

Effects of the Temporal Variability of Evapotranspiration on Hydrologic Simulation in Central Florida

By Andrew M. O'Reilly

Prepared in cooperation with the
St. Johns River Water Management District

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Conversion Factors and Datum

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
Area		
square kilometer (km ²)	0.3861	square mile (mi ²)
Flow rate		
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
Energy flux density		
watt per square meter (W/m ²)	0.001433	calorie per square centimeter per minute
Flux		
millimeter per day (mm/d)	0.03937	inch per day (in/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Acronyms and Additional Abbreviations

ET	evapotranspiration
MAD	mean absolute deviation
MAE	mean absolute error
ME	mean error
r ²	coefficient of determination
RMSE	root-mean-square error
RM%	root-mean-square error as a percentage of the mean
SJRWMD	St. Johns River Water Management District
SD	standard deviation
USGS	U.S. Geological Survey

List of Symbols

C	the effective (lateral and vertical) conductance of aquifer, $[T^{-1}]$
E^i	average evapotranspiration rate over time interval $((i - 1)\Delta t, i\Delta t)$, $[L/T]$
E_p	potential ET, in millimeters per day
$e(t)$	evapotranspiration rate, $[L/T]$
E_1	modified coefficient of efficiency, [dimensionless]
E_1'	baseline-adjusted modified coefficient of efficiency, [dimensionless]
G	soil heat flux at land surface, in watts per square meter
G_{con}	a constant rate of ground-water flow, $[L/T]$
G^i	average ground-water flow rate over time interval $((i - 1)\Delta t, i\Delta t)$, $[L/T]$
$g(t)$	ground-water flow rate, $[L/T]$
H_B	depth below datum of the water level at boundary, $[L]$
h^i	depth of water level below a datum (typically land surface) at timestep i , $[L]$
h^{i-1}	depth of water level below a datum (typically land surface) at timestep $i-1$, $[L]$
H_L	depth below which specific yield changes (typically mean land surface), $[L]$
H_R	depth below datum above which surface runoff occurs (typically mean land surface), $[L]$
$h(t)$	depth of water level below a datum (typically land surface), $[L]$
h_z^i	depth of water level below a datum (typically land surface) at time step i computed assuming surface runoff is zero, $[L]$
$h_z(t)$	depth of water level below a datum (typically land surface) computed assuming surface runoff is zero, $[L]$
i	discretization index representing time $i\Delta t$
n	number of values in time series
p^i	average precipitation rate over time interval $((i - 1)\Delta t, i\Delta t)$, $[L/T]$
$p(t)$	precipitation rate, $[L/T]$
R_a	extraterrestrial radiation, in watts per square meter
R^i	average surface runoff rate over time interval $((i - 1)\Delta t, i\Delta t)$, $[L/T]$
R_n	net radiation, in watts per square meter
$r(t)$	surface runoff rate, $[L/T]$
S	storage (water held in pore space or ponded above land surface), $[L]$
S_{y1}	specific yield at depths greater than or equal to H_L , [dimensionless]
S_{y2}	specific yield at depths less than H_L , [dimensionless]
t	time, $[T]$
T_{avg}	mean air temperature, in degrees Celsius
T_{max}	mean maximum air temperature, in degrees Celsius
T_{min}	mean minimum air temperature, in degrees Celsius
W	change in storage of energy in the water column above land surface, in watts per square meter
x_i	measured value of the quantity of interest at time step i
$\hat{x}_i$	predicted value of the quantity of interest at time step i
$\bar{x}$	mean measured value of the quantity of interest at time step i
y_i	value of the baseline time series at time step i
α	the Priestley-Taylor coefficient [dimensionless]
γ	psychrometric constant, in kilopascals per degree Celsius
Δ	slope of saturation-vapor pressure curve, in kilopascals per degree Celsius
Δt	time interval for discretization, $[T]$
λ	latent heat of vaporization, in Joules per gram
ρ_w	density of water, in grams per cubic centimeter

Effects of the Temporal Variability of Evapotranspiration on Hydrologic Simulation in Central Florida

By Andrew M. O'Reilly

Abstract

The transient response of a hydrologic system can be of concern to water-resource managers, because it is often extreme relatively short-lived events, such as floods or droughts, that profoundly influence the management of the resource. The water available to a hydrologic system for stream flow and aquifer recharge is determined by the difference of precipitation and evapotranspiration (ET). As such, temporal variations in precipitation and ET determine the degree of influence each has on the transient response of the hydrologic system.

Meteorological, ET, and hydrologic data collected from 1993 to 2003 and spanning 1- to 3²/₃-year periods were used to develop a hydrologic model for each of five sites in central Florida. The sensitivities of simulated water levels and flows to simple approximations of ET were quantified and the adequacy of each ET approximation was assessed. ET was approximated by computing potential ET, using the Hargreaves and Priestley-Taylor equations, and applying vegetation coefficients to adjust the potential ET values to actual ET. The Hargreaves and Priestley-Taylor ET approximations were used in the calibrated hydrologic models while leaving all other model characteristics and parameter values unchanged.

Two primary factors that influence how the temporal variability of ET affects hydrologic simulation in central Florida were identified: (1) stochastic character of precipitation and ET and (2) the ability of the local hydrologic system to attenuate variability of input stresses. Differences in the stochastic character of precipitation and ET, both the central location and spread of the data, result in substantial influence of precipitation on the quantity and timing of water available

to the hydrologic system and a relatively small influence of ET. The temporal variability of ET was considerably less than that of precipitation at each site over a wide range of time scales (from daily to annual). However, when precipitation and ET are of similar magnitude, small errors in ET can produce relatively large errors in available water, and accurate estimates of actual ET are more important. Local hydrologic conditions can also be an important factor influencing the hydrologic response to ET variability. Various points along a flow path in a hydrologic system respond differently to temporal variations in ET. For example, soil moisture contents in the root zone are sensitive to daily variations in ET, whereas spring flow responds to only longer term variations in ET.

Both the Hargreaves and Priestley-Taylor equations for potential ET, when applied with an annually invariant monthly vegetation coefficient derived from comparison of measured ET with computed potential ET values, can be used with a hydrologic model to produce reasonable predictions of water levels and flows. Baseline-adjusted modified coefficients of efficiency for simulated water levels ranged from 0.0, indicating that water levels were simulated equally as well with approximated ET as with actual ET values, to -0.6, indicating that water levels were simulated better with actual ET values. Simulations using the Hargreaves approximation consistently yielded larger absolute and relative errors than the Priestley-Taylor approximation. However, the differences between the Hargreaves and Priestley-Taylor simulations generally were much smaller than differences between these simulations and the simulations using actual ET. This suggests that the simpler Hargreaves equation may be an adequate substitute for the more complex Priestley-Taylor equation, depending on the level of accuracy required to satisfy the particular modeling objectives.

Introduction

The difference of precipitation and evapotranspiration (ET) provides the “available water” to a hydrologic system for stream flow and aquifer recharge. The hydrologic system in central Florida can be substantially influenced by the temporal variability of available water. The relative timing and magnitude of the temporal variations in precipitation and ET determine the temporal variability of available water, therefore determining the degree of influence each has on the transient response of the hydrologic system. The transient response of the hydrologic system can be of great concern to water-resource managers, manifest, for example, as flooding caused by a rising water table intercepting land surface during a prolonged rainy period or as declining spring flow caused by a drought.

Models are frequently used to quantify and predict the effects of natural processes or management activities on a hydrologic system. As a part of the modeling process, considerable effort is directed toward quantifying stresses acting on a hydrologic system, and this effort is magnified when transient analysis of the hydrologic system is required. As a matter of practicality, it is instructive to investigate the relative importance of these stresses on the hydrologic response of interest (typically water levels and flows) to ascertain the appropriate effort to expend in obtaining estimates of each stress. In particular, ET is a stress that often is difficult to quantify, owing to the scarcity, cost, and labor of ET measurements (Sumner, 2006a). To address this need, the U.S. Geological Survey (USGS), in cooperation with the St. Johns River Water Management District (SJRWMD), began a 1³/₄-year study in 2004 to investigate the effects of the temporal variability of ET on hydrologic simulation in central Florida.

Purpose and Scope

This report describes the temporal variability of ET measured at five sites in central Florida and implications of this variability for hydrologic simulation. At each site, meteorological, ET, and hydrologic data collected from 1993 to 2003 and spanning 1- to 3²/₃-year periods are presented. Site specific hydrologic models were developed and calibrated to measured water levels at each site. The sensitivities of water levels and flows simulated by these hydrologic models to simple approximations of ET are quantified and the adequacy of each ET approximation is assessed.

Previous Studies

Few researchers have investigated the importance of accurately modeling the temporal variability of ET and the implications of this variability on commonly modeled hydrologic variables, such as water levels, flows, and solute concentrations. Most published literature focuses on the sensitivity of

hydrologic models to potential ET; actual ET is computed by an internal algorithm unique to each model relating potential ET to actual ET. The majority of these studies concerning potential ET address the simulation of streamflow with rainfall-runoff (watershed) models. Parmele (1972, p. 358) was one of the first to note that “* * * precise daily values of potential ET may not be required and that accurate weekly or monthly estimates might be satisfactory for application in hydrologic [watershed] models at these locations [one watershed in North Carolina and two watersheds in Pennsylvania].” However, Parmele (1972) also noted that a constant bias in potential ET has a cumulative effect and results in considerable error in simulated streamflow. Paturel and others (1995) reported the lower sensitivity of a simple rainfall-runoff model to bias errors in potential ET compared to similar errors in precipitation.

Vázquez and Feyen (2003) applied the MIKE SHE model using three potential ET formulations and recalibrating the model for each potential ET data set, to assess the adaptability of model parameter values. They found differing levels of sensitivity among parameters; for example, hydraulic conductivity parameters were relatively insensitive to the different potential ET formulations, whereas specific yield and several parameters of the MIKE SHE ET algorithm were significantly sensitive to different potential ET formulations. In terms of model performance, Vázquez and Feyen (2003, p. 322-232) also found differing results, identifying significant differences in simulated streamflow and few differences in simulated ground-water levels when using different potential ET formulations.

Andréassian and others (2004) used two watershed models to test more accurate estimates of potential ET derived through regionalization of data from a network of potential ET stations. After recalibration of each model, a more accurate spatially heterogeneous (regionalized) potential ET formulation yielded essentially identical model-fit statistics compared to a spatially homogenous potential ET formulation (Andréassian and others, 2004, p. 30).

Oudin and others (2004) demonstrated the ability of watershed models to act as low-pass filters by absorbing high-frequency variations in potential ET. They used two watershed models and compared simulated streamflows using traditionally accepted potential ET input and potential ET input corrupted with random and autocorrelated errors. Oudin and others (2004, p. 9) concluded that the most plausible explanation for the insensitivity of watershed models to potential ET is the buffering effect of soil moisture, and that this insensitivity is not an artifact of model structure or conceptualization nor is it caused by invalid potential ET formulation. Oudin and others (2005a, b) presented analyses of the sensitivity of watershed models to potential ET input using four models covering 308 basins. Oudin and others (2005b, p. 286) concluded that “* * * looking for daily observed potential ET data as inputs into a rainfall-runoff model is not necessary: a long-term average regime curve [the same seasonally variable potential ET, identically repeated each year] will serve as well.” Oudin

and others (2005a) went a step further and tested 27 potential ET formulations to determine which best represented the evaporative demand at the basin scale on the basis of simulated streamflow. They concluded that “* * *very simple [potential ET] models relying only on extraterrestrial radiation and mean daily temperature are as efficient as more complex models such as the Penman model [Penman, 1948] and its variants” (Oudin and others, 2005a, p. 303).

Several researchers investigated the temporal variability of soil moisture and inferred the importance of potential ET in controlling this variability. Calder and others (1983) used soil water-balance models to demonstrate that using a simple annually invariant, sinusoidal pattern of potential ET and measured precipitation yielded essentially equal or better predictions of observed soil moisture (at six grassland sites in the United Kingdom) than more complex parameterizations of potential ET requiring daily measurement of meteorological data. In a similar investigation, Fowler (2002) used soil water-balance models and found an annually invariant, sinusoidal pattern of potential ET gave comparable soil moisture deficit results to simulations using observed values of potential ET, even during extreme dry or wet conditions. Wilson and others (2004) identified the importance of comparing the temporal variability of potential ET to precipitation, as well as considering the water storage capacity of a soil, in explaining temporal variations in soil moisture.

Few studies have examined the sensitivity of ground-water models to the temporal variability of ET. Dausman and Langevin (2005, p. 62) developed a transient variable-density ground-water model and reported that simulated salinity concentrations were insensitive to the maximum ET rate parameter used by the model to compute ET from the saturated zone.

The studies above focused on potential or maximum ET rate parameters required by many hydrologic models and did not address the more fundamental question: what knowledge of the true (actual) ET is required for hydrologic simulation? O'Reilly (2004, p. 33) developed a model to simulate transient ground-water recharge in deep water-table settings, using water-balance and transfer-function algorithms, and noted that the model was relatively insensitive to temporal variations in ET. Sumner and Belaine (2005) developed a simple mass-balance model to simulate the effects of precipitation and evaporation on salinity changes in an estuary. They noted that salinity changes simulated using daily measurements of precipitation and a constant, mean value of evaporation yielded results similar to those obtained using daily values of evaporation, and attributed this behavior to the greater temporal variability of precipitation compared to that of evaporation. Sumner (2006a) presented an approach to define the adequacy of ET approximations for hydrologic simulation and identified two important factors for making this determination: (1) relative temporal variability of precipitation and ET and (2) the amplification of ET error that can result when differencing precipitation and ET measurements that are similar in magnitude. Using measured data rather than a hydrologic

model, Swancar (2006) examined the monthly water budget over 9.5 years for a 53-hectare seepage lake in central Florida. A comparison of the variability of each water-budget component (precipitation, ET, lake withdrawals by pumping, and ground-water exchange) indicated that, on an average annual basis, evaporation had a range in temporal variation more than five times smaller than either precipitation or ground-water exchange. As such, little of the measured change in lake stage was attributed to ET (Swancar, 2006).

