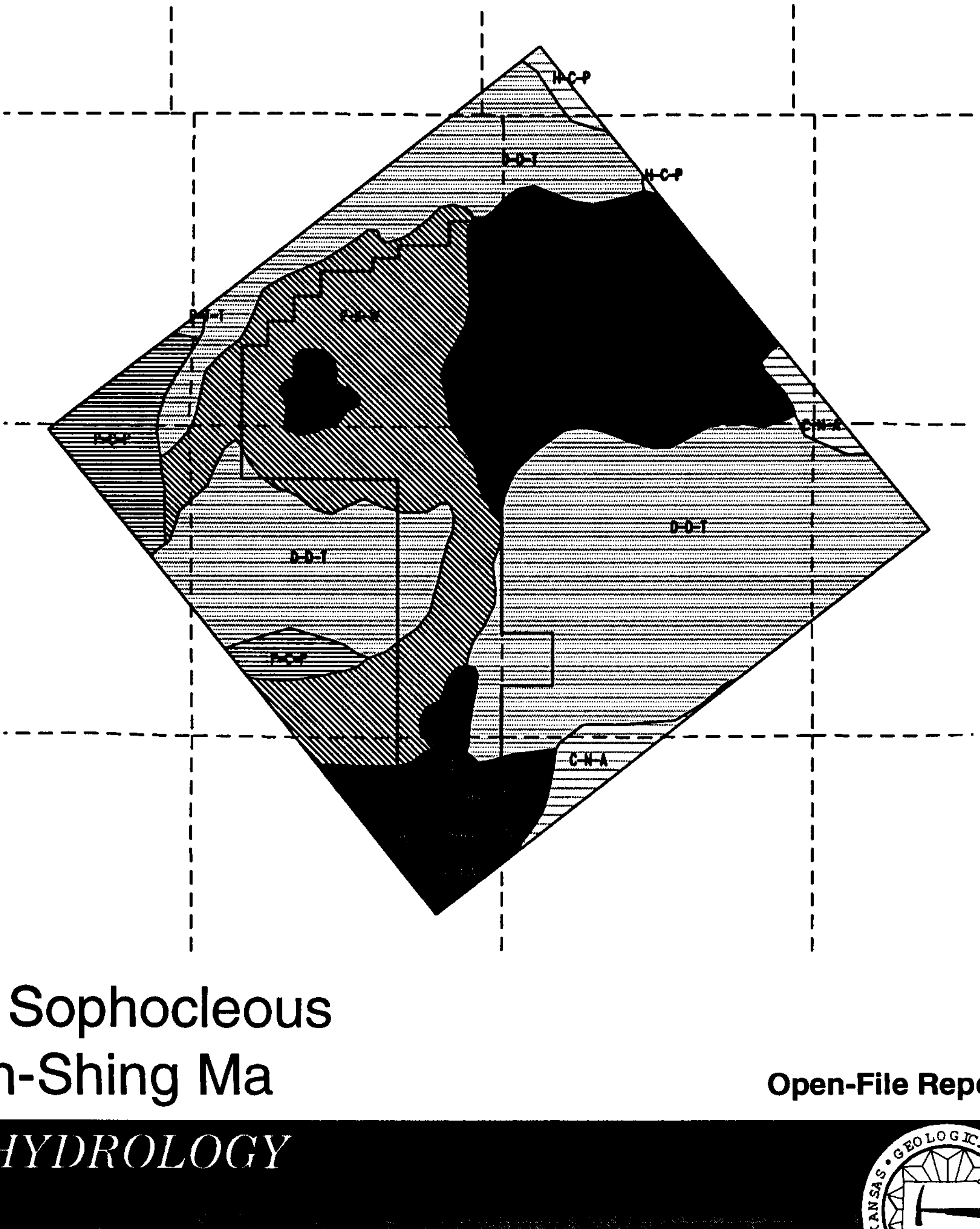
Kansas Geological Survey

# Hydrologic modeling and water budget of the Quivira National Wildlife Refuge, Kansas



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Open-File Report 93-16

*GEOHYDROLOGY*

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by
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## Executive summary

Knowledge of the components of the water budget of wetlands is essential to understanding and managing the marsh ecosystem. To quantify these components in sufficient detail, we developed a detailed but simple hydrologic budget for a portion (145 $mi^2$) of Rattlesnake watershed encompassing the Quivira National Wildlife Refuge (NWR) in south-central Kansas. With this budget, using minimal daily weather input data and the soil-plant-water system-analysis methodology, we were able to characterize the 1985–1992 distribution of the hydrologic components of the water balance in the study area. A combination of classification and meteorological methods resulted in a subbasin integration methodology.

The performance of the soil-water budget (VB) in combination with the integration methodology presented here has been shown in this report to provide a suitable tool for the subregional estimates of various hydrologic variables from standard climatic, soil, and crop data for agricultural watersheds. Precipitation was demonstrated to be the principal natural water supply, and evapotranspiration the major water-depletion process. These water-balance components dominate and control all other hydrologic variables such as runoff, deep drainage, and soil-water deficit. Soil factors, such as the available water capacity of soil profiles, play a major role in soil-water deficit development and significantly affect deep drainage.

The VB model program code was made more flexible by incorporating user-selected subroutines for infiltration and surface runoff determinations, among other changes. Thus we calculated the area-weighted hydrologic budget components for the last eight years (1985–1992) using the average of three estimation procedures (original VB, SCS-curve number, and Green and Ampt) as follows: precipitation, 25.99 in./yr; actual evapotranspiration, 24.09 in./yr; soil-water deficit, 3.84 in./yr; surface runoff, 0.90 in./yr; and deep drainage, 0.87 in./yr. These values are in agreement with what is observed in the area. It is hoped that this information will assist the Quivira NWR managers and engineers in carrying out their water-management responsibilities and in the designing of water resource systems for the refuge.

## Introduction

In this report we develop a detailed but simple hydrologic budget for a portion of the Rattlesnake Creek watershed that encompasses the Quivira National Wildlife Refuge (NWR) wetland in south-central Kansas. The detailed model area covers an area of 145 mi$^2$ (approximately 12 × 12 mi). The areal relationship of this detailed model area and the previously stream-aquifer modeled lower Rattlesnake Creek watershed area (Sophocleous and Perkins, 1993) are shown in fig. 1.

Wetlands are dynamic ecosystems with fluctuating boundaries. They can be characterized in terms of hydrology, vegetation, and soils. The three components interact with each other and with geology and topography to give a wetland its distinctive characteristics. Water entering, stored in, and leaving a wetland can be expressed in terms of a water budget. According to Carter et al. (1978), all natural wetland functions are a result of, or are closely related to, wetland hydrology. Hydrologic conditions can directly modify or change chemical and physical properties, such as nutrient availability, degree of substrate anoxia, soil salinity, sediment properties, and pH. Water inputs are almost always the major source of nutrients to wetlands; water outflows often remove biotic and abiotic material from wetlands as well. These modifications of the physiochemical environment, in turn, have a direct impact on the biotic response in the wetland (Gosselink and Turner, 1978). Thus, knowledge of the components of the water budget of the local hydrologic regime is vital to an understanding of the marsh ecosystem and its water quality (Kadlec and Kadlec, 1979).

The objectives of this aspect of the study are to quantify in sufficient detail the hydrologic components of the water budget using relatively simple tools (models) and to determine their temporal and spatial distribution in the immediate vicinity of the Quivira NWR for the years 1985–1992. It is hoped that this information will assist the Refuge managers and engineers in carrying out their water-management responsibilities and in the designing of water resource systems for the refuge. For example, as we will show later, evapotranspiration is the major water

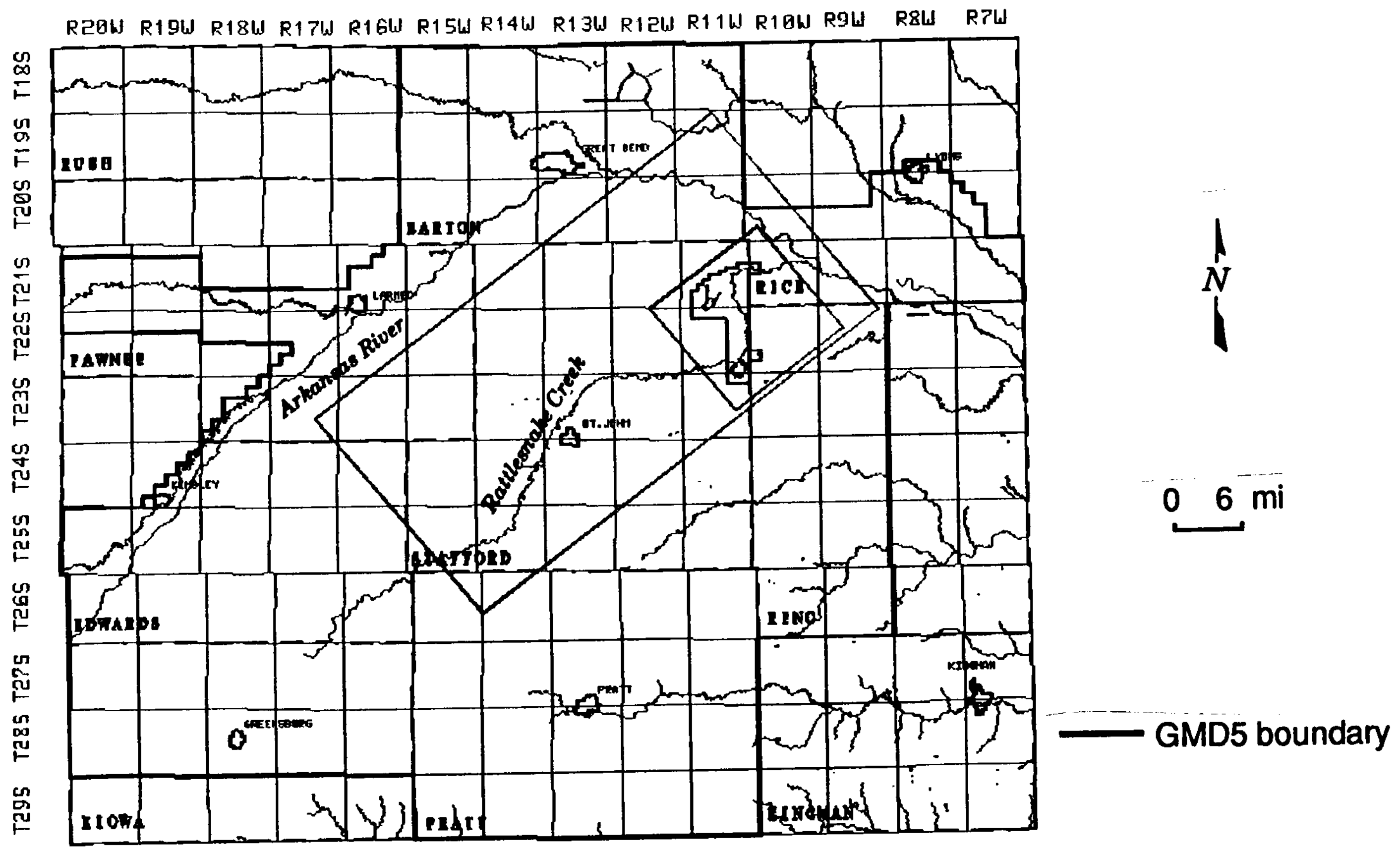

Figure 1. Location of study area.

supply loss mechanism in the area; therefore water storage methods designed to minimize evapotranspiration will significantly increase the amounts of water that can be used for management. The chosen study period covers wet (1985–1987, 1990, and 1992), dry (1988 and 1991), and average (1989) years with regard to precipitation in the study area.

## Watershed modeling approach

### Water budget

The hydrologic equation of water balance is a statement of the law of conservation of mass as applied to the hydrologic cycle. It states that in a specified period of time all water entering a specified area must either go into storage within its boundaries, be consumed therein, be exported therefrom, or flow out either on the surface or underground. The water-balance method allows the planner to compute a continuous record of soil moisture, actual evapotranspiration, ground-water recharge, and surface runoff from a meteorological record as well as some observations on the soil and vegetation.

The occurrence and distribution of soil water is a complex and integral part of any hydrologic water balance. Whether the emphasis is on surface runoff, streamflow, evapotranspiration, or ground water, soil water plays a dominant role. The infiltration and evapotranspiration processes in particular are strongly related to the time-depth status of the soil-water profile. Most ground-water recharge occurs only after the soil profile has become significantly wetted. Crop production also is highly dependent on the presence of adequate, available soil water throughout the growing season.

### Regionalizing point values

The methodology we used in regionalizing site values of the water-balance components to a much larger region of interest is that of Sophocleous and McAllister (1987). Most direct measurements of hydrologic variables, such as soil moisture and ground-water recharge, provide only point readings and do not integrate such variables in relation to space and time. Unlike common climatological observations, comparable soil-moisture or ground-water recharge measurements using standardized techniques are rarely available on a network basis. With the exception of runoff, which is an integrated measurement, the problem of areal representation of point measurements of the water-balance elements exists. The high variations of site characteristics and of physical and physiological properties of plants lead to large water-balance differences in vegetated surfaces.

"Classification methods," whereby homogeneous hydrologic-unit areas are identified within the heterogeneous structure of a watershed, can be applied to generalize and regionalize site values of the water-balance elements throughout the whole watershed (Dyck, 1985). Parameter sets can be determined for each unit area, taking into account the close coincidence of geomorphologic, soil, and vegetation distribution patterns. A basic matrix of site factor complexes can be established for the subdivision of a watershed into unit areas. For the Rattlesnake Creek watershed these include local climate, main forms of land use, types of soil classes, and vegetation types.

"Meteorological methods" for estimating components of the hydrologic balance from weather data also have been proposed to overcome difficulties encountered with point measurements (Baier and Robertson, 1966). Because these budgeting techniques keep track of changes of various hydrologic components of the water balance by using standard meteorologic observations together with some soil and vegetation information, they satisfy to some extent the need for a space-time integrating technique.

## Integrating methodology

In this study we combine aspects of the classification method with the meteorological method to derive a subbasin integration methodology. First, the basin can be divided into climatic subregions using a Thiessen-type polygon technique. Such a method is appropriate because the study area is generally a flatland plain. In the present case the area of interest is covered by only one long-term climate station located near the town of Hudson. The different soil series within each climatic subregion can be grouped into soil associations of similar soil properties using standard Soil Conservation Service (SCS) techniques (U.S. Department of Agriculture, 1975). Each soil association can be subdivided further according to land usage into irrigated cropland, nonirrigated cropland, and rangeland or grassland. This classification seems appropriate because our study area is predominantly agricultural, without any forested areas. The study area is predominantly nonirrigated grassland. Finally, crop-rotation practice can be superimposed on the land usage. We superimposed a meteorological water-budgeting procedure on this classification scheme, which is repeatedly run for each soil association, crop type, land-use practice, and climatic region. To avoid the averaging effects of monthly or other large time intervals on the water-balance components, we adopted daily input data in this study. Area-weighted averages were then taken for integrating the soil-plant-weather complexes on a subbasin or watershed scale.

The approach described here is intuitive and simple. The water-budgeting procedure, as will be explained in the next section, is not involved, requires minimal data, and therefore is inexpensive to run. Therein lies the advantage of the proposed integrating methodology.

## Versatile soil-water budget (VB)

Most water-budgeting techniques make use of the well-known concept of potential evapotranspiration as an indicator of the possible maximum loss of water from the soil under conditions of nonlimiting water supply. Penman (1963) reviewed the extensive literature pertaining to soil-water loss under conditions of nonlimiting water supply. Budgeting methods for estimating soil moisture and actual evapotranspiration from vegetated soil, when water supply is at times limited, are more complicated because they account for various soil and plant characteristics that modulate or alter the potential rate. In this report we use a meteorological soil-water budget, called the versatile budget, which is a multigeneration evolution of the Holmes and Robertson (1959) modulated budget. Most of the following discussion is based on information presented by Sophocleous and McAllister (1990) and is updated as appropriate.

The versatile soil-water budget (VB) requires as minimum input only daily observed data on precipitation and estimates of potential evapotranspiration (PE). The VB computerized procedure simulates variations in daily soil-water content by making use of physical and biological concepts of water movement in the soil and water uptake by plant roots (Baier et al., 1976). The VB output contains daily estimates of actual evapotransipiration (AE), soil-water content in several "zones" or layers in the soil profile, and water losses resulting from runoff and drainage. Because the data from climatological stations usually are considered to be representative of the surrounding area, we can assume that the soil-moisture estimates based on such data also are representative of the soil in this same area.

The basic structure of the budget can be described by the flow chart presented by Baier et al. (1979), shown in fig. 2. Model components can be split into evaporation functions, including all crop and soil-water extraction characteristics, and recharge functions, including infiltration, drainage, runoff, and snowpack submodels.

## Evapotranspiration

As mentioned previously, daily values of precipitation and PE are required as input to the VB. A variety of techniques can be used to obtain the most reliable daily PE estimates under the local experimental conditions. For the daily calculations of PE from standard climatic data, Thornthwaite's (1948) method, which is based on mean air temperature, was found to be inadequate (Ritjema, 1965). Penman's (1948) method, which generally is regarded as the most sound, requires observations on vapor pressure, wind, radiation or sunshine, and temperature; these data for a given station are often incomplete or unavailable. All other methods for estimating PE either involve special measurements or empirical coefficients of limited regional applicability or are not flexible enough to make efficient use of those meteorological factors that are available for a certain location and time period.

