	22.20	*	
	1978	37.67	**	
▨	1979	23.80	*	
▨	1980	20.45	*	
▨	1981	24.59	*	
▨	1982	19.99		
	1983	18.49		s
	1984	35.03	**	s
▨	1985	31.88	**	
▨	1986	33.02	**	
▨	1987	23.29	*	
▨	1988	28.55	*	m
▨	1989	22.71	*	
▨	1990	24.21	*	
▨	1991	37.23	**	

Explanation

*	Near mean yearly rainfall
**	Greater than one standard deviation above the mean yearly rainfall
s	Strong to very strong ENSO
m	Moderate strength ENSO
▨	Major recharge period

Yearly Rainfall Statistics	
Mean	22.088
Std. Error	0.784
Median	21.794
Mode	#N/A
Std. Dev.	7.841
Sampl. Var.	61.483
Kurtosis	0.803
Skewness	0.741
Range	41.049
Minimum	8.735
Maximum	49.784
Sum	2208.752
Count	100.000
95% Conf.	1.537

study suggest that the semi-arid Jornada area could see the initiation of another period of substantial groundwater recharge following the ENSO-enhanced precipitation events of winter 1997-1998.

Remnants of cyclones which occur along the west coast of North America can spawn large volumes of summer rain in the American Southwest, as well. The two largest single day precipitation events in the data set, 16.5 cm on August 30, 1935 and 10.4 cm on September 21, 1941, were the result of such cyclones (Kelly Redmond, Regional Climatologist and Deputy Director, Western Regional Climate Center, Desert Research Institute, *per com.* 1998). When Eastern Pacific cyclones occur in conjunction with ENSO conditions, the chance of large precipitation events increases further. The same day on which the remnants of the ENSO-enhanced cyclone produced 10.4 cm of rain at the Jornada facility, 23 cm of rain were recorded in six hours in the Guadalupe Mountains, just 100 miles away (Kelly Redmond, Regional Climatologist and Deputy Director, Western Regional Climate Center, Desert Research Institute, *per com.* 1998).

DISCUSSION

Table 6 shows the mean, maximum, and minimum values for estimated recharge in the loamy fine sand and sandy loam I and II soils used in the present study over the fully evaluated period of 92 years. The mean values for recharge on bare loamy fine sand (1.06 cm per year) and grassy loamy fine sand (0.33 cm per year) are comparable to the mean value of 0.95 cm per year estimated by Phillips *et al.* (1988) on grass and shrub vegetation near Socorro, New Mexico. The mean values estimated here are also comparable to Scanlon's (1992) estimate of 0.7 cm per year on sparsely vegetated sand. Rockhold *et al.* (1995) estimated recharge on barren loamy fine sand to be 2.2 cm per year, about twice that estimated by the present study. Mean values presented here for the loam soils are also smaller than Rockhold's estimates on silty loam: 0.12 cm per year, vegetated, and 0.08 cm per year, barren, from this study, averaged over both sandy loam soils, compared to 0.63 cm per year, barren, and 0.32 cm per year, averaged on vegetated silty loam estimated by Rockhold *et al.*. The annual pan PET at the Hanford, Washington site, lati-

Table 6. Yearly Recharge Statistics

	2m bare sand	2m grass sand	2m bare loam l	2m grass loam l	6m bare loam	6m grass loam
	Yrly recharge	Yrly recharge	Yrly recharge	Yrly recharge	Yrly recharge	Yrly recharge
Mean, cm	1.06	0.33	0.13	0.06	0.11	0.10
Max., cm	4.12	2.85	0.95	0.56	0.45	0.45
Min., cm	0.22	0.07	0.00	0.00	0.00	0.00
Std. Dev.	0.81	0.40	0.13	0.08	0.08	0.08

Table 7. Yearly Recharge Expressed as a Percentage of Yearly Precipitation

	Recharge as percentage of precipitation	Recharge as percentage of precipitation	Recharge as percentage of precipitation	Recharge as percentage of precipitation	Recharge as percentage of precipitation	Recharge as percentage of precipitation
Mean	4.83	1.57	0.61	0.30	0.51	0.45
Maximum	16.82	11.46	3.80	2.24	2.28	1.80
Minimum	1.09	0.20	0.00	0.00	0.00	0.00
Std. Dev.	3.22	1.69	0.55	0.36	0.39	0.32

tude XX, is 160 cm, much less than the 239 cm experienced at the Jornada, New Mexico site, latitude YY. This difference in annual PET likely accounts for some difference in recharge calculated at the two sites.

Table 7 expresses yearly recharge as a percentage of yearly precipitation. The estimates for yearly recharge presented in this study are approximately an order of magnitude less than those for the lysimeter study by Gee *et al.* (1994), but closer to the lysimeter results of Sammis and Gay (1979). Gee *et al.* found 25% of the yearly precipitation, 5.4 cm per year, to be either stored or recharged from their lysimeter four years after it reached equilibrium. Following a one-year study Sammis and Gay found less than 2% of precipitation (0.47 cm per year) to be retained as recharge/storage. The mean value of recharge (on barren loamy fine sand) as a percent of precipitation found in the present study is 4.83%. The widely varying results from the lysimeter studies suggest that long-term studies are needed in order to see more stability in the recharge estimates.

Of the 30 recharge periods proposed by this study (all, except the period associated with clay), 23 of them began in the months from September to December, ten of them in October, alone. October is important because it coincides with the beginning of autumn, bringing lower PET values, yet is still within the season for cyclones bringing moisture from the Pacific Ocean. Two of the major recharge periods were initiated by large rainfall events associated with remnants of Eastern Pacific cyclones. It's entirely possible that all five of the major recharge periods were enhanced by remnants of such cyclones, but more research must be done to ferret out this information. The winter months are clearly important as well, since nearly half of the yearly precipitation falls during the time of year when PET is relatively low.

Since this study was undertaken with a qualitative, first cut approach to the temporal variability of precipitation recharge, a serious sensitivity analysis on the vegetation coefficients was not performed. Results from the vegetated simulations are likely sensitive to values chosen for the seven vegetation coefficients used by SWAP. Because a lack of hard data required the estimation of three of these values as well as estimations for the seasonal root response during the growing-season, this entire study would benefit from a rigorous statistical analysis.

Underestimation of recharge is expected when using averaged PET data. Averaged values don't respond to the atmospheric conditions which surround an actual precipitation event. The cloudy and cooler conditions surrounding a rainstorm decrease the evaporative demand in the real world and the subsequent lower PET values on such days allow more infiltration to occur than is calculated using the higher, averaged PET values. It was my intention to produce conservative recharge estimates by this approach.

CONCLUSION

This study has attempted to characterize the temporal variability of precipitation recharge in the arid Southwest. Results presented here not only support the concept of precipitation recharge, but strongly suggest five major periods for its occurrence in the last century. These periods have a variety of conditions which precede recharge, ranging from a single, very large rainfall event followed by roughly average rainfall years, to several years in a row with above average rainfall while lacking any large, single event. The timing of the onset of most of these recharge periods suggests that precipitation in early fall is an important factor in the initiation of recharge. The presence of vegetation and a fine soil texture will decrease the amount of recharge seen on some barren, sandy soils, but precipitation recharge in sand (and possibly loam), and localized recharge following ponding in low permeable soils can't be ruled out during consecutive years with above average rainfall. Mean recharge values presented here are comparable, or lower than, recharge values reported elsewhere. The levels of recharge presented here contain uncertainties, but the underestimation caused by averaging the PET data supports the idea that these are conservative estimates.

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