Acknowledgments

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Hydrologic Conditions in Central Florida

Central Florida's climate is humid subtropical and characterized by warm, rainy summers and temperate, relatively dry winters. Long-term average annual precipitation is about 1,300 millimeters (mm) (51 inches (in.)), with 55–60 percent falling during the wet season (June through September) and 40–45 percent falling during the dry season (October through May) (Knowles and others, 2002, p. 30). During the wet season, daily thunderstorms are common and yield large quantities of precipitation, whereas during the dry season, precipitation generally is associated with frontal systems. Summer daily maximum air temperatures typically exceed 32 degrees Celsius; winter daily maximum air temperatures generally are mild with occasional freezes (Knowles and others, 2002, p. 9).

Precipitation provides the largest input of water to the hydrologic system in central Florida, and, on an annual basis, the largest water loss is through ET. Summarizing the results of previous investigators, Sumner and Jacobs (2005, p. 82) report that the fraction of annual precipitation returned as ET in Florida ranges from about 50 percent in settings of relatively deep water table, shallow rooted vegetation, and sandy soils (Sumner, 1996) to almost 110 percent from lakes (Swancar and others, 2000).

Stream runoff generally is the second largest water loss from the hydrologic system in central Florida. Long-term average annual stream runoff ranges from 130 mm (5 in.) in the interior parts of central Florida to 380 mm (15 in.) or more in coastal areas near Tampa Bay and Brevard and Indian River Counties (Rumenik, 1988).

Central Florida is underlain by unconsolidated sand and clay sediments that generally range in thickness from 0 to 60 meters (m), forming the surficial aquifer system (Knowles and others, 2002, p. 15). Underlying the surficial aquifer system is the intermediate confining unit, which separates the

surficial aquifer system from the deeper carbonate Floridan aquifer system. The Floridan aquifer system is divided into two aquifers of relatively high permeability—the Upper Floridan aquifer and the Lower Floridan aquifer. The water table generally is near land surface and occurs in the surficial aquifer system. In these shallow water-table settings, ET and runoff generally are higher than where the water table is deep. In many areas, however, the water table is 2 m or more deep, exceeding 20 m in some areas (fig. 1). These deep water-table settings generally exist in the ridge physiographic regions of central Florida, especially the Lake Wales Ridge, Mount Dora Ridge, and Deland Ridge (fig. 1). In the ridge areas, ET and runoff generally are lower than where the water table is shallow.

Data Collection and Analysis Methods

The approach applied in this study can be generally outlined as follows: (1) obtain ET, meteorological, and hydrologic data from five sites in central Florida; (2) develop and calibrate hydrologic models for each site using the data; and (3) test two alternative ET approximations relating calculated potential ET to actual ET by comparing water levels and flows simulated using the ET approximations to those simulated using measured ET values.

Field Measurements

Historical ET measurements spanning a variety of time periods (from about 1 to 3²/₃ years) were obtained for five sites in central Florida (sites 2, 3, 4, 5, and 10; fig. 1, table 1). Concurrent measurements of precipitation at or in the vicinity of the five ET sites were also obtained. At some ET sites it was necessary to estimate missing precipitation data from nearby gages (missing data from site 5 were estimated from sites 6 and 7; missing data from site 10 were estimated from sites 12, 13, and 15; fig. 1, table 1). ET and related meteorological data were measured at 30-minute resolution using the eddy correlation method (Monteith and Unsworth, 1990) in a manner similar to that described by Sumner and Jacobs (2005). Daily totals of precipitation and ET, derived from the 30-minute data, were used in the hydrologic models. Water-table depth was measured in a shallow well adjacent to or within 200 m of the ET and meteorological instrumentation. In the Blue Cypress Marsh Conservation Area, daily average values of surface-water stage were available at five locations throughout the marsh (sites 8, 9, 11, 12, and 14; fig. 1, table 1), in addition to the stage measurements made at the ET station (site 10).

Hydrologic Models

Hydrologic models were developed for each site using a simple water-balance approach based on the following volume-balance equation:

$$\frac{dS}{dt} = p(t) - e(t) - r(t) - g(t) , \quad (1)$$

where

S is storage (water held in pore space or ponded above land surface), [L];

$p(t)$ is precipitation rate, [L/T];

$e(t)$ is evapotranspiration rate, [L/T];

$r(t)$ is surface runoff rate, [L/T];

$g(t)$ is ground-water flow rate, [L/T];

t is time, [T]; and

L and T denote length and time units, respectively.

In equation 1 (and throughout this report) length units are used to represent a volume of water per unit of bulk area perpendicular to the direction of flow.

A change in storage is related to water-level response by specific yield. A binary representation of specific yield allows for the water table to rise above land surface and maintain ponded conditions (such as in a wetland):

$$\frac{dS}{dt} = \begin{cases} \frac{dh(t)}{dt} S_{y1} & \text{for } h(t) \geq H_L \\ \frac{dh(t)}{dt} S_{y2} & \text{for } h(t) < H_L \end{cases} , \quad (2)$$

where

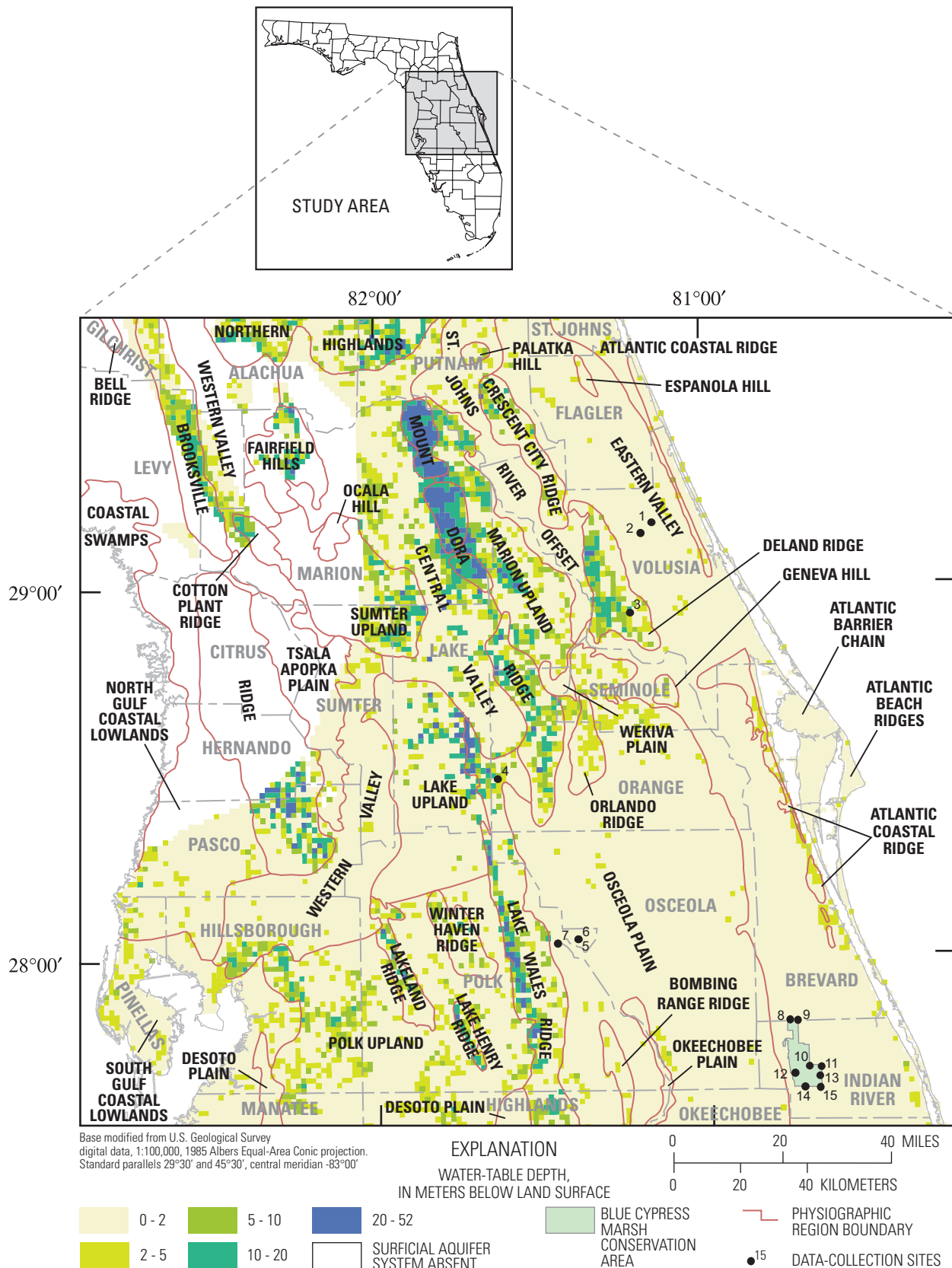
$h(t)$ is depth of water level below a datum (typically land surface), [L];

H_L is depth below which specific yield changes (typically mean land surface), [L];

S_{y1} is specific yield at depths greater than or equal to H_L , [dimensionless]; and

S_{y2} is specific yield at depths less than H_L , [dimensionless].

For simplicity, equation 2 assumes a constant (temporally) specific yield. However, specific yield can vary in time and is a function of soil-moisture retention characteristics, water-table depth, the rate of rise or decline of the water table, and gas bubble entrapment (Duke, 1972; Sophocleous, 1985; Fayer and Hillel, 1986a, b) as well as microtopography (Choi and others, 2003; Sumner, 2007).



6 Effects of the Temporal Variability of Evapotranspiration on Hydrologic Simulation in Central Florida

Table 1. Data-collection stations.

[--, not available; ET, evapotranspiration; met, meteorological; wl, water level; precip, precipitation; USGS, U.S. Geological Survey; SFWMD, South Florida Water Management District; SJRWMD, St. Johns River Water Management District]

Site number	Station identifier ^a	Station name	Latitude / Longitude	Data type	Period of record used	Collecting agency
1	02247480	Tiger Bay canal	290958 / 810918	flow	Jan. 1998 - Dec. 1999	USGS
2	--	Tiger Bay ET	290818 / 811123	ET/met/wl	Jan. 1998 - Dec. 1999	USGS
3	--	Lyonia Preserve ET	285530 / 811337	ET/met/wl	Jan. 2002 - May 2003	USGS
4	--	Lake Wales Ridge ET	282901 / 813811	ET/met/wl	Sept. 1993 - Aug. 1994	USGS
5	280256081240100	Disney Wilderness Preserve ET	280256 / 812401	ET/met/wl	Aug. 2000 - Aug. 2003	USGS
6	WRWX	Walker Ranch	280254 / 812358	precip	Aug. 2000 - Aug. 2003	SFWMD
7	CREEK_R	Creek Ranch	280219 / 812745	precip	Aug. 2000 - Aug. 2003	SFWMD
8	01290545	Blue Cypress Marsh S-250B-S	274922 / 04558	wl	Jan. 2000 - Sept. 2003	SJRWMD
9	00980400	Blue Cypress Marsh S-96C-S	274914 / 804436	wl	Jan. 2000 - Sept. 2003	SJRWMD
10	274143080424100	Blue Cypress Marsh ET	274143 / 804241	ET/met/wl	Jan. 2000 - Sept. 2003	USGS
11	01120520	Blue Cypress Marsh S-254-W	274139 / 804029	wl	Jan. 2000 - Sept. 2003	SJRWMD
12	01230507; 01230506	Blue Cypress Marsh BCMCA-W	274040 / 804519	precip/wl	Jan. 2000 - Sept. 2003	SJRWMD
13	01240511	Blue Cypress Marsh BCMCA-E	274009 / 804047	precip	Jan. 2000 - Sept. 2003	SJRWMD
14	01200448	Blue Cypress Marsh S-252A-N	273828 / 804331	wl	Jan. 2000 - Sept. 2003	SJRWMD
15	01880101	Blue Cypress Marsh S-252D	273820 / 804044	precip	Jan. 2000 - Sept. 2003	SJRWMD

^aStation identifier assigned by collecting agency.

Combining equations 1 and 2 in discretized form yields an expression for water level:

$$h^i = h^{i-1} - \frac{\Delta t}{S_y} (P^i - E^i - R^i - G^i) \quad \text{and} \quad (3)$$

$$S_y = \begin{cases} S_{y1} & \text{for } h^i \geq H_L \\ S_{y2} & \text{for } h^i < H_L \end{cases}, \quad (4)$$

where

h^i is depth of water level below a datum (typically land surface) at timestep i , [L];

h^{i-1} is depth of water level below a datum (typically land surface) at timestep $i-1$, [L];

Δt is time interval for discretization, [T];

P^i is average precipitation rate over time interval $((i-1)\Delta t, i\Delta t)$, [L/T];

E^i is average evapotranspiration rate over time interval $((i-1)\Delta t, i\Delta t)$, [L/T];

R^i is average surface runoff rate over time interval $((i-1)\Delta t, i\Delta t)$, [L/T];

G^i is average ground-water flow rate over time interval $((i-1)\Delta t, i\Delta t)$, [L/T]; and

i is discretization index representing time $i\Delta t$.

Surface runoff is conceptualized as “saturation excess” runoff—that is, occurring when the water level rises above a specified level representative of the average land surface thus indicating that the ground is fully saturated. Alternatively, a level above land surface may be specified, thus allowing the simulation of ponding. Surface runoff is described by the following equations in continuous and discretized forms, respectively:

$$r(t) = \begin{cases} 0 & \text{for } h_z(t) \geq H_R \\ (h_z(t) - H_R)S_{y2} & \text{for } h_z(t) < H_R \end{cases} \quad \text{and} \quad (5)$$

$$R^i = \begin{cases} 0 & \text{for } h_z^i \geq H_R \\ (h_z^i - H_R) S_{y2} & \text{for } h_z^i < H_R \end{cases}, \quad (6)$$

where

$h_z(t)$ is depth of water level below a datum (typically land surface) computed assuming surface runoff is zero, [L];

h_z^i is depth of water level below a datum (typically land surface) at time step i computed assuming surface runoff is zero; computed by setting $R^i = 0$ in equation 3, [L]; and

H_R is depth below datum above which surface runoff occurs (typically mean land surface), [L].