To overcome these shortcomings, Baier and Robertson (1965) proposed a regression technique for estimating daily latent-evaporation rates, which can readily be converted to PE,

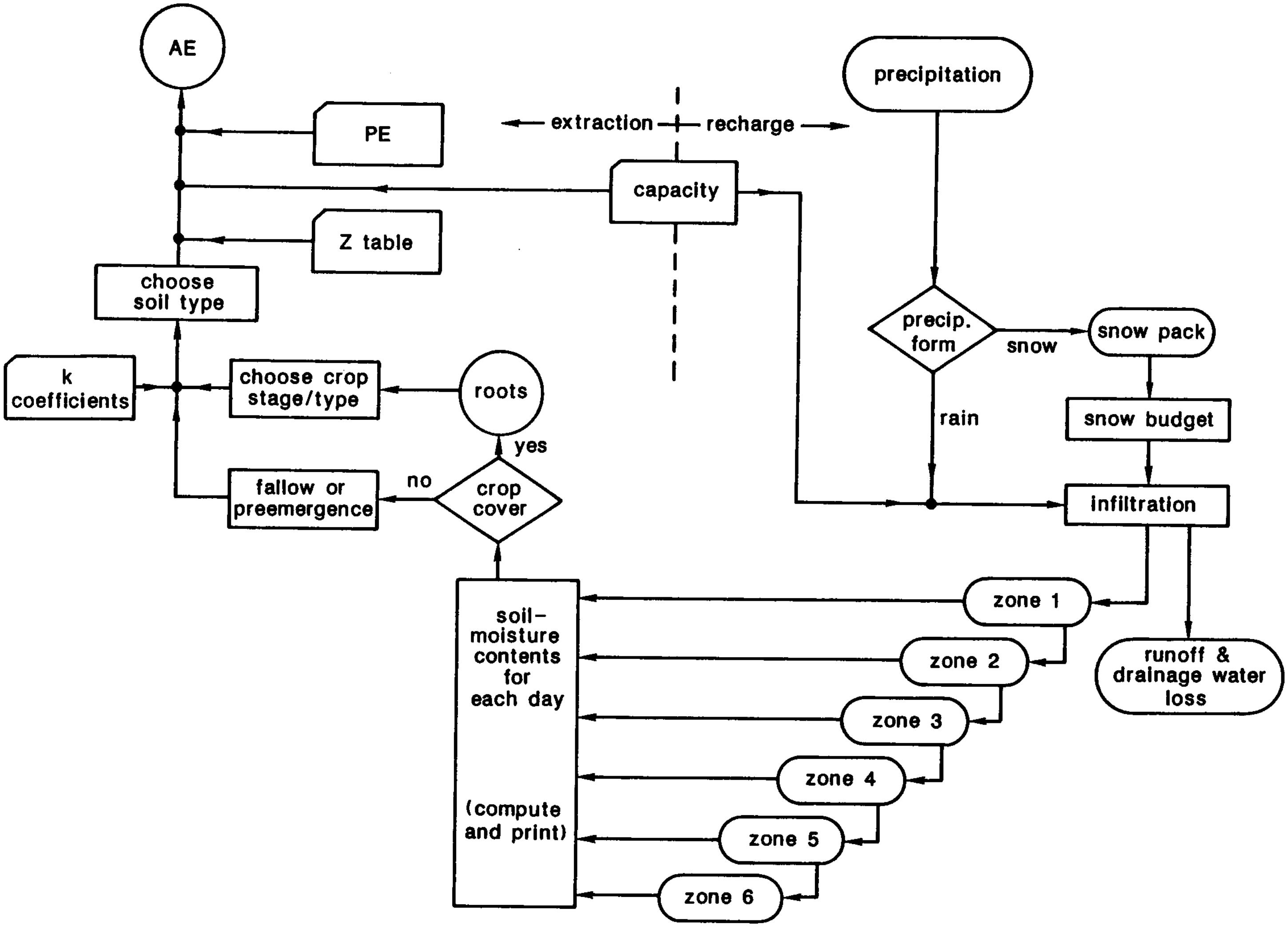

Figure 2. Versatile budget flow chart [adapted from Baier et al. (1979)].

using the standard climatic data that are available. Minimum input data requirements are daily maximum and minimum temperatures available from various weather stations and total sky and solar radiation at the top of the atmosphere ($Q_0$) available from standard tables (Russelo et al., 1974). The latter is used to evaluate the solar radiation incident on the earth's surface from easily observable or measurable quantities (Baier and Robertson, 1965). In addition to these data, if daily values of sunshine, wind, and dew-point temperatures are available, the inclusion of any one or all of these variables in different regression equations usually improves the PE estimates. This method has been used for estimating daily or monthly PE values at different locations in Canada; these estimates were compared with actual observations or estimates from Penman's formula with good reported agreement (Baier and Robertson, 1965; Baier, 1967).

In the VB, water is withdrawn simultaneously from different depths of the soil profile in relation to the rate of PE, rooting patterns, crops, different soil-moisture release characteristics, and the available water in each of several (usually six) zones of specified water-holding capacities. PE is used as a climatic parameter of the potential (maximum) rate of evapotranspiration from a dense crop freely supplied with water. Adjustments for runoff, drainage, different soil-moisture release characteristics for upper and lower zones, and the relative effect of the daily atmospheric demand rate on the AE:PE ratio as a function of available soil moisture also are incorporated. The general equation of the VB for estimating daily AE from PE is

$$\mathrm{AE} = \sum_{j=1}^{n} Z_j k_{ji} \frac{S_j}{C_j} \mathrm{PE}, \tag{1}$$

where AE is the daily actual evapotranspiration, PE is the daily potential evapotranspiration, $Z_j$ is the value from a selected soil-drying curve for the $j$th zone, $k_{ji}$ is the crop coefficient for root extraction in the $j$th zone and $i$th crop-growth stage, $S_j$ is the plant-available water for the $j$th zone at the start of the day, and $C_j$ is the plant-available water capacity for the $j$th zone.

For the purpose of this budget, plant-available soil moisture is considered to be the total amount of moisture from field capacity to permanent wilting point. The concepts of field capacity and available water capacity have been helpful in the development of improved water-management practices because of their simplicity, despite the fact that field capacity is not a precise term.

The basic concepts of soil-moisture extraction in the VB are as follows:

1. The total soil moisture available to plants is subdivided into six arbitrary "standard zones" of varying water-holding capacities, although a different number of zones also can be used (Dyer and Baier, 1980). Specifically, the six standard zones contain 5.0%, 7.5%, 12.5%, 25.0%, 25.0%, and 25.0% of the total capacity for plant-available moisture of the soil profile. The adoption of standard zones makes it possible to use one set of crop (plant or root) coefficients, *k*, for a particular crop in any type of soil. This is possible because it is assumed that the uptake of available water by crops always follows a characteristic pattern that depends on plant-rooting habits. Although the extent of the root system may differ from soil to soil, the fraction of the available water extracted from the different zones remains the same under various environmental conditions. Studies of rooting characteristics and extraction patterns by various researchers support this assumption (Vazquez and Taylor, 1958; Weaver, 1926).
2. Water is taken up by plants at a rate depending on the ratio of available water present in any zone to the capacity for available water in the same zone.
3. This rate is modified by (a) the relationship between AE/PE and available water in the particular soil; this relationship is expressed by the adjustment factor *Z* which characterizes different types of soil-dryness curves and is selected according to moisture characteristics of the soil; and (b) the crop (plant) coefficient *k*, which resembles the most probable moisture-extraction pattern according to rooting characteristics and water consumption of plants at their different development stages.

As the soil dries, it becomes increasingly difficult for additional water to be lost by evaporation and transpiration. Different investigators have suggested that the shape of the curve of decreasing evapotranspiration with soil-moisture storage can be either concave or convex. These relationships also have been shown to be controlled by soil properties, particularly texture (Baier, 1968; Salter and Williams, 1965). Baier and Robertson (1966) and Baier (1968, 1969) have combined the various proposals for the relation between AE/PE under different values of soil-moisture content in the form of *Z* tables, which are presented in graphical form in fig. 3. Descriptions of available *Z* tables and some guidelines for their selection and use are given by Baier et al. (1979). An index equation for generalizing drying curves was developed by Dyer and Baier (1979).

The *k* coefficient expresses the amount of water (percentage of PE) that can be removed by plant roots from different soil layers during the growing season. To simulate this water

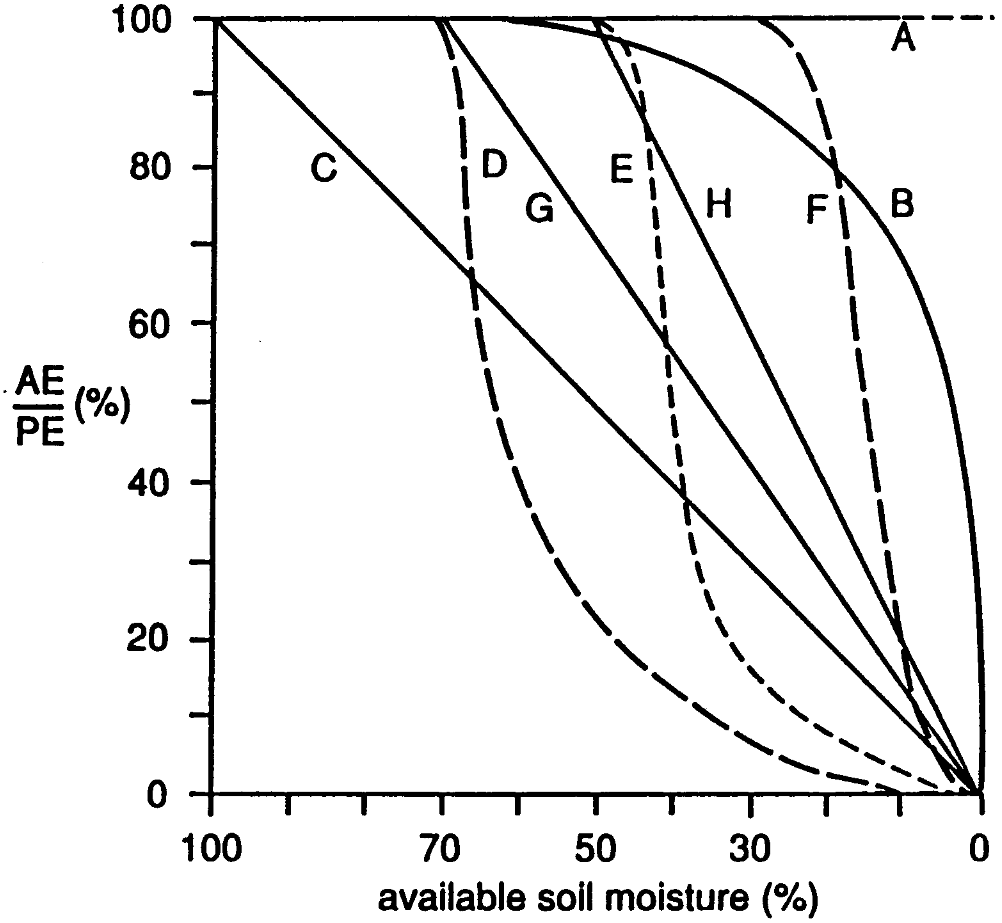

Figure 3. Various proposals for relationships between AE/PE ratio and available soil water content [from Baier et al. (1979)].

uptake, we model the *k* coefficients so that they change during the growing season according to crop-developing stages. The transition dates between crop stages must be entered into the computer program for each year.

The *k* coefficients employed in the VB have been determined by iterative comparisons between computed and measured soil moisture or were estimated so that extraction rates resemble the most probable crop-rooting pattern under the prevailing environmental conditions. Dyer and Dwyer (1982) suggested that observed root patterns could be a basis for development of new sets of *k* coefficients for different crops. Tables of *k* coefficients for different crops and growth stages are given by Baier et al. (1979) and Sophocleous and McAllister (1990).

### Runoff, infiltration, and drainage

To account for water losses through runoff, we include in the VB a simplified relationship between soil moisture in the top zone, daily-precipitation total, and runoff. On days with precipitation less than or equal to 1.0 inch, the total amount of precipitation is considered to infiltrate the soil. On days with precipitation greater than 1.0 inch, runoff is estimated

$$\text{Runoff}_i = \text{RR}_i - I \tag{2}$$

where $$I = 0.9177 + 1.811 \ \ln \text{RR}_i - 0.97 \ \ln \text{RR}_i \left( \frac{S_j}{C_j} \right), \tag{3}$$

$I$ is the amount of water infiltrating into soil, $\text{RR}_i$ is the rainfall, in inches, on day $i$, $S_j$ is the soil moisture in the $j$th zone on the day preceding the rain day, and $C_j$ is the available water capacity of the $j$th zone and $j = 1$.

Equation (3), calculated from data by Linsley et al. (1949), was based on findings by several researchers that initial soil-moisture content and rainfall mainly affect the rate of infiltration.

In the VB we assumed that the water infiltrating the soil would first bring the moisture content of the top zone to field capacity and that the remainder would infiltrate the next zone and so forth, until either all infiltration water was used up or all zones were brought to capacity.

Drainage is obtained on days when the precipitation exceeds the total of AE, runoff, and the sum of soil-water deficits over all zones. Any surplus of water was then designated as drainage. .

In estimating AE on days with measurable rainfall, we presumed that most evapotranspiration on day $i$ took place first and at a rate depending on the soil-moisture content at the end of day $i - 1$ but that rainfall occurred later in the $i$th day. This assumption is based on the fact that rainfall over a landmass in summer is typically of a showery nature and usually associated with the formation of cumulus clouds, which reach their maximum in the afternoon after strong convection earlier in the day.

In climates where snow occurs, the computation of soil moisture includes the amount of water penetrating the soil from snow. A simple snow budget was developed for use in the VB with minimum additional data. The reader is referred to Baier et al. (1979) and Dyer and Mack (1984) for further details and additional features.

## Versatile budget model modifications

As a result of this project and in accordance with recommendations made by Sophocleous and McAllister (1990), the original VB model was further modified to increase its generality and accuracy and to improve its output capability. Thus the program code was modified to handle multiple years of computation, to summarize the water budgets for each year and for the total period of simulation, to display hydrologic balance errors (residuals), to output cumulative and daily hydrologic budget components, and to convert any number of soil layers to the standard zones required by VB. In addition, the program code was modified to handle any one of three user-specified infiltration and runoff calculating procedures: (1) the standard regression-based VB procedure outlined previously, (2) the SCS-based curve number method, and (3) the more physically based Green and Ampt methodology. The added methods are outlined in what follows.

## Calculating runoff based on the Soil Conservation Service curve number method

The popularity of the well-known Soil Conservation Service curve number (SCS-CN) method as a runoff prediction tool lies in the fact that it is simple to use, does not require calibration, and is purported to give reliable results. The curve number runoff equation is given (U.S. Department of Agriculture, 1972) as

$$Q = \begin{cases} \dfrac{(P-0.2s)^2}{P+0.8s} & \text{if } P > 0.2s, \\ 0 & \text{if } P < 0.2s, \end{cases} \tag{4}$$

where $Q$ is the daily runoff, $P$ is the daily rainfall, and $s$ is a retention parameter, all having dimensions of length (inches).

The retention parameter $s$ is related to soil water:

$$s = s_{\max}\left(\frac{\mathrm{UL}-\mathrm{SM}}{\mathrm{UL}}\right), \tag{5}$$

where SM is the soil-water content in the root zone, UL is the upper limit of soil-water storage in the root zone, and $s_{\max}$ is the maximum value of $s$. $s_{\max}$ is estimated with the antecedent soil-moisture condition I (for dry soils but not to wilting point) curve number (CN), using the SCS hydrology handbook (U.S. Department of Agriculture, 1972) equation

$$s_{\max} = \frac{1{,}000}{\mathrm{CN_I}} - 10, \tag{6}$$

where $\mathrm{CN_I}$ is the moisture condition I CN. Condition II (normal or average moisture conditions) curve numbers $\mathrm{CN_{II}}$ can be obtained using the SCS hydrology handbook (U.S. Department of Agriculture, 1972). For computing purposes, $\mathrm{CN_I}$ was related to $\mathrm{CN_{II}}$ using the following polynomial equation by Smith and Williams (1980):

$$\mathrm{CN_I} = -16.91 + 1.348(\mathrm{CN_{II}}) - 0.01379(\mathrm{CN_{II}})^2 + 0.0001177(\mathrm{CN_{II}})^3. \tag{7}$$

The curve number is a relative measure of retention of water by a given soil–vegetation–land use complex and takes a value from 0 to 100. This number is derived from the character of the soil, vegetation, land use, and management practice and is tabulated in the hydrology handbook (U.S. Department of Agriculture, 1972).

Fluctuations in soil-water content cause the retention parameter to change according to the equation (Smith and Williams, 1980)

$$s = s_{\max}\left[1.0 - \sum_{i=1}^{N} W_i\left(\frac{\mathrm{SM}i}{\mathrm{UL}i}\right)\right], \tag{8}$$

where $W_i$ is a weighting factor, $SM_i$ is the water content, and $\mathrm{UL}_i$ is the upper limit of water storage in storage $i$. The root zone is divided into $N$ layers and weighting factors. The weighting factors decrease with depth according to the equation (Smith and Williams, 1980)

$$W_i = 1.016\{\exp[-4.16(D_{i-1}/\mathrm{RD})] - \exp[-4.16(D_i/\mathrm{RD})]\}, \tag{9}$$

where $D_i$ is the depth to the bottom of storage $i$, and RD is the root zone depth. Equation (9) ensures that $\sum_{i=1}^{N} W_i = 1$.

A major limitation of the curve number method is that rainfall intensity and duration are not considered, only total volume. However, the method is a familiar procedure that has been used for many years in the United States with reasonable estimates of runoff for a variety of conditions.

## Calculating infiltration and runoff based on the Green and Ampt equation

A great challenge in hydrology today is the development of models that can give reliable predictions of runoff from ungaged watersheds and yet can be flexible enough to be used to evaluate different management scenarios. Time-based infiltration models, such as the Green and Ampt (GA) model, have been proposed as better alternatives for predicting rainfall excess because they attempt to simulate the hydrologic processes involved. Conceptually, time-based infiltration models can better mimic the impacts of land use on runoff because infiltration parameters can be directly related to watershed characteristics (Brakensiek and Rawls, 1982). One limitation to using time-based infiltration models is that they require not only a rainfall amount but also a rainfall distribution (hyetograph), which is not always available. However, SCS developed dimensionless 24-hour rainfall distributions using the Weather Bureau's *Rainfall Frequency Atlas* for different regions of the United States. Kansas falls in the region for type II storms, for which the peak is found to occur during the middle of the storm.

Another limitation of time-based infiltration models has been the difficulty of model parameterization. Direct estimates of the needed parameters require intensive and time-consuming soil measurements and tests. Recently, significant progress has been made in removing this limitation. Techniques have been developed for estimating the parameters for the Green and Ampt infiltration equation using readily available soil information (Rawls and Brakensiek, 1982, 1983, 1985, 1988; Brakensiek and Rawls, 1982, 1988).

The Green and Ampt infiltration rate equation is

$$f = K\left(1 + \frac{n\psi_f}{F}\right), \tag{10}$$

and its integrated form is

$$F - n\psi_f \ln\left(1 + \frac{F}{n\psi_f}\right) = Kt, \tag{11}$$

where $K$ is the hydraulic conductivity [L/T]; $\psi_f$ is the wetting-front capillary pressure head, [L]; $n$ is the available soil porosity, which is calculated as the effective porosity, $\theta_e$ (i.e., total porosity $\phi$ minus residual saturation $\theta_r$) reduced by antecedent (initial) soil-water content; $f$ is the infiltration rate [L/T]; $F$ is the infiltration (cumulative) amount, [L], and $t$ is time [T].

Application of the Green and Ampt infiltration requires estimates of the hydraulic conductivity ($K_j$), effective porosity ($\theta_e$) and wetting-front capillary pressure head ($\psi_f$). Brakensiek et al. (1981) presented a method for determining the Green and Ampt parameters using the Brooks and Corey (1964) equation. Rawls et al. (1983) used this method to analyze approximately 5,000 soil horizons across the United States and determined average values of the Green-Ampt parameters $\phi$, $\theta_e$, $\psi_f$, and $K$ for different soil texture classes.

Brakensiek and Rawls (1982) presented equations for applying the Green and Ampt infiltration equation to the SCS type II 24-hour standardized rainfall distribution using the tabulated Green and Ampt parameters as a function of soil texture. This procedure was coded in Fortran as a subroutine, attached as a user-defined option in the VB program, and applied to all soil associations present in the Quivira NWR and vicinity using the Rawls et al. (1983) tabulated Green and Ampt parameters. The Green and Ampt method is emphasized in this report.

## Hydrologic-budget implementation and synthesis

Having outlined the elements of the basinwide integration methodology and the VB soil-water accounting procedure, we now outline the implementation steps and synthesis of the hydrologic budget for the detailed model area encompassing the Quivira NWR.

### Hydroclimatic zones

The Rattlesnake Creek watershed was subdivided by Sophocleous and McAllister (1990) into four climatic zones, based on the distribution of available National Oceanic and Atmospheric Administration (NOAA) climatological stations covering the watershed. The study area in this report consists of only one hydroclimatic zone, covered by the Hudson climatic station, which records daily precipitation and temperature.

### Soils

Eight soil associations are found in the detailed model area around the Quivira NWR (fig. 4) based on the SCS State Soil Geographic Information System (GIS) soil coverage STATSGO. For each soil association the STATSGO GIS soil coverage reports the available water capacity of the soil profile (60 inches deep), other hydraulic properties, soil texture, and area of the soil association among other data. Soil associations, soil texture, available water capacities, area of each association in the detailed model area and in the Quivira NWR proper, and fractional areas are presented in table 1.

