Estimation of Evapotranspiration in the Rainbow Springs and Silver Springs Basins in North-Central Florida

By Leel Knowles, Jr.

U.S. Geological Survey

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meters
foot per mile (ft/mi)	0.1894	meter per kilometer
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
	Flow	
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Pressure	
bar	100	kilopascal
	Hydraulic gradient	
foot per mile (ft/mi)	0.1786	meter per kilometer
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day

Equations for temperature conversion between degrees Celsius (ºC) and degrees Fahrenheit (ºF):

$$^\circ C = 5/9\ (^\circ F - 32)$$
$$^\circ F = 9/5\ (^\circ C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Additional Abbreviations

cm	cubic centimeter
eq	equation
in/mo	inches per month
in/yr	inches per year
(J/kg)/ºC	joule per kilogram per degree Celsius
µm	micrometer
m	meter
min	minute
W/m^2	watt per square meter
yr	year

Acronyms

ET	evapotranspiration
EBBR	energy-balance Bowen ratio
ECEBBR	eddy-correlation energy-balance Bowen ratio
ECEBR	eddy-correlation energy-balance residual variant
LAI	leaf-area index
MET	meteorological data-collection site
PET	potential evapotranspiration
PT	Priestley-Taylor
PVC	polyvinylchloride
SJRWMD	St. Johns River Water Management District
SR	State Road
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey

SYMBOLS USED IN THIS REPORT

Symbol	Meaning	Units
c_p	Specific heat of air at constant pressure, 1.01	joules per gram per degree Kelvin
c_s	Specific heat of dry mineral soil, 840	joules per kilogram per degree Celsius
c_w	Specific heat of soil water; 4,190	joules per kilogram per degree Celsius
C	Energy-balance closure error	dimensionless
C_s	Soil heat capacity	joules per cubic meter per degree Celsius
CW	Consumptive withdrawal (pumping)	inches
D	Depth to heat-flux plate, 0.08	meters
E	Evaporation rate	grams per square meter per second
ET	Evapotranspiration	inches
G_p	Measured flux at 0.08 m depth with heat-flux plate	watts per square meter
G_s	Soil heat flux at land surface	watts per square meter
H	Sensible heat flux	watts per square meter
LAI	Leaf-area index (two-sided)	dimensionless
L_s	Fraction of green leaves seen at an angle of 30×º	dimensionless
M_w	Molecular weight of water, 18	grams per mole
P_a	Mean ambient barometric pressure at MET site, 100.9	kilopascals
R	Molar gas constant, 8.314	joules per mole per degree Kelvin
R_n	Net radiation flux	watts per square meter
RF	Rainfall	inches
S	Average stored energy in top 0.08 m of soil	watts per square meter
S_c	Rate of heat storage in the plant canopy	watts per square meter
SP	Springflow	inches
$\overline{ST}$	Average net streamflow	inches
ΔS	Total change in ground-water storage	inches
ΔS_A	Net change in aquifer storage	inches
ΔS_L	Net change in lake storage	inches
t	Time interval, 1200	seconds
T_a	Air temperature	degrees Kelvin
T_s	Current 20-minute mean soil temperature	degrees Celcius
T_{s-1}	Previous 20-minute mean soil temperature	degrees Celcius
W	Water content of soil	kilograms of water per kilogram of soil
α	Priestley-Taylor evaporation coefficient	dimensionless
D	Slope of the saturation vapor pressure-temperature curve	kilopascals per degree Kelvin
ε	Ratio of molecular weight of water vapor to air, 0.622	dimensionless
g	Psychrometer constant	kilopascals per degree Kelvin
λ	Latent heat of vaporization of water	joules per gram
λE	Latent heat flux	watts per square meter
ρ_a	Air density	grams per cubic meter
r_b	Bulk density of soil	kilograms per cubic meter
r_n	Vapor density	grams per cubic meter
w	Vertical windspeed	meters per second
′	Represents a momentary fluctuation from the mean	unitless
—	Signifies the mean of an averaging period	unitless

Estimation of Evapotranspiration in the Rainbow Springs and Silver Springs Basins in North-Central Florida

By Leel Knowles, Jr.

Abstract

Estimates of evapotranspiration (ET) for the Rainbow and Silver Springs ground-water basins in north-central Florida were determined using a regional water-budget approach and compared to estimates computed using a modified Priestley-Taylor (PT) model calibrated with eddy-correlation data. Eddy-correlation measurements of latent (λE) and sensible (H) heat flux were made monthly for a few days at a time, and the PT model was used to estimate λE between times of measurement during the 1994 water year.

A water-budget analysis for the two-basin area indicated that over a 30-year period (1965-94) annual rainfall was 51.7 inches. Of the annual rainfall, ET accounted for about 37.9 inches; springflow accounted for 13.1 inches; and the remaining 0.7 inch was accounted for by streamflow, by ground-water withdrawals from the Floridan aquifer system, and by net change in storage. For the same 30-year period, the annual estimate of ET for the Silver Springs basin was 37.6 inches and was 38.5 inches for the Rainbow Springs basin. Wet- and dry-season estimates of ET for each basin averaged between nearly 19 inches and 20 inches, indicating that like rainfall, ET rates during the 4-month wet season were about twice the ET rates during the 8-month dry season. Wet-season estimates of ET for the Rainbow Springs and Silver Springs basins decreased 2.7 inches, and 3.4 inches, respectively, over the 30-year period; whereas, dry-season estimates for the basins decreased about 0.4 inch and 1.0 inch, respectively, over the 30-year period. This decrease probably is related to the general decrease in annual rainfall and reduction in net radiation over the basins during the 30-year period.

ET rates computed using the modified PT model were compared to rates computed from the water budget for the 1994 water year. Annual ET, computed using the PT model, was 32.0 inches, nearly equal to the ET water-budget estimate of 31.7 inches computed for the Rainbow Springs and Silver Springs basins. Modeled ET rates for 1994 ranged from 14.4 inches per year in January to 51.6 inches per year in May. Water-budget ET rates for 1994 ranged from 12.0 inches per year in March to 61.2 inches per year in July. Potential evapotranspiration rates for 1994 averaged 46.8 inches per year and ranged from 21.6 inches per year in January to 74.4 inches per year in May. Lake evaporation rates averaged 47.1 inches per year and ranged from 18.0 inches per year in January to 72.0 inches per year in May 1994.

INTRODUCTION

Evapotranspiration (ET) is a major component of the hydrologic budget and generally is difficult to quantify. For a closed (internally-drained) ground-water basin, ET can be computed as the residual in a water-budget analysis by subtracting recharge and internal surface runoff from rainfall and any other influx of water to the ground-water basin. Recharge is computed by summing springflow, change in storage, and pumping. For an open ground-water basin where streamflow or subsurface flow crosses the boundaries of the basin, ET is computed by subtracting the contributing surface runoff to streams, and by adding any subsurface influx or subtracting any subsurface leakage from rainfall.

The Rainbow Springs and Silver Springs ground-water basins located in north-central Florida can be considered closed basins because recharge is equivalent to spring discharge in each of the basins (fig. 1). The spring basins mainly are internally drained so that streamflow that exits the basins is generated mostly by springflow and diffuse upward leakage of ground water. Little, if any, surface runoff occurs in either spring basin. In addition, total ground-water withdrawals (pumpage) from the Floridan aquifer system and subsurface flow are relatively small in comparison to the other components of the water budget.

Long-term hydrologic data available for the Rainbow Springs and Silver Springs basins provide a unique opportunity to compute water budgets for these two basins and estimate the long-term average ET losses as a residual term to these budgets. Water-budget components of rainfall, springflow, net changes in lake and aquifer storage, streamflow, and pumpage are known and comparable in accuracy for both spring basins.

ET, second only to rainfall in importance to hydrologic budgets for Florida, is influenced by seasonal changes in climate and can vary considerably among basins with different types of vegetation or different proportions of open-water surfaces (Jones and others, 1984). Although the range of ET rates is known for the region, ET rates within the study area remain poorly defined for less than annual time periods. Measurements of ET are needed to identify seasonal variations in ET as well as to provide a check on the water-budget estimates.

Water-budget estimates of ET for west-central Florida, which includes the Rainbow Springs and Silver Springs basins, are well documented but not well verified. Regional ET rates range from a minimum of 30 in/yr (Knochenmus and Hughes, 1976) to a maximum of about 50 in/yr (Visher and Hughes, 1975). Regional average pan-evaporation rates range from 60 to 66 in/yr; 36 to 40 in. during the warm season (May to October) and 24 to 26 in. during the cool season (November to April) (Farnsworth and others, 1982). Pan-evaporation data typically is used to estimate potential evapotranspiration (PET), which is the water loss when there is not a deficiency of water in the soil for use by vegetation. The present study provided new information on ET rates for the spring basins.

Micrometeorological methods for estimating ET have not been previously used in the study basin. Although the physics of evaporation are well known, the technology to measure ET has only recently become readily available. Increasingly, field studies have focused on micrometeorological methods for estimating ET, specifically using the method of eddy correlation which currently is the most direct measure of ET (Monteith and Unsworth, 1990). Water-budget estimates of ET usually are made for annual periods and occasionally for shorter periods, such as monthly. However, monthly or shorter-period estimates of ET can be confounded by the time lag between rainfall and the basin streamflow or ground-water discharge. Micrometeorological methods have the advantage over water-budget methods by providing estimates of ET for a much shorter time period, such as on a daily basis.

Water-budget and micrometeorological methods also differ in the spatial scale of the ET estimates. The water-budget estimate of ET is for the water basin, whereas micrometeorological methods characterize ET from a limited area. Thus, the most transferable results would be obtained by selecting a site where the landscape and plant canopy are most representative of the entire basin.

The present study was conducted in cooperation with the Southwest Florida Water Management District (SWFWMD) and the St. Johns River Water Management District (SJRWMD) to define a water budget and quantify ET rates for the Rainbow Springs and Silver Springs basins. This information is needed for future planning and resource development. An accurate estimate of ET is needed because ET represents such a large part of the water budget in these ground-water basins.

This report presents estimates of ET in the Rainbow Springs and Silver Springs basins computed using (1) a regional water-budget approach, and (2) a micrometeorological method—namely a modified Priestley-Taylor (PT) model calibrated with eddy-correlation measurements made at a meteorological data-collection (MET) site within the two-basin area during the 1994 water year. Regional estimates of ET were computed from a water budget for a 30-year period,

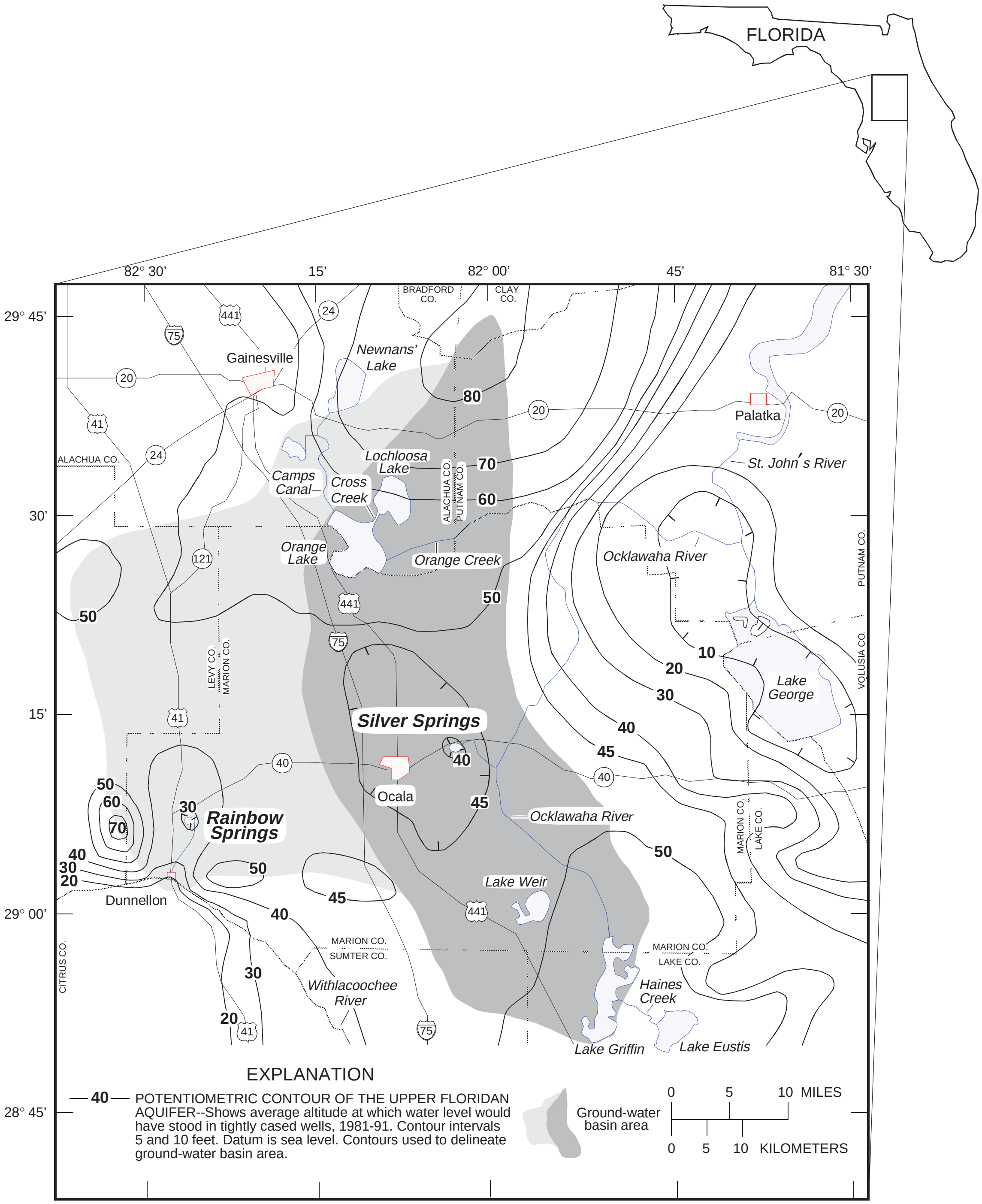

Figure 1. Location of study area, Rainbow Springs, and Silver Springs basins, Florida.

1965-94, using rainfall, springflow, streamflow, water-level, and pumping data. Measured ET then was compared to the regional estimate for 1 year. The purpose of measuring ET was to determine whether the measured (point) value was within the expected range of ET computed using the regional water budget.

Description of the Study Area

The Rainbow Springs and Silver Springs ground-water basins (study area) are located in north-central Florida and have a total land-surface area of 1,552 mi^2. Rainbow Springs is located about 4 mi northeast of Dunnellon in southwest Marion County and its basin encompasses about 640 mi^2. Silver Springs is located about 5 mi east of Ocala in Marion County and its basin encompasses about 912 mi^2. The ground-water basins are delineated using water-level contours representing an average Upper Floridan potentiometric-surface condition for 1981-91 (fig. 1).

The study area is located along an extensive north-south ridge in the center of the Floridan peninsula. Locally, surficial sands and clays can support a perched water table or small lake, but generally limestone lies at or near land surface. Terrain in the western part of the area is mainly irregular karst topography, characterized by numerous sinkholes and poorly developed surface drainage. In the eastern half, the topography is more subdued, characterized by numerous swamps, lakes, and shallow sinkholes. Land-surface altitude ranges from about 30 ft above mean sea level near Dunnellon to about 215 ft above mean sea level in the east-central part of the Rainbow Springs basin. Land-surface altitude generally is highest at the northern and southern ends of the study area where the Upper Floridan potentiometric-surface contours also are highest. The terrain gently slopes downward to the springs, therefore the lowest land-surface altitude is at the boundaries of the study area where spring discharge exits the basin.

Climate

Climate in the study area is subtropical and marked by long, warm humid summers and mild, dry winters. The mean annual air temperature at Ocala is 70.7 °F for 1961-90 (NOAA, 1992). Mean monthly air temperature ranges from 57.5 °F in January to 81.5 °F in July. Diurnal temperature variation is modest, typically about 20 °F in summer and about 25 °F in winter. Because dewpoints are close to the daily minimum air temperature during much of the year, the air at night becomes saturated and the formation of fog is common. Thunderstorm activity can enhance nighttime fog formation during the summer.

During a typical year, rainfall can be characterized by two distinct seasons: a wet season (June through September) and a much longer dry season (October through May). Mean annual precipitation at Ocala is about 52 in. for 1961-90 with more than 50 percent falling during the summer wet season. Diurnal thunderstorm activity is most prominent during the summer months when moist tropical air moving in from the Gulf of Mexico and the Atlantic Ocean is uplifted by differential solar heating of the land surface. These thunderstorms can produce several inches of rain in one location and little or no rain a mile or even a few hundred feet away. Tropical systems, such as tropical storms and hurricanes, can generate copious amounts of rainfall over a much larger part of the study area. Generally, these systems affect the study area during the wet season; however, occasionally tropical activity can extend into the first several months of the dry season. Rainfall during the dry season usually is associated with frontal systems and is more evenly distributed areally than rainfall during the wet season.

Surface Drainage

The spring basins are located within the Ocklawaha River and Withlacoochee River basins, but contribute little surface runoff; therefore, rainfall in the basins primarily percolates directly to (recharges) the underlying Floridan aquifer system or is lost to ET. The surface-water basins generally coincide with the spring basins, except for drainage alterations made to the Orange Creek and Ocklawaha River basins. Inter-basin diversion of surface water is routed within the Orange Creek basin from south of Gainesville into Camps Canal at the northwestern basin boundary and within the Ocklawaha River basin into Lake Griffin through Haines Creek at the southeastern basin boundary. The northern third of the Silver Springs basin (about 500 mi^2) and a much smaller part of the Rainbow Springs basin is drained by Orange Creek (Phelps, 1994). Weir overflow from Orange Lake drains into Orange Creek which then flows eastward out of the study area. There is very little, if any, surface drainage in the southern parts of both spring basins. The Ocklawaha River crosscuts the Silver

Springs basin and flows northward receiving discharge from Silver Springs (fig. 1). Rainbow Springs discharges into the Withlacoochee River bordering the southwest edge of the basin.