Ground-water flow is described by the following equations in continuous and discretized forms, respectively:

$$g(t) = G_{con} + C(H_B - h(t)) \quad \text{and} \quad (7)$$

$$G^i = G_{con} + C(H_B - h^{i-1}), \quad (8)$$

where

G_{con} is a constant rate of ground-water flow, [L/T];

C is the effective (lateral and vertical) conductance of aquifer, [T^{-1}]; and

H_B is depth below datum of the water level at boundary, [L].

The use of h^{i-1} in equation 8 rather than h^i is a method to linearize the equation, thereby avoiding the need to apply an iterative solution method. A mass-balance error was introduced by using this approximation, but it was small (daily mass-balance error averaged less than 0.6 percent of the total outflow) for each simulation.

Equations 3, 4, 6, and 8 constitute the water-balance model used for hydrologic simulation, which is depicted schematically in figure 2. The water-balance model is applied using a daily time step (Δt , eq. 3). Not every component of this model is used for the hydrologic model at each site. According to the local hydrologic conditions, the model was tailored to fit each site during the model construction and calibration process. For example, surface runoff does not necessarily occur at each site; likewise, ground-water flow at one site may be adequately described by a constant rate (G_{con} , eq. 8) precluding the need for a more complex head-dependent formulation (parameters C and H_B , eq. 8).

The water-balance model is a simple hydrologic model, which does not account for complex processes such as unsaturated flow. To investigate the importance of storage

and transmission of water within the unsaturated zone in attenuating high frequency variations in available water (precipitation minus ET), the USGS variably saturated flow model VS2DT (Lappala and others, 1987; Healy, 1990) was applied at one site with a relatively deep water table (Lake Wales Ridge, site 4, table 1). VS2DT is a finite-difference model that simulates variably saturated transient water flow and solute transport in one or two dimensions. Site-specific details about application and calibration of the water-balance and VS2DT models are discussed in later sections.

Evapotranspiration Approximations

ET was approximated by computing potential ET and multiplying by vegetation coefficients to adjust the potential ET values to actual ET. Two simple models were used to compute potential ET: (1) Hargreaves and Samani (1985) temperature-based model; and (2) Priestley and Taylor (1972) radiation-based model. These models were chosen because they are relatively simple, and previous studies have shown that they compare favorably with more complex models (Amatya and others, 1995; Jacobs and Satti, 2001; Oudin and others, 2005a). The Priestley-Taylor equation is (Priestley and Taylor, 1972):

$$E_p = \alpha \left(\frac{86.4}{\rho_w \lambda} \right) \left(\frac{\Delta}{\Delta + \gamma} \right) (R_n - G - W), \quad (9)$$

where

E_p is potential ET, in millimeters per day;

α is the Priestley-Taylor coefficient, generally estimated to be 1.26 for potential ET conditions (Sumner, 2001, p. 18), dimensionless;

ρ_w is density of water, in grams per cubic centimeter;

λ is latent heat of vaporization, in Joules per gram;

Δ is slope of saturation-vapor pressure curve, in kilopascals per degree Celsius;

γ is psychrometric constant, in kilopascals per degree Celsius;

R_n is net radiation, in watts per square meter;

G is soil heat flux at land surface, in watts per square meter; and

W is change in storage of energy in the water column above land surface, in watts per square meter.

Values for λ , Δ , and γ were computed using published equations: λ from Stull (1988), Δ from Monteith and Unsworth (1990, p. 10), and γ from Allen and others (1998, ch. 3, eq. 8). The soil heat flux (G) was assumed to be zero for all sites because

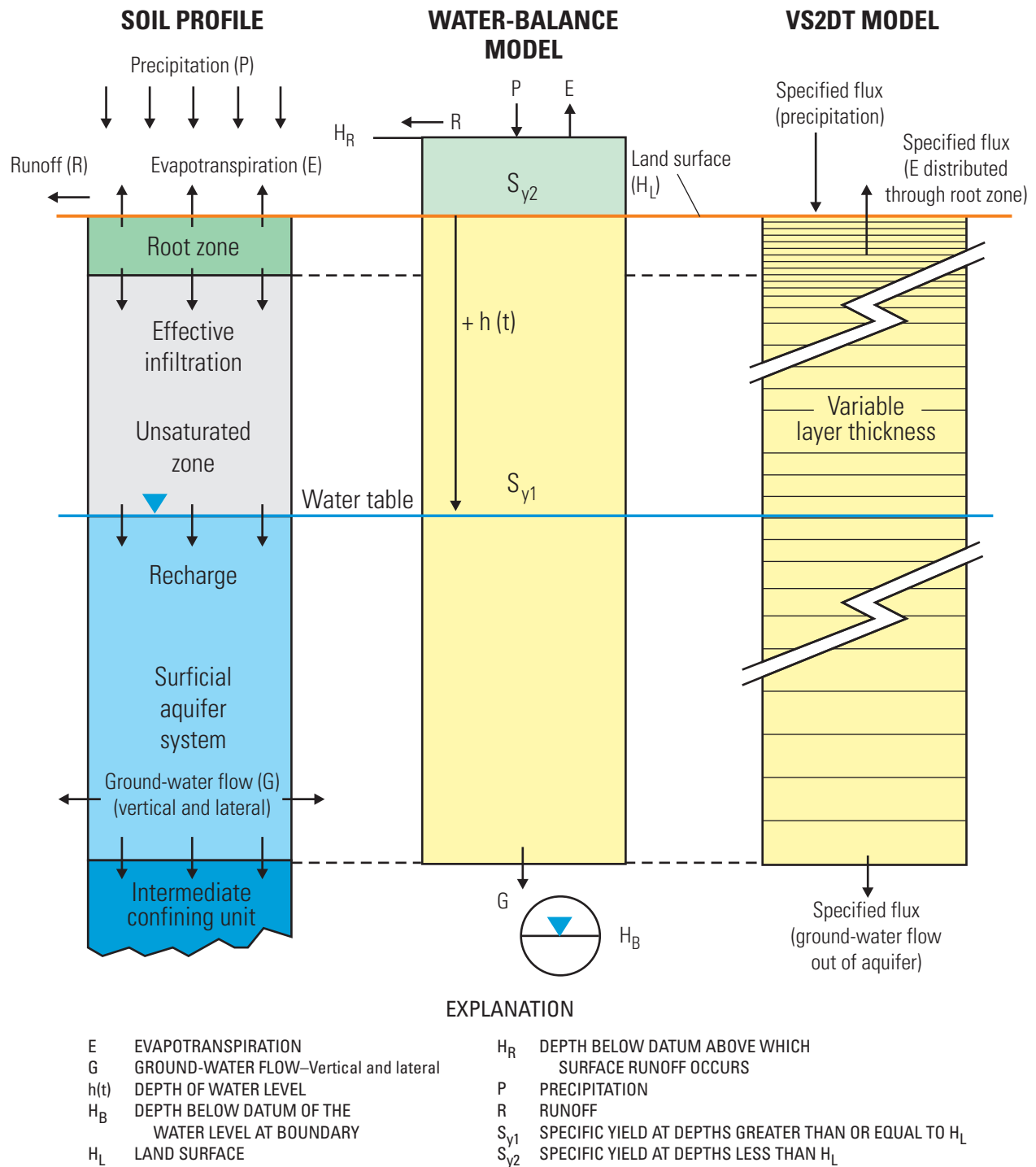


Figure 2. Typical soil profile and equivalent schematic diagrams of the water-balance model and the one-dimensional VS2DT model.

the Priestley-Taylor equation was applied at a daily time resolution. Neglecting G introduces little error, because G generally is small when averaged over a diurnal cycle. At the Disney Wilderness Preserve (site 5) where soil heat flux data were available, a good correlation existed between E_p calculated using equation 9 with and without G [$r^2 = 0.99$, standard error = 4.6 percent of mean E_p , mean error = 0.00 millimeters per day (mm/d)]. The change in energy stored in the water column (W) was computed for the Blue Cypress Marsh site (site 10) because the water level was usually above land surface. At all other sites, W was zero or negligible because the water level either was always below land surface or was above land surface only briefly.

The Hargreaves equation is (Hargreaves and Samani, 1985):

$$E_p = \left(\frac{86.4}{\rho_w \lambda} \right) 0.0023 R_a (T_{max} - T_{min})^{0.5} (T_{avg} + 17.8), \quad (10)$$

where

R_a is extraterrestrial radiation, in watts per square meter;

T_{max} is mean maximum air temperature, in degrees Celsius;

T_{min} is mean minimum air temperature, in degrees Celsius; and

T_{avg} is mean air temperature, in degrees Celsius.

Extraterrestrial radiation (R_a) is the radiation striking a surface perpendicular to the sun's rays at the top of the earth's atmosphere (Allen and others, 1998) and is solely a function of latitude and day of year. Values for R_a were computed using equation 21 reported by Allen and others (1998, ch. 3). Daily minimum and maximum values for R_a vary from 242 to 474 watts per square meter (W/m^2) at the southernmost site (Blue Cypress Marsh, site 10, fig. 1) to 234 to 475 W/m^2 at the northernmost site (Tiger Bay, site 2, fig. 1). The "sinusoidal-like" curve of R_a bears a strong resemblance (in shape and scale) to seasonal trends of R_n , with R_a being greater in magnitude. R_n and R_a control much of the variability in E_p predicted using the Priestley-Taylor and Hargreaves equations, respectively. However, substantial short-term fluctuations in E_p are introduced by the temperature variables in the Hargreaves equation. The Hargreaves method generally should be applied with 5-day or longer time steps due to the influence of weather fronts and large variations in wind speed or cloud cover that are not adequately represented by the temperature range (Hargreaves and Allen, 2003, p. 62). However, the Hargreaves equation was applied at a daily time resolution to allow a direct comparison to daily values of measured ET and for input into the hydrologic model for each site.

Measured ET and potential ET were plotted and a positive correlation was noted for each site (fig. 3). Coefficients of determination (r^2) indicate that Priestley-Taylor potential ET explains much of the variability in measured ET, ranging from 71 to 96 percent. As previously noted, neglecting the soil heat flux introduces little error as indicated by comparisons made at the Disney Preserve station—including G in equation 9 yields an r^2 of 0.80 whereas excluding G yields an r^2 of 0.78. Hargreaves potential ET is not as good an explanatory variable for measured ET, although Hargreaves potential ET explains 45 to 73 percent of the variability in measured ET and requires only commonly available measurements of air temperature. Several plots indicate a possibly nonlinear relation between potential and measured ET (fig. 3); therefore, the strength of any nonlinear (monotonic) association that may exist is underestimated because Pearson's r (square root of r^2) assumes a linear relation.

Annually invariant monthly vegetation coefficients were used to convert potential ET to an approximated actual ET. Potential ET time series were computed using both the Hargreaves equation and the Priestley-Taylor equation. Monthly vegetation coefficients were computed as the ratio of monthly average measured ET and monthly average potential ET for each month and for each of the five sites. For example, all daily ET and potential ET values for the first 31 days of each year were averaged and a monthly coefficient was computed and used for each January of every year. Considerable variation in monthly vegetation coefficients exists from year-to-year at each site (fig. 4). In addition, a comparison of the annually invariant monthly vegetation coefficients yields insight into the variation of ET with site conditions, particularly the availability of water (fig. 5). That is, the vegetation coefficient will equal 1 under potential conditions where water is freely available (for example, well watered grass). Vegetation coefficients occasionally exceed 1 for the Hargreaves potential ET and are indicative of the greater error inherent in this simple equation. In general, as the site becomes increasingly moisture deficient the vegetation coefficient will drop further below a value of 1. The following sites have successively greater water-table depths, on average: Blue Cypress Marsh, Tiger Bay, Disney Wilderness Preserve, and Lake Wales Ridge. Accordingly, the vegetation coefficients generally are greatest for the Blue Cypress Marsh site and smallest for the Lake Wales Ridge site. For the Lyonia Preserve site, the vegetation coefficients differ somewhat from the other sites for several reasons: (1) the water-table depth varies considerably, from about 2 m in low lying areas to greater than 10 m under the ridges (Knowles and others, 2005), so it is difficult to discern a representative water-table depth; (2) rainfall was unusually high during the period of data collection (for example, 2,300 mm or 91 in. for 2002), so water probably was often available on vegetated surfaces and as increased soil-moisture contents in the unsaturated zone; and (3) vegetation included pine and oak trees, which may have deeper roots tapping soil moisture in the lower unsaturated zone and possibly the saturated zone.