Given the sandy nature of most soils in the Rattlesnake Creek basin, a *Z* table typical of sandy soils (curve F in fig. 3) was chosen. The *Z* table represents the relationship between the AE/PE ratio and the plant-available soil moisture. This ratio remains constant from 100% to 30%, below which the AE/PE ratio declines sharply according to an exponential decay relationship with the drying of the soil.

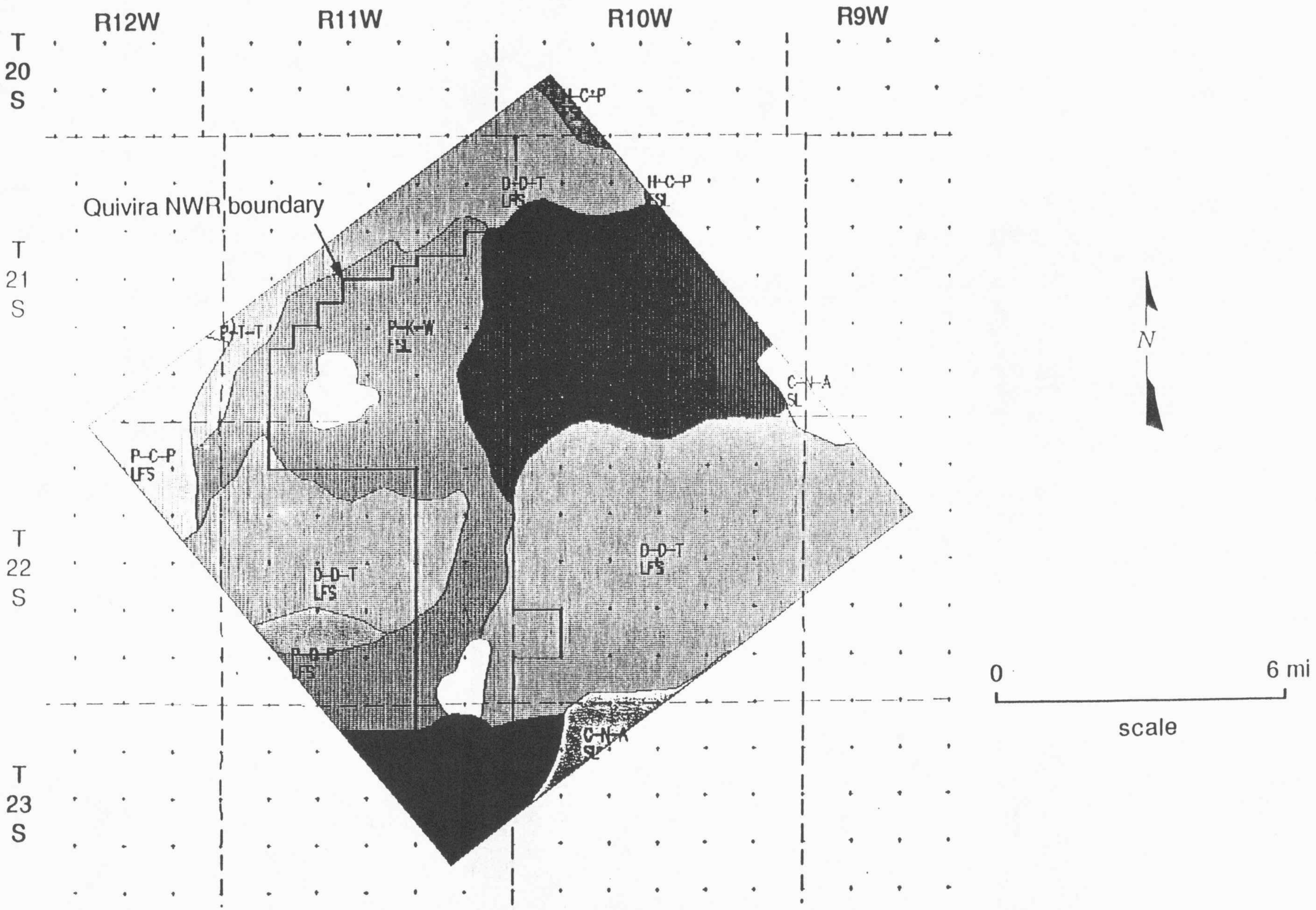

Figure 4. Soil associations in the study area (refer to table 1 for explanation of abbreviations).

Table 1. Characteristics of soil associations[a] in the vicinity of Quivira National Wildlife Refuge.

| Soil association name | Texture | Available water capacity (in./60-in. soil profile) | Acreage within detailed model area | Percentage of detailed model area | Acreage within Quivira NWR proper | Percentage of Quivira NWR area[b] |
|---|---|---|---|---|---|---|
| 1. Dillwyn-Dillwyn-Tivoli (DDT) | Loamy fine sand (LFS) | 5.13 | 41,511 | 45.61 | 3,057 | 15.02 |
| 2. Plevna-Kanza-Waldeck (PKW) | Fine sandy loam (FSL) | 7.54 | 19,713 | 21.66 | 13,083 | 64.29 |
| 3. Carwile-Farnum-Farnum (CFF) | Loam (L) | 9.46 | 16,843 | 18.51 | 3,349 | 16.46 |
| 4. Farnum-Blanket-Blanket (FBB) | Silty loam (SiL) | 9.46 | 5,282 | 5.80 | 860 | 4.23 |
| 5. Pratt-Carwile-Pratt (PCP) | Loamy fine sand (LFS) | 7.01 | 4,535 | 4.98 | 0 | 0 |
| 6. Carwile-Naron Attica (CNA) | Sandy loam (SL) | 9.27 | 2,517 | 2.77 | 0 | 0 |
| 7. Hord-Canadian-Platt (HCP) | Fine sandy loam (FSL) | 7.09 | 499 | 0.55 | 0 | 0 |
| 8. Pratt-Tivoli-Tivoli (PTT) | Loamy fine sand (LFS) | 5.13 | 106 | 0.12 | 0 | 0 |

a. Data source: SCS STATSGO.

b. This percentage excludes 1,749 acres of Little Salt and Big Salt marshes.

The water-budgeting procedure was initiated at the start of calendar year 1985 with the soil assumed to be initially at its maximum available water capacity and continued until the end of December 1992. This initial condition allowed the soil-available water capacity to equilibrate with the local climatic conditions before the more recent time period of interest.

## Vegetation and land use

The vegetation parameters are represented by crop coefficients. Each soil "zone" has a coefficient for each stage of crop growth. At different plant-growth stages, the roots can utilize the moisture in the soil profile at different depths and rates. Crop coefficients adopted for natural grassland, which was simulated as brome grass, are those presented by Baier et al. (1979) and reproduced by Sophocleous and McAllister (1990). A runoff curve number for type II (average) conditions was selected under land use cover of "pasture or range" using the hydrologic handbook classification (U.S. Department of Agriculture, 1972). We assume that this SCS land-use classification best represents the prairie grassland of our study area.

### Subbasin-wide integration

The VB water-budgeting procedure was applied to each soil association and vegetation-cover combination (only native grassland in our case) in each hydroclimatic zone (only one zone characterized by the Hudson climatic station in our case) to obtain daily values of the water-balance components during 1985–1992. The areas of each soil association were determined from the SCS STATSGO GIS coverages (table 1). The components of the water balance for the different types of soil–vegetation–climatic region complexes were determined by areally weighting the average of all three methods (GA, VB, SCS-CN) by the fractional (percentage) areas of each soil association complex (table 1) and summing the results.

## Results and discussion

Climatic, soil, crop, and land-use parameters all affect the amount and distribution of the various hydrologic variables, namely, runoff, evapotranspiration, deep drainage, and soil-water deficit. Figures 5 through 9 display the cumulative daily hydrologic balance components from 1985 through 1992 for all major soil associations in the detailed model area, assuming native grass vegetation cover and starting with initial soil profile water content at field capacity, i.e., starting with zero soil-water deficit. These results were obtained from the VB model using the Green and Ampt equations for estimating infiltration and surface runoff.

### Climatic factors

Solar radiation and temperature greatly affect the evaporative regime of an area; consequently, evapotranspiration varies seasonally (figs. 5–9) in response to these climatic factors. Thus, during the winter period, the evapotranspiration regime is at its minimum. Local climate, irrigation, variations in transpiration rates among different crops, and soil factors exert

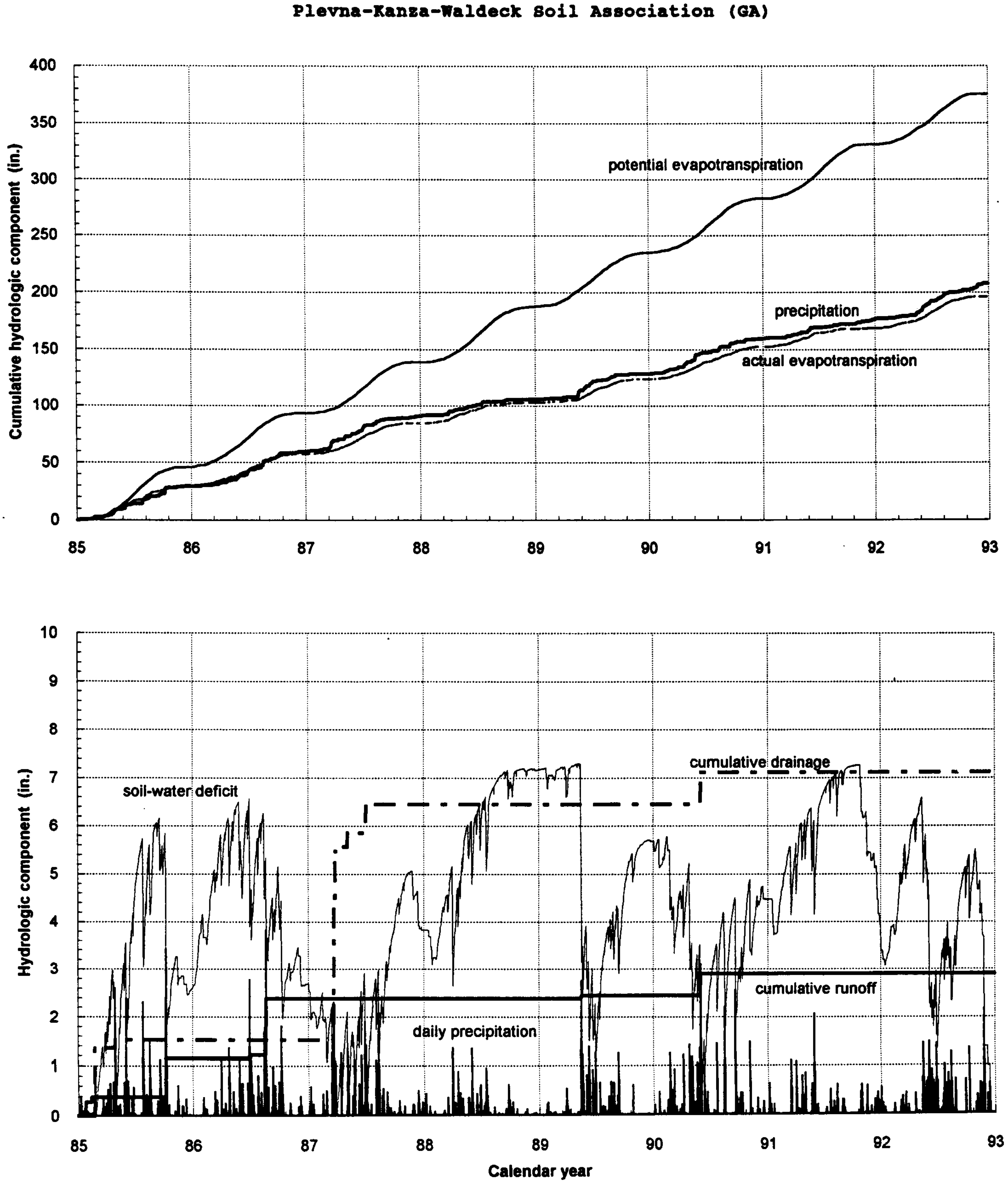

Figure 5. Cumulative daily hydrologic balance components from 1985 through 1992 for Plevna-Kanza-Waldeck soil association.

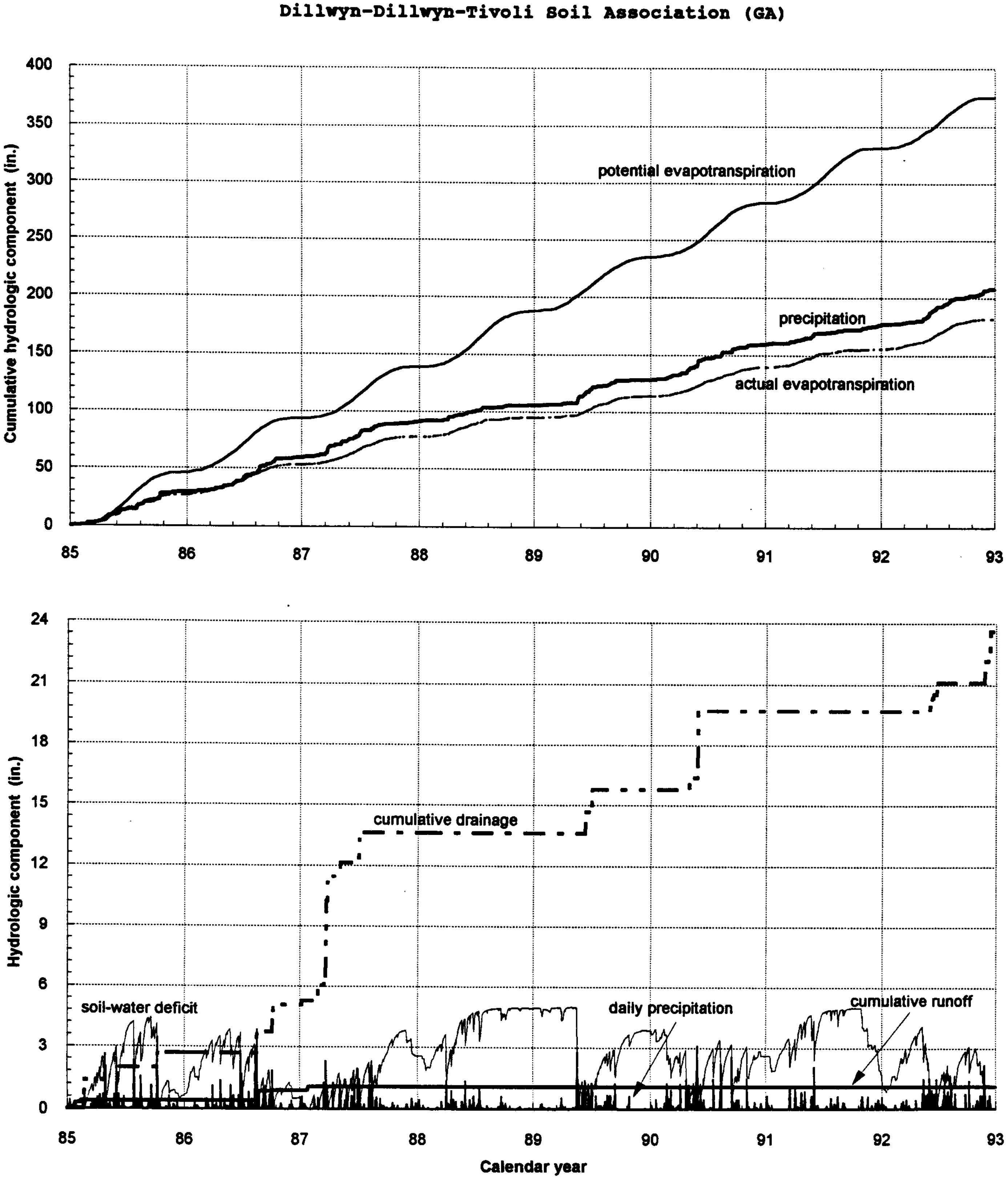

Figure 6. Cumulative daily hydrologic balance components from 1985 through 1992 for Dillwyn-Dillwyn-Tivoli soil association.

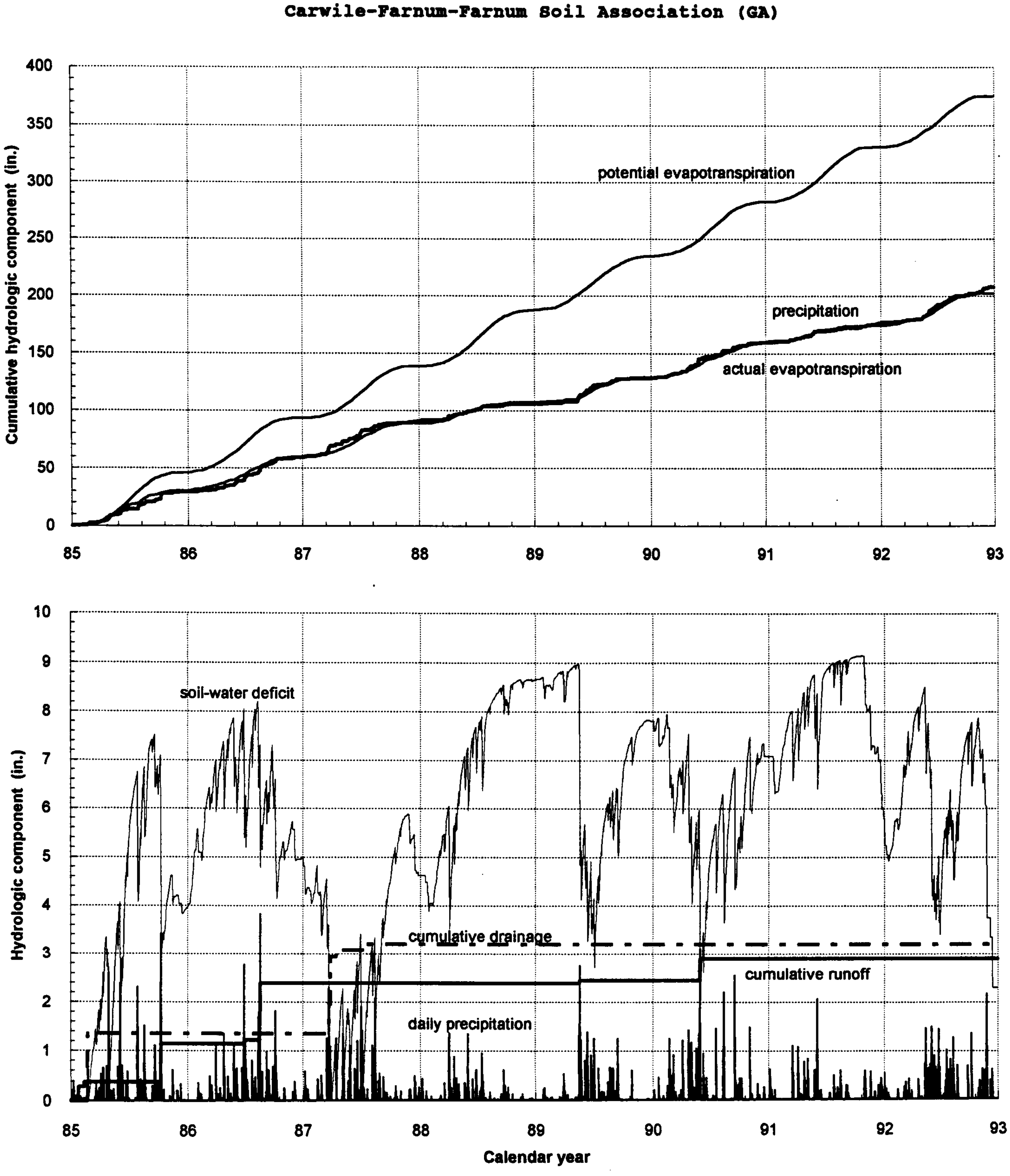

Figure 7. Cumulative daily hydrologic balance components from 1985 through 1992 for Carwile-Farnum-Farnum soil association.