There are several large lakes (greater than 9 mi^2) in the Silver Springs basin, including Lake Griffin, Lake Weir, Orange Lake, and Lochloosa Lake. Some of the lakes are perched on materials of low permeability overlying limestone, but others (such as Orange Lake) have a direct connection to the Upper Floridan aquifer (Phelps, 1994). There are no large lakes in the Rainbow Springs basin. The study area also contains numerous closed sinkhole depressions which have permeable bottoms and do not hold water. Sinkholes are most prevalent in the mature karst terrane west of the Ocklawaha River.

Hydrogeology

The Floridan aquifer system consists of a thick sequence of highly permeable carbonate rocks of Tertiary Age and includes the Ocala Limestone, the Avon Park Formation, the Oldsmar Formation, and part of the Cedar Keys Formation (fig. 2). The Floridan aquifer system in west-central Florida generally is subdivided into the Upper and Lower Floridan aquifers separated by the middle semiconfining unit, a less permeable layer containing intergranular evaporites. The middle semiconfining unit is present in the Rainbow Springs basin. However, in the Silver Springs basin, the middle semiconfining unit generally is absent and the Upper and Lower Floridan aquifers are well connected, although water is known to be more highly mineralized in the lower Floridan (Ryder, 1985, p. 7). The thickness of the Floridan aquifer system ranges from about 600 ft in the Rainbow Springs basin to about 1,800 ft in the Silver Springs basin.

The Upper Floridan aquifer is estimated to be unconfined in about 55 percent of the study area (Faulkner, 1973). The sands that overlie the Upper Floridan are highly permeable and well-drained, and the potentiometric surface generally is 15 ft or more below the land surface. Thick surficial clayey sands can confine the Upper Floridan aquifer locally; sometimes these clayey sands are thick enough to form a surficial aquifer, but generally such aquifers are of very limited extent and importance (Phelps, 1994).

Transmissivity of the Upper Floridan aquifer is a function of primary and secondary porosity of the aquifer. Secondary porosity features resulting from solution channels enhance permeability but, because of the irregular distribution of these channels, the transmissivity of the aquifer varies widely. Well-developed solution channels increase the transmissivity of the Ocala Limestone, especially in the vicinity of both spring vents, allowing large volumes of water to be discharged. Transmissivities of the Upper Floridan aquifer generally range from 1,000,000-10,000,000 ft^2/d and have been estimated to be as large as 25,000,000 ft^2/d in the vicinity of the spring vents (Ryder, 1985).

Recharge areas of the Upper Floridan aquifer in the study area generally are located in the topographically higher lands mainly along the perimeter of the basins where the intermediate confining unit is absent or thin. High recharge rates of 10-20 in/yr provide rapid replenishment of water to the Floridan aquifer system (Ryder, 1985). Hydraulic gradients toward the springs are about 0.2-0.5 ft/mi. The mean residence time of the flow system (the average time required for rainfall within the basin to be discharged from either spring) is estimated to be about 4 yrs. This estimate is based on concentrations of tritium measured in rainfall and spring discharge during the mid 1960’s (Faulkner, 1973).

The largest component of ground-water discharge in the two-basin area is spring discharge. In terms of average flow, Silver Springs is one of the largest freshwater spring groups in Florida (Rosenau and others, 1977). For the 30-yr period 1965-94, the combined annual discharge of Silver Springs and Rainbow Springs was nearly 1,500 ft^3/s; 783 ft^3/s for Silver Springs and 715 ft^3/s for Rainbow Springs (U.S. Geological Survey, 1966-95). Generally, the daily and annual discharges of Silver Springs are slightly higher than that of Rainbow Springs; however, during drier and more recent years, discharge from Rainbow Springs occasionally has exceeded that of Silver Springs.

Ground water in the Rainbow Springs and Silver Springs basins is pumped mainly from the Upper Floridan aquifer for agricultural and municipal use; pumpage averaged 49 Mgal/d (76 ft^3/s) for Marion County in 1990 (Marella, 1992). The amount of water pumped from the Upper Floridan is equivalent only to about 10 percent of the discharge from Silver Springs. Although small in comparison to the other components, ground-water withdrawal was included in the water-budget analysis.

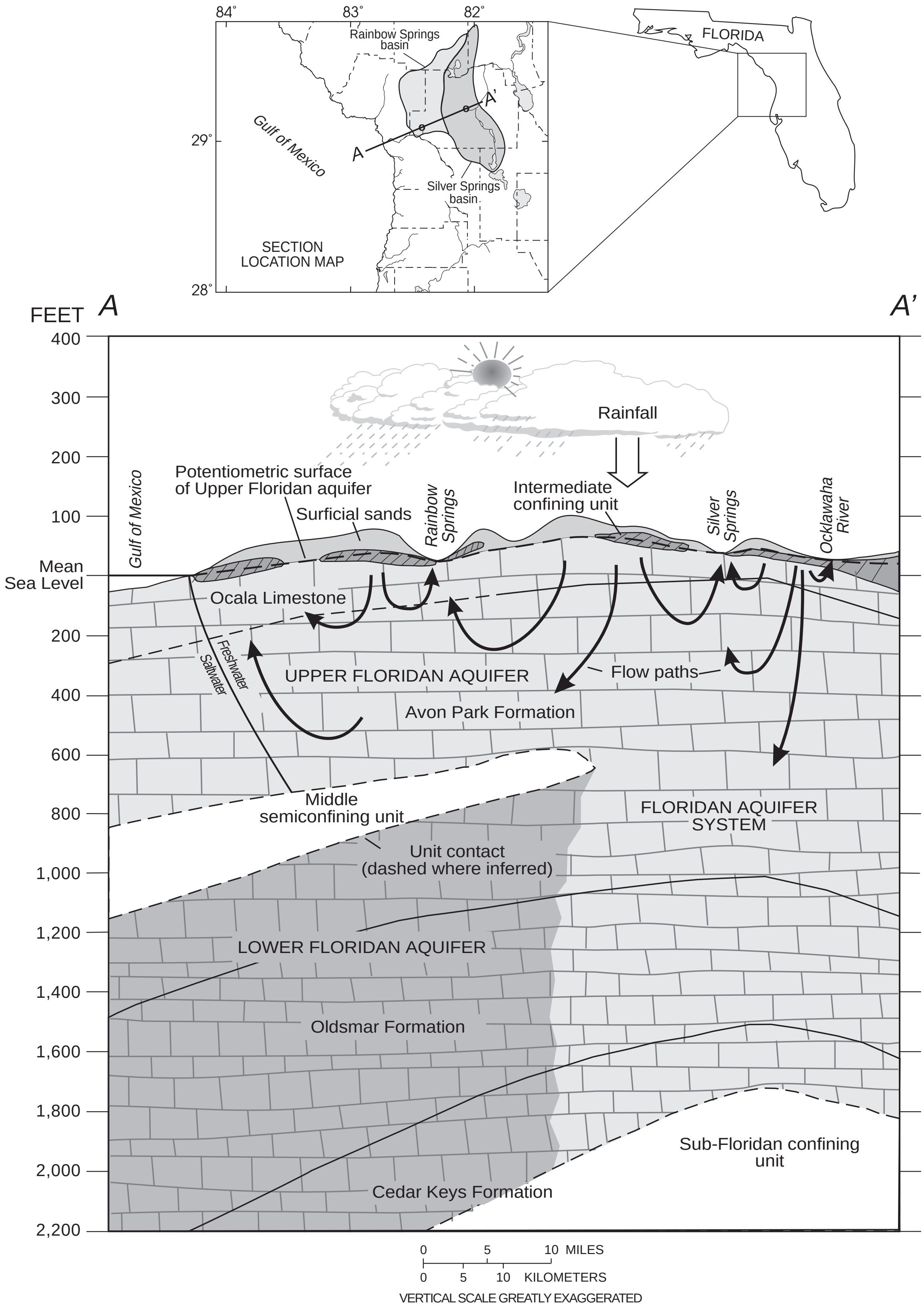

Figure 2. Generalized hydrogeologic section A-A′ showing the Upper and Lower Floridan aquifer in the Rainbow Springs and Silver Springs basin area (modified from Ryder, 1985).

Meteorological (MET) Data-Collection Site

The MET site was established to collect data during the 1994 water year. The site was located in the northern part of the study area, about 6 mi north of Cross Creek (fig. 1). Field measurements were made in a 0.3-mi^2 immature slash pine (*Pinus elliottii*) tree farm with an average tree height of 4-5 ft. The area was bedded, or furrowed, to promote drainage from pine flatwoods at a higher elevation southeast toward adjacent wooded swampland. The farm also was adjacent to undisturbed forest and other tree farms. Most of the bordering treeline was in excess of 1,000 ft from the data-collection sensors; however, an 80-ft high tree line bordering the eastern edge of the area was within 500 ft of the sensors.

The soil at the MET site generally is an organic, clayey sand that contains wood chips and other cellulosic debris remaining from previous land clearing. The top several inches of the surficial soil is sandier than the deeper soil and is highly porous. Clay hardpan of indeterminate thickness is present 4 to 6 ft below land surface. This hardpan is the base for the water table in the area and possibly is the top of the intermediate confining unit above the Upper Floridan aquifer. The water table generally was within 3 to 4 ft, but was nearer to land surface during much of the winter and for short periods during the wet season. Surface and subsurface drainage at the site generally was very slow in response to rainfall; widespread ponding of water generally lasted for many days after heavy rainfall.

The variety of vegetation types at the MET site was representative of vegetation found throughout much of the study area. Table 1 lists 23 species identified at the MET site. Evergreen plants dominate the MET site area in areal coverage, although a majority of the plants are deciduous. This indicates that transpiration is a year-round process at the site. Understory vegetation generally was 2-4 ft high and consisted mainly of shrubs, vines, ferns, and grasses. Young slash pine, an evergreen, was most abundant, followed by turkey oak (*Quercus laevis*). Pine trees were planted approximately 6 ft apart and grew from an average height of 3.5 ft to approximately 6 ft during the study. Small tap roots extended down 3-4 ft from the base of the tree and lateral roots extended for many feet intertwining with root systems of nearby trees. Although the pine trees were still very young (about 5 years of age), the shallow root systems were indicative of a predominantly high water table. The vigorous growth of the trees during the study period possibly introduced some bias in the determination of ET resulting in a slight overestimation of ET during the early part of the study and slight underestimation in the later part of the study

Table 1. Flatwood vegetation species identified at the MET site

[Species listed alphabetically and not by density of coverage]

Scientific Name	Common Name
Groundcover species	
Andropogon sp	chalky blue-stem (broomsedge)
Aristida sp	three-awned grass
Aristida stricta	wire grass
Asimina sp	pawpaw
Centella asiatica	centella
Eleocharis sp	spike-rush
Hypericum sp	St. Johnswort
Juncus effusus	soft rush
Panicum sp	panic grass
Polygala lutea	polygala
Pteridium aquilinum	bracken fern
Rhynchospora sp	beakrush
Xyris sp	yellow-eyed grass
Vaccinium sp	blueberry
Shrub and vine species	
Ilex glabra	gallberry
Myrica cerifera	wax myrtle
Quercus sp	oak
Rhus copallina	winged (shining) sumac
Rubus sp	cat briar (blackberry)
Serenoa repens	saw palmetto
Vitis sp	grape
Tree species	
Pinus elliottii	slash pine
Quercus laevis	turkey oak

Previous Studies

A number of reports are available which describe the geohydrology of the study area. The potential hydrological effects on the Upper Floridan aquifer as a result of constructing the Cross-Florida Barge Canal are described by Faulkner (1970, 1973) and Rohrer (1984). Hydrologic and regional flow-modeling studies on the Upper Floridan aquifer including the Rainbow Springs and Silver Springs ground-water basins are described by Ryder (1982, 1985). One of the most recent studies, Phelps (1994), provides an updated description of the hydrogeology and inventory of potential contamination sources of the Upper Floridan aquifer, and describes the potential movement of contaminants within the Upper Floridan in the Silver Springs ground-water basin.

Literature on the theory of eddy correlation and its applicability to energy-budget analyses is widely available. Principles of environmental physics, including the theory of eddy correlation, are thoroughly discussed by Monteith and Unsworth (1990). Dyer (1961) presents the development of the first eddy-correlation system, called the “Evapotron.” Tanner (1967) states that “ultimately eddy-correlation methods should prove to be the most accurate of the micrometeorological methods and least dependent on surface conditions.”

Stannard (1993) successfully used eddy-correlation measurements of latent and sensible heat flux with measurements of net radiation, soil heat flux, and other micrometeorological variables to develop a modified form of the PT model and compare the results from this model to results from the Penman-Monteith and the Shuttleworth-Wallace evaporation models. The modified PT model estimated ET from a sparse canopy significantly better than the Penman-Monteith model; whereas, the PT and Shuttleworth-Wallace models performed about equally well. In the PT model, a nonlinear relation was determined between alpha (α), an evaporation coefficient, and two site variables.

Annual lake evaporation often is estimated using regional pan-evaporation data for lakes by applying a pan-to-lake coefficient. Sacks and others (1994) computed pan-to-lake coefficients for two north Florida lakes and estimated lake evaporation for the two lakes based on nearby pan-evaporation data; the relation of pan evaporation to lake evaporation was used to estimate lake evaporation in this report.

Acknowledgments

The author wishes to thank Sydney T. Bacchus of the Institute of Ecology at the University of Georgia for her assistance in identifying vegetation at the MET site. This information is valuable and necessary to establish a better understanding of the magnitude of ET associated with specific vegetation species. The author also is grateful to the Georgia-Pacific Corporation for permitting the USGS to establish the MET data-collection site on their property. Special thanks to the employees of Lake Weir Aquatic Preserve (Rainbow Springs State Park) and Florida Leisure (Silver Springs) for allowing access into the parks for a reconnaissance of spring-discharge areas.

METHODS, INSTRUMENTATION, AND DATA COLLECTION

A water-budget analysis and a modified PT model calibrated using eddy-correlation data were used to estimate annual and seasonal average ET for each water year during 1965-94 and monthly average ET for the 1994 water year. Pan-evaporation data were adjusted based on monthly pan-to-lake coefficients to estimate lake evaporation in the water-budget analysis. A monthly time step was used in the initial computations of ET for both methods used in the study.

Water-Budget Analysis

The Rainbow Springs and Silver Springs basin area, as defined for the water-budget analysis, included the Floridan aquifer system. Basin boundaries were delineated only from the potentiometric surface (water levels) of the Upper Floridan aquifer because well data were insufficient to define lateral boundaries of the Lower Floridan aquifer. Therefore, the following three assumptions for the modeled area of the aquifer were used in the water-budget analysis: (1) water levels in the Lower Floridan aquifer are closely related to water levels in the Upper Floridan aquifer; (2) the basin boundaries are equal to no-flow Upper Floridan aquifer boundaries; (3) all recharge ultimately is discharged at either spring (no additional losses); and, (4) changes in surficial-aquifer and unsaturated-zone storage were negligible.

A network of 9 Upper Floridan ground-water wells, 12 meteorological stations, and 12 surface-water stations were used in the water-budget analysis (table 2, fig. 3). Stations were selected based on location and availability of long-term record. Approximately 75 long-term, monitoring wells with 20 to 60 years of partial record are located within the study area. Of these, nine Upper Floridan aquifer wells were used to compute the change in ground-water storage in the water-budget analysis. Change in surficial-aquifer storage was ignored in this analysis; therefore, surficial wells were not used.

Table 2. Hydrologic-data stations used for analysis

[Source agency maintaining data record: USGS, U.S. Geological Survey; SJRWMD, St. Johns River Water Management District; SWFWMD, Southwest Florida Water Management District; and NOAA, National Oceanic and Atmospheric Administration]

Station number (fig. 3)	Station name	Latitude	Longitude	Source agency
	Ground-water wells			
1	Mar-48 near Ocklawaha, Fla.	28°59′20″	81°49′05″	USGS
2	Rainbow Springs Well near Dunnellon, Fla.	29°05′14″	82°27′07″	USGS
3	Sharpes Ferry Well, Marion 5 near Ocala, Fla.	29°11′15″	81°59′25″	USGS
4	CE-31 at Ocala, Fla.	29°11′15″	82°10′29″	USGS
5	CE-66 at Sparr, Fla.	29°20′19″	82°06′42″	USGS/SJRWMD
6	Devil′s Den Sink	29°24′30″	82°28′30″	USGS/SWFWMD
7	Yearling Restaurant	29°29′09″	82°09′51″	USGS
8	A-0071 Hawthorne Tower Deep	29°35′56″	82°04′34″	SJRWMD
9	A-0005 Owens-Illinois	29°35′39″	82°11′26″	SJRWMD
	Meteorological			
10	Lisbon	28°52′00″	81°47′00″	NOAA
11	Wildwood Tower	28°51′57″	82°04′43″	SWFWMD
12	West Oxford	28°57′53″	82°08′42″	SWFWMD
13	Dunnellon Tower	29°03′13″	82°23′26″	SWFWMD
14	Lynne	29°12′00″	81°56′00″	NOAA
15	Ocala (City Water Plant)	29°12′00″	82°05′00″	NOAA
16	Romeo	29°13′40″	82°26′50″	SWFWMD
17	Blichton Tower	29°16′16″	82°19′52″	SWFWMD
18	Usher Tower	29°25′00″	82°49′00″	NOAA
19	Meteorological (MET) site	29°33′39″	82°11′12″	USGS
20	Gainesville Municipal Airport	29°41′00″	82°16′00″	NOAA
21	Gainesville 11 WNW	29°41′00″	82°30′00″	NOAA
	Surface-water			
22	Haines Creek at Lisbon, Fla.	28°52′14″	81°47′02″	USGS
23	Ocklawaha River at Moss Bluff, Fla.	29°04′52″	81°52′51″	USGS
24	Rainbow Springs near Dunnellon, Fla.	29°06′08″	82°26′16″	USGS
25	Silver Springs near Ocala, Fla.	29°12′44″	82°03′15″	USGS
26	Ocklawaha River near Conner, Fla.	29°12′52″	81°59′10″	USGS
27	Orange Lake Outlet near Citra, Fla.	29°26′30″	82°06′33″	USGS
28	Orange Creek at Orange Springs, Fla.	29°30′34″	81°56′47″	USGS
29	Camps Canal near Rochelle, Fla.	29°34′33″	82°15′00″	USGS
30	Lake Griffin at Leesburg, Fla.	28°51′48″	81°51′31″	USGS/SJRWMD
31	Lake Weir at Ocklawaha, Fla.	29°02′23″	81°55′44″	USGS
32	Orange Lake at Orange Lake, Fla.	29°25′37″	82°12′26″	USGS
33	Lochloosa Lake at Lochloosa, Fla.	29°30′07″	82°06′12″	USGS

Data Availability

Continuous records of daily rainfall are available for 6 NOAA meteorological stations (11, 15, 16, 19, 21, and 22) beginning in 1898, and for 6 SWFWMD meteorological stations (7, 12, 13, 14, 17, and 18) beginning in 1970. Pan-evaporation data are available for 2 NOAA meteorological stations (11 and 22) beginning in 1953 and 1960, respectively.