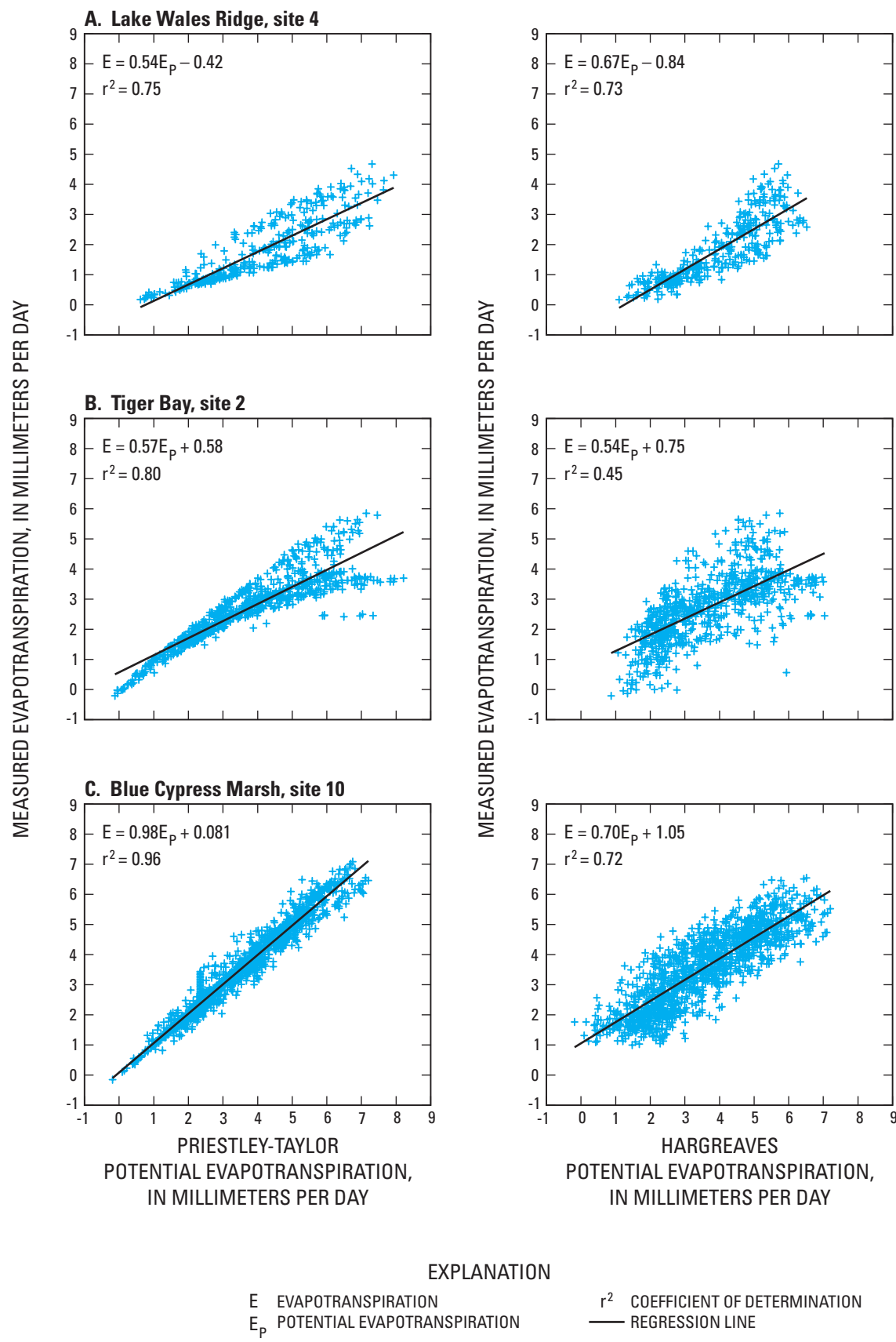


Figure 3. Measured evapotranspiration and Priestley-Taylor and Hargreaves potential evapotranspiration.

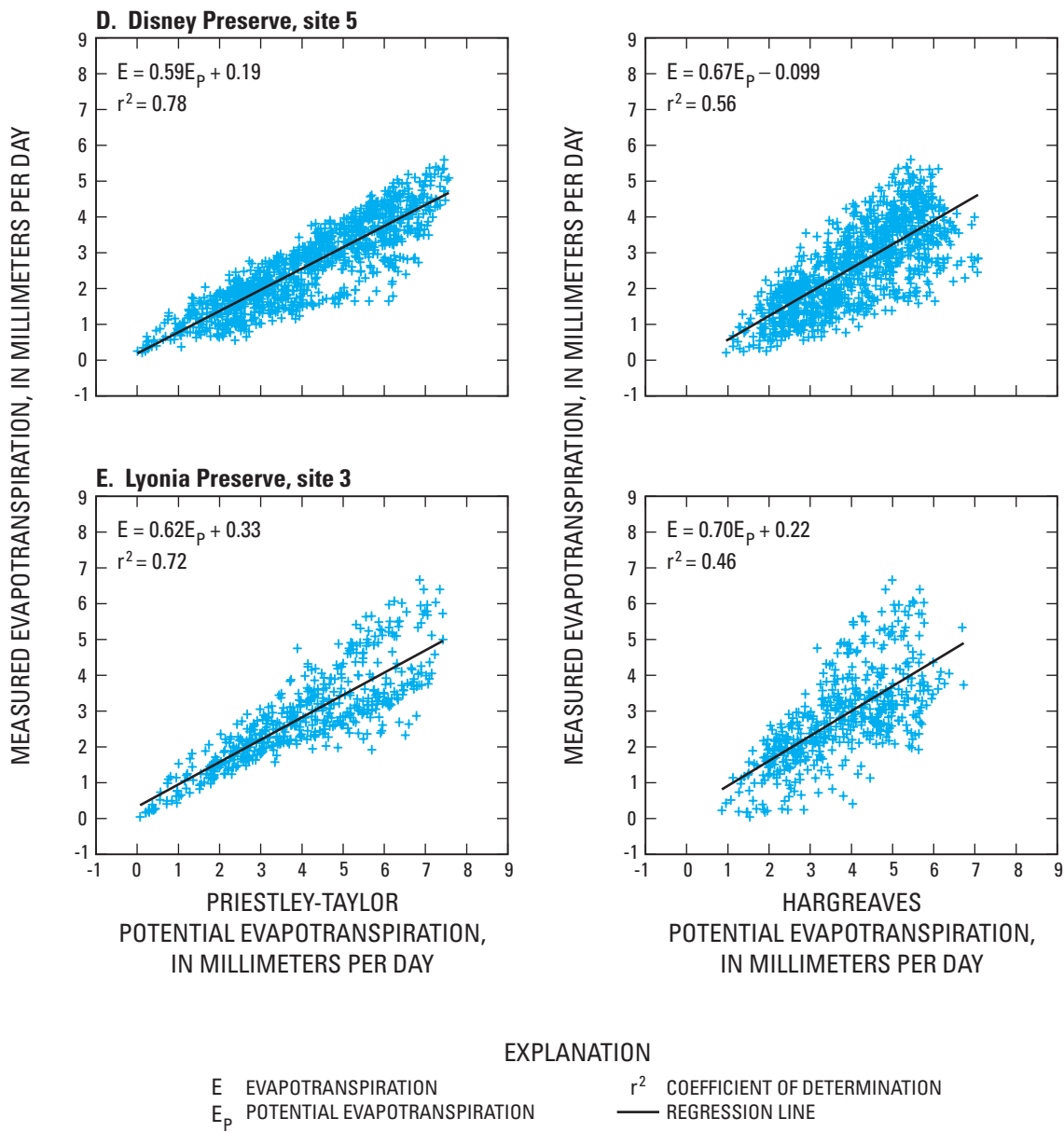


Figure 3. (Continued) Measured evapotranspiration and Priestley-Taylor and Hargreaves potential evapotranspiration.

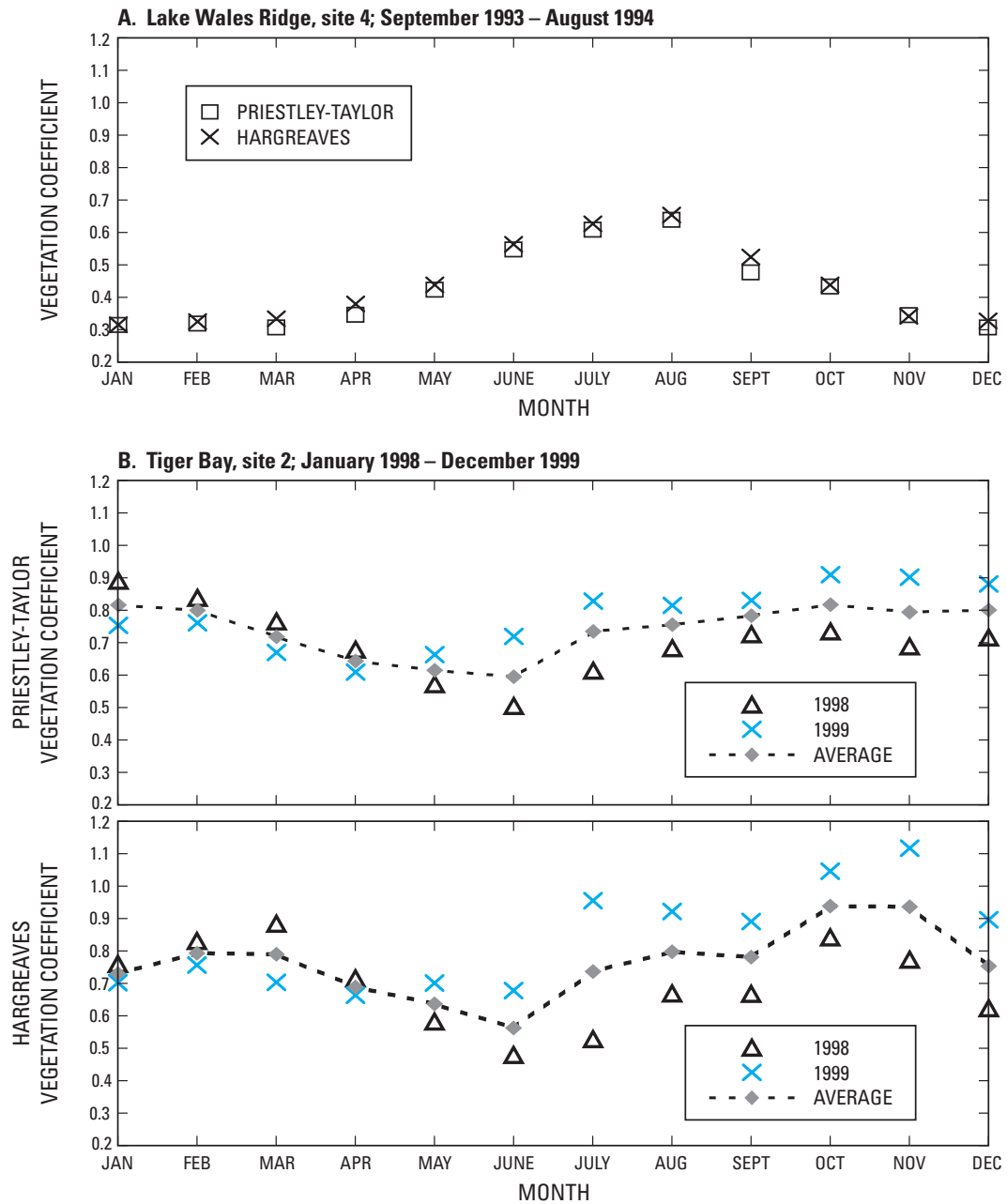


Figure 4. Monthly vegetation coefficients for Priestley-Taylor and Hargreaves potential evapotranspiration.

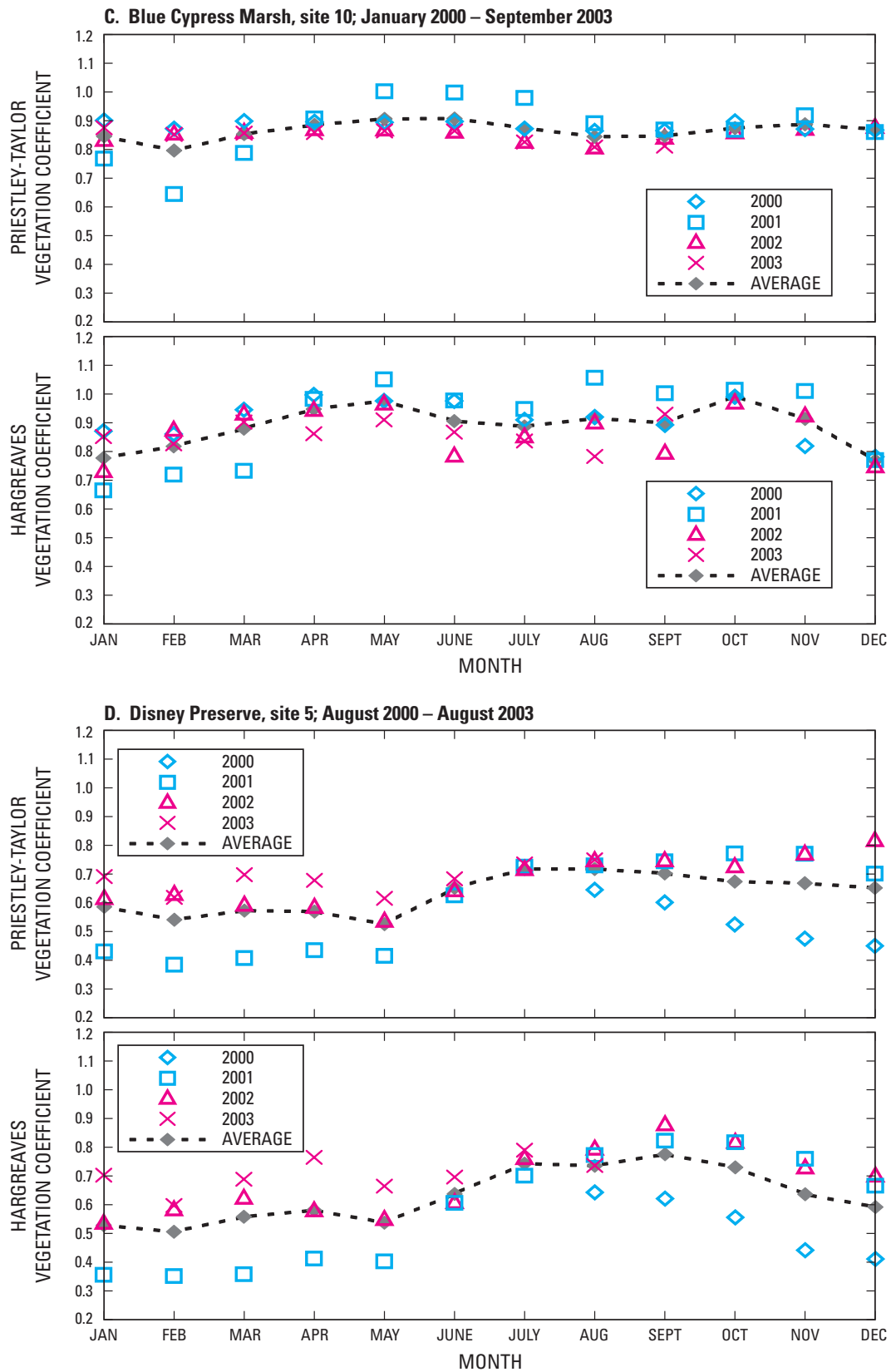


Figure 4. (Continued) Monthly vegetation coefficients for Priestley-Taylor and Hargreaves potential evapotranspiration.