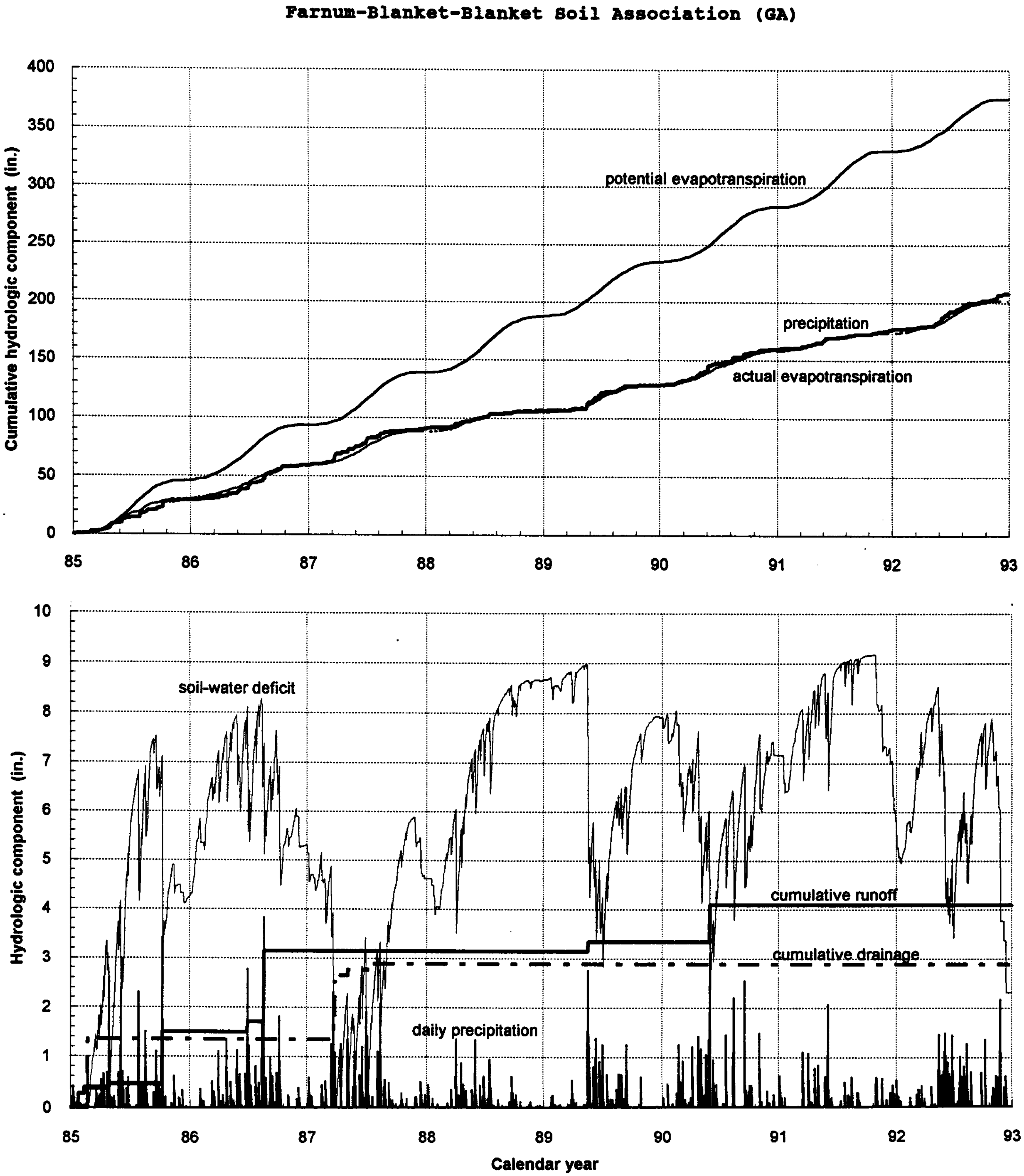

Figure 8. Cumulative daily hydrologic balance components from 1985 through 1992 for Farnum-Blanket-Blanket soil association.

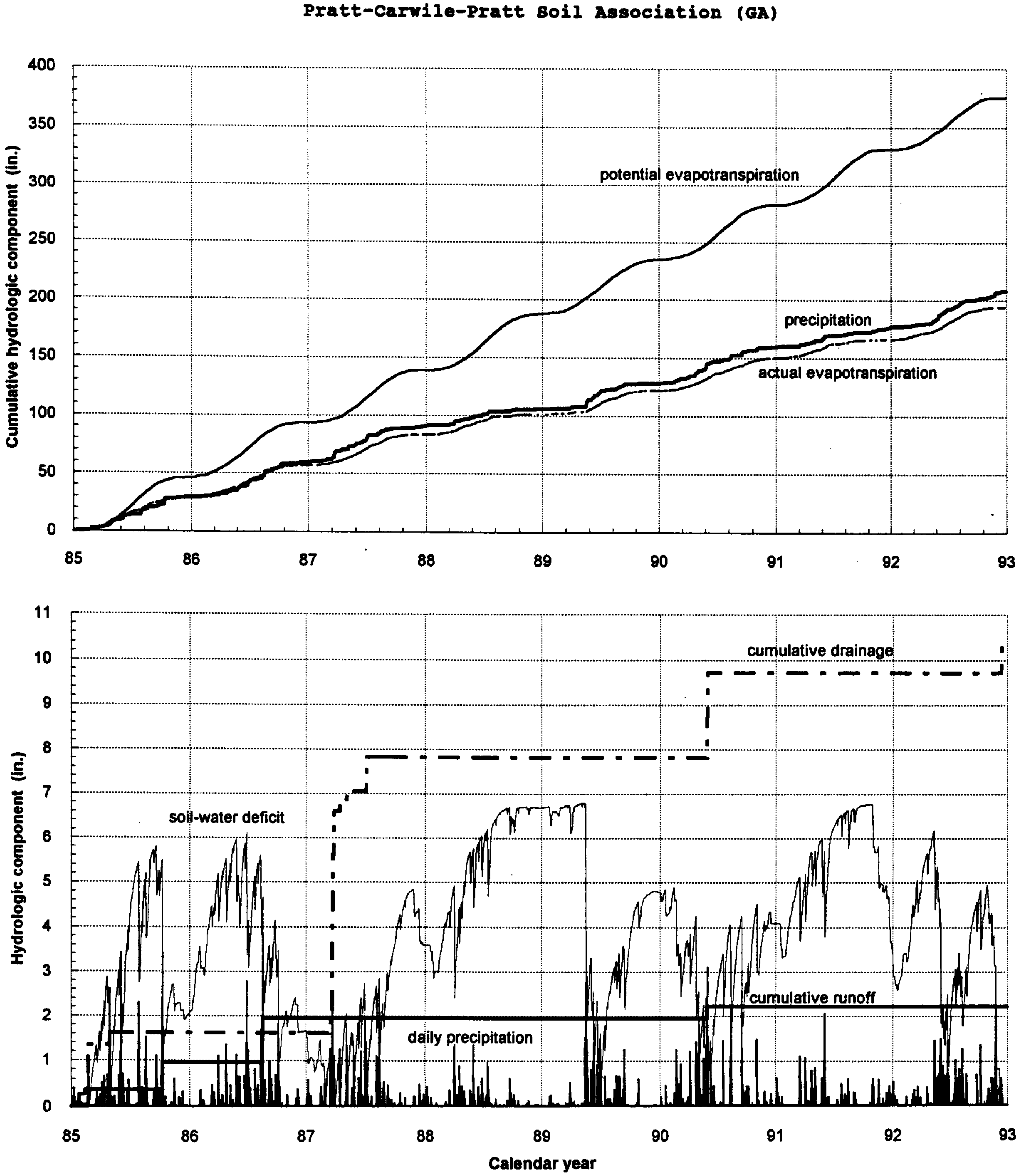

Figure 9. Cumulative daily hydrologic balance components from 1985 through 1992 for Pratt-Carwile-Pratt soil association.

additional influences on evapotranspiration, as demonstrated by Sophocleous and McAllister (1990).

Potential evapotranspiration is much higher than the amount of annual precipitation received in the area, whereas actual evapotranspiration is of the same order of magnitude as precipitation. Precipitation is the primary water-supply source in the area and exerts a major influence on the components of the hydrologic cycle. Average annual precipitation during the last 8 years (1985–1992) at the Hudson climatic station is 25.99 inches, and average annual potential and actual evapotranspiration for the dominant soil association in the Quivira NWR (Plevna-Kanza-Waldeck) are 46.94 and 24.52 inches, respectively. The annual water-balance components from 1985 through 1992 for all soil associations in the area calculated from daily values using the Green and Ampt infiltration and runoff procedure are shown in figs. 10 through 14. The same water-balance components are presented in table form (tables I.1–I.5 of Appendix I) using all three runoff estimation procedures (GA, VB, SCS-CN). Appendix II contains the annual water-balance components in graphical form using the original VB results.

## Soil factors

The basic soil parameter affecting the hydrologic variables in this model is the available water capacity (AWC) of the root zone. The soil hydraulic conductivity is incorporated indirectly in the model through the choice of a Z table in the original VB model or directly as a parameter in the Green and Ampt procedure of the model as a function of soil texture. The AWC of each soil determines the maximum limit of actual evapotranspiration that can be extracted without additional infiltration and the maximum soil-water deficit possible. Thus, given the same hydroclimatic conditions and vegetation cover, a soil with a relatively low AWC will exhibit a relatively small soil-water deficit, and smaller amounts of water will be lost through ET compared with losses from a soil with a higher AWC. This response differential can be clearly seen (figs. 5–14; tables I.1–I.5, Appendix I) by comparing the water-balance components of the Dillwyn-Dillwyn-Tivoli soil association, which has the lowest AWC (5.13 in./5-ft. soil profile),

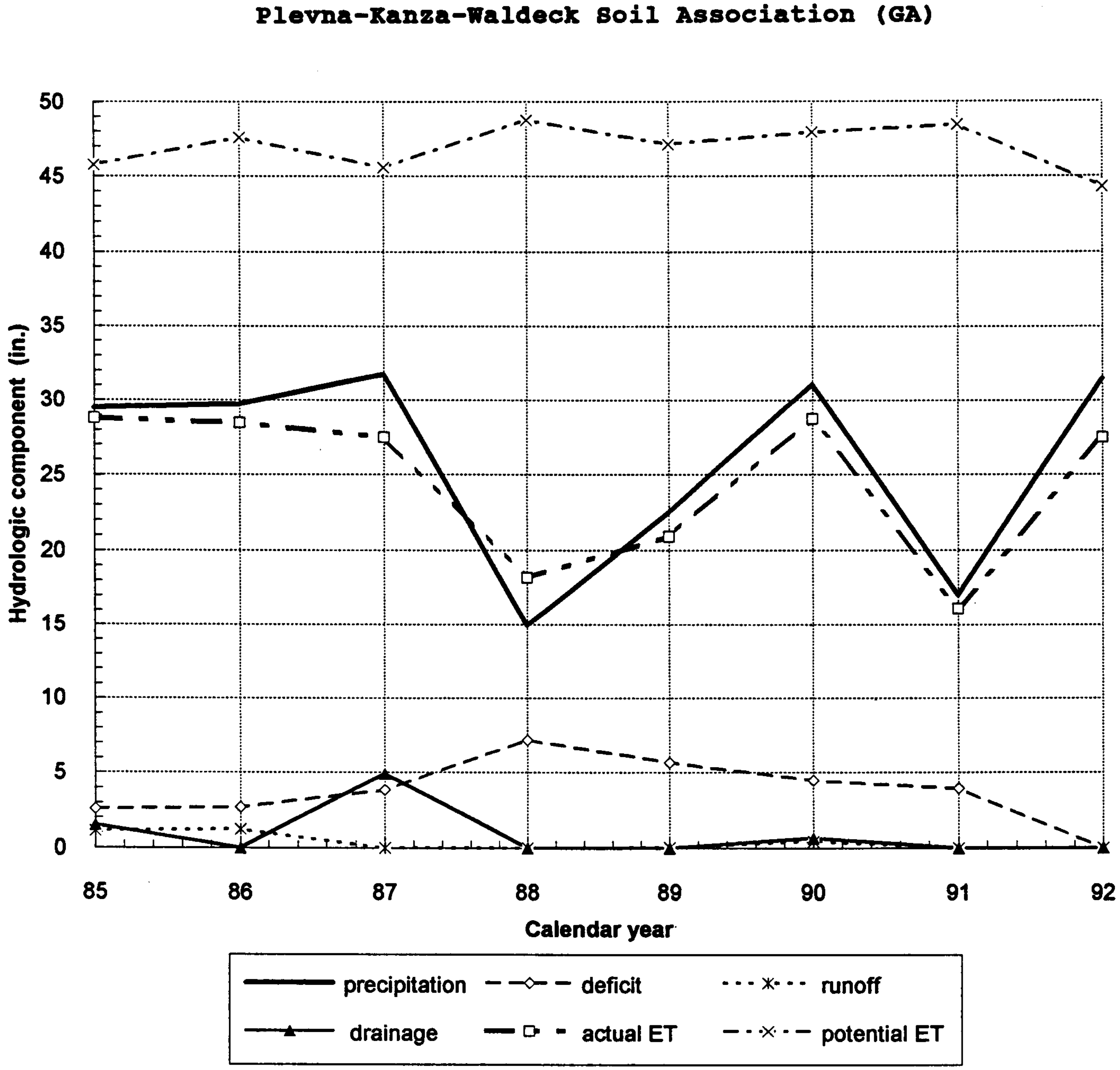

Figure 10. Annual water-balance components from 1985 through 1992 for Plevna-Kanza-Waldeck soil association.

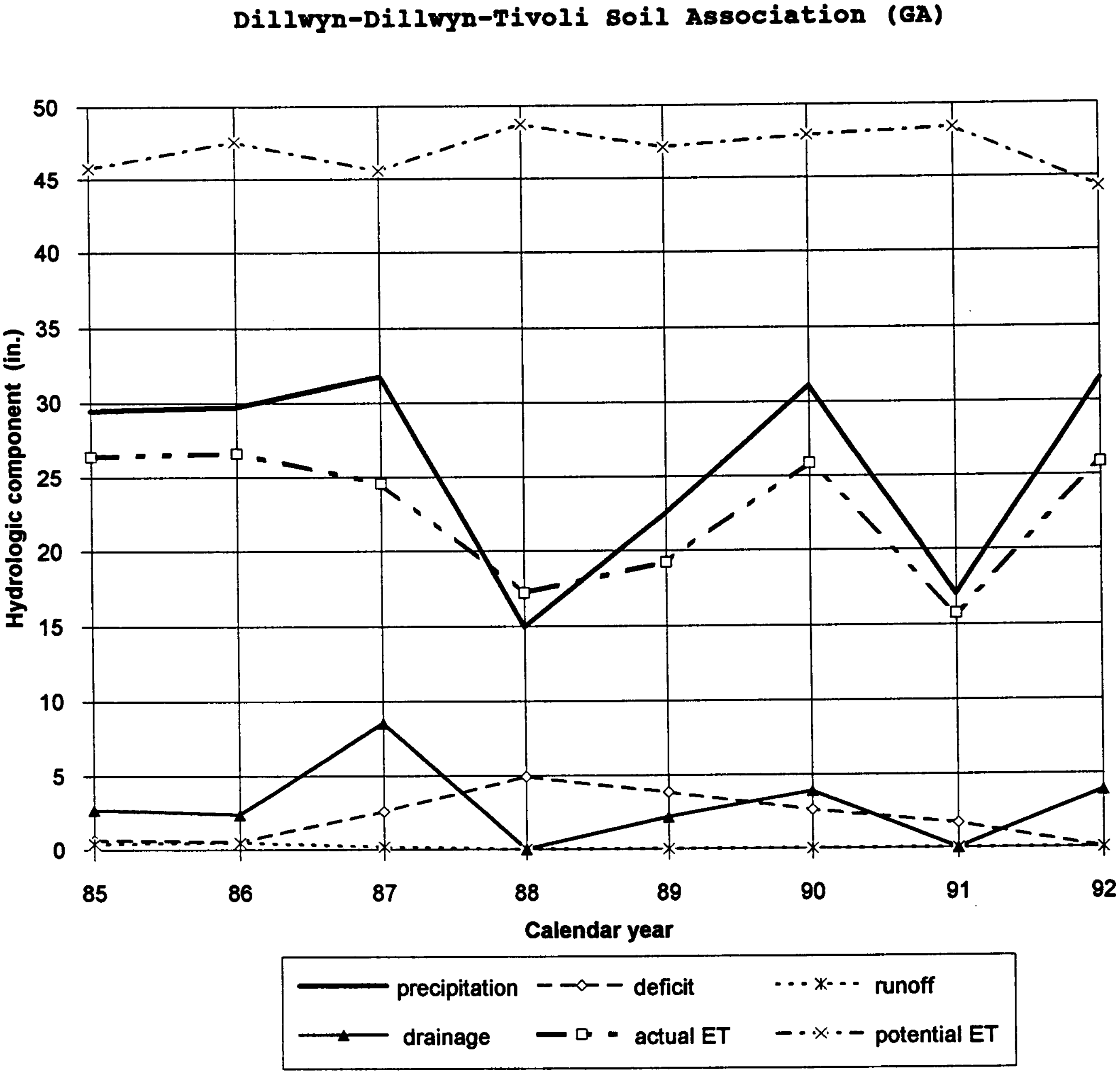

Figure 11. Annual water-balance components from 1985 through 1992 for Dillwyn-Dillwyn-Tivoli soil association.