Complete continuous-discharge records for Silver Springs and Rainbow Springs begin in 1932 and 1965, respectively (U.S. Geological Survey, 1966-95, v. 1A). Discharges for Rainbow Springs and Silver Springs are measured at surface-water stations (24 and 25, respectively) downstream of the spring vents. These discharges are related to water levels of the potentiometric surfaces at specific wells in the basins. Continuous water-level data, recorded at Sharpes

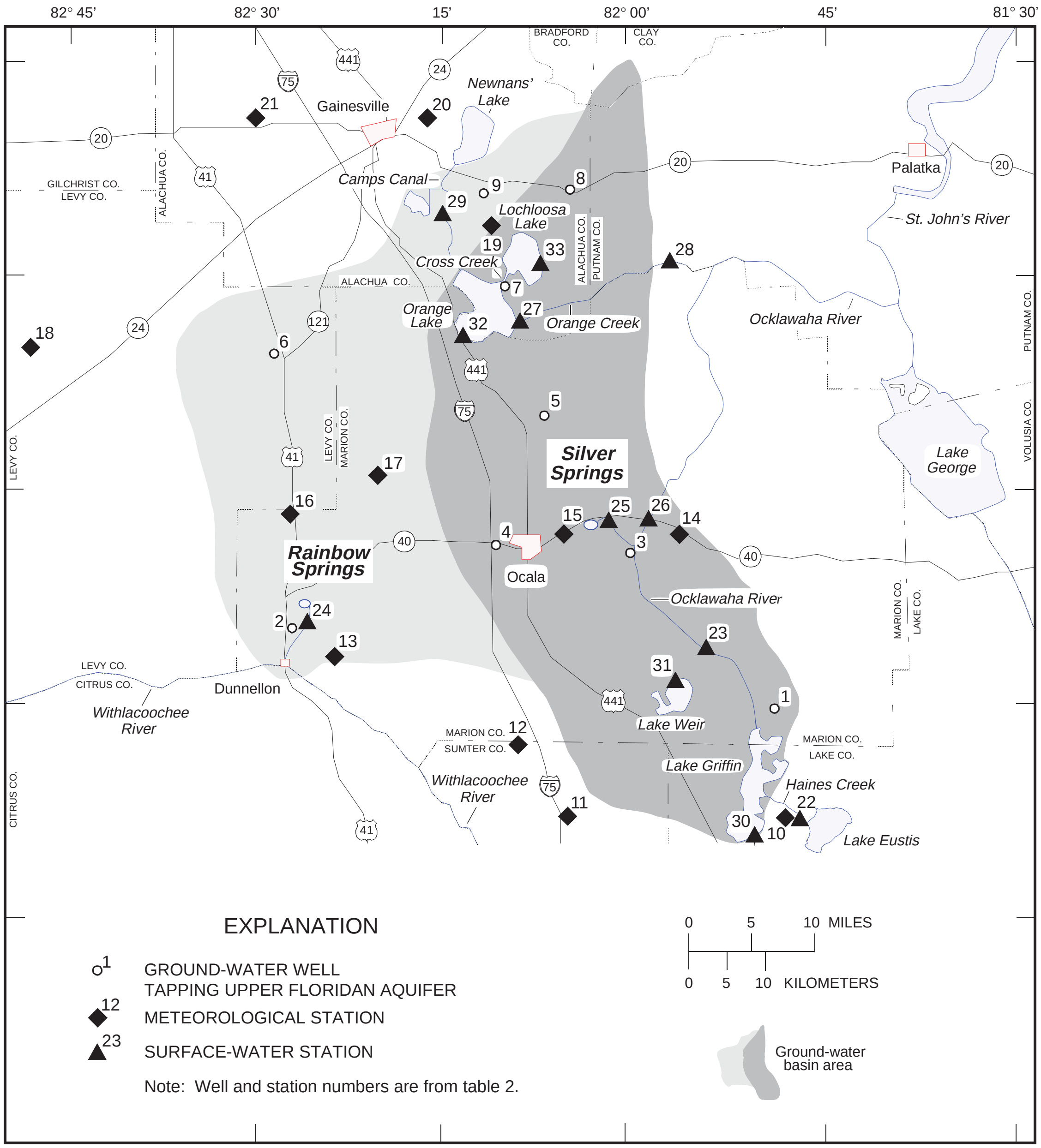

Figure 3. Location of data stations used for analysis in the Rainbow Springs and Silver Springs study area.

Ferry Well, Marion 5 near Ocala, Fla., (station 3) are used to compute discharge from Silver Springs, and continuous water-level data from the Rainbow Springs Well near Dunnellon, Fla., (station 2) are used to compute discharge from Rainbow Springs.

Partial records of streamflow are available for six of the remaining surface-water stations. For the Ocklawaha River, streamflow record is available from 1942 to 1978 and from 1985 to present for Haines Creek at Lisbon, Fla. (station 22); from 1943 to 1955 and from 1967 to present for Ocklawaha River at Moss Bluff, Fla., (station 23); and, from 1930 to 1946 and from 1977 to present for Ocklawaha River near Conner, Fla., (station 26). For Orange Creek, streamflow record is available from 1947 to 1955 and from 1982 to present for Orange Lake Outlet near Citra, Fla., (station 27); from 1942 to 1952, 1955 to 1971, and from 1975 to present for Orange Creek at Orange Springs, Fla., (station 28); and from 1957 to 1960 and from 1978 to present for Camps Canal near Rochelle, Fla., (station 29).

Stage data for Lake Griffin (station 30), Lake Weir (station 31), Orange Lake (station 32), and Lochloosa Lake (station 33) were used to compute the change in lake storage (U.S. Geological Survey, 1966-95, v. 1B). Continuous stage records for 1965-94 are available for Lake Griffin, Lake Weir, and Orange Lake, although a part of the record for Lake Griffin is incomplete. Supplemental stage data for Lake Griffin were supplied by the SJRWMD. Stage record is fragmentary for Lochloosa Lake prior to 1989, but becomes continuous after 1989. Gaps in stage record were estimated from trends in available nearby lake and streamflow data.

Compilations of water-use data were started on a nationwide basis in 1950 by the USGS with reports of water use categorized only on a state-by-state basis. Ground-water withdrawal data categorized by county in Florida generally were published at 5-year intervals in USGS reports beginning in 1965. Estimated water-use data and inventories for Florida were published in a series of reports by Pride (1973, 1975), Leach (1977), Leach and Healy (1980), Leach (1982), and Marella (1988, 1992). Pumpage of ground water by county in Florida for 1980 also can be obtained from a map report by Leach (1983). Additional ground-water resource availability and use are given in a report by Snell and Anderson (1970).

Water-Budget Equation

The general water-budget equation used for the Rainbow Springs and Silver Springs basins and arranged to solve for ET is:

$$ET = RF - \Delta S_A - \Delta S_L - SP - \overline{ST} - WD \qquad (1)$$

where all components are in inches per unit time;

- ET is evapotranspiration;
- RF is rainfall;
- ΔS_A is net change in aquifer storage;
- ΔS_L is net change in lake storage;
- SP is springflow;
- $\overline{ST}$ is average net streamflow (for 1947-55 and 1981-94); and
- WD is withdrawal from Floridan aquifer (pumping).

Areal estimates of RF and ΔS_A used in equation 1 were determined using the Theissen method (Fetter, 1980). This method adjusts for nonuniform station distribution by applying a weighting factor for each station. The factor is based on the size of the area within the irregular polygon which is constructed around and closest to each station. Based on the spatial variability in rainfall and that 12 stations (with an average area of 129 mi^2 per station) were used, maximum likely error in the monthly estimate of RF probably was less than 20 percent for the two-basin area. An error of 6 in. in the water-level data for the ground-water station areas would result in maximum likely error of about 10 percent in the estimate of ΔS_A for the two-basin area.

ΔS_A and ΔS_L were estimated using the difference between the water levels on the first day of each month. In this analysis, the entire Upper Floridan aquifer was considered unconfined in both ground-water basins. ΔS_A was computed using water levels in the Upper Floridan aquifer and a value for specific yield of 0.2 (Ryder, 1985). The change in lake storage was computed for individual lakes using a corresponding average lake-surface area. A surface area of 13.7 mi^2 was used for Lochloosa Lake, 20.6 mi^2 for Orange Lake, 9.0 mi^2 for Lake Weir, and 16.7 mi^2 for Lake Griffin. ΔS_L is the sum of the net changes in storage for these lakes.

Total storage in the ground-water basins is defined as the sum of aquifer and lake storage. Therefore, in the water-budget equation the total change in ground-water basin storage (ΔS) is the sum of the changes in ΔS_L and ΔS_A. Changes in surficial-aquifer and unsaturated zone-storage transfer time were not taken into account in the water-budget analysis and could induce error in the monthly estimates of ET, especially during times when change in storage in the unsaturated zone is relatively large in comparison to the other components. Maximum likely errors in ΔS caused by ignoring changes in surficial aquifer and unsaturated zone storage probably were less than 20 percent.

SP was estimated using monthly mean discharge data for Rainbow Springs and Silver Springs and then was converted to units of depth by dividing by the basin area. Although springflow contributes to streamflow in the study area, it is considered as a separate component in this analysis. Springflow measurements mostly are rated good to fair, indicating that maximum likely error in the estimate of springflow generally is about 5 to 8 percent.

Streamflow (and lake storage) were considered only in the Silver Springs basin because there are no streams or large open-water bodies in the Rainbow

Springs basin. $\overline{ST}$ represents average net streamflow, or surface runoff; however, much of this "runoff" may actually be diffuse upward leakage of ground water adding to streamflow within the study area. Net streamflow was computed by subtracting springflow, and streamflow entering the basin area, from streamflow exiting the basin area. An $\overline{ST}$ of 1.02 in/yr (average flow for 1947-55 and 1981-94) was used in the analysis because of incomplete record and because streamflow accounts for only a very small part of the water-budget in the basin. However, actual monthly streamflow data were used in the water-budget analysis for the 1994 water year. Maximum likely error in the estimate of net streamflow probably was less than 20 percent.

WD was estimated using annual and monthly water-use data for Marion County and was a reasonable estimation that accounted for the very small amount of pumpage in the two-basin area. Maximum likely error in the estimate of pumpage probably was less than about 20 percent.

Lake evaporation was estimated from pan-evaporation data by applying pan-to-lake coefficients. Pan data from NOAA stations 10 and 21 (fig. 3) were averaged and multiplied by coefficients presented by Sacks and others (1994, p. 326) to estimate lake evaporation in the study area. Monthly pan-to-lake coefficients for 1990 averaged 0.88 and ranged from 0.61 in January to 0.96 in August and October. The error (coefficient of variation) in the estimate of lake evaporation was about 7 percent and was determined by dividing the standard error of 0.42 in. (1.07 cm) by mean lake evaporation (Sacks and others, 1994, p. 325)

Micrometeorological Approach

ET also was estimated using eddy correlation. Measurements were made within about 3 m above a surface, within the surface sublayer of the atmospheric boundary layer. Discrete eddy-correlation measurements made monthly for a few days at a time were used in conjunction with measurements of net radiation, soil heat flux, and other micrometeorological variables to calibrate a modified PT model for predicting ET. The modified PT model is a one-component simplified form of the Penman-Monteith model in which a coefficient, α, is computed from measurements of ET made using eddy correlation and then related to meteorological and other site variables. The modified PT model then was used to estimate ET on non-measured days (between monthly visits) at the MET site.

Energy Balance of a Vegetated Surface

In the absence of horizontal advection, the energy balance of a vegetation canopy can be written:

$$R_n - G - S_c = H + \lambda E\,, \qquad (2)$$

where: the left side represents the available energy and the right side represents the turbulent flux, all terms are in W/m^2;

R_n is net radiation flux;

G is soil heat flux at land surface;

S_c is rate of heat storage in the plant canopy;

H is sensible heat flux; and

λE is latent heat flux. λ is latent heat of vaporization of water, in J/g, and E is evaporation rate, in (g/m^2)/s.

S_c was ignored in equation 2 because the plant canopy (immature forest) is not massive at the MET site. The sign conventions for flux directions are: R_n is positive when net radiation is directed toward the land surface; H and λE are positive when the fluxes are directed away from the land surface; and G is positive when the subsurface heat is directed downward. The ratio of sensible to latent heat flux, $H/\lambda E$, is the Bowen ratio.

Micrometeorological data were collected at the MET site from September 1993 to September 1994 and included net radiation, wind speed and direction, air temperature, relative humidity, depth to water table, rainfall, soil temperature within the upper 0.08 m, soil heat flux at 0.08 m depth, and soil moisture. All variables were sampled at 1-min intervals and stored as 20-min averages by a data logger. Data-collection equipment was serviced and data were retrieved during monthly visits. Net radiation was measured by deploying a net radiometer 3 m above the land surface, or about 1.5 m above the canopy. Wind speed and direction were measured with an anemometer and wind vane, and air temperature and relative humidity were measured with a radiation-shielded sensor probe. The anemometer and sensor probes were mounted on a tripod about 1 m above the canopy. Depth-to-water table was measured monthly at an on-site, shallow 2.5 m well, cased with a 5-cm PVC pipe.

Rainfall was measured by a tipping-bucket rain gage mounted 1 m above the land surface in an area void of obstructing vegetation. Nearby low-cut vegetation and the proximity of the gage to the land surface helped to reduce the negative effects of wind on rainfall capture. A laboratory-calibration correction was applied to 1-min rainfall data before summing into 20-min totals to account for measurement deficits resulting from inadequate tipping-bucket response during high-intensity rainfall at the site.

Measurements of soil heat flux were made by burying one heat-flux plate (at a depth of 8 cm) and four soil-temperature probes (two probes at a depth of 2 cm and two at 6 cm). The energy stored above the plate is then added to the flux measured by the plate to obtain the soil heat flux (G) at land surface, in W/m^2:

$$G = G_p + S \ , \tag{3}$$

where:

G_p is heat flux at 0.08 m depth measured by plate, in W/m^2;

S is average change in stored energy in the top 0.08 m of soil, in W/m^2, and is obtained by:

$$S = \frac{(T_s - T_{s-1}) D C_s}{t} \ , \tag{4}$$

where:

T_s is current 20-min mean soil temperature, in °C;

T_{s-1} is previous 20-min mean soil temperature, in °C;

D is depth to heat-flux plate, in m, or 0.08 m at the MET site;

C_s is soil heat capacity, in (J/m^3)/°C; and

t is time interval, in seconds, or 1200 s at the MET site.

The 20-min mean soil temperature was computed by averaging the measurements from all four soil probes.

C_s, the heat capacity of moist soil on a volume basis in (J/m^3)/°C is determined by

$$C_s = \rho_b (W c_w + c_s) \ , \tag{5}$$

where:

ρ_b is bulk density of soil, in kg/m^3;

W is water content of the soil, in kg water/kg soil

c_w is specific heat of water, in (J/kg)/°C; and

c_s is specific heat of dry mineral soil, in (J/kg)/°C.

The heat capacity of the soil at the MET site was determined from 135 soil samples using constant values of 4,190 (J/kg)/°C for c_w and 840 (J/kg)/°C for c_s. Soil samples had an average ρ_b of 1,540 kg/m^3, an average W of 15 percent, and an average porosity of 45 percent.

Soil moisture in the top 0.08 m of soil was measured continuously at the MET site using two gypsum soil-moisture blocks. But, because of poor response of these blocks to changing soil conditions, the data were questionable, and three soil samples were collected approximately each week at the site from the top 0.08-m of soil during much of the study. Because the land was furrowed, samples were taken from the top of small ridges, in the furrows, and approximately halfway between the ridge and furrow. Sampling was performed in this manner to obtain measurements of soil moisture and soil characteristics representative of the site area. Trends in the gypsum-block data and rainfall data were used to estimate daily soil moisture between the weekly samples. Measured and estimated soil moisture are compared to daily rainfall (fig. 4). The record indicates that the water table was near the land surface in early November, January through mid-March, and during mid-September. The shallow water table was verified during the weekly visits when ponded water was observed in the furrows at the MET site.

Leaf-area index (LAI), which typically is related to ET, is the total (two-sided) leaf area per unit ground area and is unitless. Calculation of LAI involved estimating the fraction of green leaves in the canopy when viewed at an angle of about 30° below the horizon. LAI is computed by the following equation:

$$LAI = -\ln(1 - L_s) \tag{6}$$

where

L_s is fraction of green leaves viewed at an angle of 30°.

The relation between L_s and LAI is nearly the same for all types of canopy (Monteith and Unsworth, 1990). LAI was estimated monthly by visual inspection and by taking ground photographs of the MET site during visits. Daily values of LAI for the MET site were prorated for periods between monthly visits and ranged from a minimum of 0.51 in mid-January to a maximum of 2.30 in July.