Figure 4. (Continued) Monthly vegetation coefficients for Priestley-Taylor and Hargreaves potential evapotranspiration.

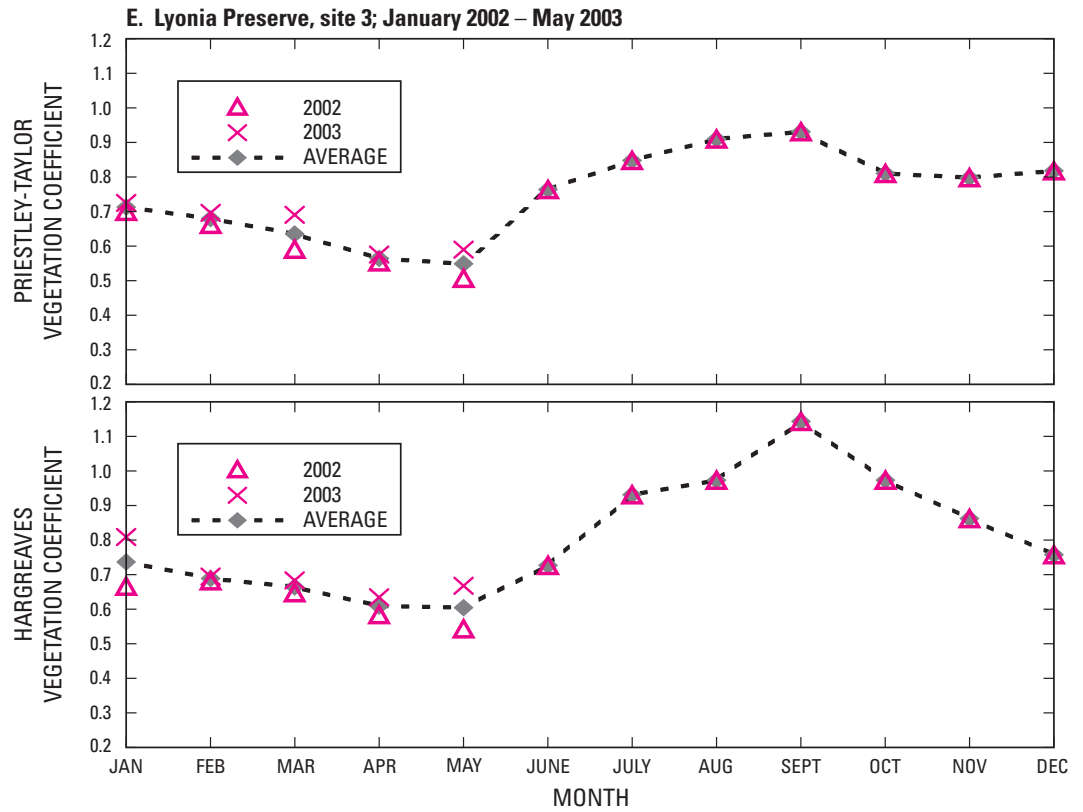
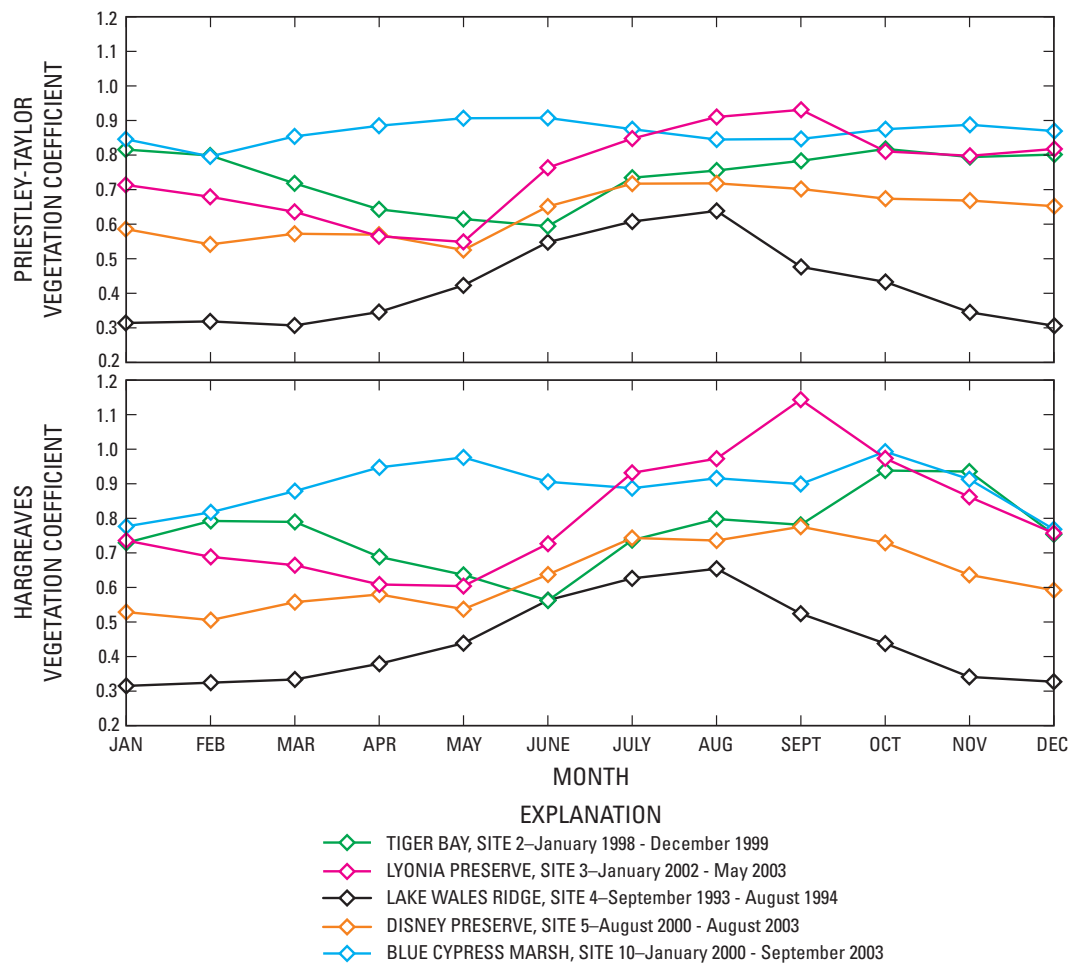


Figure 5. Annually invariant monthly vegetation coefficients for Priestley-Taylor and Hargreaves potential evapotranspiration.



Comparison of the Temporal Variability of Precipitation and Evapotranspiration

A strong temporal variation in ET is due primarily to meteorological variables (such as precipitation, solar radiation, windspeed, and humidity) and the plant/hydrologic system response to these variables. In central Florida, the wet season (June through September) mostly coincides with the plant growing season (largely dictated by seasonal variations in solar radiation), resulting in increased ET during summer months. The temporal variability of ET in central Florida, however, is considerably less than that of precipitation over a wide range of time scales (from daily to annual) (Sumner, 2006a). A comparison of the standard deviations of precipitation and ET at time scales of 1 to 91 days indicates that this disparity in variability between precipitation and ET exists at the five sites (fig. 6). The short periods of record (3 calendar years or less) precluded computation of meaningful annual statistics. A graphical comparison of summary statistics further demonstrates (at the monthly scale) the differences in the stochastic character of precipitation and ET at each site (fig. 7). Precipitation data generally follow an extreme-event distribution (Wanielista and others, 1997, p. 41); ET is more smoothly varying, as a result of differing hydroclimatic processes and their interactions. An examination of the correlation between available water and its two components, precipitation and ET, indicates that precipitation

strongly influences available water. Precipitation explains 98-99 percent of the variability in available water, whereas ET explains only 1-12 percent (table 2). Because of covariation between precipitation and ET at some sites, the r^2 values do not necessarily sum to 1 at each site. As will be demonstrated in the following sections, differences in the stochastic character of precipitation and ET have substantial impact on the importance of these inputs on predictions derived from hydrologic models.

Hydrologic Model Calibration

Hydrologic models were developed for the five ET sites (sites 2, 3, 4, 5, and 10; fig. 1, table 1) using the water-balance model previously described (eqs. 3, 4, 6, and 8). Models were calibrated to the measured water-table depth (or surface-water level for Blue Cypress Marsh). Additionally, a variably saturated flow model was developed for the Lake Wales Ridge site using VS2DT.

The water-balance models were implemented using Microsoft Excel spreadsheet software. The Solver capability of Microsoft Excel was used to minimize the sum-of-squared errors. The errors, or residuals, are computed as measured minus simulated water level. The VS2DT model was calibrated by trial and error to minimize the sum-of-squared residuals.

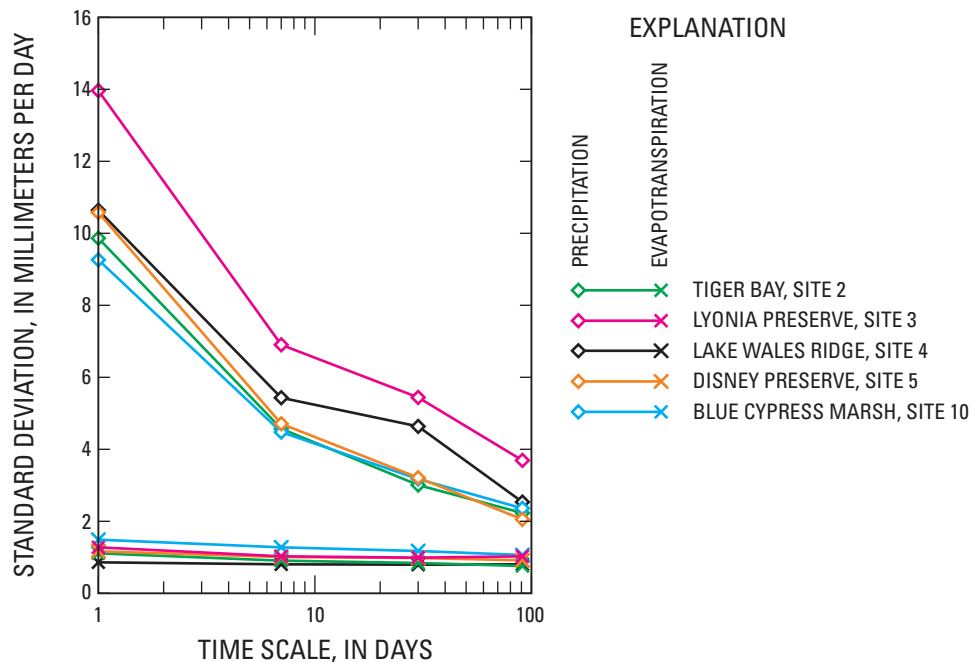


Figure 6. Variability of precipitation and evapotranspiration at daily, weekly, monthly, and seasonal time scales.

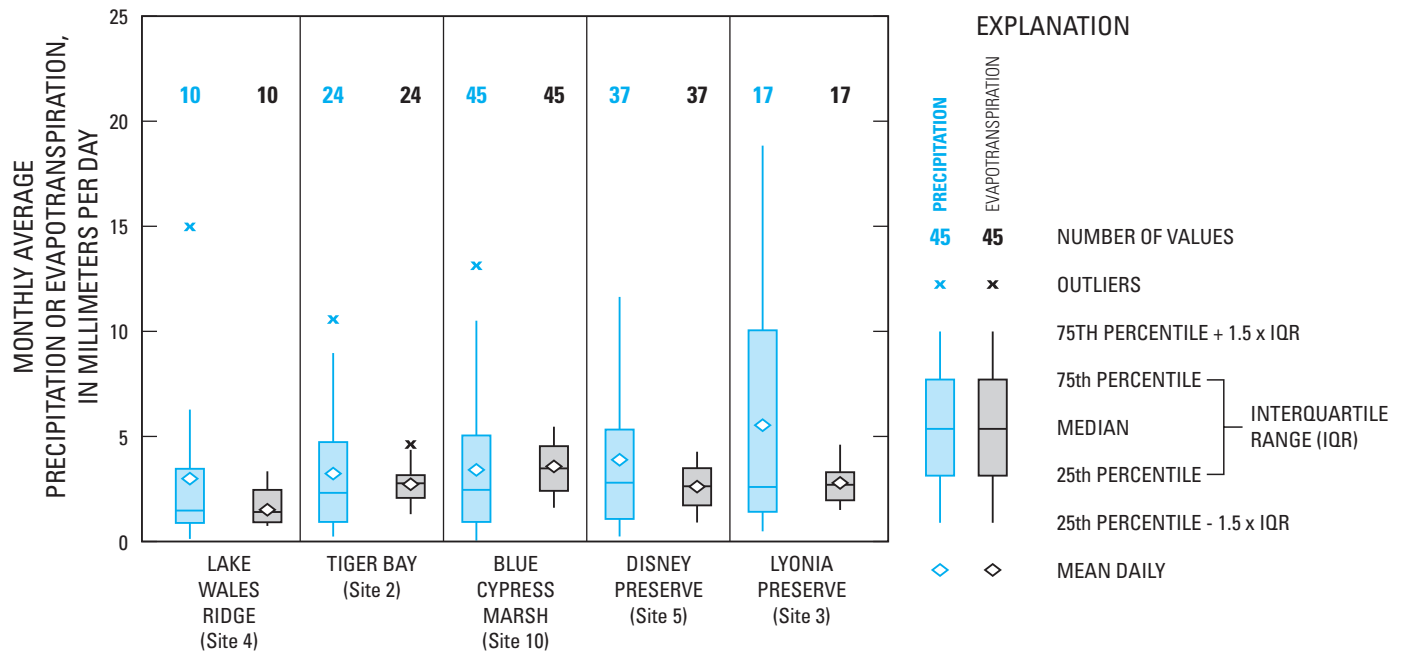


Figure 7. Monthly average precipitation and evapotranspiration.