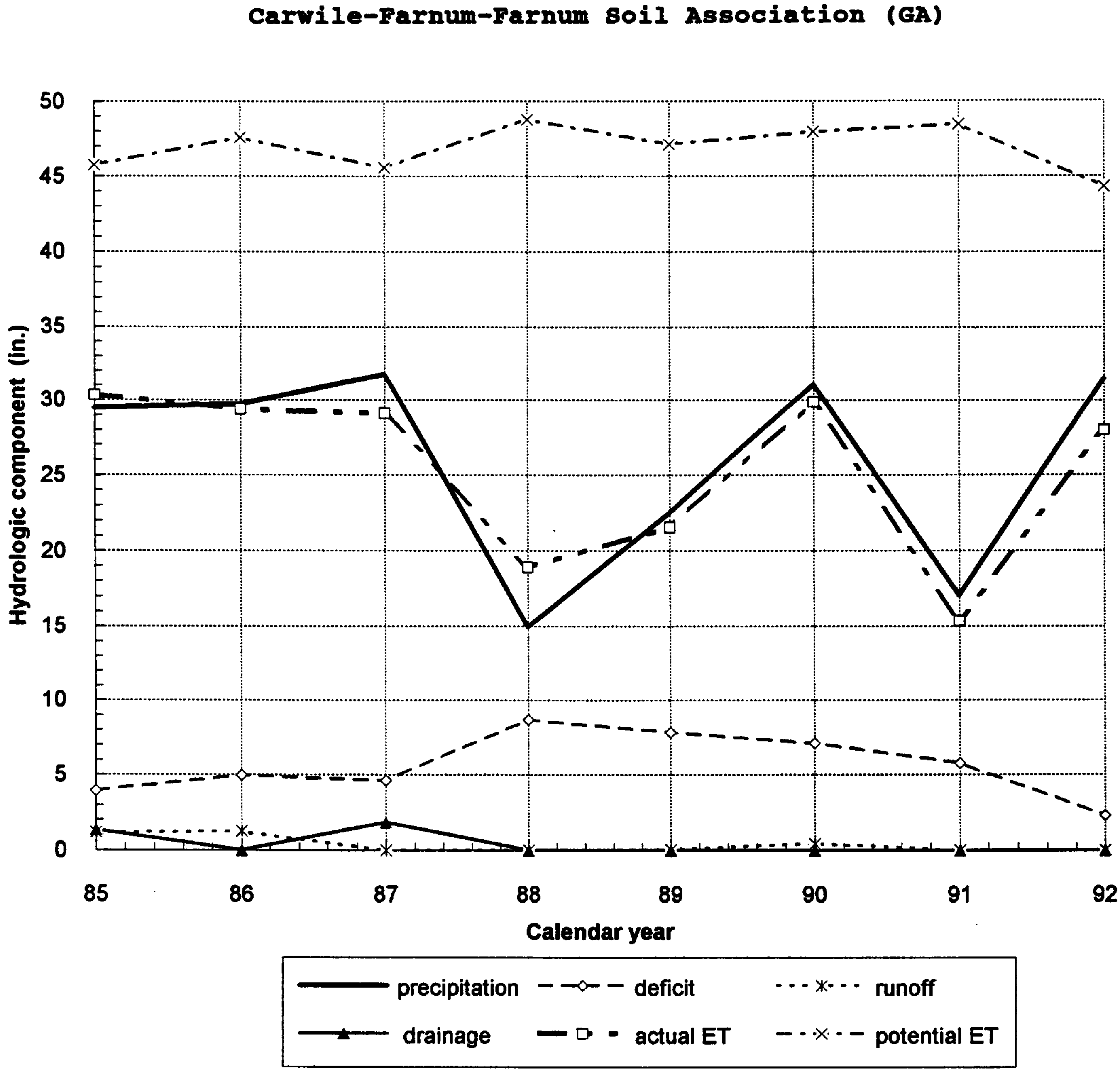

Figure 12. Annual water-balance components from 1985 through 1992 for Carwile-Farnum-Farnum soil association.

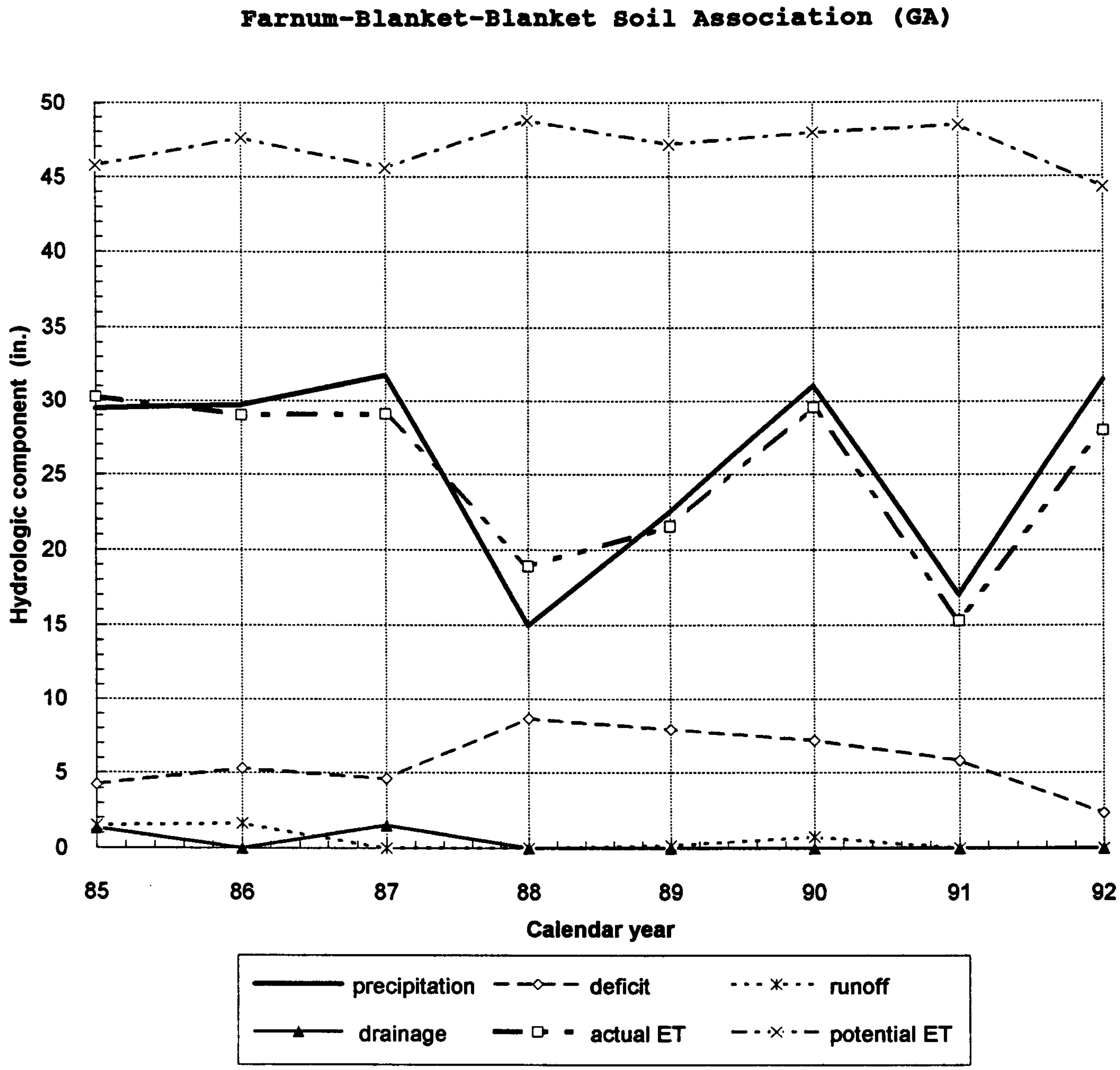

Figure 13. Annual water-balance components from 1985 through 1992 for Farnum-Blanket-Blanket soil association.

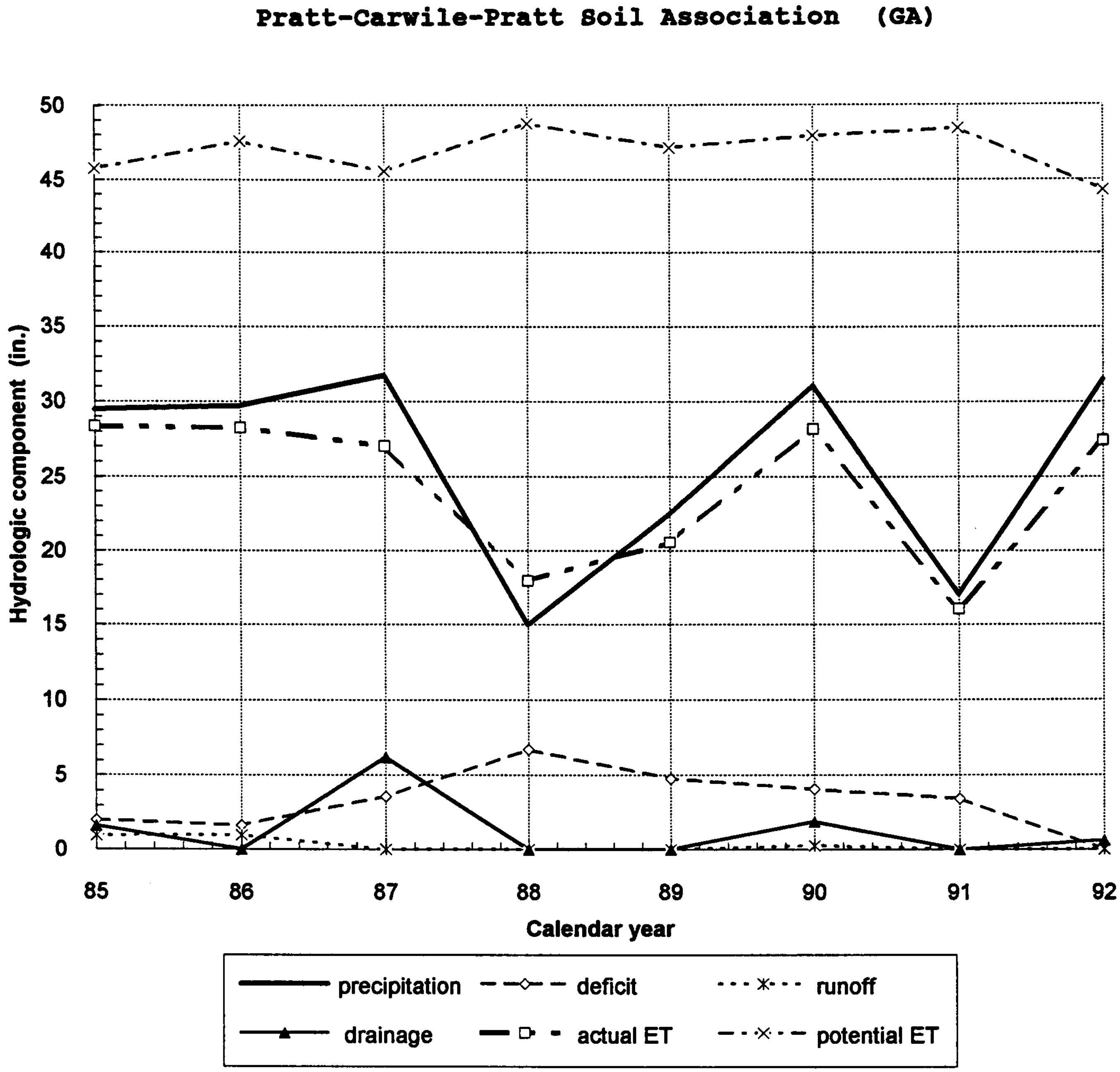

Figure 14. Annual water-balance components from 1985 through 1992 for Pratt-Carwile-Pratt soil association.

with the Farnum-Blanket-Blanket and Carwile-Farnum-Farnum soil associations, which have the highest AWC (9.46 in./5-ft. soil profile) of all the soil associations in the detailed study area. Final soil-water deficit values are not monotonically cumulative as are the values of precipitation, evapotranspiration, drainage, and runoff, but are a running algebraic total (with positive and negative values). The final soil-moisture deficit total is responsive mainly to the weather conditions of the previous few weeks.

The AWC also determines the amount of water that can infiltrate the soil before deep drainage occurs. The AWC acts as a buffer for infiltrating water. Thus deep drainage decreases with increasing AWC (figs. 5–14; tables I.1–I.5). Given the same initial moisture conditions, a soil with higher AWC can absorb more infiltrating water than low-AWC soils. The soil-moisture conditions, especially the current soil-moisture deficit, affect the quantity of water that can infiltrate and run off from the various soils. The original VB and SCS-CN runoff estimation procedure resulted in generally higher surface runoff values compared with the Green and Ampt results, which we believe reproduce the field observations more closely. As a result of the lower surface runoff, the Green and Ampt-derived deep drainage values are relatively higher than the original VB and SCS-CN ones (figs. 5–14; tables I.1–I.5). However, all three different estimation procedures (original VB, GA, and SCS-CN) resulted in estimates of the same order of magnitude.

The average water-balance components based on all three methods (GA, VB, and SCS-CN) for the different types of soil–vegetation–climatic region complexes, weighted by the proportion of each soil association over the entire area of the Quivira NWR, are shown in figs. 15 and 16 and table 2. The predominance of the precipitation and evapotranspiration components over the relatively minuscule runoff and drainage components is clearly evident.

### Vegetation and land use

The water balance also is greatly influenced by the plant cover and land-use practice. The impact of vegetation on the hydrologic balance is complex and depends on such factors as

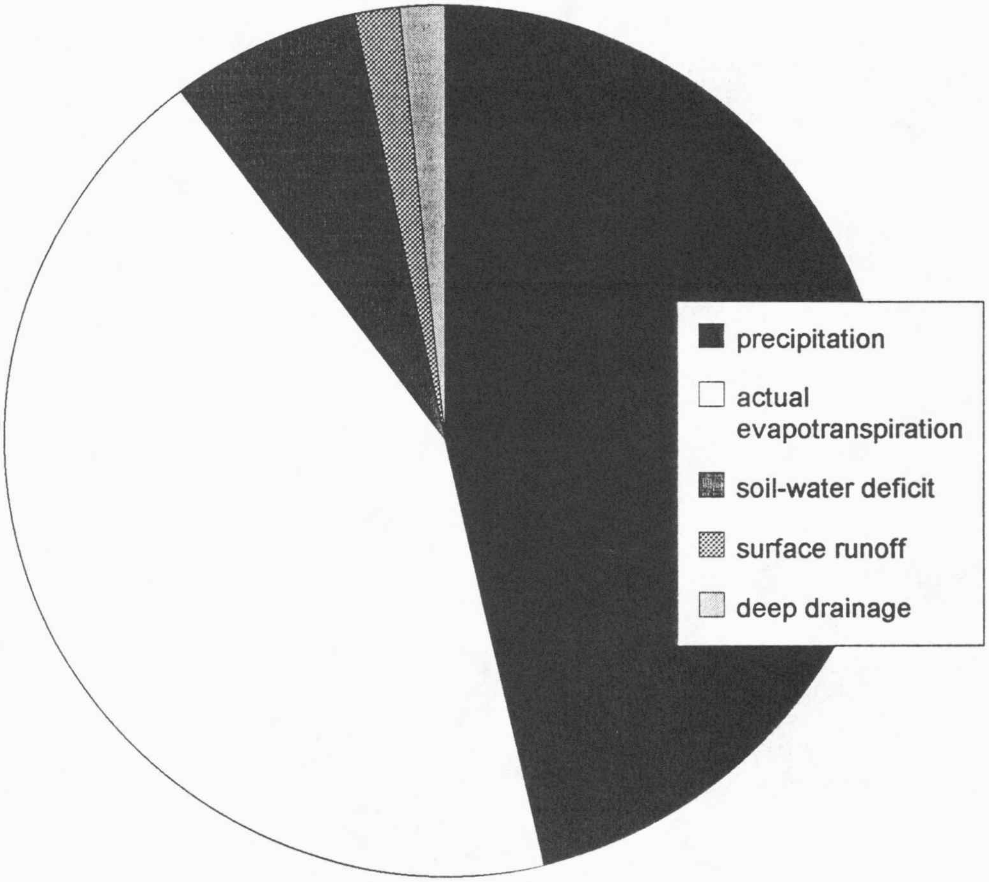

Figure 15. Area-weighted three-method (original VB, GA, and SCS-CN) average water-balance pie diagram for the Quivira NWR area.

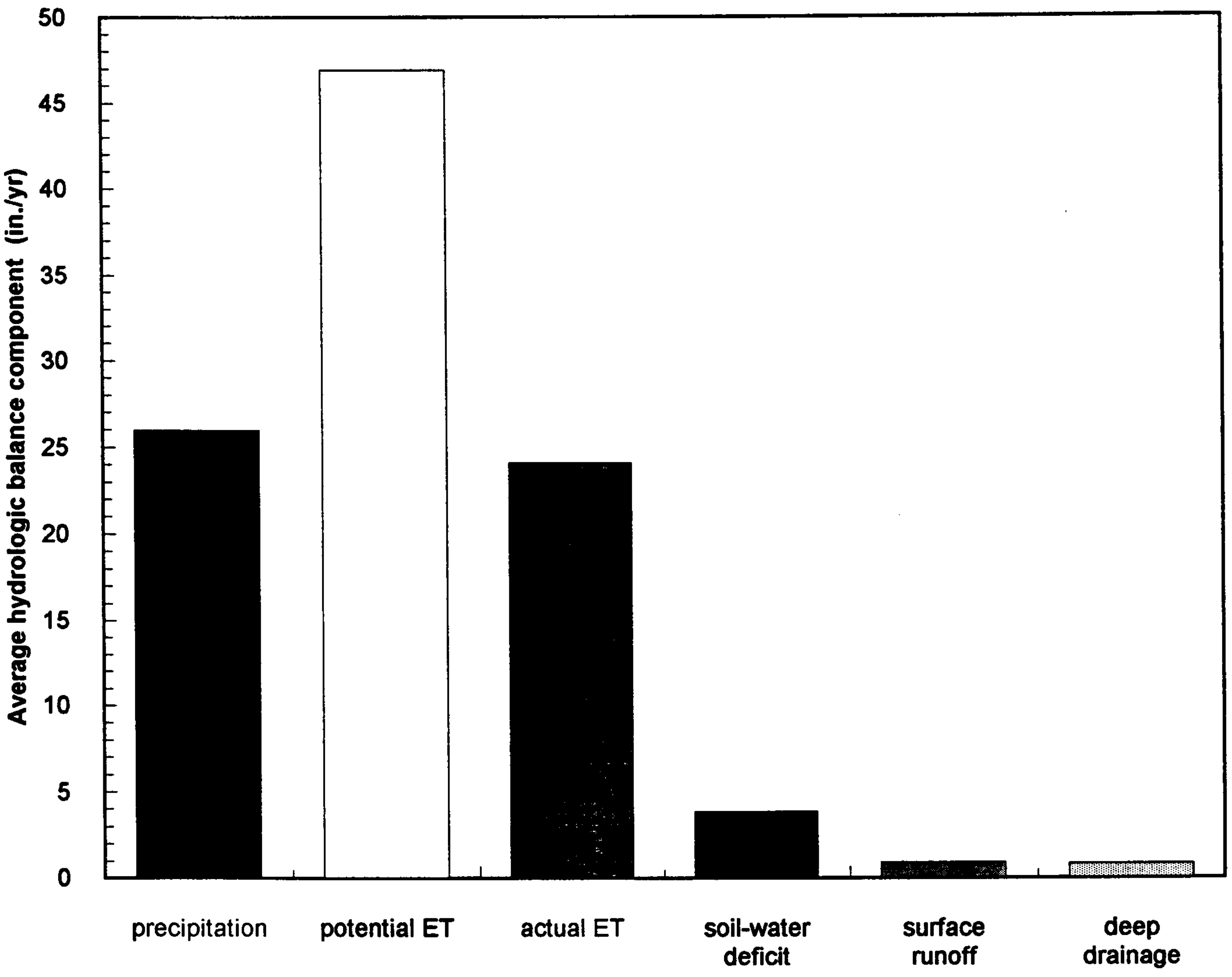

Figure 16. Area-weighted three-method (original VB, GA, and SCS-CN) average water-balance bar graph for the Quivira NWR area.