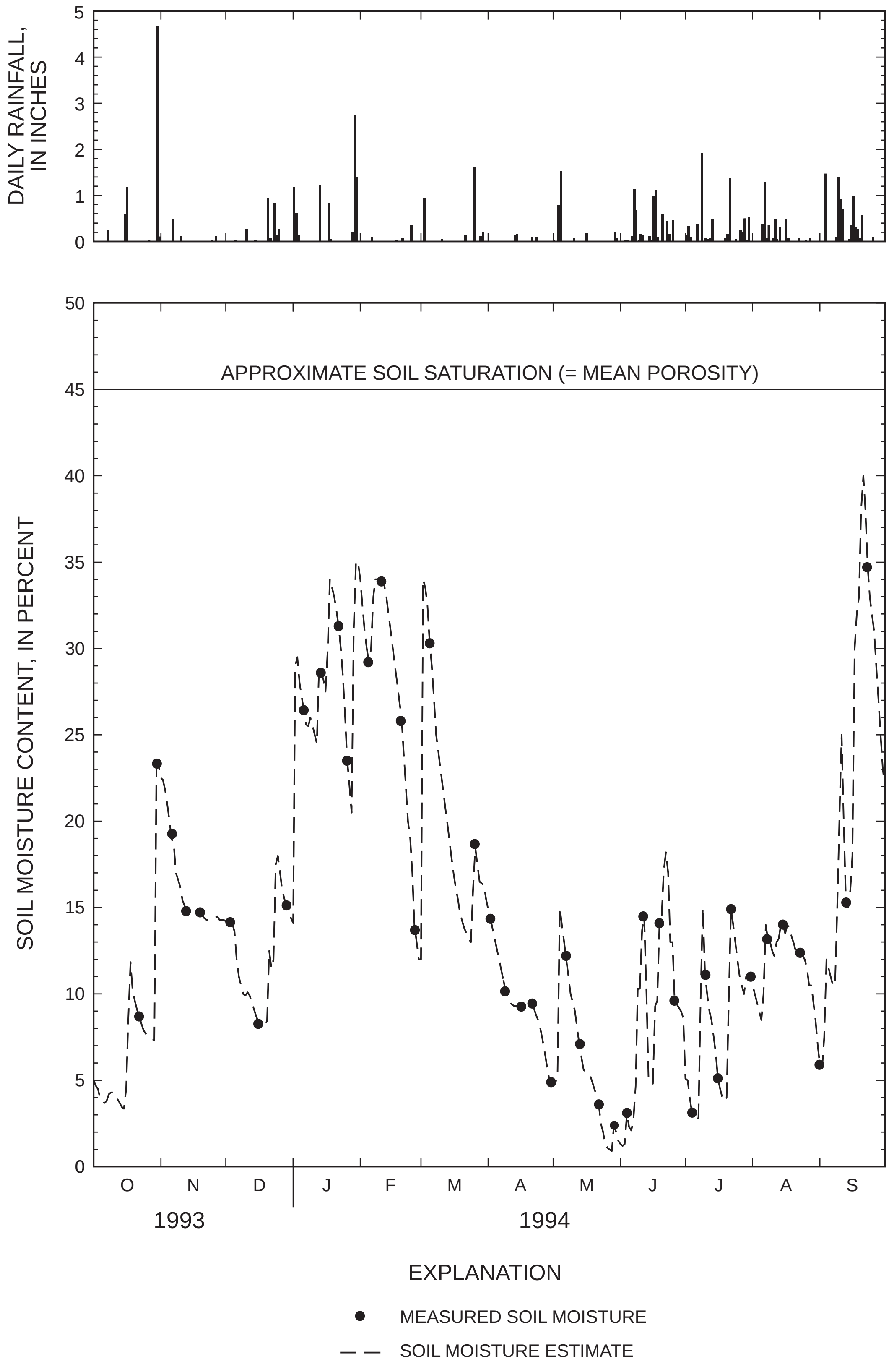

Figure 4. Soil moisture content and rainfall at the MET site, 1994 water year.

Eddy Correlation

Eddy correlation is used to measure the vertical flux of a quantity, such as water vapor, in the boundary layer immediately above a land or water surface. Eddy-correlation measurements are made by making a rapid succession of measurements, typically 10 measurements per second, in order to obtain an adequate sampling of their departure from the mean vapor density and vertical wind speed. If vapor density and vertical wind speed are measured rapidly, the degree to which they are correlated with one another is related to vapor-flux density. During the daytime, wetter, warmer eddies typically tend to move up from a heated, moist surface; however, drier, cooler eddies tend to move downward. Eddy correlation measures the vertical transport of water vapor by these eddies, the energy equivalent of which is latent heat flux and sensible heat flux, which is heat that moves by virtue of a temperature gradient. In this study, ET was measured for short time periods using a standard eddy-correlation method presented by Bidlake and others (1993).

Principal sensing components of the eddy-correlation system were a one-dimensional sonic anemometer, a fine-wire thermocouple air-temperature sensor, and a krypton hygrometer. The sonic anemometer measured vertical wind speed by detecting phase shifts in sound waves emitted and received by two sonic transducers that were spaced 10 cm apart, one above the other. Air-temperature fluctuations were measured with a chromel-constantan thermocouple (diameter 13 μm) which was laterally displaced 4 cm from the middle of the 10-cm path between two sonic transducers. The hygrometer, displaced about 10 cm from the sonic path, measured vapor density over a 1-cm path by measuring the attenuation of ultraviolet radiation.

Sensors were mounted on a tripod 3-4 ft above the average height of vegetation, or canopy, to ensure that the measurements were being made within the local surface-boundary layer estimated to be approximately 5-10 ft thick. As wind passes from one type of land or water surface to another, such as from a mature forest to cleared land, horizontal gradients can develop across the leading edge of the downwind surface because the airstream begins to exchange momentum, heat, and water vapor with the different downwind surface. Downwind from the surface-change boundary, the layer of equilibrated air begins to rebuild from the surface at a rate of approximately 1 ft (vertically) per 100 ft (horizontally) of fetch. Fetch is the horizontal extent of the uniform surface below the boundary layer. Land surface within the fetch area should be homogeneous and flat with no abrupt changes in vegetation. A height-to-fetch ratio of 1:100 was used for determining the placement of the sensors to ensure that they would operate within the equilibrated layer of air (Tanner, 1988). Therefore, if the fetch surrounding the sensors extended from 500 to 1,000 ft, then the surface-boundary layer should be approximately 5-10 ft above the zero displacement plane, which is located at about two-thirds of the average height of the plant canopy (Monteith and Unsworth, 1990).

The two vertically aligned transducers of the sonic anemometer were oriented so that airflow past them was unobstructed by the sensor supports. Sampling must be frequent enough to detect high-frequency fluctuations in air parcels, and the averaging period must be long enough to adequately sample the low-frequency fluctuations (McBean, 1972). As suggested by Tanner (1988), a 10-Hz sampling frequency and a 20-min averaging period were used in this study.

ET was measured with the portable eddy-correlation system for a 1- to 3-day period coinciding with the monthly MET site visits, yielding a total of 17 “measured days” during the 1994 water year. Only daytime eddy-correlation measurements were used because dew formation and saturated-air conditions at night, including at dawn and dusk, interfered with the hygrometer and caused erratic readings. Eddy-correlation measurements were interrupted during rain or conditions of heavy fog or dew because transducers on the sonic anemometer are damaged when they come into direct contact with water. Thin-wire thermocouples are damaged by the impact of raindrops. Rainfall conditions resulted in several abbreviated data sets.

General equations for turbulent transport can be simplified when they are applied to vertical atmospheric transport near an extensive homogeneous surface (Brutsaert, 1982, p.190). In the absence of horizontal gradients and by ignoring transport by molecular diffusion, equations for sensible heat flux (H) and latent heat flux (λE) used in this study are:

$$H = \rho_a C_p \overline{\omega' T_a'} , \qquad (7)$$

and

$$\lambda E = \lambda \overline{\omega' \rho'_v} , \qquad (8)$$

where:

ρ_a is air density, in g/m^3;

C_p is specific heat of air at constant pressure (1.01 (J/g)/K);

ω is vertical wind speed, in m/s;

T_a is air temperature, in K;

ρ_v is vapor density, in g/m^3;

$'$ represents a momentary fluctuation from the mean;

— signifies the mean of an averaging period; and other terms are as previously defined.

In the standard application of the eddy-correlation method, the variables ω, T_a, and ρ_v are sampled simultaneously and a series of samples are used to compute the covariances $\overline{\omega' T_a'}$ and $\overline{\omega' \rho'_v}$. Covariance is a measure of the strength of association between two variables. Standard application of the eddy-correlation method yields sensible and latent heat fluxes that are determined independently of the remaining terms in the energy balance (eq 2).

The energy balance can be rearranged to provide a check on the accuracy among the measured terms. Energy-balance closure (C) in units of W/m^2 is unitless and evaluated by the equation

$$C = R_n - G - H - \lambda E, \tag{9}$$

where all terms are as previously defined.

Eddy-correlation measurements of H and λE and micrometeorological measurements of R_n and G for the same 20-min time period are substituted into equation 9. A value of 0 for C indicates an exact balance, although the turbulent flux (H and λE) and available energy (R_n - G) terms still could be under- or overestimated. If C is computed to be less than 0, one or both of the turbulent fluxes are overestimated or available energy is underestimated. The reverse holds true for values of C greater than 0.

The ratio of turbulent flux to available energy, (R_n - G) / (H + λE), also was used as a check on the accuracy of the measured terms. A ratio of 1 indicates an exact balance, although the turbulent flux and available energy terms could be under- or overestimated by the exact same magnitude. When the ratio is less than 1, one or both of the turbulent fluxes are overestimated, or available energy is underestimated. The reverse holds true for ratios greater than 1.

The ratio of turbulent flux to available energy and equation 9 were used to filter eddy-correlation measurements with large errors. When turbulent flux was more than 20 percent different than available energy or C was greater than 50 W/m^2, data for that 20-min period were removed. This filter is slightly more restrictive than that of Stannard (1993) which removed data when both criteria were exceeded, except that Stannard used a closure of 20 W/m^2.

Fluxes of H and λE during times when standard eddy-correlation data were discarded, were estimated with an eddy-correlation energy-balance Bowen ratio (ECEBBR) computation method which uses the Bowen ratio, $H/\lambda E$ (Bidlake and others, 1993). The rationale for using the ECEBBR method is that the sonic anemometer measurement error will proportionally affect λE and H equally, so that even though direct measurements of λE and H are in error, the ratio of the two is correct. Filtered 20-min data were replaced with 20-min estimates computed by the ECEBBR method to obtain measured daily values of ET on days eddy correlation was used.

Modified Priestley-Taylor Model

A majority of PET models have been developed for well-watered agricultural crops, including the Priestley-Taylor (PT) model, which is a simplified form of the Penman model. This model was developed to estimate PET under conditions of minimal, lateral advection (Priestley and Taylor, 1972). The PT equation is:

$$\lambda E = \alpha\Delta(R_n - G)/(\Delta + \gamma), \tag{10}$$

where

α is the PT evaporation coefficient (dimensionless);

Δ is the slope of the saturation vapor pressure-temperature curve, in kPa/K;

γ is the psychrometer constant, in kPa/K; and R_n, G, and λ, and E are previously defined.

The terms λ and Δ from equation 10 are related to air temperature by the following equations:

$$\lambda = 2500.25 - 2.365(T_a - 273), \text{ and} \tag{11}$$

$$\Delta \cong \lambda M_w 0.611 exp\,[17.27(T_a - 273)/(T_a - 36)]\,/(RT_a^2), \tag{12}$$

where

M_w is the molecular weight of water, 18 g/mol;

R is the molar gas constant, 8.314 (J/mol)/K; and other terms are as previously defined.

Equation 12 is an approximation for Δ developed by Monteith and Unsworth (1990, p. 10) and is valid for values of air temperature up to 313 °K (40 °C).

The psychrometer constant, γ, in kPa/K, from equation 10 is

$$\gamma = \frac{C_p P_a}{\varepsilon\lambda} , \tag{13}$$

where:

P_a is ambient atmospheric pressure at the MET site, (100.9 kPa estimated at the MET site and assumed constant);

ε is the ratio of molecular weight of water vapor to air, 0.622 (dimensionless); and other terms are as previously defined.

As indicated by equation 13, λ is not a true constant, as it is related to air temperature and barometric pressure. However, for typical pressure changes at the site, γ varied by less than ±0.5 percent.

Standard application of the PT model (eq 10) is used to compute PET in a well-watered location. Computation of PET assumes $\alpha = 1.26$, and requires only on-site air temperature, net radiation, and soil heat flux data. The simplicity and accuracy of the PT model in well-watered conditions led to the use of modified forms of the equation to estimate λE for partially dry surfaces. Priestley and Taylor (1972) estimated that when water was amply supplied, the value of α was about 1.26. It was reasoned that, as a canopy became water-stressed, α would decrease below 1.26. From field studies, α was related empirically to soil moisture (Davies and Allen, 1973; Barton, 1979; Flint and Childs, 1991) and to sensible heat flux (Pereira and Villa Nova, 1992). De Bruin (1983) noted that the diurnal variation of α primarily is related to solar radiation. This implies that α can be determined empirically using solar radiation data, or data related to solar radiation, such as air temperature. Equation 10 also can be used to compute the actual value of α when ET is measured by eddy correlation, hence the “modified” PT model.

Nighttime values of ET were assumed to be zero because the PT model often indicated dewfall (λE term became negative) and, because the transducers might be damaged by moisture from fog, dew, or rain, the eddy-correlation device was not used most nights. Therefore, values of net radiation less than negative 10 W/m^2 were not included in the computation of ET, effectively removing all nighttime data.

ESTIMATION OF EVAPOTRANSPIRATION

Water-Budget Analysis

A water-budget analysis for the Rainbow Springs and Silver Springs basins was performed at monthly and annual intervals for the period 1965-94 and the results were used to determine the long-term, annual and seasonal estimates of ET, net change in storage, springflow, streamflow, and pumpage. Estimates for the components of the water budget then were compared to each other.

Long-Term Analysis

Rainfall and springflow, the two largest measured water-budget components in the spring basins, are shown in figure 5. Mean annual springflow for both basins is 13.1 in. (15.2 in. for Rainbow Springs and 11.6 in. for Silver Springs) and accounts for about 25 percent of the annual rainfall. The magnitude of annual springflow is closely related to rainfall from the preceding year(s). Annual springflow ranges from 10.3 in. in 1992, following a general trend of below average rainfall, to 16.8 in 1965 following wet conditions in 1964 (not shown) and 1965.

A water budget, constructed using 30-yr mean annual values (1965-94), is shown in figure 6. Rainfall, representing total available water, averages about 52 in/yr and is the largest component in the water budget. ET is the largest output component in the water budget and averages about 38 in/yr, or about 73 percent of the annual rainfall. The remaining 14 in/yr in the water budget is divided between recharge to the Floridan aquifer (13 in/yr, or 25 percent of annual rainfall) and streamflow (1 in/yr, or 2 percent of annual rainfall). Pumpage and seepage from the Upper Floridan aquifer to streams account for less than 1 in/yr, or about 1 percent of annual rainfall, which also is equivalent to the net change in storage.

Annual values of components in the water budget are shown in figure 7. Net change in storage, and to a lesser extent, estimated ET follow trends in rainfall. Springflow appears to be a damped, lagged response to rainfall. The magnitude of net change in storage can be about as large as springflow during some years, although the mean net change in storage is only -0.6 in/yr. For example, net change in storage accounts for nearly 20 in., or 40 percent of the total rainfall in 1982. Streamflow and pumpage account for only 1.3 in., or about 2.5 percent of the annual rainfall.

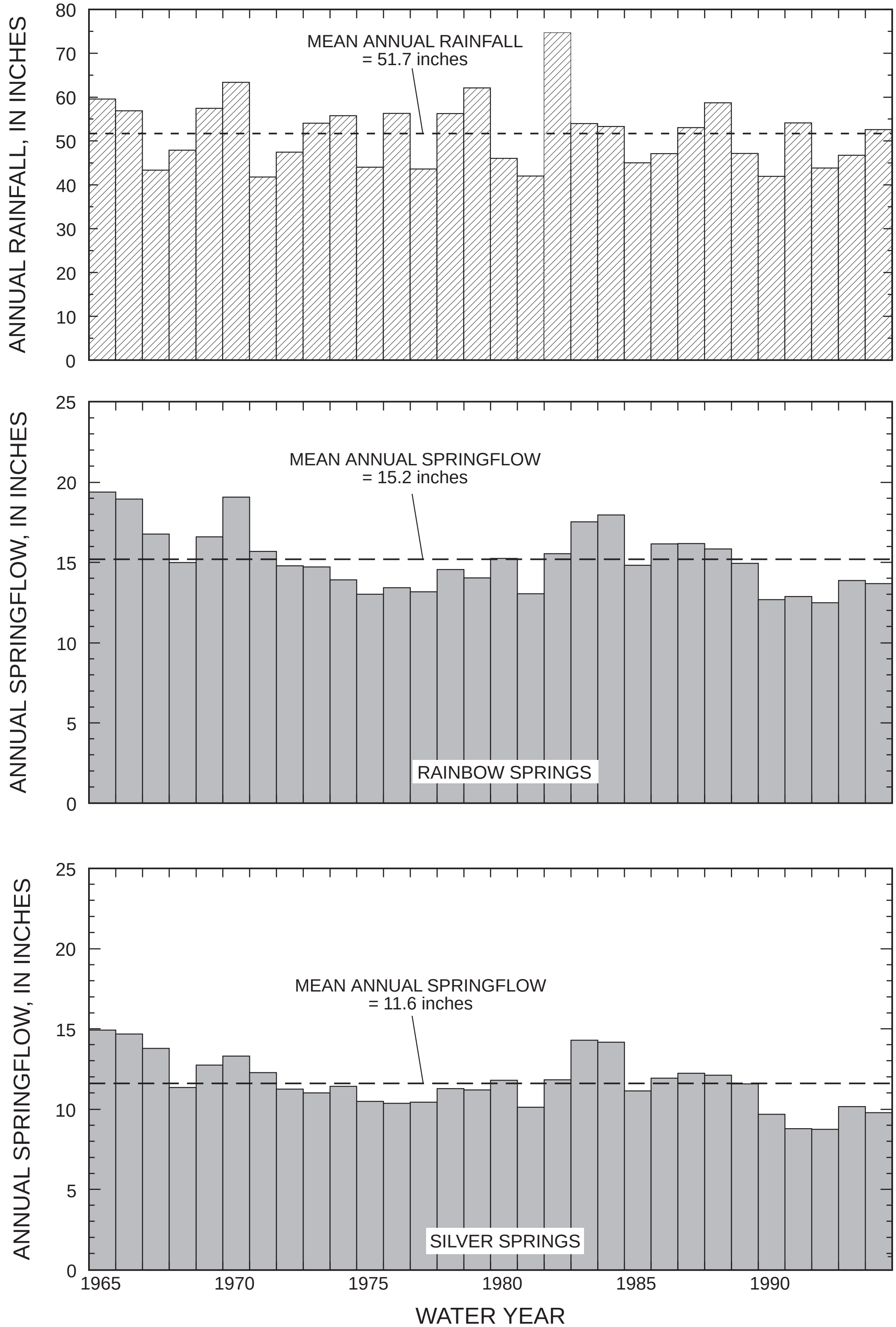

Figure 5. Annual rainfall and springflow for the Rainbow Springs and Silver Springs basins, 1965-94.