Table 2. Coefficients of determination between daily values of available water and precipitation or evapotranspiration.

[r^2 , coefficient of determination; P, precipitation; ET, evapotranspiration]

Site number	Station	r^2 between available water and P or ET	
		P	ET
4	Lake Wales Ridge	0.99	0.01
2	Tiger Bay	.99	.12
10	Blue Cypress Marsh	.98	.08
5	Disney Wilderness Preserve	.99	.02
3	Lyonia Preserve	.99	.04

Model fit was measured with mean, standard deviation, mean error, mean absolute error (MAE), and root-mean-square error (RMSE). A less commonly used statistic—the modified coefficient of efficiency—was also computed:

$$E_1 = 1 - \frac{\sum_{i=1}^n |x_i - \hat{x}_i|}{\sum_{i=1}^n |x_i - \bar{x}|}, \quad (11)$$

where

E_1 is modified coefficient of efficiency, [dimensionless];

x_i is measured value of the quantity of interest at time step i ;

$\hat{x}_i$ is predicted value of the quantity of interest at time step i ;

$\bar{x}$ is mean measured value of the quantity of interest at time step i ; and

n is number of values in time series.

E_1 is proposed by Legates and McCabe (1999) as being a more robust statistic (less influenced by outliers than correlation based measures, such as r^2) for evaluation of the goodness-of-fit of hydrologic models. Values of E_1 closer to 1.0 indicate a better model fit.

Lake Wales Ridge

Sumner (1996) operated micrometeorological instruments to measure ET at a field site on the Lake Wales Ridge in west Orange County (site 4, fig. 1). The site was a field of mostly herbaceous, successional vegetation, with a root depth that rarely exceeded 0.3 m, which typically grows in cleared areas of central Florida (Sumner, 1996, p. 2). The site had well-drained sandy soils of the Candler series (Doolittle and Schellentrager, 1989), a relatively deep water table (2 to 3.5 m), and negligible surface runoff. Data were available for nearly 1 year (September 1993–August 1994).

Two hydrologic models were developed for this site: a water-balance model and a variably saturated flow model. The water-balance model consisted of two parameters, S_{y1} and G_{con} (table 3). The water table does not rise above land surface and surface runoff is negligible, so parameters S_{y2} , H_L , and H_R were not used. Also, a head-dependent flux boundary for ground-water flow (parameters C and H_B , eq. 8) did not improve model calibration appreciably to justify this

additional complexity over a constant-flux boundary (G_{con} , eq. 8). The simulated water level fit the measured water level in an adjacent monitor well (completed in the surficial aquifer system) reasonably well (table 4, fig. 8).

The water-level hydrograph simulated using the water-balance model is more “spikey” than the measured values (fig. 8); the measured hydrograph is smoother because recharge passes through a 3-m-thick unsaturated zone. In order to investigate the importance of the unsaturated zone in attenuating high frequency variations in available water (precipitation minus ET), the USGS variably saturated flow model VS2DT was applied. The VS2DT model consists of a one-dimensional vertical column with uniform soil properties extending from land surface to the base of the surficial aquifer system (fig. 2). The van Genuchten (1980) equations describing the moisture-characteristic curve (volumetric moisture content as a function of pressure head), specific moisture capacity (slope of the moisture-characteristic curve), and unsaturated hydraulic conductivity of the soil were used.

Table 3. Calibrated water-balance model parameter values.

[S_{y1} , specific yield at depths greater than or equal to H_L ; S_{y2} , specific yield at depths less than H_L ; H_L , depth below which specific yield changes (typically mean land surface); H_R , depth below datum above which surface runoff occurs (typically mean land surface); G_{con} , constant rate of ground-water flow at boundary; C , effective (lateral and vertical) conductance of aquifer; H_B , depth below datum of the water level at boundary; m, meter; mm/d, millimeter per day; d^{-1} , per day]

Site number	Site	S_{y1}	S_{y2}	H_L (m)	H_R (m)	G_{con} (mm/d)	C (d^{-1})	H_B (m)
4	Lake Wales Ridge	0.25	--	--	--	0.79	--	--
2	Tiger Bay	.14	--	--	0.0 ^a	-.31	--	--
8	Blue Cypress Marsh Station S-250B-S	.14	1.0 ^a	-1.1	--	--	.0012	-1.2
9	Blue Cypress Marsh Station S-96C-S	.25	1.0 ^a	-1.2	--	--	.00085	-1.2
10	Blue Cypress Marsh ET station	.27	1.0 ^a	0.0 ^a	-.33	-.36	--	--
11	Blue Cypress Marsh Station S-254-W	.33	1.0 ^a	-1.3	--	--	.0012	-1.3
12	Blue Cypress Marsh Station BCMCA-W	.14	1.0 ^a	-1.4	--	--	.0069	-1.5
14	Blue Cypress Marsh Station S-252A-N	.56	1.0 ^a	-1.8	--	--	.0084	-1.9
5	Disney Wilderness Preserve	.23	--	--	.0 ^a	--	.00062	1.9
3	Lyonia Preserve	.37	--	--	--	1.68	.00028	6.3

^aThis parameter was specified and not adjusted during calibration.

Table 4. Water-level error statistics for the calibrated water-balance models using actual evapotranspiration and two evapotranspiration approximations.

[ET, evapotranspiration; SD, standard deviation; ME, mean error; MAE, mean absolute error; RMSE, root-mean-square error; E_1 , modified coefficient of efficiency; E_1' baseline-adjusted modified coefficient of efficiency; --, not applicable]

Station name and statistics	Measured water level, in meters	Measured ET, in meters	ET approximation	
			Hargreaves, in meters	Priestley-Taylor, in meters
Lake Wales Ridge, site 4				
Mean	3.07	3.02	3.02	3.02
SD	.45	.49	.49	.49
ME	--	-.05	-.05	-.05
MAE	--	.13	.14	.14
RMSE	--	.35	.35	.35
E ₁	--	.69	.68	.68
E ₁ '	--	--	-.01	-.01
Tiger Bay, site 2				
Mean	.46	.41	.48	.47
SD	.42	.45	.49	.49
ME	--	.04	-.02	-.02
MAE	--	.10	.15	.13
RMSE	--	.13	.20	.17
E ₁	--	.72	.57	.63
E ₁ '	--	--	-.54	-.33
Blue Cypress Marsh, sites 8, 9, 10, 11, 12, and 14				
Mean	-1.20	-1.20	-1.22	-1.21
SD	.55	.53	.53	.53
ME	--	.00	.02	.01
MAE	--	.09	.09	.09
RMSE	--	.12	.12	.12
E ₁	--	.80	.80	.80
E ₁ '	--	--	.00	.02
Disney Wilderness Preserve, site 5				
Mean	.72	.66	.73	.71
SD	.44	.46	.60	.58
ME	--	.05	-.01	.00
MAE	--	.13	.21	.18
RMSE	--	.16	.26	.22
E ₁	--	.63	.42	.50
E ₁ '	--	--	-.56	-.36
Lyonia Preserve, site 3				
Mean	4.15	4.14	4.18	4.17
SD	.71	.70	.70	.70
ME	--	.01	-.03	-.02
MAE	--	.07	.08	.08
RMSE	--	.10	.11	.11
E ₁	--	.88	.87	.87
E ₁ '	--	--	-.10	-.09

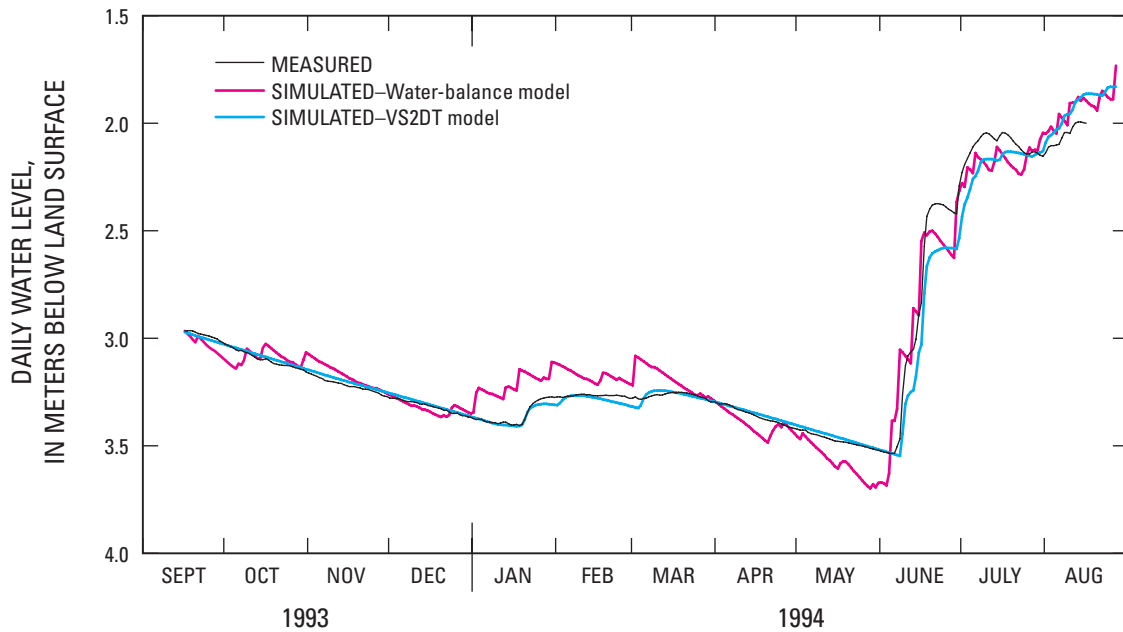


Figure 8. Measured and simulated daily water-table depth at the Lake Wales Ridge evapotranspiration station, site 4, using both the water-balance and VS2DT models.

The upper boundary consisted of a specified flux equal to the daily precipitation. Measured daily values of ET were uniformly distributed throughout the 0.3-m-thick root zone. A specified flux of 0.834 mm/d served as the lower boundary condition representing leakage to the Upper Floridan aquifer. This flux was calculated as the product of a specific yield of 0.22 and the observed water-table trend during a period of little precipitation and nearly constant water-table decline (September–December 1993, fig. 8). An equilibrium profile (pressure head is equal to the negative of elevation above the water table) was used as the initial condition because field moisture-content measurements indicated that the soil profile was near residual saturation (O'Reilly, 2004, p. 18).

A variable spatial discretization was used: a uniform 0.01-m node spacing to a depth of 0.3 m (the estimated thickness of the root zone), increasing to a 0.1-m node spacing from 0.3- to 0.6-m depths; a uniform 0.1-m node spacing to a depth of 4 m (below the maximum measured water-table depth), increasing to a 1-m node spacing from 4- to 7-m depths; and a uniform 1-m node spacing to a depth of 20 m (the base of the surficial aquifer system). A variable temporal discretization was used with an initial time step of 0.001 day, minimum time step of 0.0001 day, and maximum time step of 0.01 day; VS2DT automatically adjusts the time step so that a user-specified maximum change in pressure head is not exceeded at any node between successive time steps (Lappala and others, 1987, p. 35). For a similar model, O'Reilly (2004,

p. 19) determined the spatial and temporal discretizations specified above resulted in little truncation error from the finite-difference approximation.

The VS2DT model was calibrated by adjusting the van Genuchten (1980) parameters in a systematic manner to minimize the sum-of-squared errors, yielding the values listed in table 5. Water-table depth simulated by the VS2DT model for the Lake Wales Ridge site matched well the measured water-table depth (fig. 8, table 6). Storage and transmission of water within the unsaturated zone is an important factor attenuating high frequency variations in available water (fig. 8).

Table 5. Calibrated VS2DT model parameters for the Lake Wales Ridge site (site 4).

Parameter symbol	Parameter value	Parameter description
K_{sat}	45	Saturated hydraulic conductivity, in meters per day
θ_s	.24	Saturated volumetric moisture content
θ_r	.02	Residual volumetric moisture content
α	3.8	van Genuchten (1980) coefficient, reciprocal of which approximately equals the pressure head at the inflection point of the moisture-characteristic curve (for the β value used here)
β	3.5	van Genuchten (1980) coefficient characterizing slope of the moisture-characteristic curve

Table 6. Water-level error statistics for the calibrated VS2DT model using actual evapotranspiration and two evapotranspiration approximations at the Lake Wales Ridge site (site 4).

[ET, evapotranspiration; SD, standard deviation; ME, mean error; MAE, mean absolute error; RMSE, root-mean-square error; E_1 , modified coefficient of efficiency; E_1' baseline-adjusted modified coefficient of efficiency; --, not applicable]

Statistic	Measured water level, in meters	Measured ET, in meters	ET approximation	
			Hargreaves, in meters	Priestley-Taylor, in meters
Mean	3.07	3.083	3.081	3.082
SD	.45	.443	.446	.444
ME	--	-.009	-.007	-.007
MAE	--	.032	.033	.032
RMSE	--	.057	.059	.056
E_1	--	.908	.904	.907
E_1'	--	--	.075	-.010

Discrepancies exist in the magnitude of some water-table rises and declines during the wet season. Some combination of the following factors is likely causing these discrepancies: variable specific yield resulting from entrapment and dissolution of gas bubbles, hysteresis in soil water-retention properties, and lateral and vertical flow of ground water. The first two factors cannot be investigated with the VS2DT code. Ground-water flow can be investigated by examining water levels in the nearby surficial aquifer system and Upper Floridan aquifer wells. The head difference between the surficial aquifer system and Upper Floridan aquifer averaged about 15 m, ranging from about 3 percent less to 5 percent greater than the average during August 1993–September 1994. Therefore, temporal variations in leakage to the Upper Floridan aquifer are small and probably have a small effect on the measured water-table fluctuations. Lateral gradients in the surficial aquifer system vary significantly in time as a result of rapid infiltration basin loading approximately 250 m north of the ET site. However, surficial aquifer system water-level trends at background monitoring wells not affected by rapid infiltration basin loading are similar to those at the ET site, implying that the water table at the ET site is not greatly influenced by lateral ground-water flow induced by loading of the rapid infiltration basins.