Table 2. Three-method (GA, VB, SCS) average yearly hydrologic balance components for the area pertaining exclusively to the Quivira National Wildlife Refuge (climatic data from Hudson NOAA station).[a]

| Year | Precipitation | PE | AE | Deficit | Runoff | Drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 28.19 | 2.44 | 1.77 | 1.33 |
| 1986 | 29.68 | 47.59 | 28.15 | 2.23 | 0.76 | 0.44 |
| 1987 | 31.75 | 45.57 | 27.12 | 3.73 | 1.57 | 4.11 |
| 1988 | 14.98 | 48.78 | 18.00 | 6.94 | 0.06 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.58 | 5.83 | 0.60 | 0.18 |
| 1990 | 31.05 | 47.93 | 28.02 | 4.96 | 1.71 | 0.45 |
| 1991 | 17.04 | 48.46 | 15.49 | 3.82 | 0.04 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.21 | 0.76 | 0.73 | 0.45 |
| 8-yr total | 207.91 | 375.52 | 192.76 | 30.70 | 7.22 | 6.96 |
| 8-yr average | 25.99 | 46.94 | 24.09 | 3.84 | 0.90 | 0.87 |

a. All data in inches/year.

crop coefficients, growth stages, rooting depths, and soil, water, and climatic conditions as used in this simulation model. However, because our detailed model area is predominantly natural grassland, the vegetation cover and land-use practice effects are not demonstrated here. The interested reader is referred to Sophocleous and McAllister (1987, 1990) for a detailed analysis of those effects. We only quote here some of the relevant conclusions:

> Vegetation and land use (i.e., dryland or irrigated farming) play a significant role in the components of the water balance, especially in the ET process. Thus, evapotranspiration from irrigated-alfalfa acreages is approximately triple that from wheat-fallow fields, and ET amounts from cornfields are approximately double that from wheat-fallow acreages. ET from grasslands is almost 30% higher than that from dryland wheat-fallow fields. Most of the irrigation amounts for summer crops, such as sorghum and soybean, are spent in ET activities with negligible amounts for deep drainage. Deep drainage from irrigated wheat fields is significantly higher than from dryland wheat fields and minimal from alfalfa fields. Dryland wheat-soybean rotations and cornfields create significantly higher soil-moisture deficits compared to irrigated wheat-sorghum fields, assuming that farmers irrigate the appropriate amounts for each crop. Everything else being equal, the lowest runoff values occurred from prairie grasslands and alfalfa fields. We therefore conclude that the effects of vegetation and land use are too significant to be ignored, and therefore, more research efforts into the biological phase of water-balance computations are in order. (Sophocleous and McAllister, 1990, p. 58.)

## Temporal distributions of climatic and hydrologic variables

The time distribution of important climatic and hydrologic components (maximum and minimum air temperature, precipitation, soil-water deficit of the root zone, deep drainage, and surface runoff as well as cumulative values of potential and actual evapotranspiration and precipitation) are graphically presented for the two predominant soil associations [Dillwyn-Dillwyn-Tivoli (DDT), and Plevna-Kanza-Waldeck (PKW)] in the detailed model area and for the vegetation cover (native grassland) for the 1986 (DDT) and 1990 (PKW) calendar years (figs. 17 and 18). Note the coincidence of highest precipitation and deep drainage that occurs during the spring. The relatively high water consumption of grasslands, as reflected by their high crop coefficients, compared with wheat reduces deep-drainage amounts during the spring when most deep drainage occurs.

## Areal distribution of hydrologic variables

Information on the distribution of deep drainage, evapotranspiration, and runoff over the entire Rattlesnake watershed resulting from the VB methodology is reported by Sophocleous and McAllister (1987, 1990). They concluded that the smallest deep drainage values (in the range of 0–2 inches) occurred in the northeastern portion of the watershed because a significant portion is natural grassland (which possesses a deep rooting system and a long active life cycle) with no significant irrigation development, relatively high moisture capacity soils such as the Rattlesnake Creek alluvium-derived Plevna-Kanza-Waldeck soil association, and relatively lower precipitation compared with the upper (southwestern) portion of the watershed, as represented by the Bucklin climatic station. The lowest runoff values (0.2–0.5 inches) occurred in the northeast portion of the watershed, which is covered to a large extent by grassland, nonirrigated crops, and relatively high soil-moisture capacities in combination with relatively low precipitation.

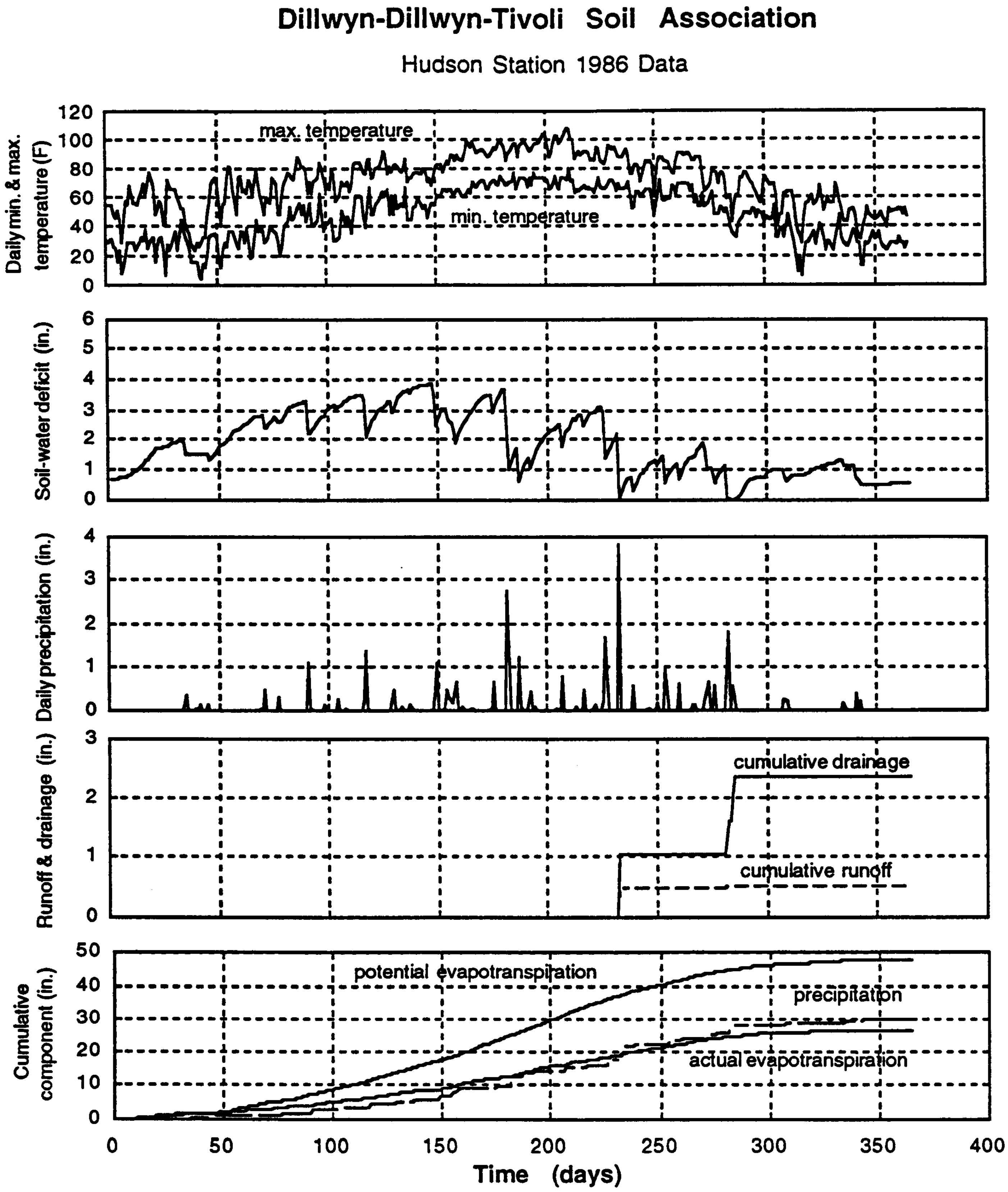

Figure 17. Time patterns of water-balance components for the 1986 calendar year for the Dillwyn-Dillwyn-Tivoli soil association in the Quivira NWR area.

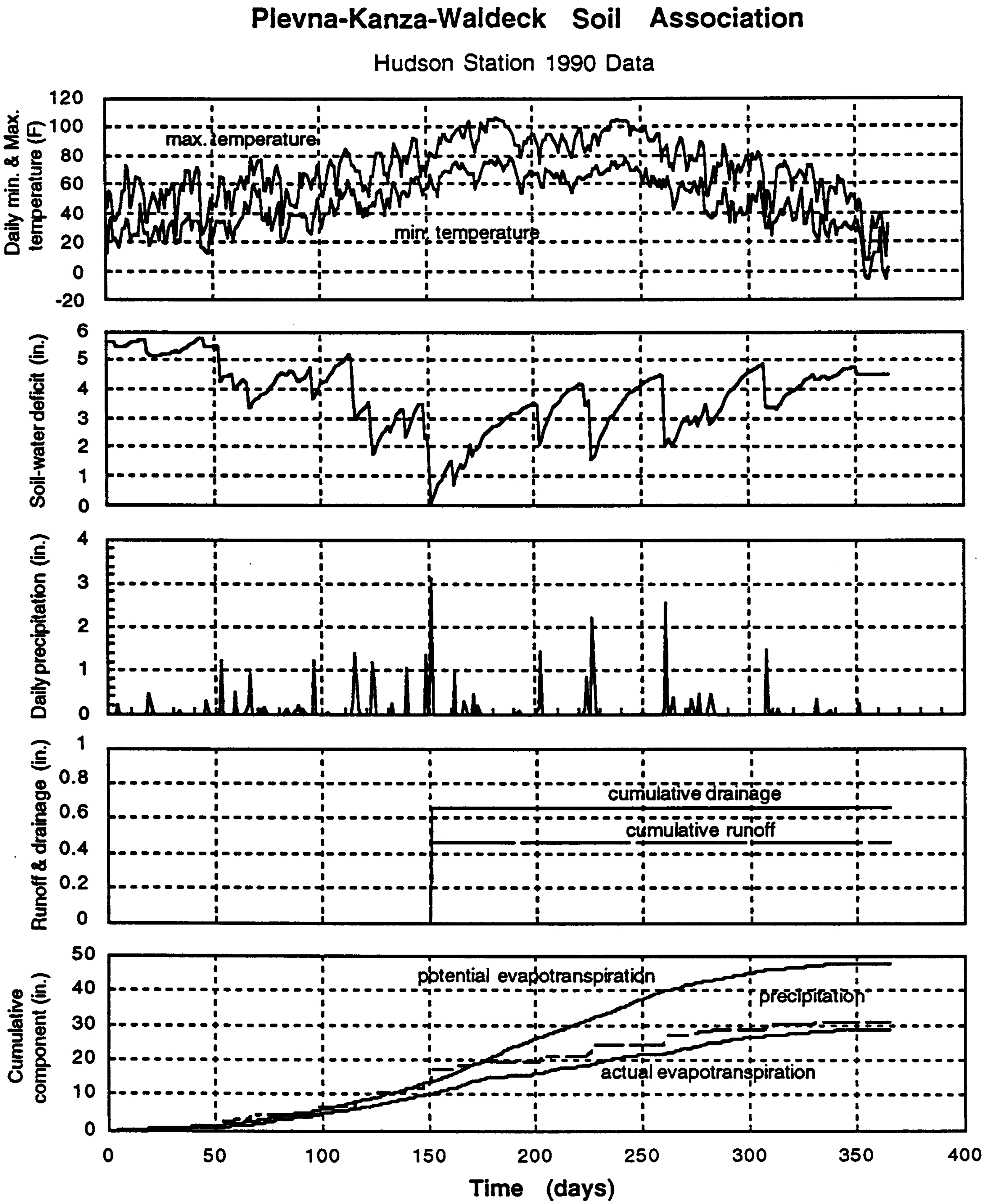

Figure 18. Time patterns of water-balance components for the 1990 calendar year for the Plevna-Kanza-Waldeck soil association in the Quivira NWR area.

## Predictive capabilities

To demonstrate the power of such water-budgeting methodology, we quote the following section from Sophocleous and McAllister (1990, p. 48).

> A computerized water-balance procedure can be used to predict human and natural impacts on the hydrologic cycle. The hydrologic effects of vegetation changes, weather modification, extreme weather conditions, and so on can be readily estimated during the planning process. Thus, had the Rattlesnake watershed been entirely covered by prairie grasses, as it probably was during predevelopment time, and had the 1982–83 precipitation pattern and amount prevailed, the overall watershed deep drainage would have been 1.13 inches (2.87 cm), compared to 0.15 inches (0.38 cm) if alfalfa were planted exclusively in the watershed. If the entire watershed were planted with dryland wheat under 1982–83 precipitation conditions, the overall watershed deep drainage would have been 5.1 inches (12.9 cm). Such figures can be arrived at by multiplying the deep-drainage amounts for the corresponding crop and soil complex ... by the planted area ... summing these figures, and dividing by the area of interest ... Similarly, the hydrologic effects of manipulating the proportion of various crops and the amounts of irrigation within any soil-association area can thus be assessed.
>
> Provided that future precipitation patterns can be established, then, under known vegetation and land-use practices, various components of the water balance, such as deep drainage and surface runoff, can be readily predicted within the watershed using the presented methodology.

Daily weather generation routines, such as those of Richardson and Wright (1984), can be added to the water budgeting procedures so that future hydrologic budget components can be more reliably predicted.

## Model assumptions and verification

Many assumptions are inherent in the simplification of complex problems such as simulating the water balance of the Rattlesnake watershed or a portion thereof. The most important variables contributing to the water budget are believed to be accounted for in this study, and the various assumptions and simplifications made are believed to contribute only minor errors in comparison to the scale and totality of the problem. Sophocleous and McAllister (1987, 1990) outlined the main assumptions in the VB methodology. The major simplifications and assumptions have also already been mentioned in the "Versatile soil-moisture budget" and "Versatile budget model modifications" sections of this report. With regard to the Green and Ampt method, we assumed that the SCS standardized type II rainfall distribution and the Rawls et al. (1983) tabulated average Green and Ampt parameters are typical of the conditions in the model area. We also assumed for the CN selection that the SCS land-use classification for "pasture and range" with high-infiltration soils (soil group A—low runoff potential) reasonably represents the conditions of the study area.

The estimates from the VB have been extensively verified by comparing them to measured data and by evaluating the efficiency of such estimates in explaining variations of observed crop yields (Baier et al., 1976, 1979; Dyer and Mack, 1984). Sophocleous and McAllister (1987, 1990) demonstrated the validity of the VB-based hydrologic balance results for the Rattlesnake Creek watershed in addition to pointing out studies by other researchers who also demonstrated the validity of the VB methodology.

R. De Jong, 1988, of Agriculture Canada, compared and tested the VB and the more elaborate and therefore more data-requiring soil-plant-air-water (SPAW) model (Saxton et al., 1974; Sudar et al., 1981) against soil-water content data from a long-term experiment in which wheat was grown on fallow land in the semi-arid zone of Saskatchewan, Canada (De Jong, 1988). Quoting from the conclusions of that study (p. 24–26):

> The predicted cumulative [water] flow values were very similar [as calculated by the two models] under the semi-arid conditions in this study. ...Both models predicted similar drainage across the 15-cm depth [layer] during rainy periods [and] both models gave reasonable estimates of evapotranspiration....
>
> For the soil and semi-arid conditions of this study, both the VSMB [i.e., VB] and the SPAW model satisfactorily predicted water contents at various times during the growing season. With either model the mean absolute difference in soil water content to a depth of 120 cm was less than 2.0 cm at any growth stage during the 12 y [years] of investigation. Estimated distribution of water in the profile was also satisfactory with both models....More detailed soil and crop information is needed as input to this [SPAW] model as compared with the VSMB [VB].

De Jong (1988) concluded that "a choice between the two models, to be used under semi-arid growing conditions, will depend on the availability of input data and the required level of output" (p. 17).

## Summary and conclusions

In this report we developed a detailed but simple hydrologic budget for a portion of Rattlesnake watershed encompassing the Quivira NWR (145 mi$^2$) in south-central Kansas. With this budget, using minimal daily weather input data and the soil-plant-water system-analysis methodology, we were able to characterize the 1985–1992 distribution of the hydrologic components of the water balance in the study area. A combination of classification and meteorological methods resulted in a subbasin integration methodology. The classification method consisted of dividing the watershed into climatic subregions (one, in our case), grouping soil series into major soil associations (already done in the STATSGO GIS), dividing each soil association into land-use classes, such as irrigated and nonirrigated cropland and grassland (only grassland in our case), and finally superimposing a crop rotation practice on the land usage (nonapplicable for our study area). The meteorological method consisted of running the VB water-budgeting procedure for each soil association, crop type, land-use practice, and climatic region combination. Area-weighted averages were then calculated to integrate the soil-plant-weather complexes on the Quivira NWR scale.

The validity and performance of the VB procedure for providing sufficiently accurate estimates of daily soil moisture have been extensively covered in the literature. The performance of the budget in combination with the integration methodology presented here has been shown in this report to provide a suitable tool for the subregional estimates of various hydrologic variables from standard climatic, soil, and crop data for agricultural watersheds. The VB procedure employed in this study is simple to understand and use. Thus the objective of this study—to develop a sufficiently detailed and relatively simple hydrologic budget able to characterize the temporal and spatial distribution of the hydrologic components for the Quivira NWR—has been achieved.

For the Rattlesnake watershed, precipitation was demonstrated to be the principal natural water supply, and evapotranspiration is the major water-depletion process. These water-balance components dominate and control all other hydrologic variables, such as runoff, deep drainage, and soil-water deficit. Thus storage methods designed to minimize evapotranspiration, such as minimizing the surface area of water impoundments by using deep-water storage, will significantly increase the amount of water that can be used for management.

Soil factors, such as the available water capacity (AWC) of soil profiles, play a dominant role in soil-water deficit development; the larger the AWC, the larger the resulting soil-water deficit, given appropriate and equal conditions. Soil factors also significantly affect deep drainage; the lower the AWC, the higher the deep drainage, everything else being equal.

The VB model program code was made more flexible by incorporating user-selected subroutines for infiltration and surface runoff determinations, among other changes. The physically based Green and Ampt infiltration-based runoff estimation procedure was found particularly useful for our case study. With this procedure, we calculated the area-weighted hydrologic budget components for the last eight years (1985–1992) using the average of the three estimation procedures (original VB, SCS-CN, and GA) as follows (the GA results are shown in parentheses): precipitation, 25.99 in./yr; actual ET, 24.09 (24.41) in./yr; soil-water deficit, 3.84 (3.95) in./yr; surface runoff, 0.90 (0.33) in./yr; and deep drainage 0.87 (1.1) in./yr. These values are in agreement with what is observed in the area. Note that the deep drainage is practically equal to ground-water recharge because of the relatively shallow depth to water table in the Quivira NWR. This estimate is of the same order of magnitude as the independently derived recharge estimate for the region based on parameter estimation by inverse modeling techniques of the stream-aquifer system described by Sophocleous and Perkins (1993).

## Acknowledgments

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## References

Baier, W., 1967. Recent advances in the use of standard climatic data for estimating soil moisture. Annals of Arid Zone, v. 6, no. 1, p. 1–21.

Baier, W., 1968. Relationships between soil moisture, actual, and potential evapotranspiration; *in*, Soil Moisture: Proceedings, Hydrology Symposium 6, Queen's Printer, Ottawa, p. 155–204.

Baier, W., 1969. Concepts of soil-moisture availability and their effects on soil-moisture estimates from a meteorological budget: Agricultural Meteorology, v. 6, p. 165–178.

Baier, W., and Robertson, G. W., 1965. Estimation of latent evaporation from simple weather observations: Canadian Journal of Plant Science, v. 45, p. 276–284.

Baier, W., and Robertson, G. W., 1966. A new versatile soil-moisture budget: Canadian Journal of Plant Science, v. 46, p. 299–315.

Baier, W., Dyer, J. A., and Sharp, W. R., 1979. The versatile soil moisture budget: Technical Bulletin 87, Agrometeorology Section, Research Branch, Agriculture Canada, Ottawa, Ontario, 52 p.

Baier, W., Davidson, H., Desjardins, R. L., Ouellet, C. E., and Williams, G. D. V., 1976. Recent biometeorological applications to crops: International Journal of Biometeorology, v. 20, no. 2, p. 108–127.