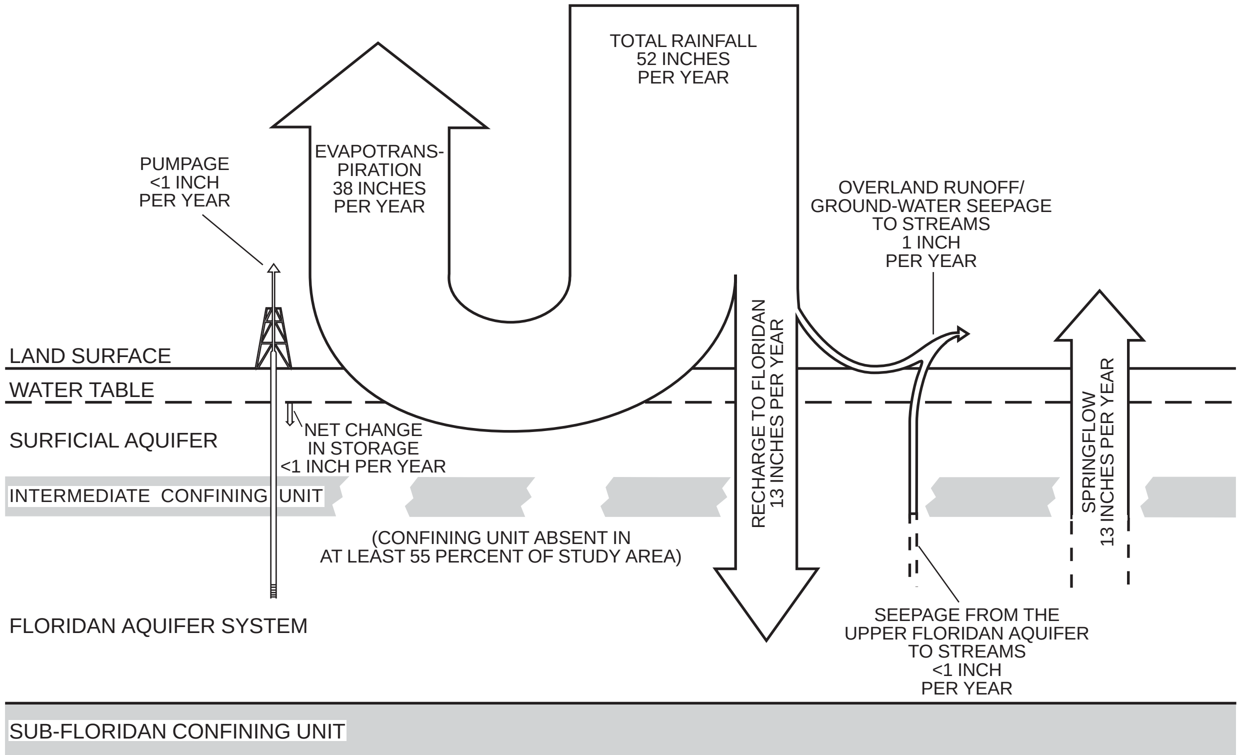

Figure 6. Water budget for the Rainbow Springs and Silver Springs basin area, 1965-94.

Long-term trends in the water-budget components for 1965-94 were examined using least-squares linear regression. Results indicate that rainfall and ET decreased at rates of nearly 0.14 in/yr, or about 4.0 in. over the 30-year period. Springflow decreased at a rate of about 0.10 in/yr (3.1 in. over the 30-year period); whereas, net change in storage and streamflow and pumpage increased at a rate of about 0.08 in/yr and nearly 0.02 in/yr (2.7 in. and 0.5 in. over the 30-year period), respectively.

ET, which averaged about 38 in/yr, ranged from about 30 in. in 1978 to nearly 50 in. in 1979. The lowest estimates of ET generally correspond to years with low rainfall; however in 1994, ET was less than 32 in., but rainfall was more than 53 in., which was slightly above average. Sometimes ET accounts for a very large part of the water-budget, especially during periods of low rainfall. During an extremely dry period in 1981 when rainfall was 42.0 in., ET was 38.5 in., or more than 90 percent of the annual rainfall.

Maximum error in the water-budget estimate of ET for the Rainbow Springs and Silver Springs basins is about 28 percent, or ±10.5 in. Therefore, the estimate of ET which is 37.9 in. for the spring basins ranges from 27.4 in. to 48.4 in. This error is based on the maximum probable errors associated with each of the water-budget components which is 20 percent for rainfall, 8 percent for springflow, 10 percent for total storage, and 20 percent for streamflow and pumpage.

Annual and Seasonal Analysis

Annual and seasonal rainfall and ET for the combined Rainbow Springs and Silver Springs basins during 1965-94 is shown in figure 8. Summary statistics of the water-budget components are listed in table 3 which presents the annual and seasonal estimates for the individual and combined basins and includes the mean and range of estimates during 1965-94. For the 30-year period, mean annual rainfall is 51.7 in.; 26.3 in. falls during the wet season (June through September) and 25.4 in. falls during the dry season (October through May). Annual rainfall ranges from 41.8 in. (1971) to 74.7 in. (1982). Using least-squares linear regression, results indicate that of the 4.0-in. decrease in rainfall over the 30-year period, wet-season rainfall decreased at a rate of nearly 0.15 in/yr (4.4 in. over the 30-year period) and dry-season rainfall increased about 0.01 in/yr (0.4 in. over the 30-year period).

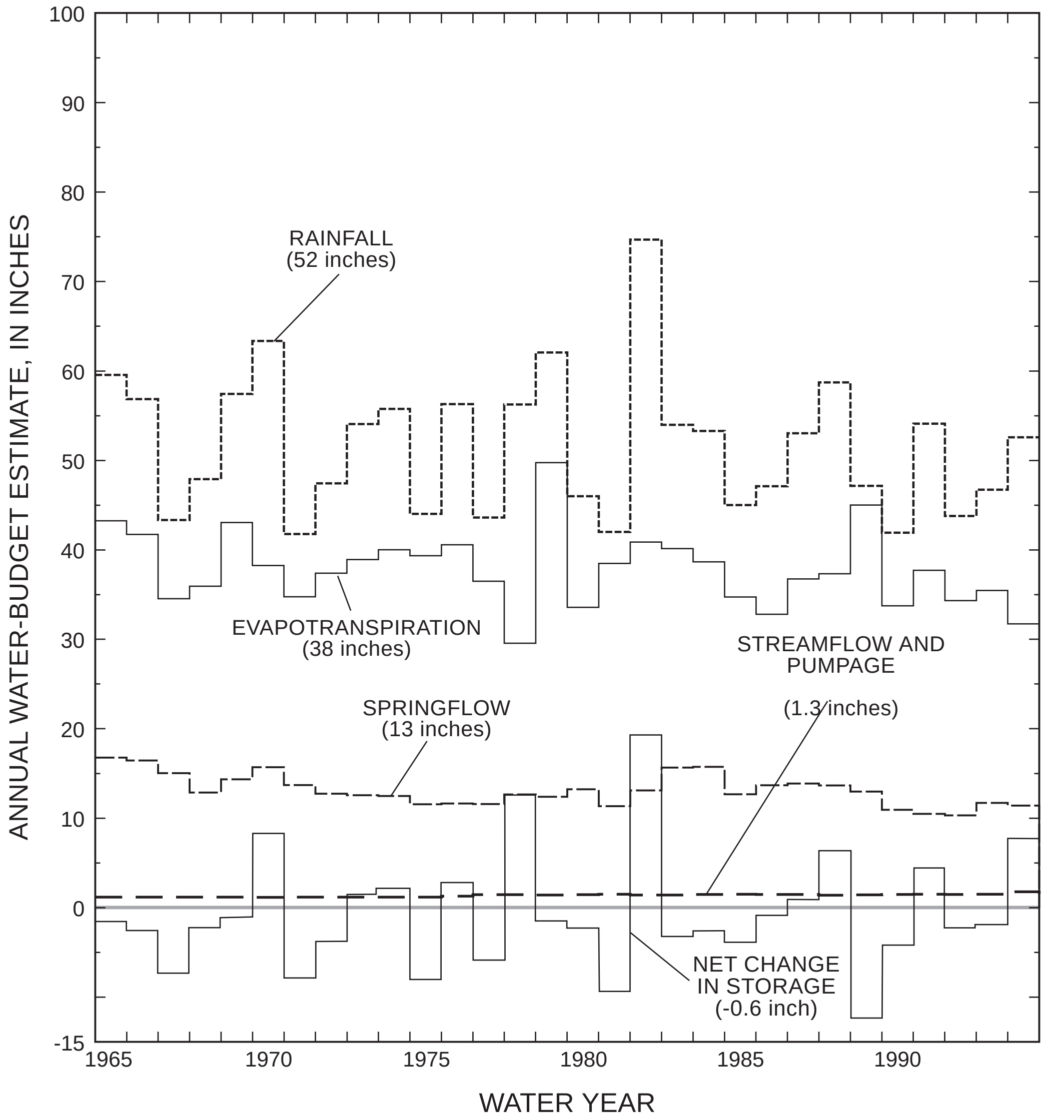

Figure 7. Water-budget estimates of rainfall, evapotranspiration, springflow, net change in storage, and streamflow and pumpage for the Rainbow Springs and Silver Springs basins, 1965-94 (30-year mean values are shown in parentheses).

ET estimates for the Rainbow Springs and Silver Springs basins are similar. Mean annual ET for the combined basins is 37.9 in.; 37.6 in. for the Silver Springs basin and 38.5 in. for the Rainbow Springs basin (table 3). Dry-season ET estimates of nearly 19 in. (for 4 months) are approximately equal to the wet-season estimates of ET of about 20 in. (for 8 months); therefore, ET estimates during the 4-month wet season are about twice the ET rates during the 8-month dry season. Using least-squares linear regression, wet-season estimates of ET for the Rainbow Springs and Silver Springs basins decreased 2.7 in. and 3.4 in., respectively, over the 30-year period. However, dry-season estimates of ET for the Rainbow Springs and Silver Springs basins

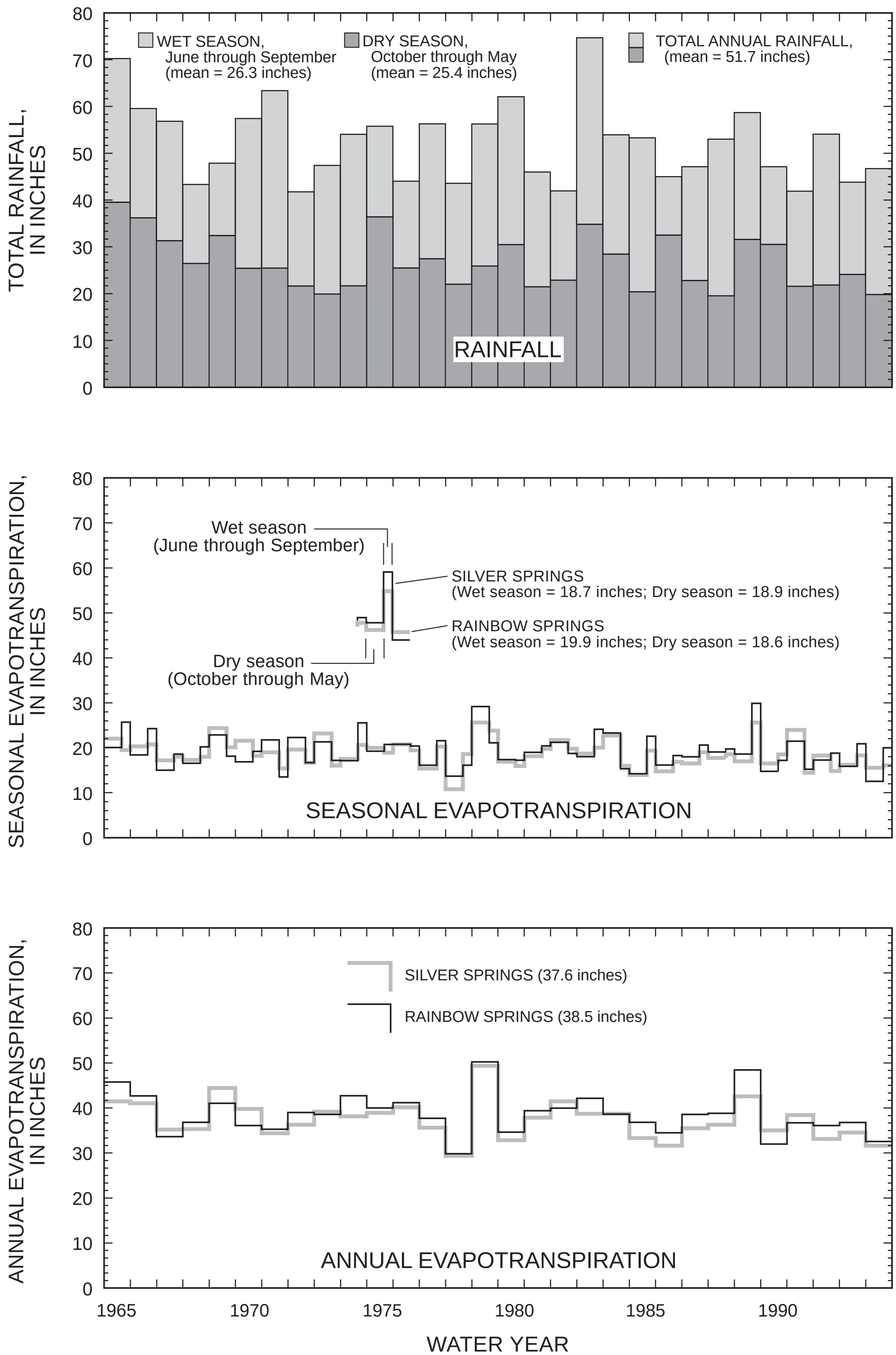

Figure 8. Seasonal and annual rainfall and water-budget estimates of evapotranspiration for the Silver Springs and Rainbow Springs basins, 1965-94 (30-year mean values are shown in parentheses).

Table 3. Summary statistics of water-budget components for the Silver Springs and Rainbow Springs basins, 1965-94

[All units are inches; <, less than]

Water-budget component	Silver Springs basin		Rainbow Springs basin		Combined basins[1]	
	Mean	Range	Mean	Range	Mean	Range
Annual estimates						
Rainfall	50.5	40.1 - 75.8	53.2	42.5 - 73.2	51.7	41.8 - 74.7
Springflow	11.6	8.8 - 14.9	15.2	12.5 - 19.4	13.1	10.3 - 16.8
Net change in storage	-0.6	-10.1 - 20.1	-0.8	-15.5 - 18.2	-0.6	-12.3 - 19.3
Streamflow and consumptive use	1.9	1.8 - 2.0	0.3	0.2 - 0.6	1.3	1.1 - 1.5
Evapotranspiration	37.6	29.4 - 49.4	38.5	29.8 - 50.3	37.9	29.6 - 49.8
Dry-season estimates[2]						
Rainfall	24.9	11.8 - 41.5	26.0	13.5 - 38.4	25.4	12.5 - 39.9
Springflow	7.7	5.4 - 9.8	10.1	8.1 - 12.9	8.7	6.5 - 11.1
Net change in storage	-3.0	-11.9 - 11.5	-2.9	-12.8 - 9.0	-2.9	-11.1 - 9.9
Streamflow and consumptive use	1.3	1.2 - 1.4	0.2	<0.1 - 0.3	0.9	0.8 - 1.0
Evapotranspiration	18.9	11.0 - 25.8	18.6	12.5 - 29.2	18.7	12.0 - 27.1
Wet-season estimates[3]						
Rainfall	25.6	18.7 - 35.7	27.2	20.2 - 38.3	26.3	19.5 - 36.4
Springflow	3.9	3.0 - 5.2	5.1	4.1 - 6.5	4.4	3.5 - 5.7
Net change in storage	2.4	-5.2 - 10.3	2.1	-5.3 - 10.7	2.3	-5.3 - 9.4
Streamflow and consumptive use	0.6	0.6 - 0.7	0.1	<0.1 - 0.1	0.4	0.4 - 0.5
Evapotranspiration	18.7	14.6 - 25.7	19.9	13.5 - 29.9	19.2	14.6 - 27.4

[1]Combined rate computed from weighted basin rates.
[2] Values are for the 8-month period, October through May.
[3] Values are for the 4-month period, June through September.

decreased about 0.4 in. and 1.0 in., respectively, over the 30-year period. This decrease probably is related to the general decrease in annual rainfall and reduction in net radiation over the basins during the 30-year period. However, there is insufficient data to support the later conclusion.

Lake evaporation, which can be comparable to other estimates of ET, was estimated from pan-evaporation data by applying pan-to-lake coefficients. Lake-evaporation estimates are not necessarily assumed to be basin-wide values because the pan data represent only two sites within the basin. Nonetheless, this method can provide a way to partition the evaporation component into lake- and land-evaporation terms. The surface area of lakes and streams in the study area account for about 4 percent of the total area. Applying the pan-to-lake coefficients to monthly pan-evaporation estimates yields an annual lake evaporation of 53.2 in. Pan evaporation for the same 30-year period was determined to be 62.6 in. Evapotranspiration from land surface can be determined using area-weighted estimates for each of the evaporative terms. If the water-budget ET is 37.9 in. and the weighted lake-evaporation term is 53.2 in. for 4 percent of the area, then the weighted land-evaporation surface term is {[37.9 - 53.2(0.04)]/0.96} in., or 35.7 in. for 96 percent of the area.