Tiger Bay

Sumner (2001) operated micrometeorological instruments to measure ET at a field site in the Tiger Bay watershed in north-central Volusia County (site 2, fig. 1). The site was a cypress and pine forest, which had been subjected to

natural fires in 1998. The site also had permeable sandy soils of the Smyrna series (Baldwin and others, 1980), which were poorly drained as a result of a shallow water table (generally less than 1 m deep), and a long-term annual surface runoff of 200 millimeters per year (mm/yr) (1978–1999 average for the entire Tiger Bay watershed; Sumner, 2001, p. 45). Data were available for 2 years (January 1998–December 1999).

The water-balance model for the Tiger Bay site consisted of three parameters, S_{y1} , H_R , and G_{con} (table 3). The model was calibrated by adjusting two parameters, S_{y1} and G_{con} , resulting in a good fit to the measured water level (fig. 9, table 4). H_R (the level at which runoff commences) was assumed equal to mean land surface and assigned a value of zero. The best-fit values are 0.14 for S_{y1} and -0.31 mm/d for G_{con} (table 3). The value of 0.14 for S_{y1} is reasonable in comparison to estimates derived from laboratory analyses. Based on laboratory measurements of moisture-characteristic curves for eight soil cores collected at this site during a previous study (J.A. Tindall, U.S. Geological Survey, written commun., 2001), specific yield ranges from 0.03 to 0.35 with an average of 0.20. The negative value of G_{con} indicates a net inflow of ground water. Regional ground-water flow models indicate the Tiger Bay watershed is an area of recharge to the Upper Floridan aquifer (Knowles and others, 2002, p. 89; McGurk and Presley, 2002, p. 134; Sepulveda, 2002, p. 78); therefore, the net inflow may be indicative of lateral ground-water flow within the surficial aquifer system not simulated by regional flow models. The timing of surface runoff simulated by the water-balance model also agrees well with runoff measured at the Tiger Bay canal (site 1, fig. 1), which drains the 7,500 hectare [29 square mile (mi²)] watershed (fig. 9). The simulated and measured runoff rates do not agree in magnitude, because the simulated runoff is representative of a discrete site at the ET station, whereas measured runoff at the watershed outlet (Tiger Bay canal) incorporates the attenuating effects of various watershed characteristics, such as drainage patterns, slope, roughness, and infiltration capacity of the soil. Parameters S_{y2} and H_L were not used because the water table rarely rose above land surface even though the water table often was near land surface.

Blue Cypress Marsh

At a field site in west-central Indian River County, micrometeorological instruments were used to measure ET (site 10, fig. 1) (D.M. Sumner, U.S. Geological Survey, written commun., 2004). The site is located in the Blue Cypress Marsh Conservation Area, which is part of a large system of floodplain wetlands at the headwaters of the St. Johns River (Brenner and Schelske, 1995). The site has poorly drained peat soils of the Terra Ceia series (Wettstein and others, 1987), a water table that is above land surface except during extended dry periods, and an indeterminate amount of surface runoff. Data were available for 3²/₃ years (January 2000–September 2003).

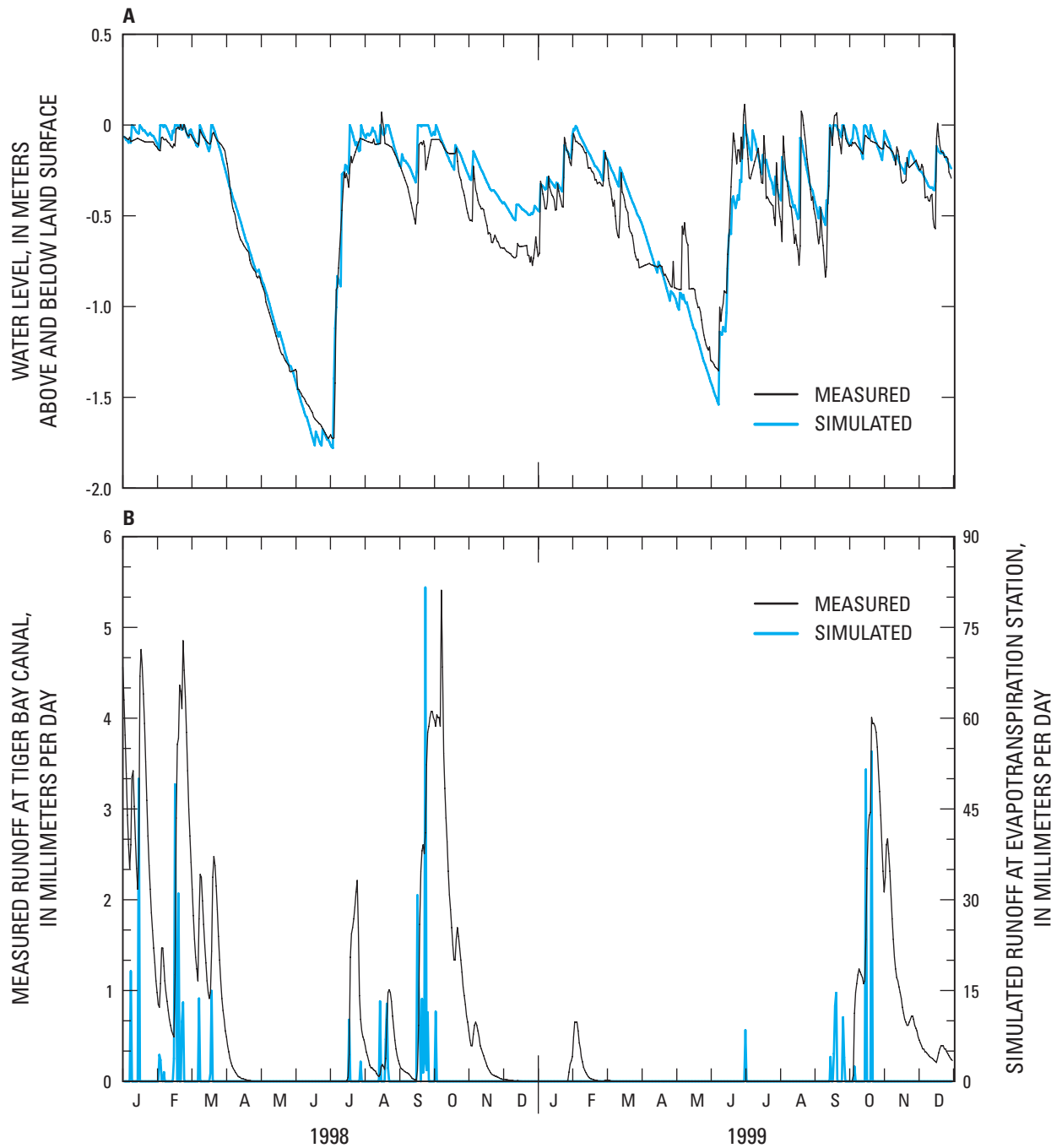


Figure 9. Measured and simulated data at the Tiger Bay evapotranspiration station, site 2: (A) daily water-table depth, and (B) daily discharge at Tiger Bay canal and simulated runoff at evapotranspiration station.

Because Blue Cypress Marsh Conservation Area is a large marsh system covering 11,700 hectares (45 mi²), a site-specific model for a single stage station cannot adequately characterize the complex hydrology. Therefore, water-balance models were developed for six stage stations located throughout the marsh (sites 8, 9, 10, 11, 12, and 14; fig. 1, table 1). Precipitation and ET were assumed to be uniform across the marsh. Precipitation was measured at the SJRWMD station at structure S-252D (site 15, fig. 1); ET was measured at the USGS station (site 10, fig. 1). Parameters were selected for each water-balance model based on model calibration and sensitivity analyses. All six models used the binary specific-yield formulation (eq. 4; parameters S_{y1} , S_{y2} , and H_L , table 3). The model for the ET station site (site 10) simulated surface runoff and a constant ground-water flow (parameters H_R and G_{con} , table 3). The models for the remaining five sites did not include surface runoff but did simulate a varying ground-water flow (parameters C and H_B , table 3).

Calibrated parameter values are reasonable (table 3). Simulated and measured water levels generally agree well (fig. 10, table 4). The water levels shown in figure 10 represent the depth of the measured or simulated water level below a uniform datum of 5.79 m, based on an estimated land-surface altitude of 19 feet above NGVD 29 (USGS 7.5-minute topographic quadrangles). At the ET station (site 10) a shallow well was installed to collect measurements of water-table depth during dry periods (fig. 10). Measured land-surface altitudes were not available at the data-collection sites, so H_L values were determined by model calibration. Additionally, H_L would not necessarily be expected to equal land surface at a single point, because the measured stage, as well as the model parameters, represents an integration of hydrologic forces and responses over some areal extent. Therefore, H_L represents the level of the average "effective" land surface.

The variation of specific yield, from 0.14 to 0.56, among the sites is not unexpected. Soils in the Blue Cypress Marsh Conservation Area are a peat of the Terra Ceia series, which commonly exceed 1.5 m in depth (Wettstein and others, 1987, p. 114). Organic-matter content generally exceeds 90 percent by weight (Brenner and Schelske, 1995, p. 2). Moisture-characteristic data reported for a similar peat (Gator series) from a pasture site just outside the Conservation Area indicate moisture contents from approximately 0.8 to 0.5 for matric heads of 0 to 2 m, respectively (University of Florida, 2004). Based on the functional dependence of specific yield on the capillary properties of soils presented by Duke (1972), specific yield would be expected to vary from nearly 0 (water-table depth of 0.1 m) to 0.28 (water-table depth of 2 m). Most specific-yield values fall within this range (table 3), although considerable variation in soil properties is common and might explain further spatial variability.

Ground-water flow rates simulated at each site range from -0.07 to -0.36 mm/d, representing 26 to 130 mm/yr of ground-water inflow. These values are higher than those simulated by regional ground-water flow models, which indicate an average

upward ground-water flow from the Upper Floridan aquifer in this area of 1.3 mm/yr (Sepulveda, 2002) to 13 mm/yr (Tibbals, 1990). An explanation for this discrepancy is not apparent; however, all values may be within the range of uncertainty of this poorly known quantity.

Disney Wilderness Preserve

At a field site in the Disney Wilderness Preserve in eastern Polk County, micrometeorological instruments were used to measure ET (site 5, fig. 1) (D.M. Sumner, U.S. Geological Survey, written commun., 2004). The site is an unimproved, ungrazed pasture of bahia grass interspersed with patches of other herbaceous vegetation and saw palmetto. The site has permeable sandy soils of the Archbold and Imokalee series (Ford and others, 1990), which are poorly drained as a result of a shallow water table (generally less than 1 m deep), and an indeterminate amount of surface runoff. Data were available for about 3 years (August 2000–August 2003).

The water-balance model for the Disney Wilderness Preserve site consisted of four parameters: S_{y1} , H_R , C , and H_B (table 3). The model was calibrated by adjusting three parameters, S_{y1} , C , and H_B , resulting in a good fit to the measured water level (fig. 11, table 4). H_R (the level at which runoff commences) was assumed equal to mean land surface and assigned a value of zero accordingly. The value of 0.23 for S_{y1} is close to estimates derived from laboratory analyses. Based on laboratory measurements of moisture-characteristic curves for 10 soil cores collected at this site during the current study (J.A. Tindall, U.S. Geological Survey, written commun., 2004), specific yield ranged from 0.19 to 0.26 with an average of 0.24. Ground-water flow was simulated by a head-dependent flux boundary (parameters C and H_B), which indicated a net outflow of 274 mm/yr. An outflow of ground water is expected based on the downward head gradient within the surficial aquifer system measured at this site. Parameters S_{y2} and H_L were not used because the water table rarely rose above land surface even though the water table often was near land surface.

Lyonia Preserve

Knowles and others (2005) operated micrometeorological instruments to measure ET at a field site in the Lyonia Preserve in southwest Volusia County (site 3, fig. 1). The upland areas where the ET station was located are a habitat of typical Florida scrub vegetation and scrub-dependent animals, and consist of a mix of herbaceous vegetation forested mainly with pine and oak (Knowles and others, 2005, p. 8). The site has well-drained sandy soils of the Orsino and Paola series (Baldwin and others, 1980), a deep water table (3 to 6 m deep near the ET station), and negligible surface runoff. Data were available for approximately 1½ years (January 2002–May 2003).