Brakensiek, D. L., and Rawls, W. J., 1982. An infiltration based runoff model for a standardized 24-hour rainfall, Transactions of the American Society of Agricultural Engineers, no. 6, p. 1,607–1,611.

Brakensiek, D. L., and Rawls, W. J., 1988. Effects of agricultural and rangeland management systems on infiltration: Proceedings of the American Society of Agricultural Engineers, Symposium on Modeling Agricultural, Forest, and Rangeland Hydrology, p. 244–251.

Brakensiek, D. L., Englewan, R. L., and Rawls, W. J., 1981. Variation within texture classes of soil water parameters: Transactions of the American Society of Agricultural Engineers, v. 24, no. 2, p. 335–339.

Brooks, R. H., and Corey, A. T., 1964. Hydraulic properties of porous media. Hydrology Paper 3, Colorado State University, Fort Collins.

Carter, V., Bedinger, M. A., Novitzki, R. P., and Wilen, W. O., 1978. Water resources and wetlands; *in,* Wetland Functions and Values the State of our Understanding; P. E. Greeson, J. R. Clark, and J. E. Clark, (eds.): National Symposium on Wetlands, American Water Resources Association, Minneapolis, Minnesota, p. 344–376.

De Jong, R., 1988. Comparison of two soil-water models under semi-arid growing conditions: Canadian Journal of Soil Science, v. 68, p. 17–27.

Dyck, S., 1985. Overview of the present status of the concepts of water balance models; *in*, New approaches in water balance computations, A. Van der Beken and A. Herrman (eds.): International Association of Scientific Hydrology Publication, 148, p. 3–19.

Dyer, J. A., and Baier, W., 1979. An index for soil-moisture drying patterns: Canadian Agricultural Engineering v. 21, p. 117–118.

Dyer, J. A., and Baier, W., 1980. The influence of zones in budgeting plant available soil moisture: Canadian Agricultural Engineering, v. 22, p. 65–70.

Dyer, J. A., and Dwyer, L. M., 1982. Root-extraction coefficients for soil-moisture budgeting derived from measured root densities: Canadian Agricultural Engineering, v. 24, no. 2, p. 81–86.

Dyer, J. A., and Mack, A. R., 1984. The versatile soil-moisture budget—version three: Technical Bulletin 1984-1E, Agriculture Canada, Research Branch, 24 p. plus appendices.

Gosselink, J. G., and Turner, R. E., 1978. The role of hydrology in freshwater wetland ecosystems; *in,* Good, R. E., Whigham, D. F., and Simpson, R. L. (eds.): Freshwater Wetlands: Ecological Processes and Management Potential, p. 63–78, Academic Press, New York.

Holmes, R. M., and Robertson, G. W., 1959. A modulated soil-moisture budget: Monthly Weather Review, v. 87, p. 101–106.

Kadlec, R. A., and Kadlec, J. A., 1979. Wetlands and water quality; *in* Greeson, P. E., Clark, J. R., and Clark, J. E. (eds.): Wetland functions and values: The state of our understanding, p. 436–456, American Water Resources Association, Minneapolis, Minnesota.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H., 1949. Applied hydrology: McGraw-Hill Book Co., Inc., New York, 689 p.

Penman, H. L., 1948. Natural evaporation from open water, bare soil, and grass. Proceedings Royal Society, London, v. 193, p. 120–145.

Penman, H. L., 1963. Vegetation and hydrology: Commonwealth Agricultural Bureau, Farnham Royal, Bucks, Engineering, Technical Communication No. 5.

Rawls, W. J., and Brakensiek, D. L., 1982. Estimating soil water retention from soil properties, Journal of Irrigation Drainage, American Society of Civil Engineering, 108(IR2), 166–171.

Rawls, W. J., and Brakensiek, D. L., 1983. A procedure to predict Green and Ampt infiltration parameters. Proceedings American Society of Agricultural Engineering Conference on Advances in Infiltration, Chicago, Illinois, p. 102–112.

Rawls, W. J., and Brakensiek, D. L., 1985. Prediction of soil water properties for hydrologic modeling, Proceedings of the American Society of Civil Engineering Watershed Management in the Eighties Symposium, pp. 102–112.

Rawls, W. J., and Brakensiek, D. L., 1988. An infiltration model for evaluation of agricultural and range management systems, Proceedings of the American Society of Agricultural Engineering Symposium on Modeling Agricultural, Forest, and Rangeland Hydrology, p. 168–175.

Rawls, W. J., Brakensiek, D. L., and Miller, N., 1983. Green-Ampt infiltration parameters from soils data. Journal of Hydraulic Engineering, v. 109, no. 1, p. 62–70.

Richardson, C. W., and Wright, D. A., 1984. WGEN—A model for generating daily weather variables: Report ARS-8, U. S. Department of Agriculture, Agricultural Research Service, 83 p.

Ritjema, P. E., 1965. An analysis of actual evapotranspiration: Agricultural Research Report No. 659, Centre for Agricultural Publications and Documentation, Wegeningen, Netherlands.

Russelo, D., Edy, S., and Godfrey, J., 1974. Selected tables and conversions used in agrometeorology and related fields: Publication 1522, Canada Department of Agriculture, 275 p.

Salter, P. J., and Williams, J. B., 1965. The influence of texture on the moisture characteristics of soils, 1—A critical comparison of techniques for determining the available-water capacity and moisture-characteristic curve of a soil: Journal of Soil Science v. 16, p. 1–15.

Saxton, K. E., Johnson, H. P., and Shaw, R. M., 1974. Modeling evapotranspiration and soil moisture. Transactions of the American Society of Agricultural Engineering, v. 17, p. 673–677.

Smith, R. E., and Williams, J. R., 1980. Simulation of surface water hydrology: *in*; CREAMS—A field-scale model for chemicals, runoff, and erosion from Agricultural Management Systems, Knisel, W. G. (ed.): Conservation Report 26, U. S. Dept. of Agriculture, 643 p.

Sophocleous, M. A., and McAllister, J. A., 1987. Basinwide water-balance modeling with emphasis on spatial distribution of ground-water recharge. Water Resources Bulletin, v. 23, no. 6, p. 997–1,010.

Sophocleous, M. A., and McAllister, J. A., 1990. Hydrologic-balance modeling of the Rattlesnake Creek watershed, Kansas: Ground Water Series 11, Kansas Geological Survey, 72 p.

Sophocleous, M. A., and Perkins, S. P., 1993. Stream-aquifer modeling and preliminary mineral intrusion analysis of the lower Rattlesnake Creek basin with emphasis on the Quivira National Wildlife Refuge: Open-File Report 93-7, Kansas Geological Survey, in press.

Sudar, R. A., Saxton, K. E., and Spomer, R. G., 1981. A predictive model of water stress in corn and soybeans: Transactions of the American Society of Agricultural Engineering, v. 24, p. 97–102.

Thornthwaite, C. W., 1948. An approach toward a rational classification of climate: Geography Review, v. 38, p. 85–94.

U.S. Department of Agriculture, 1972. Soil Conservation Service National Engineering Handbook, section 4, Hydrology: NEH Notice 4-102, Soil Conservation Service, ch. 7–10.

U.S. Department of Agriculture, 1975. Soil taxonomy—a basic system of soil classification for making and interpreting soil surveys: Handbook 436, Soil Conservation Service, U.S. Department of Agriculture, 754 p.

Vazquez, R., and Taylor, A., 1958. Simulated root distribution and water-removal rates from soil: Soil Science Society of America, Proceedings v. 22, p. 106–110.

Weaver, J. E., 1926. Root development of field crops: McGraw-Hill Book Co., New York, 291 p.

# Appendix I

Tabulated values of annual water-balance components from 1985 through 1992 for all soil associations in the Quivira NWR area using all three runoff estimation procedures (GA, original VB, and SCS-CN).

Table I.1a. Yearly hydrologic balance components for Plevna-Kanza-Waldeck soil association using Green and Ampt methodology

Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 28.78 | 2.59 | 1.14 | 1.53 |
| 1986 | 29.68 | 47.59 | 28.46 | 2.70 | 1.24 | 0.00 |
| 1987 | 31.75 | 45.57 | 27.50 | 3.83 | 0.00 | 4.93 |
| 1988 | 14.98 | 48.78 | 18.19 | 7.17 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.91 | 5.68 | 0.06 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.74 | 4.48 | 0.46 | 0.66 |
| 1991 | 17.04 | 48.46 | 16.12 | 3.93 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.49 | 0.13 | 0.00 | 0.06 |
| 8-yr total | 207.91 | 375.52 | 196.19 | 30.51 | 2.90 | 7.17 |
| 8-yr average | 25.99 | 46.94 | 24.52 | 3.81 | 0.36 | 0.90 |

Table I.1b. Yearly hydrologic balance components for Plevna-Kanza-Waldeck soil association using original VB methodology

Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 28.21 | 3.43 | 2.73 | 1.35 |
| 1986 | 29.68 | 47.59 | 27.57 | 2.26 | 0.68 | 0.00 |
| 1987 | 31.75 | 45.57 | 27.50 | 3.88 | 1.50 | 3.91 |
| 1988 | 14.98 | 48.78 | 17.98 | 7.18 | 0.18 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.23 | 6.21 | 1.26 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.38 | 5.65 | 2.11 | 0.00 |
| 1991 | 17.04 | 48.46 | 14.90 | 3.99 | 0.11 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.15 | 0.74 | 1.07 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 191.91 | 33.33 | 9.64 | 5.26 |
| 8-yr average | 25.99 | 46.94 | 23.99 | 4.17 | 1.21 | 0.66 |

Table I.1c. Yearly hydrologic balance components for Plevna-Kanza-Waldeck soil association using SCS curve number methodology

Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 26.99 | 0.81 | 1.63 | 1.05 |
| 1986 | 29.68 | 47.59 | 28.00 | 0.52 | 0.49 | 0.81 |
| 1987 | 31.75 | 45.57 | 25.84 | 3.02 | 3.46 | 4.49 |
| 1988 | 14.98 | 48.78 | 17.90 | 6.06 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.54 | 4.69 | 0.55 | 0.00 |
| 1990 | 31.05 | 47.93 | 26.95 | 3.63 | 3.05 | 0.00 |
| 1991 | 17.04 | 48.46 | 16.07 | 3.04 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 26.95 | 0.01 | 1.35 | 0.14 |
| 8-yr total | 207.91 | 375.52 | 189.24 | 21.78 | 10.53 | 6.50 |
| 8-yr average | 25.99 | 46.94 | 23.65 | 2.72 | 1.32 | 0.81 |

Three-method (GA, VB, SCS) averages

| | | | | | | |
|---|---|---|---|---|---|---|
| overall average | 25.99 | 46.94 | 24.06 | 3.57 | 0.96 | 0.79 |

Table I.2a. Yearly hydrologic balance components for Dillwyn-Dillwyn-Tivoli soil association using Green and Ampt methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 26.41 | 0.64 | 0.40 | 2.70 |
| 1986 | 29.68 | 47.59 | 26.64 | 0.54 | 0.50 | 2.36 |
| 1987 | 31.75 | 45.57 | 24.60 | 2.58 | 0.19 | 8.55 |
| 1988 | 14.98 | 48.78 | 17.21 | 4.94 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 19.21 | 3.86 | 0.00 | 2.17 |
| 1990 | 31.05 | 47.93 | 25.88 | 2.62 | 0.00 | 3.92 |
| 1991 | 17.04 | 48.46 | 15.73 | 1.69 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 25.89 | 0.13 | 0.00 | 3.91 |
| 8-yr total | 207.91 | 375.52 | 181.57 | 17.01 | 1.08 | 23.61 |
| 8-yr average | 25.99 | 46.94 | 22.70 | 2.13 | 0.14 | 2.95 |

Table I.2b. Yearly hydrologic balance components for Dillwyn-Dillwyn-Tivoli soil association using original VB methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 26.29 | 1.50 | 2.73 | 1.34 |
| 1986 | 29.68 | 47.59 | 25.98 | 0.54 | 1.00 | 1.65 |
| 1987 | 31.75 | 45.57 | 24.60 | 2.60 | 1.54 | 7.21 |
| 1988 | 14.98 | 48.78 | 17.02 | 4.95 | 0.18 | 0.00 |
| 1989 | 22.50 | 47.14 | 19.16 | 3.86 | 1.18 | 1.04 |
| 1990 | 31.05 | 47.93 | 25.72 | 3.20 | 2.32 | 2.34 |
| 1991 | 17.04 | 48.46 | 15.04 | 1.70 | 0.12 | 0.00 |
| 1992 | 31.47 | 44.30 | 25.84 | 0.01 | 0.97 | 2.98 |
| 8-yr total | 207.91 | 375.52 | 179.66 | 18.36 | 10.04 | 16.56 |
| 8-yr average | 25.99 | 46.94 | 22.46 | 2.29 | 1.25 | 2.07 |

Table I.2c. Yearly hydrologic balance components for Dillwyn-Dillwyn-Tivoli soil association using SCS curve number methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 26.62 | 0.65 | 1.51 | 1.37 |
| 1986 | 29.68 | 47.59 | 27.85 | 0.54 | 0.42 | 1.22 |
| 1987 | 31.75 | 45.57 | 25.49 | 2.79 | 3.14 | 4.92 |
| 1988 | 14.98 | 48.78 | 17.01 | 4.96 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.18 | 3.93 | 0.93 | 0.33 |
| 1990 | 31.05 | 47.93 | 26.64 | 2.95 | 3.44 | 0.00 |
| 1991 | 17.04 | 48.46 | 15.47 | 1.76 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 26.97 | 0.13 | 1.58 | 1.17 |
| 8-yr total | 207.91 | 375.52 | 186.23 | 17.71 | 11.01 | 9.02 |
| 8-yr average | 25.99 | 46.94 | 23.28 | 2.21 | 1.38 | 1.13 |

Three-method (GA, VB, SCS) averages

| | | | | | | |
|---|---|---|---|---|---|---|
| overall average | 25.99 | 46.94 | 22.81 | 2.21 | 0.92 | 2.05 |

Table I.3a. Yearly hydrologic balance components for Carwile-Farnum-Farnum soil association using Green and Ampt methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 30.32 | 3.95 | 1.14 | 1.35 |
| 1986 | 29.68 | 47.59 | 29.38 | 4.98 | 1.25 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.09 | 4.63 | 0.00 | 1.85 |
| 1988 | 14.98 | 48.78 | 18.89 | 8.67 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 21.56 | 7.82 | 0.06 | 0.00 |
| 1990 | 31.05 | 47.93 | 29.87 | 7.09 | 0.45 | 0.00 |
| 1991 | 17.04 | 48.46 | 15.36 | 5.79 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 28.00 | 2.31 | 0.00 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 202.46 | 45.23 | 2.90 | 3.20 |
| 8-yr average | 25.99 | 46.94 | 25.31 | 5.65 | 0.36 | 0.40 |

Table I.3b. Yearly hydrologic balance components for Carwile-Farnum-Farnum soil association using original VB methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 29.48 | 4.70 | 2.73 | 1.35 |
| 1986 | 29.68 | 47.59 | 28.68 | 4.56 | 0.77 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.06 | 5.16 | 1.63 | 1.21 |
| 1988 | 14.98 | 48.78 | 18.37 | 8.86 | 0.18 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.74 | 8.39 | 1.26 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.59 | 8.01 | 2.08 | 0.00 |
| 1991 | 17.04 | 48.46 | 14.40 | 5.85 | 0.10 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.61 | 3.09 | 1.11 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 196.92 | 48.62 | 9.86 | 2.56 |
| 8-yr average | 25.99 | 46.94 | 24.62 | 6.08 | 1.23 | 0.32 |

Table I.3c. Yearly hydrologic balance components for Carwile-Farnum-Farnum soil association using SCS curve number methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 30.48 | 3.37 | 1.23 | 0.52 |
| 1986 | 29.68 | 47.59 | 30.71 | 4.49 | 0.00 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.72 | 5.20 | 2.14 | 0.15 |
| 1988 | 14.98 | 48.78 | 18.53 | 8.88 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 21.96 | 8.37 | 0.00 | 0.00 |
| 1990 | 31.05 | 47.93 | 29.85 | 7.67 | 0.49 | 0.00 |
| 1991 | 17.04 | 48.46 | 14.92 | 5.92 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 28.22 | 2.67 | 0.05 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 204.38 | 46.56 | 3.91 | 0.67 |
| 8-yr average | 25.99 | 46.94 | 25.55 | 5.82 | 0.49 | 0.08 |

Three-method (GA, VB, SCS) averages

| | | | | | | |
|---|---|---|---|---|---|---|
| overall average | 25.99 | 46.94 | 25.16 | 5.85 | 0.69 | 0.27 |

Table I.4a. Yearly hydrologic balance components for Farnum-Blanket-Blanket soil association using Green and Ampt methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 30.24 | 4.23 | 1.50 | 1.35 |
| 1986 | 29.68 | 47.59 | 29.03 | 5.31 | 1.64 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.08 | 4.63 | 0.00 | 1.53 |
| 1988 | 14.98 | 48.78 | 18.89 | 8.67 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 21.53 | 7.92 | 0.19 | 0.00 |
| 1990 | 31.05 | 47.93 | 29.55 | 7.17 | 0.75 | 0.00 |
| 1991 | 17.04 | 48.46 | 15.30 | 5.81 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.99 | 2.33 | 0.00 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 201.61 | 46.08 | 4.09 | 2.88 |
| 8-yr average | 25.99 | 46.94 | 25.20 | 5.76 | 0.51 | 0.36 |

Table I.4b. Yearly hydrologic balance components for Farnum-Blanket-Blanket soil association using original VB methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 29.48 | 4.70 | 2.73 | 1.35 |
| 1986 | 29.68 | 47.59 | 28.68 | 4.56 | 0.77 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.06 | 5.16 | 1.63 | 1.21 |
| 1988 | 14.98 | 48.78 | 18.37 | 8.86 | 0.18 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.74 | 8.39 | 1.26 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.59 | 8.01 | 2.08 | 0.00 |
| 1991 | 17.04 | 48.46 | 14.40 | 5.85 | 0.10 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.61 | 3.09 | 1.11 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 196.92 | 48.62 | 9.86 | 2.56 |
| 8-yr average | 25.99 | 46.94 | 24.62 | 6.08 | 1.23 | 0.32 |

Table I.4c. Yearly hydrologic balance components for Farnum-Blanket-Blanket soil association using SCS curve number methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 30.48 | 3.37 | 1.23 | 0.52 |
| 1986 | 29.68 | 47.59 | 30.71 | 4.49 | 0.00 | 0.00 |
| 1987 | 31.75 | 45.57 | 29.72 | 5.20 | 2.14 | 0.15 |
| 1988 | 14.98 | 48.78 | 18.53 | 8.88 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 21.96 | 8.37 | 0.00 | 0.00 |
| 1990 | 31.05 | 47.93 | 29.85 | 7.67 | 0.49 | 0.00 |
| 1991 | 17.04 | 48.46 | 14.92 | 5.92 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 28.22 | 2.67 | 0.05 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 204.38 | 46.56 | 3.91 | 0.67 |
| 8-yr average | 25.99 | 46.94 | 25.55 | 5.82 | 0.49 | 0.08 |

Three-method (GA, VB, SCS) averages

| | | | | | | |
|---|---|---|---|---|---|---|
| overall average | 25.99 | 46.94 | 25.12 | 5.89 | 0.74 | 0.25 |