Lake evaporation estimates can be compared to the water-budget estimates of ET and used to check if the water-budget estimates are less than the lake evaporation and PET estimates. Annual estimates of lake evaporation and water-budget ET are shown in figure 9. Annually, the mean difference between lake evaporation and water-budget ET is about 15 in., ranging from about 5 in. in 1979 to greater than 27 in., in 1978.

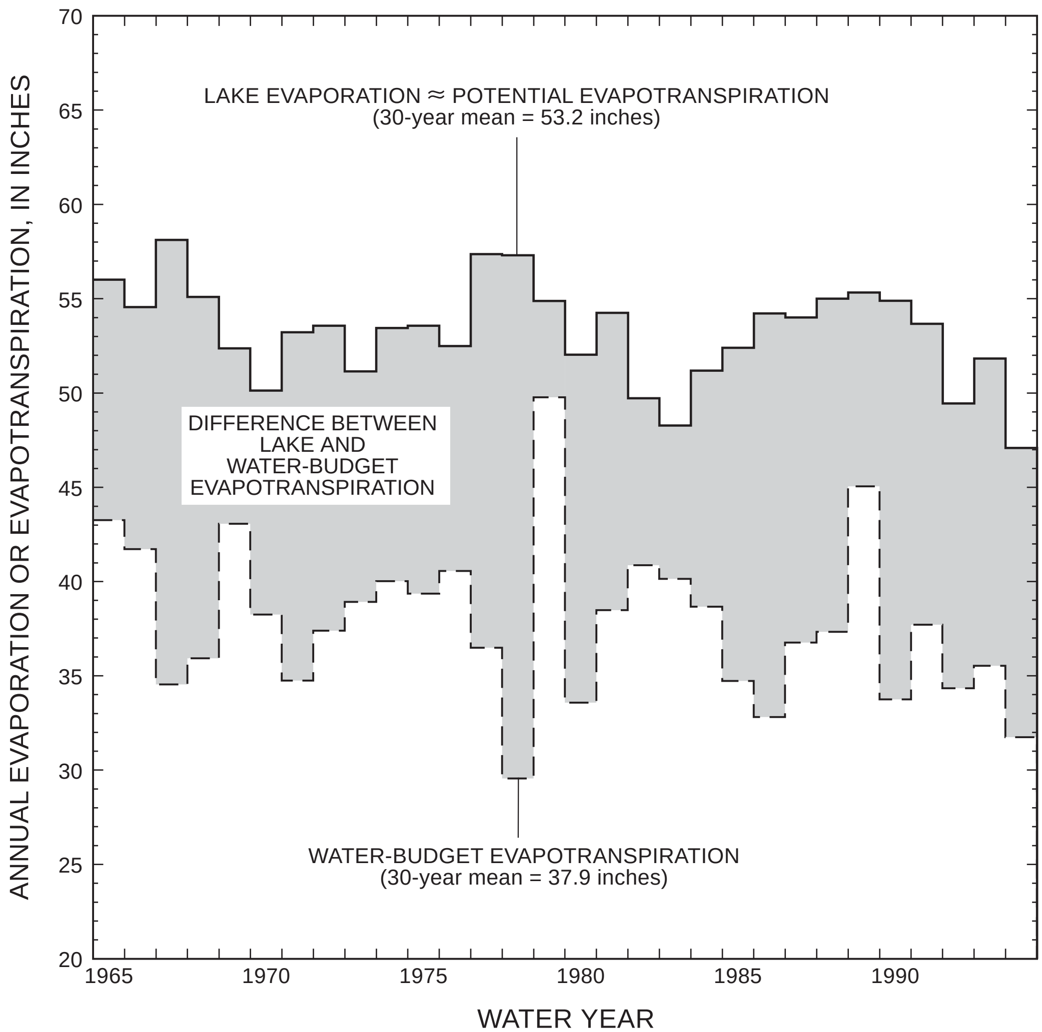

Figure 9. Annual lake evaporation and water-budget evapotranspiration for the Rainbow Springs and Silver Springs basin study area, 1965-94.

Modified Priestley-Taylor Model

Development of α Using Measurements of Eddy Correlation

Estimates of ET were computed with a modified PT model calibrated using measurements of eddy correlation for a location in the study area (MET site) as a comparison to the water-budget ET estimate. Measurements were made on 17 days during the study with each unfiltered data set (1- to 3-day period) containing from 42 to 126 measurements. Eddy-correlation measurements of λE, averaged at 20-min intervals and meeting the acceptance criteria, were used to compute “measured” values of α in the PT equation (eq 10).

The energy-balance closure (eq 9) and ratio of turbulent flux to available energy criterion were used to filter the data set which removed more than half of the daily data. At the MET site, when the prevailing wind was easterly (from the direction of the 80-ft tall tree line), it was possible that the surface-boundary layer criterion (1:100 height-to-fetch ratio) was not met. Therefore, all flux data collected during these times also were removed. The resulting filtered data set consisted of 201 acceptable measurements. The ratio of turbulent flux to available energy averaged 0.97 which indicated that the turbulent flux generally was slightly underestimated or the available energy was slightly overestimated.

Multiple linear and nonlinear regression analyses were used to test the dependence of α on the following independent site variables: R_n, T_a, W, depth to water table, wind speed, and *LAI*. Analyses indicate that at the MET site, α only was significantly related to R_n, T_a, and *LAI*. Water availability, of which α typically is dependent, was found not to be a limiting factor at the site or significantly related to α because shallow well measurements indicated that the water table probably was always within the rooting zone at the MET site.

The best-fit predictive equation for α from multiple nonlinear regression that produced the smallest sum of squared differences between modeled and measured values of λE is

$$\alpha = 0.645 + 1.00 exp(-0.00929 R_n) + 0.00317 exp[0.0688(T_a - 273)] + 0.0681 LAI \quad (14)$$

where all terms are as previously defined.

The coefficient of determination, R^2, of modeled and measured values of λE is 0.91. The coefficient of variation is 0.15 and is equal to the standard error of modeled values of λE divided by the mean of the measured values of λE. The slope and intercept of the best fit line through values of measured λE versus modeled λE, using the method of least squares, is 0.91 and 13.9 W/m^2, respectively. The mean bias error is 0.38 W/m^2 and is equal to the mean of the modeled values of λE minus the mean of the measured values of λE. The estimation of *LAI* in this study may contribute some proportion of the error in the modeled values of λE. Considering the crude techniques used in the field, the value of *LAI* may be in error by up to 20 percent of the true value during any given month. However, considering the relative significance of *LAI* with a coefficient of 0.0681 (eq 14), the error in modeled α is only about 2 percent.

Equation 14 indicates that at the MET site, α was inversely related to R_n, a relation which De Bruin (1983) also determined. Typically at the MET site, a maximum value of α occurred whenever R_n was a minimum during the day--early morning, late afternoon, or midday during brief periods when clouds significantly reduced incoming solar radiation. Minimum values of α occurring during midday can be explained by a large increase in vapor-pressure deficit concurrent with a small increase in (R_n - G) which would result in a positive correlation between α and some measure of radiative input.

Predicted values of α (eq 14) are plotted as a function of the values determined from eddy-correlation measurements to evaluate how well α is modeled (fig. 10). The line of equality represents unity or an exact agreement between modeled and measured values. Most of the values of α are less than the empirical maximum of 1.26 with a median of 0.80. Scatter in the data is thought to be caused by erroneously measured flux values at times when heat fluxes are small and relative errors in measured fluxes (or R_n) are large. For this reason, the model coefficients in equation 14 were determined from regression on λE, rather than on α in equation 10.

The maximum likely error in the estimate of ET computed by the modified PT model probably is about 25 percent, which also is about the same error in the water-budget estimate. The error in the estimate of ET is determined by assuming that the error associated with the filtered eddy-correlation data is less than 20 percent and the error using the predictive equation (eq 14) is 15 percent, as indicated by the coefficient of variation.

Evapotranspiration Rates

Modeled 20-min ET estimates were computed using equations 10 and 14 for the 17 days over which eddy-correlation measurements were made. The relation between 20-min values of ET (displayed in units of inches per day) computed by the modified PT model and measured by eddy correlation (filtered data set) is shown in figure 11. About 60 percent of the modeled ET rates are within 10 percent and nearly 95 percent of the ET rates are within 25 percent of the measured ET rates. The PT model has the most difficulty in predicting ET rates of greater than about 0.23 in/d (shown by the large degree of scatter in the model); however, about 50 percent of the modeled rates are within 10 percent and about 85 percent are within 25 percent of the measured rates. ET rates for the 17 measuring days are well distributed in the scatter, indicating that errors are not clustered or biased to a particular day.

Daily ET for eddy-correlation "measured" days was computed by summing the filtered 20-min measured values filling in with 20-min estimates obtained from the ECEBBR method where needed. Similarly, modeled estimates of daily ET were summed from the modeled 20-min values of ET. The relation between daily ET computed by the modified PT model and measured by eddy correlation is shown in figure 12.

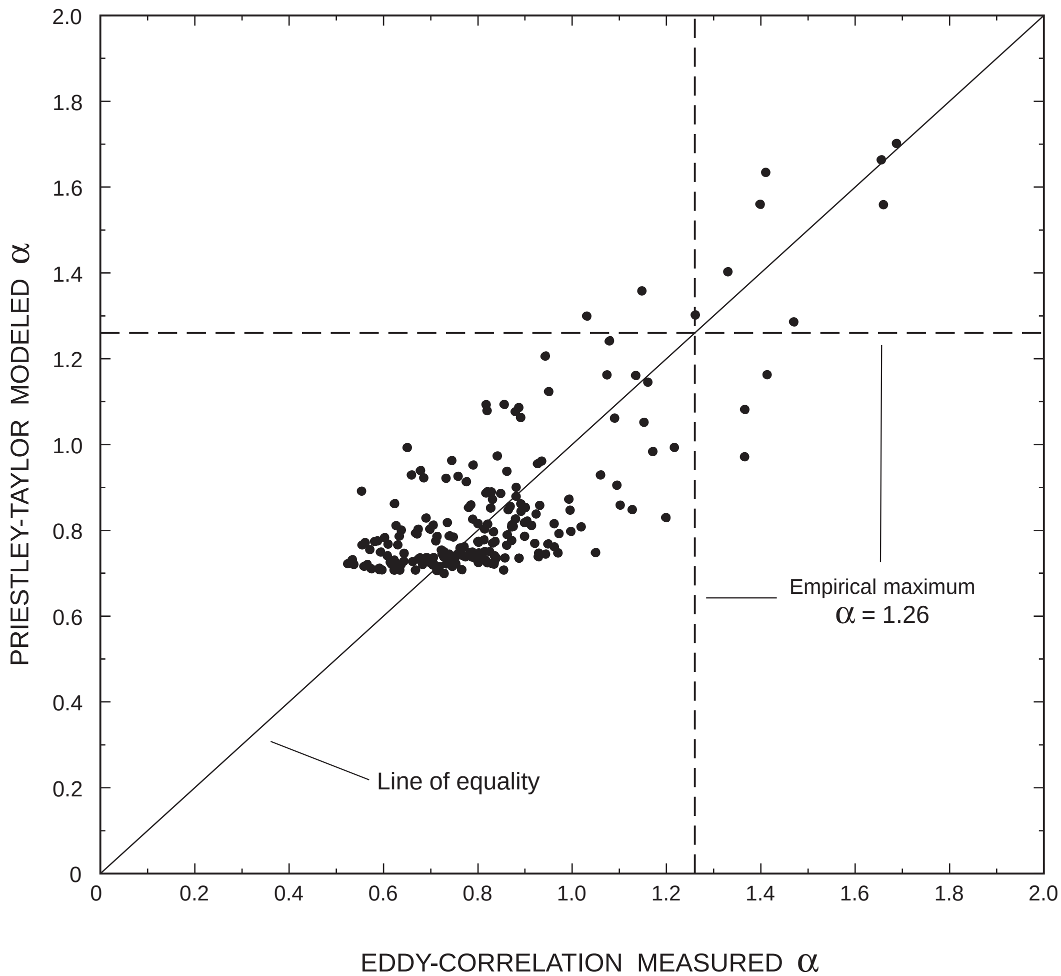

Figure 10. Relation between Priestley-Taylor modeled and eddy-correlation measured daytime alpha (α) (Priestley-Taylor evaporation coefficient).

Generally, there is good agreement between measured and modeled daily ET with error averaging about 6 percent for the year; 5 percent during the dry season and 7 percent during the wet season. Only two days have greater than 10 percent error; one in May, and the other in September. Poor agreement between measured and modeled daily ET generally is associated with days having variable cloud cover which is typical during the wet season (June through September). Daily ET is lowest during winter months, greatest from April to September, and ranges from slightly more than 0.03 in. in January to more than 0.15 in. in May and September.

The relative importance and diurnal nature of the energy-balance components, R_n, G, λE, and H, were examined by analyzing each of their magnitudes on a set of eddy-correlation-measured days with no rainfall. The diurnal variation of the surface energy-balance components and selected micrometeorological data are illustrated in figure 13. λE accounts for about 58 percent, H accounts for nearly 20 percent, and G accounts for about 22 percent of R_n. Components are largest during midday when available energy is large and fluctuate mainly because of changes in R_n which are attributed mostly to the effects of cloud coverage.

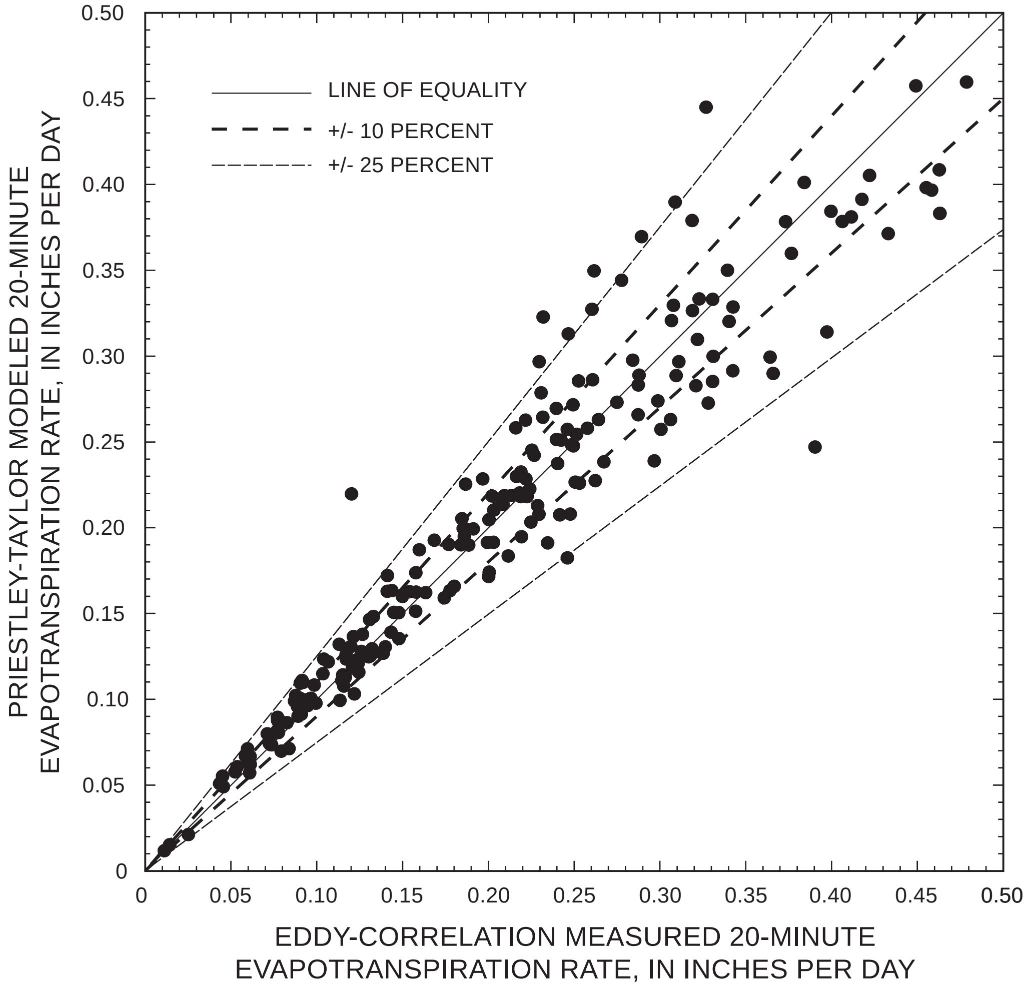

Figure 11. Relation between 20-minute evapotranspiration rates computed by the modified Priestley-Taylor model and measured by eddy correlation.

G responds more slowly to fluctuations in R_n than do the other components. After sunrise, R_n becomes positive and increases rapidly. Little fluctuation of R_n is the result of a cloudless sky on September 22.

Eddy-correlation measurements to quantify any nighttime ET were made on the night of September 21-22, 1994, during exceptionally dry climatic conditions. λE were above and below zero during the night, and had a mean close to zero. Slightly negative nighttime λE indicated the potential for dew formation (fig. 13). A spike in λE at 0700 hrs may have indicated a brief upward flux of moisture shortly after sunrise. During this study, similar spikes occurring for periods of 20-40 min were identified on many of the other early mornings. These spikes may have been the evaporation of dew. Although the magnitude of dew formation could not be quantified in this study, observations made during the study indicate dewfall may be more significant than previously considered (Abtew and Obeysekera, 1995).

A comparison of measured and modeled 20-min values of ET in inches per day for September 21-22, 1994, is shown in figure 14. Generally, the agreement between measured and modeled ET is good with an average difference of less than 3 percent on both days. The ratio of turbulent flux to available energy for 25 filtered 20-min values during this two-day period is 0.97. Measured daily ET is 0.14 and 0.15 in. on September 21 and 22, respectively; and modeled daily ET is 0.14 and 0.15 in. on September 21 and 22, respectively.

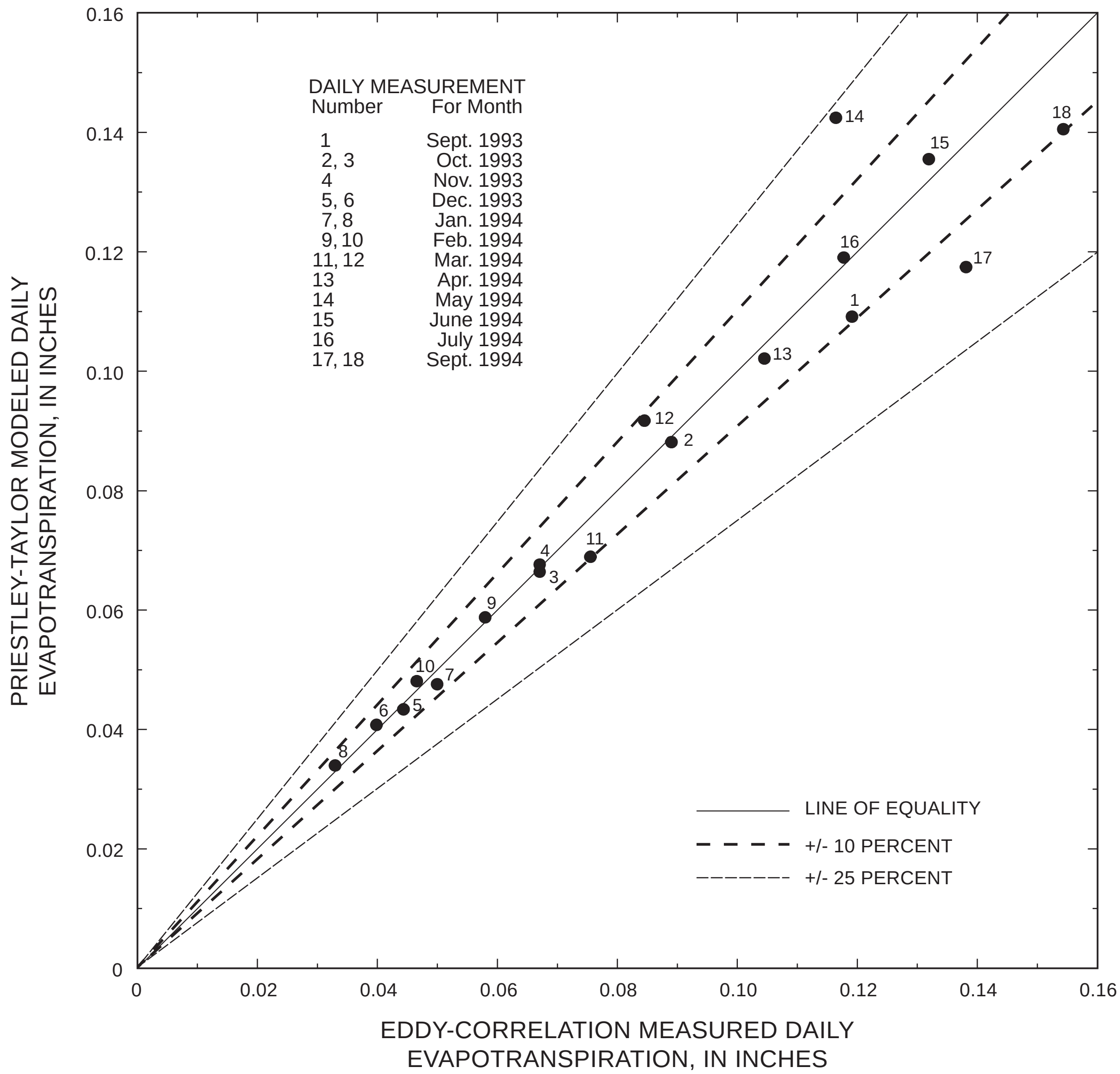

Figure 12. Relation between daily evapotranspiration computed by the modified Priestley-Taylor model and measured by eddy correlation, September 1993-94.

Daily estimates of ET and PET at the MET site are computed by averaging the modeled 20-min daytime values of ET (using eq 10) and PET (using $\alpha = 1.26$), respectively (fig. 15). For the 1994 water year, ET averaged 32 in. (about 0.09 in/d) and PET averaged nearly 47 in. (about 0.13 in/d). A 31-day (centered) sliding mean for the daily ET and PET time-series curves is used to “smooth” out the daily fluctuations, making general trends easier to identify. The estimates of ET for the 17 eddy-correlation-measured days also are shown in figure 15.

Seasonal variation of ET is indicated in the record with daily ET rates typically 3-4 times higher during June and July than during December and January. The highly variable nature of ET on a day-to-day basis is indicated by large fluctuations in the daily record. Minimum ET and PET rates were less than 0.01 in/d on January 28, 1994; and maximum ET and PET rates were about 0.17 in/d and 0.25 in/d, respectively, on June 13, 1994. Minimum 31-day mean ET and PET rates occurred simultaneously in late December, the week following winter solstice; however, maximum 31-day mean ET and PET rates occur about two months apart in early May and early July, respectively, which agrees with the timing of ET rates presented by Bidlake and others (1993). The 31-day mean ET rates ranged from a minimum of less than 0.04 in/d on December 24, 30, and 31, 1993, to a maximum of

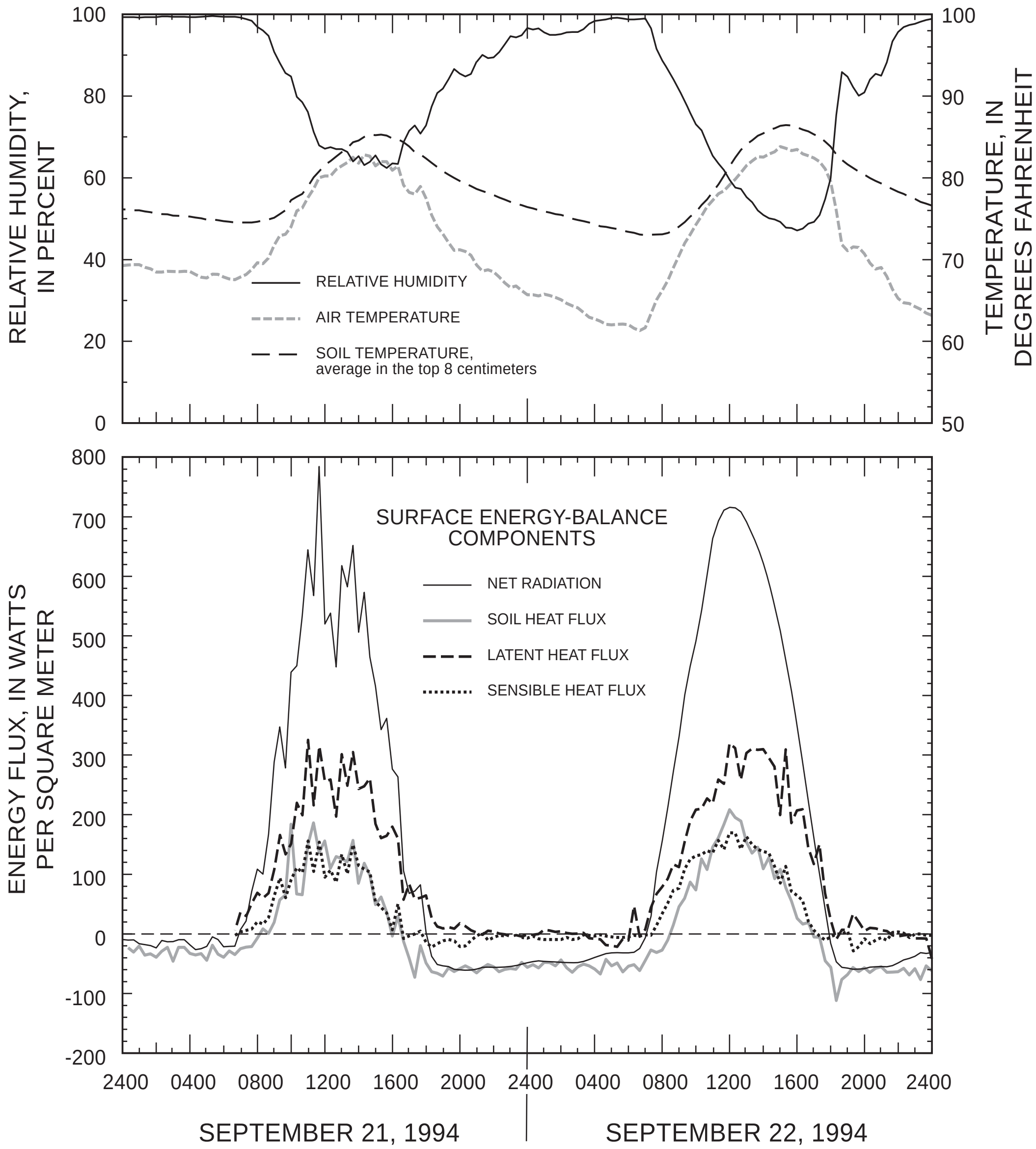

Figure 13. Diurnal variation of surface energy-balance components in conjunction with eddy-correlation measurements and meteorological conditions at the MET site, September 21-22, 1994.

nearly 0.14 in/d on July 5, 1994; and 31-day mean PET rates ranged from a minimum of about 0.05 in/d on December 30 and 31, 1993, to a maximum of nearly 0.20 in/d on May 12, 1994.

A comparison of cumulative rainfall and modeled estimates of ET and PET at the MET site illustrates how the rate of accumulated rainfall compares with that of accumulated ET (fig. 16). During the dry or wet season, the proportion of seasonal accumulated rainfall to annual total rainfall is nearly the same as the proportion of accumulated ET. For example, wet-season rainfall accounts for 49 percent of the annual rainfall and wet-season ET accounts for 46 percent of the annual ET. The rate of accumulated rainfall nearly doubles from the dry season to the wet season (fig. 16). The rate of accumulated ET is doubled during March through September as compared to the rest of the year.

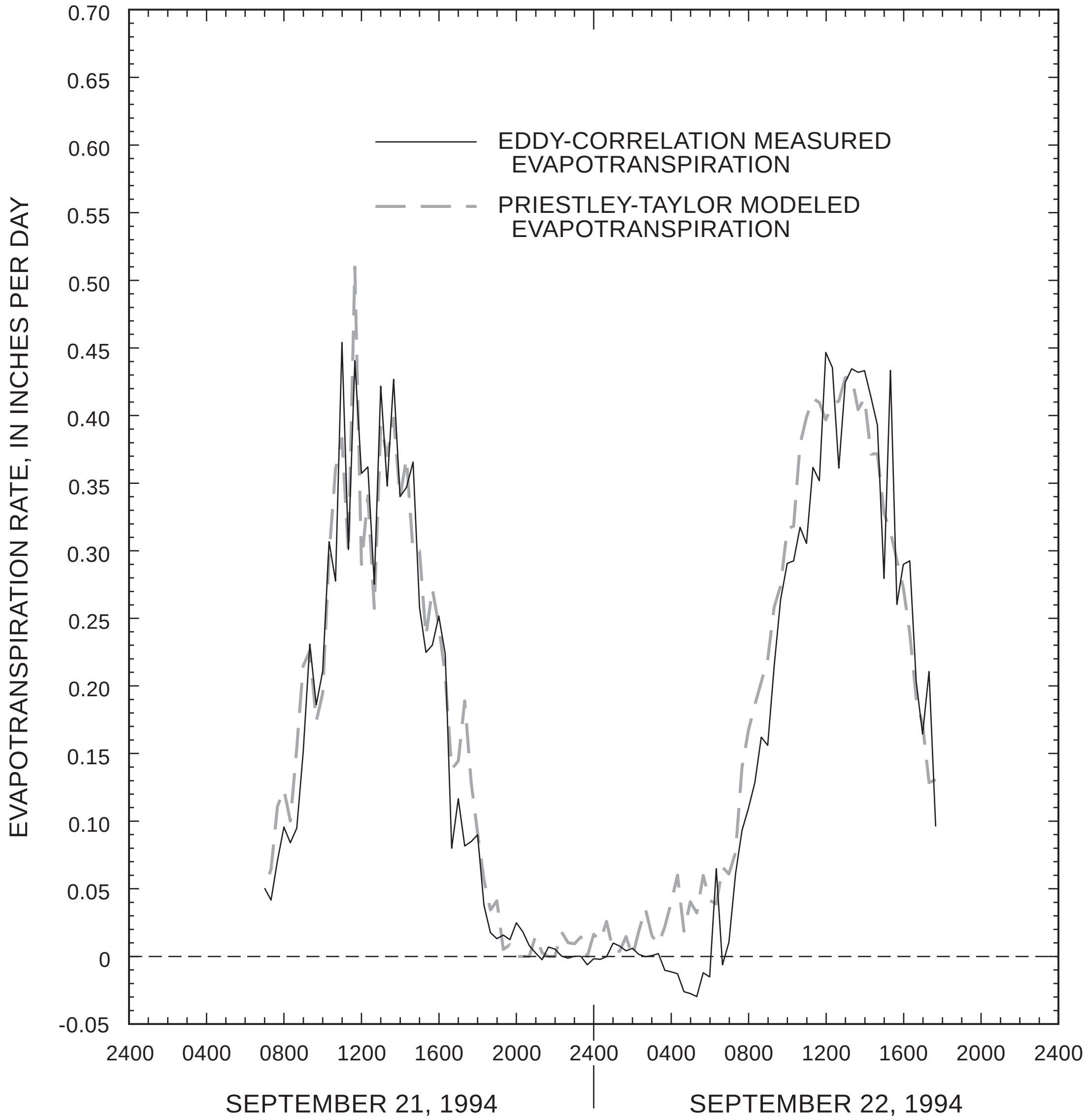

Figure 14. Evapotranspiration rates measured by eddy correlation and computed by the modified Priestley-Taylor model at the MET site, September 21-22, 1994.

COMPARISON OF EVAPOTRANSPIRATION ESTIMATES

Estimates of ET for sites and regions with large differences in area typically are not compared because they would not necessarily be expected to agree. However, the rationale for comparing the results obtained from this study is to determine whether the site-measured ET is within the expected range of ET estimated using a regional water budget. To help improve the comparability of the site-measured estimate with the regional estimate, the location of the MET site was chosen because a variety of vegetation types at the site was representative of the vegetation found throughout the study area.

Monthly estimates of ET computed from the water-budget analysis, from lake evaporation, from an unmodified PT model, and from the modified PT model for 1994 generally are in good agreement with each other (fig. 17). Seasonal variations in estimates of ET, PET, and lake evaporation are similar, with minimum rates in December and January and maximum

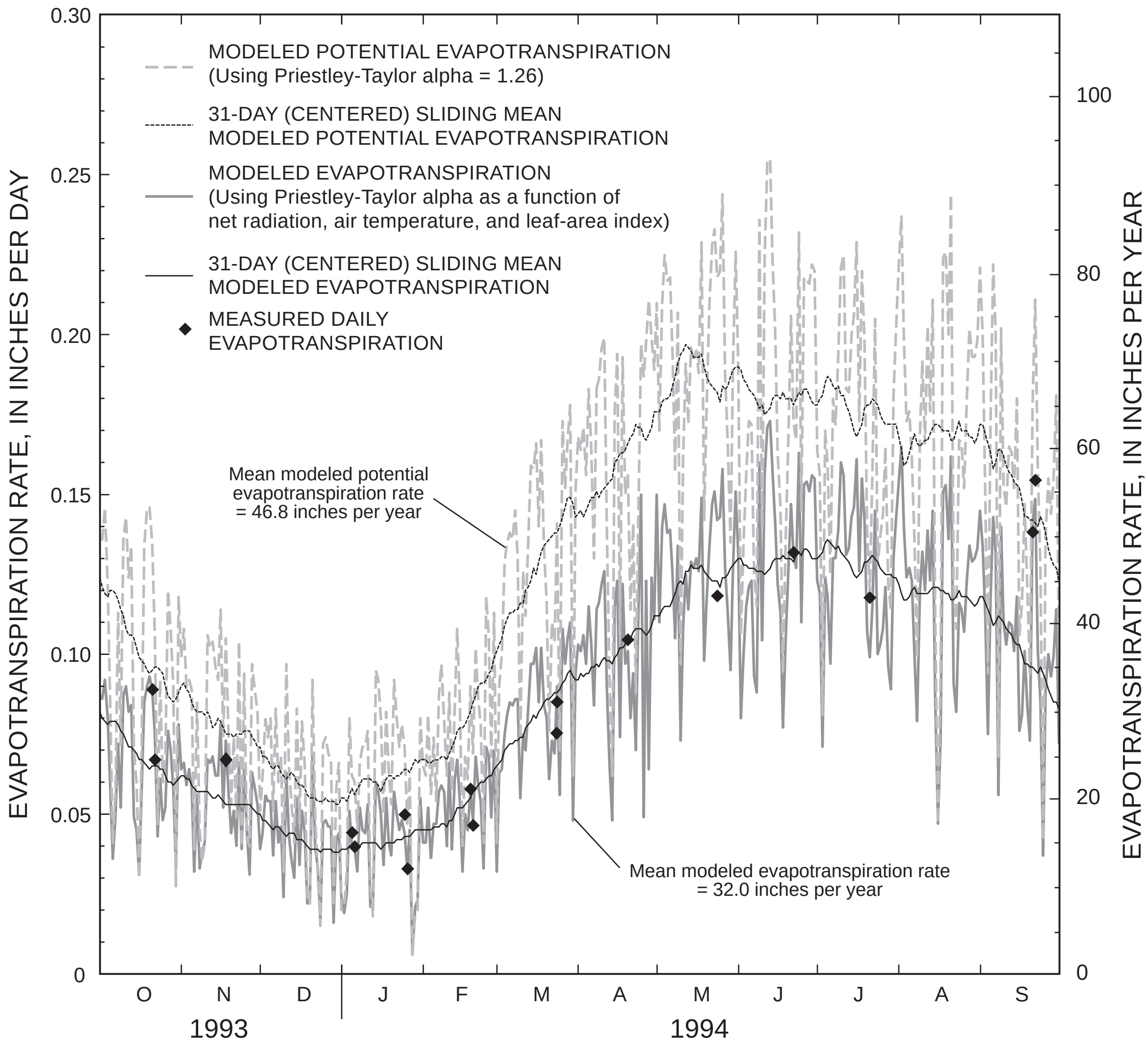

Figure 15. Daily evapotranspiration measured by eddy correlation and computed by the modified Priestley-Taylor model at the MET site, 1994 water year.

rates between April and July. Similarly, seasonal variations in R_n, T_a, and *LAI*, were found to be significant in determining ET (fig. 17). Annual lake evaporation is 47.1 in. which is slightly more than the annual PET value of 46.8 in. (computed using modified PT model with $\alpha = 1.26$). PET rates range from 1.8 in/mo (21.6 in/yr) in January to 6.2 in/mo (74.4 in/yr) in May. Lake evaporation rates range from 1.5 in/mo (18.0 in/yr) in January to 6.0 in/mo (72.0 in/yr) in May. Annual modeled ET of 32.0 in. is nearly equal to the water-budget ET estimate of 31.7 in. Modeled ET rates range from 1.2 in/mo (14.4 in/yr) in January to 4.3 in/mo (51.6 in/yr) in May. Water-budget ET rates range from 1.0 in/mo (12.0 in/yr) in March to 5.1 in/mo (61.2 in/yr) in July.