Table I.5a. Yearly hydrologic balance components for Pratt-Carwile-Pratt soil association using Green and Ampt methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 28.33 | 2.03 | 0.95 | 1.61 |
| 1986 | 29.68 | 47.59 | 28.24 | 1.68 | 1.00 | 0.00 |
| 1987 | 31.75 | 45.57 | 27.01 | 3.60 | 0.00 | 6.21 |
| 1988 | 14.98 | 48.78 | 17.95 | 6.69 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.56 | 4.79 | 0.00 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.18 | 4.09 | 0.28 | 1.90 |
| 1991 | 17.04 | 48.46 | 16.03 | 3.45 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.42 | 0.13 | 0.00 | 0.61 |
| 8-yr total | 207.91 | 375.52 | 193.71 | 26.46 | 2.23 | 10.32 |
| 8-yr average | 25.99 | 46.94 | 24.21 | 3.31 | 0.28 | 1.29 |

Table I.5b. Yearly hydrologic balance components for Pratt-Carwile-Pratt soil association using original VB methodology
Hudson station 1985-1992 data in inches

| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 27.88 | 3.10 | 2.73 | 1.34 |
| 1986 | 29.68 | 47.59 | 27.09 | 1.46 | 0.87 | 0.00 |
| 1987 | 31.75 | 45.57 | 27.00 | 3.60 | 1.44 | 5.00 |
| 1988 | 14.98 | 48.78 | 17.76 | 6.69 | 0.18 | 0.00 |
| 1989 | 22.50 | 47.14 | 20.28 | 5.75 | 1.24 | 0.00 |
| 1990 | 31.05 | 47.93 | 27.91 | 4.77 | 2.16 | 0.00 |
| 1991 | 17.04 | 48.46 | 15.24 | 3.47 | 0.12 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.21 | 0.27 | 1.06 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 190.37 | 29.10 | 9.80 | 6.34 |
| 8-yr average | 25.99 | 46.94 | 23.80 | 3.64 | 1.23 | 0.79 |

Table I.5c. Yearly hydrologic balance components for Pratt-Carwile-Pratt soil association using SCS curve number methodology
Hudson station 1985-1992 data in inches

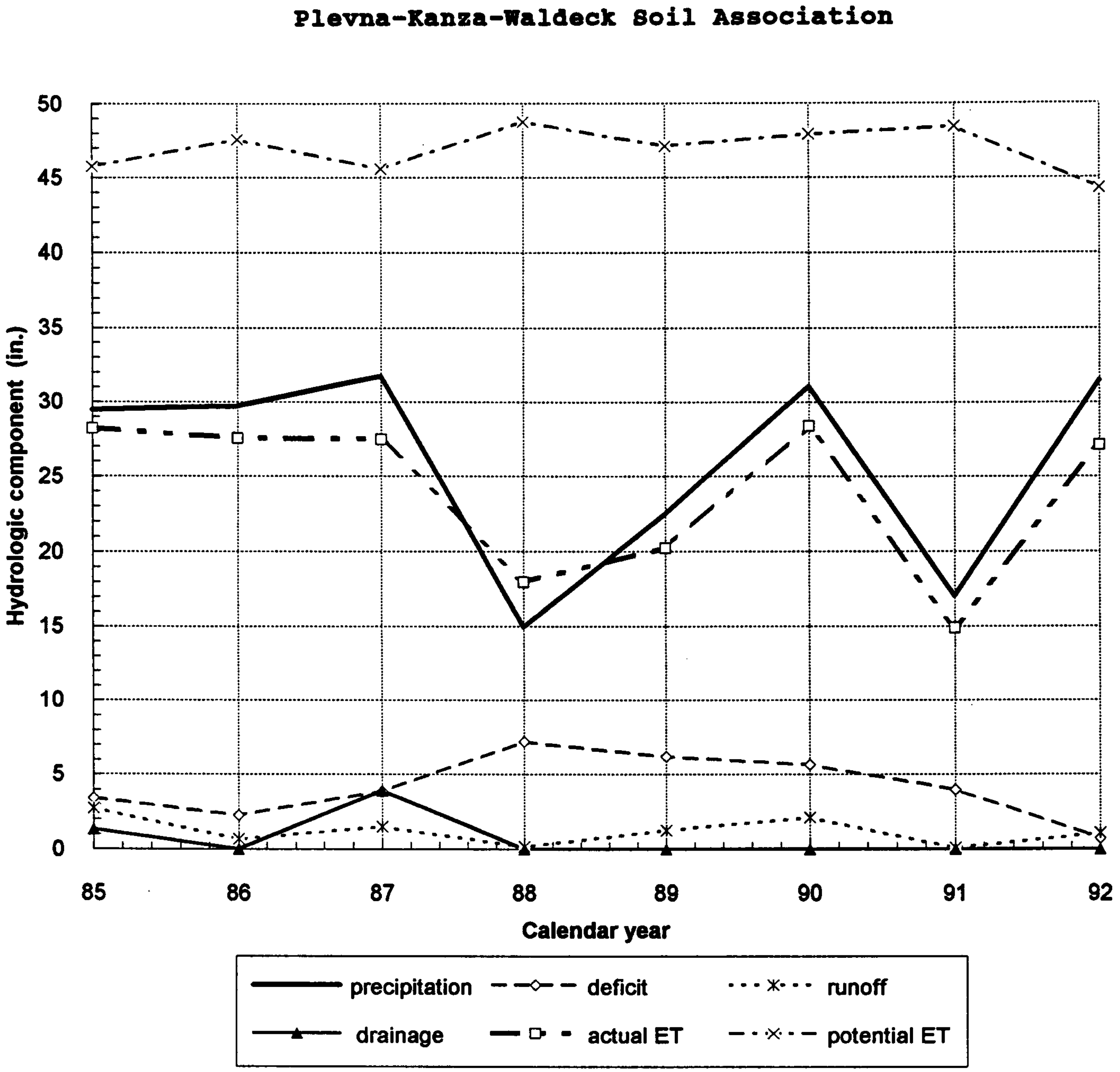
| year | precipitation | potential ET | actual ET | deficit | runoff | drainage |
|---|---|---|---|---|---|---|
| 1985 | 29.44 | 45.75 | 28.47 | 1.65 | 1.31 | 0.72 |
| 1986 | 29.68 | 47.59 | 29.58 | 1.71 | 0.08 | 0.00 |
| 1987 | 31.75 | 45.57 | 27.61 | 3.69 | 2.79 | 2.88 |
| 1988 | 14.98 | 48.78 | 17.87 | 6.71 | 0.00 | 0.00 |
| 1989 | 22.50 | 47.14 | 21.31 | 5.77 | 0.22 | 0.00 |
| 1990 | 31.05 | 47.93 | 28.70 | 5.12 | 1.70 | 0.00 |
| 1991 | 17.04 | 48.46 | 15.09 | 3.55 | 0.00 | 0.00 |
| 1992 | 31.47 | 44.30 | 27.94 | 0.48 | 0.47 | 0.00 |
| 8-yr total | 207.91 | 375.52 | 196.56 | 28.66 | 6.57 | 3.60 |
| 8-yr average | 25.99 | 46.94 | 24.57 | 3.58 | 0.82 | 0.45 |

Three-method (GA, VB, SCS) averages

| | | | | | | |
|---|---|---|---|---|---|---|
| overall average | 25.99 | 46.94 | 24.19 | 3.51 | 0.77 | 0.84 |

# Appendix II

Annual water-balance-component graphs from 1985 through 1992 for all soil associations in the Quivira NWR using the original versatile budget model results.



Plevna-Kanza-Waldeck Soil Association

Figure II-1.

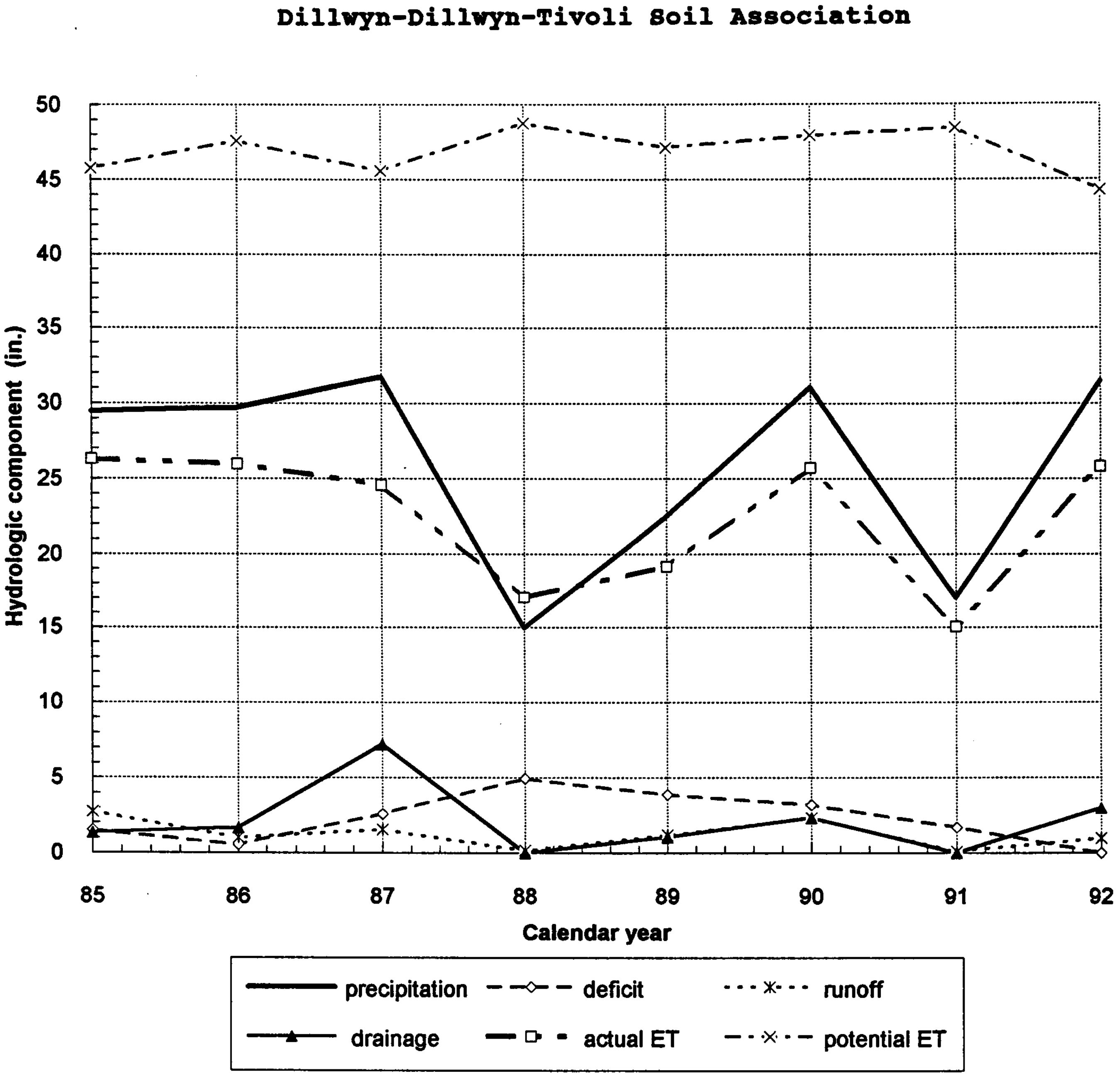

Dillwyn-Dillwyn-Tivoli Soil Association
Hydrologic component (in.)
50
45
40
35
30
25
20
15
10
5
0
85
86
87
88
89
90
91
92
Calendar year
precipitation
deficit
runoff
drainage
actual ET
potential ET

Figure II-2.

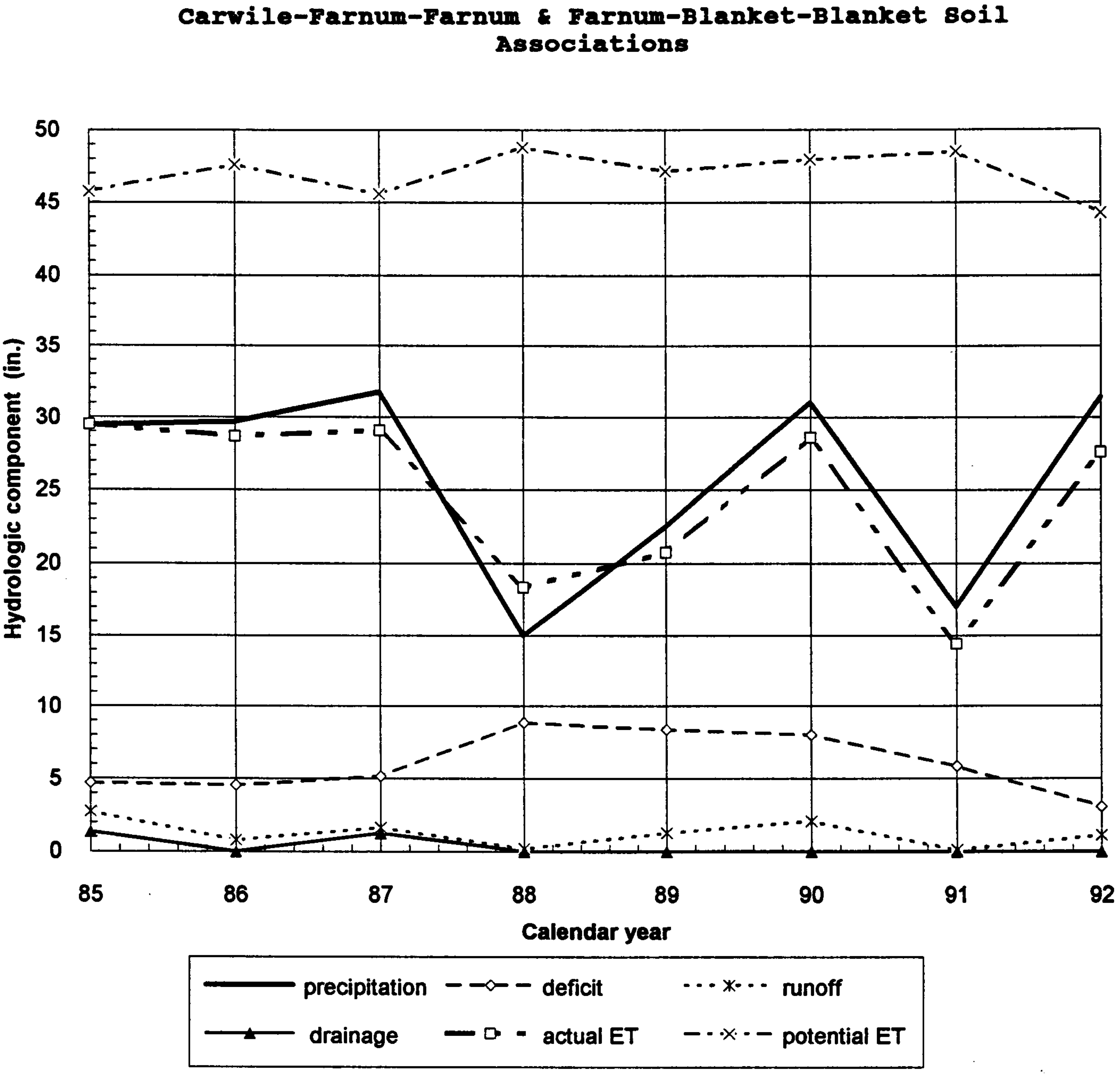

Carwile-Farnum-Farnum & Farnum-Blanket-Blanket Soil Associations
50
45
40
35
30
25
20
15
10
5
0
Hydrologic component (in.)
85
86
87
88
89
90
91
92
Calendar year
precipitation
deficit
runoff
drainage
actual ET
potential ET

Figure II-3.

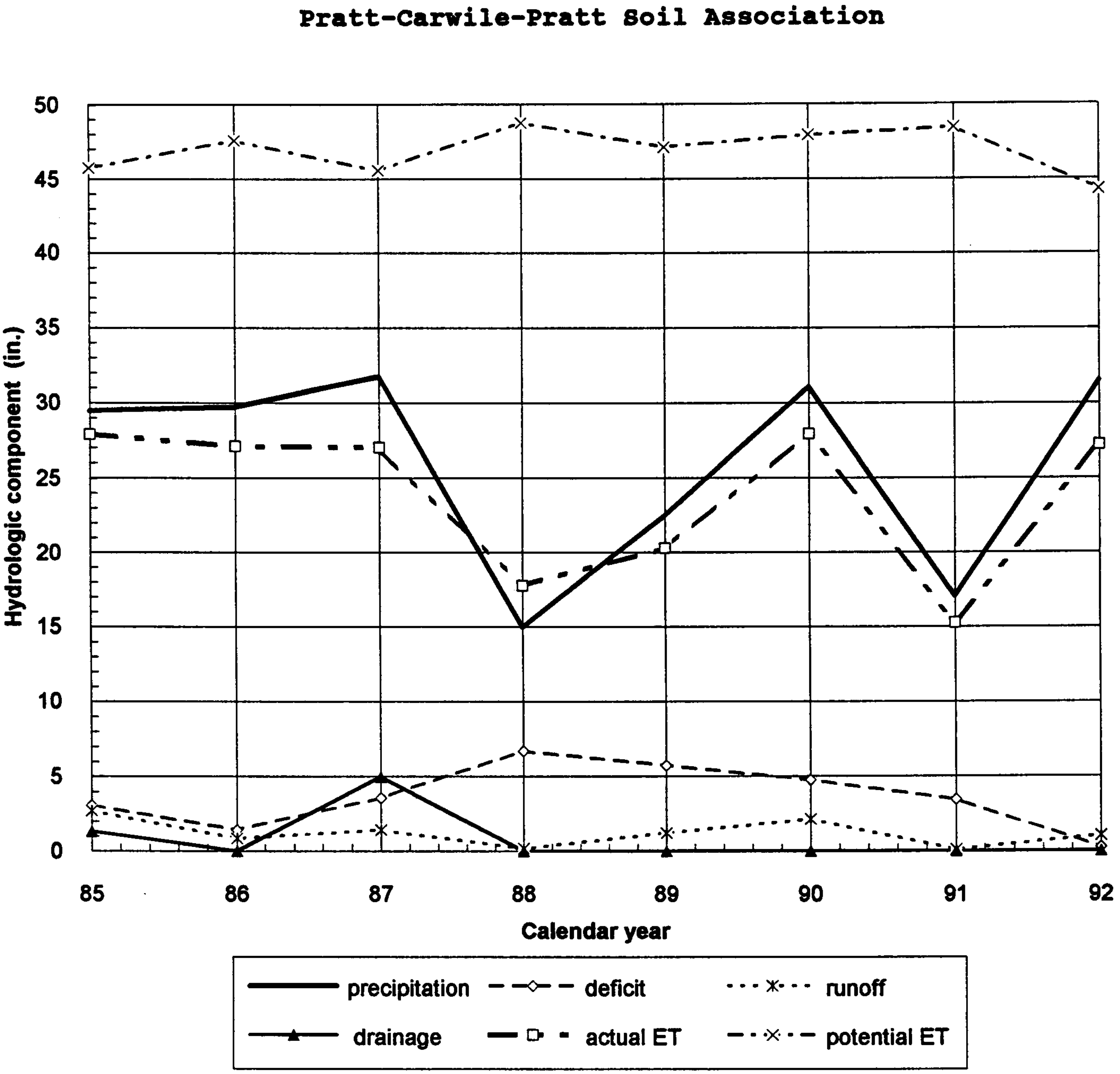

Pratt-Carwile-Pratt Soil Association
Hydrologic component (in.)
50
45
40
35
30
25
20
15
10
5
0
85
86
87
88
89
90
91
92
Calendar year
precipitation
deficit
runoff
drainage
actual ET
potential ET

Figure II-4.