As previously discussed, error for the water-budget and modeled estimates of ET is about 30 percent and error for the lake evaporation estimate is about 7 percent. Therefore, the expected range of the 1994 water-budget ET estimate is ±0.30x31.7 in., or 22.9-41.2 in. The expected ranges of the modeled ET and PET estimates are 22.4-41.6 in. (±0.30x32.0 in.), and 32.8-60.8 in. (±0.30x46.8 in.), respectively. For lake evaporation, the expected range is ±0.07x53.2 in., or 49.5-56.9 in.

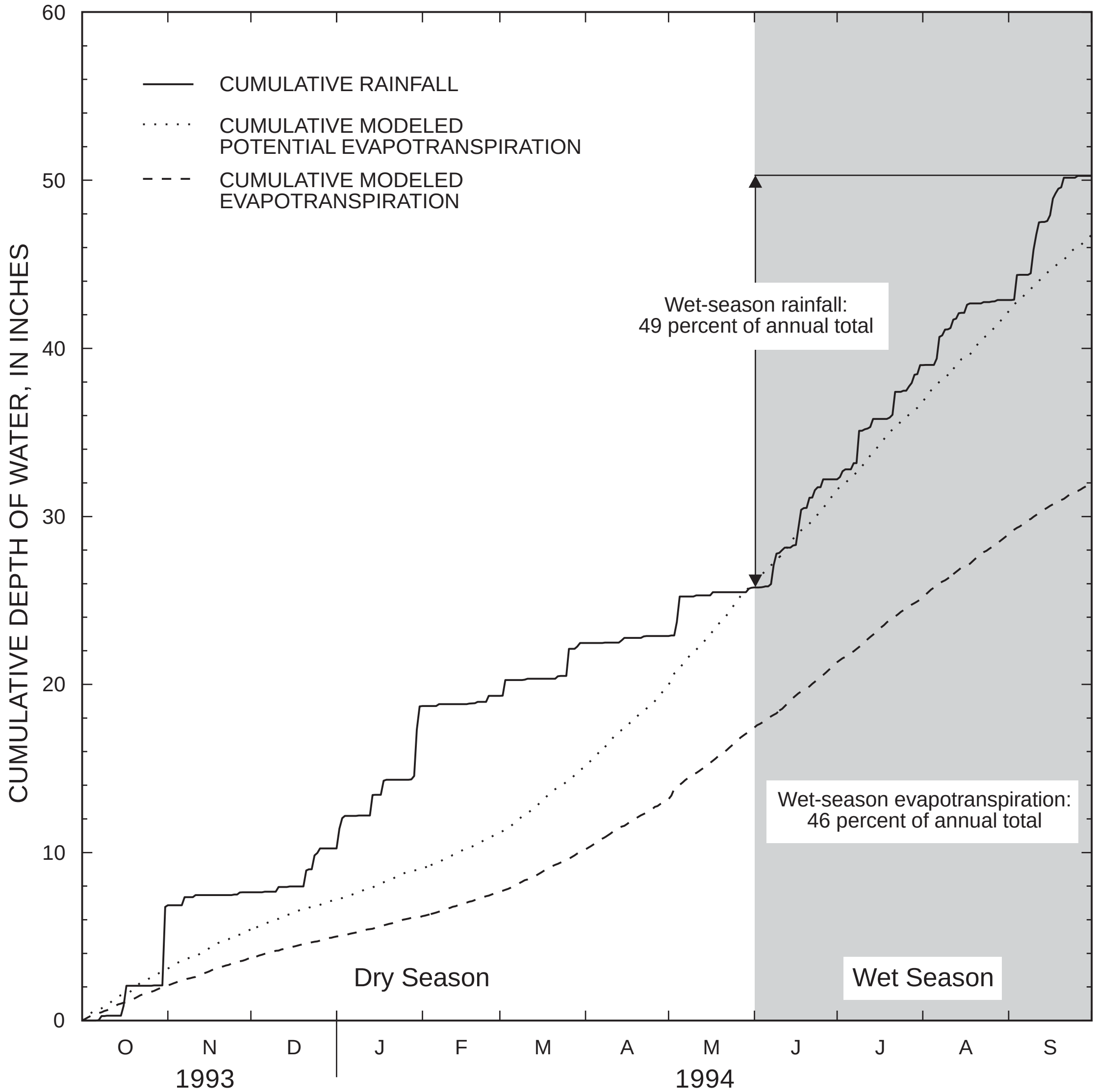

Figure 16. Cumulative rainfall and estimates of evapotranspiration at the MET site, 1994 water year.

POTENTIAL ERROR IN THE ESTIMATES OF EVAPOTRANSPIRATION

Several conditions which are potential sources of error in the estimates of ET are: (1) unaccounted for net changes in surficial-aquifer and unsaturated-zone storage in the water-budget analysis, (2) movement of ground-water across basin boundaries within the Lower Floridan aquifer, (3) effects of horizontal advection of heat upon eddy correlation at the MET site, and (4) effects of vigorous growth of young slash pine trees during the study. Because of the lack of data to substantiate the conditions leading to these assumptions, the magnitude of the potential errors as a result of these assumptions are indeterminate.

Net changes in surficial-aquifer and unsaturated-zone storage were assumed to be small considering that the Upper Floridan aquifer in the study area was mostly unconfined with surficial sands permitting rapid recharge. However, these net changes in storage would be greater in comparison to the other components of the water budget if the analysis were

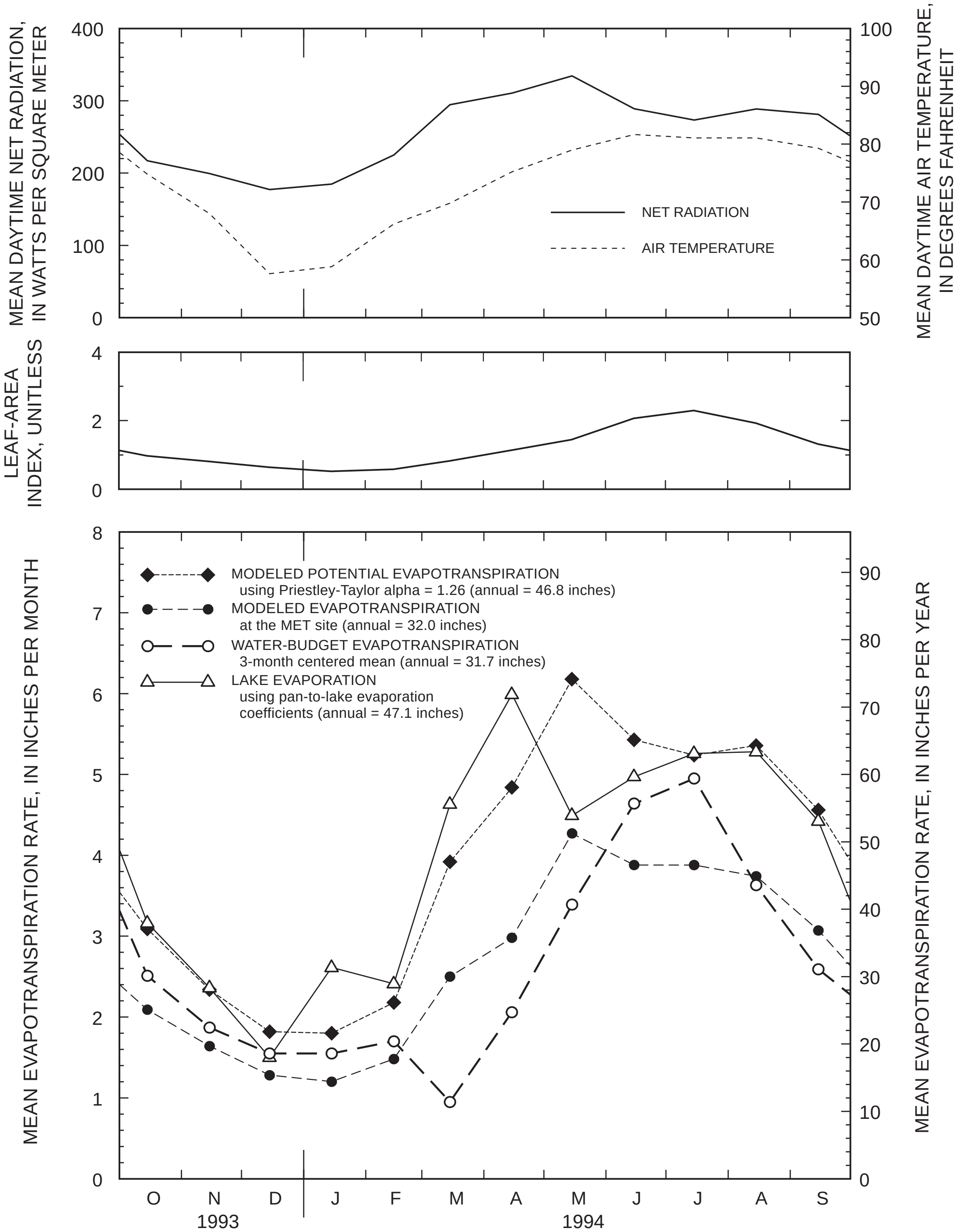

Figure 17. Monthly evapotranspiration rates with mean daytime net radiation, air temperature, and leaf-area index at the MET site, 1994 water year.

performed at the monthly interval used in this study. These net changes probably resulted in a lag of about a month in the water-budget estimates of ET in comparison to the modeled ET (fig. 17). The error associated with changes in surficial-aquifer and unsaturated-zone storage, which actually is a function of time for surficial water to transfer to the Upper Floridan aquifer, becomes much less significant on an annual basis. Considering this lag, it is possible that heavy rainfall near the end of the wet season (September)—which would be accounted for in the water budget for that water year—would not be accounted for in the ground-water components of the water budget until the following water year.

Movement of ground-water across the ground-water basin boundaries (as losses or gains) also was assumed to be relatively small in comparison to other components in the water budget. This assumption was used because the ground-water basin area fluctuated only 5 percent during the 1981-91 period during which extremes in rainfall occurred (1981 was unusually dry and 1991 was unusually wet). This assumption also was supported by the presence of highly mineralized water within the Lower Floridan aquifer which generally indicates sluggishly moving water. Although the response by the movement of water in the aquifer to changing external conditions is poorly understood, it is likely that the water budget would become much more sensitive to movement of ground water across basin boundaries during prolonged periods of drought. During periods of low rainfall, the relative magnitude of these losses or gains become significantly larger in comparison to other components in the water budget.

The main objective in using the energy-balance closure, the ratio of turbulent flux to available energy, and wind direction filter criteria was to remove eddy-correlation data with large errors, including those errors associated with horizontal advection. (Proper location of eddy-correlation equipment is the best way to minimize the effects of horizontal advection.) Still, some of these data with large compensating errors may have been used to calibrate the modified PT model. Extremely high values of α, perhaps greater than 1.4 (fig. 10), could be the result of sensible heat being advected into the MET site and, thus, would tend to overestimate modeled values of ET.

Slash pine trees at the MET site nearly doubled in height during the one-year study period. Slash pines transpire water at tremendously increasing rates during the first 8 years of tree growth (Sydney Bacchus, University of Georgia, oral commun., 1994). Because of this vigorous tree growth, some bias possibly was introduced in the eddy-correlation data used to calibrate the modified PT model, although this bias is not indicated to be significant in the daily estimates of ET shown in figure 12. Error in the modeled annual estimate of ET as a result of this growth probably is compensating. However, daily or even monthly values of ET modeled early in the study would tend to be slightly overestimated, whereas daily or monthly values of ET modeled later in the study would tend to be slightly underestimated.

SUMMARY AND CONCLUSIONS

A study was conducted to estimate evapotranspiration for two contiguous, “closed” ground-water basins of north-central Florida, Rainbow Springs and Silver Springs. ET was estimated using a regional water-budget approach and a micrometeorological method—a modified Priestley-Taylor (PT) model calibrated with eddy-correlation measurements. Regional water-budget estimates of ET were computed for a 30-year period (1965-94) using monthly estimates of rainfall, springflow, streamflow, water-level, and pumping data. ET was modeled for a 12-month period (1994 water year) at a meteorological (MET) site. Measured ET then was compared to the regional estimate. The purpose of measuring ET was to determine whether the measured (point) value was within the expected range of ET computed using the regional water budget.

Results from a water-budget analysis of the two-basin area indicated that rainfall, representing the total available water, was the largest component and averaged about 52 inches per year (in/yr). ET was the largest output component and averaged 38 in/yr, or about 73 percent of the annual rainfall of 52 in/yr. The remaining 14 in/yr in the water budget was divided between recharge to the Floridan aquifer (13 in/yr, or 25 percent of annual rainfall) and streamflow (1 in/yr, or 2 percent of annual rainfall). Pumpage and seepage from the Upper Floridan aquifer to streams accounted for less than 1 in/yr, or about 1 percent of annual rainfall, which was equivalent to the net change in storage.

Results from least-squares linear regression indicated that rainfall and ET decreased at rates of nearly 0.14 in/yr, or about 4.0 in. over the 30-year period. Springflow decreased at a rate of about 0.10 in/yr (3.1 inches (in.) over the 30-year period).

Net change in storage and streamflow and pumpage increased at a rate of about 0.08 in/yr and nearly 0.02 in/yr (2.7 in. and 0.5 in. over the 30-year period), respectively.

Annual ET for both spring basins was 37.9 in. (37.6 in. for the Silver Springs basin and 38.5 in. for the Rainbow Springs basin) for 1965-94 and ranged from about 30 in. in 1978 to nearly 50 in. in 1979. Wet- and dry-season estimates of ET for each basin averaged between nearly 19 in. and 20 in., indicating that like rainfall, ET rates during the 4-month wet season were about twice the ET rates during the 8-month dry season. Using least-squares linear regression, wet-season estimates of ET for the Rainbow Springs and Silver Springs basins decreased at rates of 2.7 in. and 3.4 in., respectively, over the 30-year period. Dry-season estimates of ET for the Rainbow Springs and Silver Springs basins decreased about 0.4 in. and 1.0 in., respectively, over the 30-year period. The lowest estimates of ET generally corresponded to years with low rainfall during which ET sometimes accounted for a very large part of the water budget. In 1981, when rainfall was 42.0 in., ET was 38.5 in., or more than 90 percent of the annual rainfall.

Estimates of ET for the MET site were computed using a modified PT model calibrated with eddy-correlation measurements. Eddy-correlation measurements of latent heat flux, averaged in 20-min intervals, were filtered using energy-balance criteria and then used to compute "measured" values of α in the PT model. The resulting filtered data set consisted of 201 acceptable measurements. The ratio of turbulent flux to available energy averaged 0.97 which indicated that the turbulent flux generally was slightly underestimated or the available energy was slightly overestimated. Multiple nonlinear regression was used to develop a predictive equation of α which only was significantly related to net radiation, air temperature, and leaf-area index (the total leaf area per unit ground area). Measured α had a median value of 0.80 which was less than the empirical maximum of 1.26 for PET.

Nighttime ET, assumed to be zero in the PT model, was verified by eddy-correlation measurements made on a night with little or no dewfall when measurements indicated that latent heat flux fluctuated slightly above and below zero during the night, but had a mean close to zero. Although the magnitude of dew could not be quantified in this study, observations made during the study indicate dewfall may be more significant than previously considered.

Estimates of ET for sites and regions with large differences in area typically are not compared because they would not necessarily be expected to agree. However, by comparing the ET estimates, a determination can be made as to whether or not the site-measured ET is within the expected range of ET estimated using a regional water budget. Generally, the estimates of ET, PET, and lake evaporation for 1994 are in good agreement with each other. Seasonal variations in ET are similar to each other, with minimum ET rates in December and January and maximum between April and July. Annual modeled ET and water-budget estimates of ET each were about 32 in. Modeled ET rates ranged from 1.2 inches per month (in/mo) (14.4 in/yr) in January to 4.3 in/mo (51.6 in/yr) in May. Water-budget ET rates ranged from 1.0 in/mo (12.0 in/yr) in March to 5.1 in/mo (61.2 in/yr) in July. PET rates averaged 46.8 in/yr and ranged from 1.8 in/mo (21.6 in/yr) in January to 6.2 in/mo (74.4 in/yr) in May. Lake evaporation rates, averaging 47.1 in/yr, ranged from 1.5 in/mo (18.0 in/yr) in January to 6.0 in/mo (72.0 in/yr) in May.

Error for the water-budget and modeled estimates of ET is about 30 percent and error for the lake evaporation estimate is about 7 percent. Therefore, the expected range of the 1994 water-budget ET estimate is ±0.30x31.7 in., or from 22.9-41.2 in. The expected ranges of the modeled ET and PET estimates are from 22.4-41.6 in. (±0.30x32.0 in.), and from 32.8-60.8 in. (±0.30x46.8 in.), respectively. For lake evaporation, the expected range is ±0.07x53.2 in., or from 49.5-56.9 in.

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