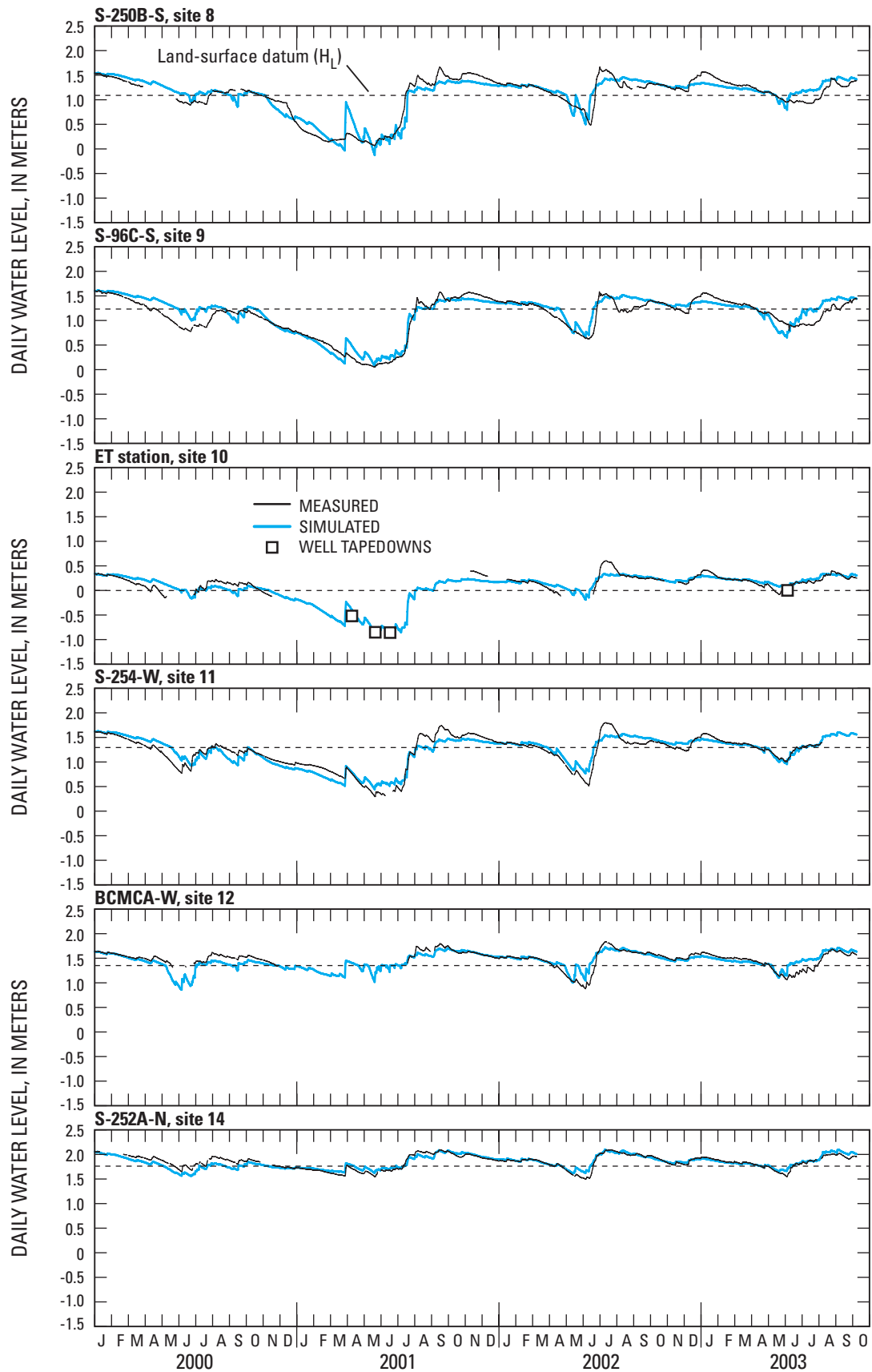


Figure 10. Measured and simulated daily water level in Blue Cypress Marsh Conservation Area at six sites.

The water-balance model for the Lyonia Preserve site was calibrated by adjusting four parameters, S_{y1} , C , H_B , and G_{con} (table 3), resulting in a reasonably good fit to the measured water level (fig. 12, table 4). Site characteristics are such that the water table is not expected to rise above land surface and surface runoff is negligible, so parameters S_{y2} , H_L , and H_R were not used. The value of 0.37 for S_{y1} agrees well with estimates derived from laboratory analyses of similar soils. Based on moisture-characteristic curves for five Orsino fine sand soil cores collected at a site in Flagler County (University of

Florida, 2004), specific yield ranges from 0.33 to 0.40 with an average of 0.37. If ground-water flow is conceptualized at the Lyonia Preserve such that the head-dependent flux boundary represents leakage through the intermediate confining unit and the constant-flux boundary represents horizontal ground-water flow in the surficial aquifer system, then parameters C and H_B represent the leakance of the intermediate confining unit and the depth of the Upper Floridan aquifer potentiometric surface below land surface, respectively. The value of 2.8×10^{-4} per day (d^{-1}) for C agrees well with intermediate confining unit

Figure 11. Measured and simulated daily water-table depth at the Disney Wilderness Preserve evapotranspiration station, site 5.

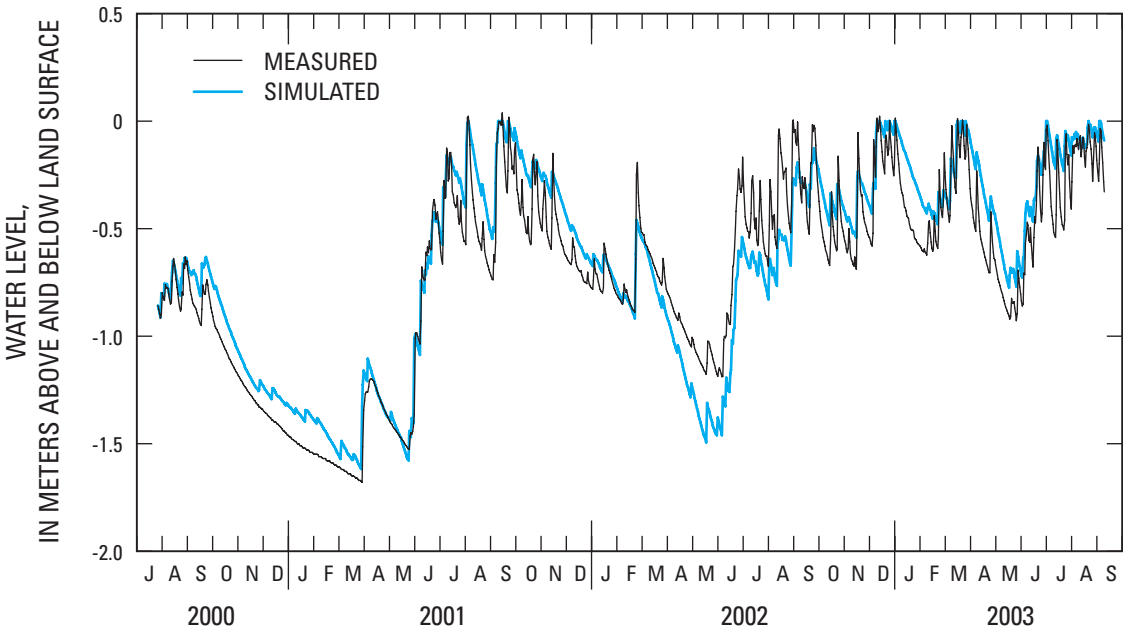
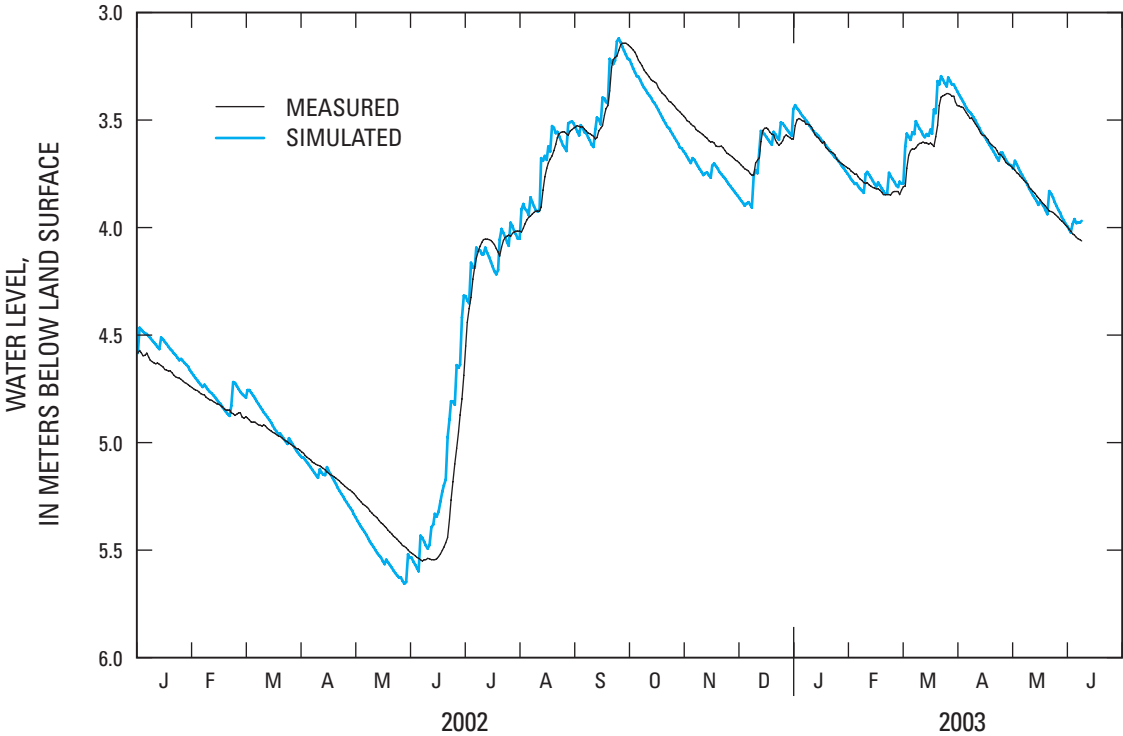


Figure 12. Measured and simulated daily water-table depth at the Lyonia Preserve evapotranspiration station, site 3.



leakances simulated by regional ground-water flow models: $2 \times 10^{-4} \text{ d}^{-1}$ (Sepulveda, 2002, p. 76), $3 \times 10^{-4} \text{ d}^{-1}$ (S.A. Williams, St. Johns River Water Management District, written commun., 2003), and $1 \times 10^{-3} \text{ d}^{-1}$ (Knowles and others, 2002, p. 76). Likewise, the depth to the Upper Floridan aquifer potentiometric surface (H_B) of 6.3 m estimated by the water-balance model is within the range of measured values of 4.6 to 6.5 m.

Effects of Evapotranspiration Approximations on Hydrologic Simulation

The adequacy of each ET approximation is evaluated by examining the sensitivities of water levels and flows simulated by the hydrologic models. The time series of approximated ET computed using the Hargreaves and Priestley-Taylor equations were input into each calibrated hydrologic model. All other model characteristics and parameter values were left unchanged to ascertain the simulated response of the hydrologic system to variability in ET.

Comparisons are made between the water levels simulated using the two ET approximations and (1) measured water levels, and (2) water levels simulated using measured ET, which serve as the “baseline” data set. For comparison with the baseline data, the baseline-adjusted modified coefficient of efficiency was computed:

$$E_1' = 1 - \frac{\sum_{i=1}^n |x_i - \hat{x}_i|}{\sum_{i=1}^n |x_i - y_i|}, \quad (12)$$

where

- E_1' is baseline-adjusted modified coefficient of efficiency, [dimensionless];
- x_i is measured value of the quantity of interest at time step i ;
- $\hat{x}_i$ is predicted value of the quantity of interest at time step i ;
- y_i is value of the baseline time series at time step i ; and
- n is number of values in time series.

Similar to the modified coefficient of efficiency (E_1) used to ascertain model fit (tables 4 and 6), E_1' was proposed by Legates and McCabe (1999) as being a more robust statistic (less influenced by outliers than correlation-based measures, such as r^2) for evaluation of the goodness-of-fit of hydrologic models. Values of E_1' closer to 0.0 indicate that the time series in question is closer to the baseline time series of interest.

A negative value of E_1' indicates that the baseline time series is a better predictor of the measured data than the predicted time series, whereas a positive value of E_1' indicates that the predicted time series is a better predictor of the measured data than the baseline time series. As applied here, if E_1' is close to 0.0, the water level simulated using an ET approximation is similar to that simulated using the actual ET values, because the water level simulated using actual ET serves as the baseline data. A value of E_1' near 0.0 indicates that the ET approximation serves as a good surrogate for actual ET, from the perspective of simulated water level.

Additionally, comparisons are made between the hydrologic simulations, using approximated and actual ET for the following simulated flows: surface runoff, ground-water recharge, and ground-water flow. Ground-water recharge is an internal flow not explicitly simulated by the water-balance model and is equal to precipitation minus the sum of ET and runoff. Because measurements of the flows are not available, comparisons are only made between flows simulated using the two ET approximations and flows simulated using actual ET. In this case, E_1 is used, with a value near 1.0 indicating that the ET approximation serves as a good surrogate for actual ET, from the perspective of the simulated flow. In order to facilitate comparison among sites, the RMSE as a percentage of the mean (RM%) was also computed. RM% is the RMSE standardized using the mean value of the respective flow, in much the same way different sample standard deviations are standardized by the commonly used coefficient of variation.

Lake Wales Ridge

Both the water-balance and VS2DT models developed for the Lake Wales site were used with each time series of approximated ET. Both models produced similar water-level results when compared to their baseline simulation (E_1' values near 0.0, tables 4 and 6), even though differences between actual ET and Hargreaves and Priestley-Taylor ET approximations are fairly large (RM% is 19 and 9 percent, respectively, table 7). Simulated water levels were nearly identical for the VS2DT model (fig. 13). Simulated water levels were also nearly identical for the water-balance model and are not shown.

Ground-water recharge was slightly affected by error in the ET approximations: RMSE and E_1 were 0.35 mm and 0.95, respectively, for the Hargreaves ET; and 0.17 mm and 0.98, respectively, for the Priestley-Taylor ET (table 7). Because there is no surface runoff at this site, recharge is simply equal to the available water (precipitation minus ET) for the water-balance model. Consequently, any error introduced by an ET approximation is directly transmitted to the recharge flow. (Note that the MAE and RMSE are identical between the ET and recharge flows, table 7.) Also, because ground-water flow is simulated as constant (G_{con} , table 3), the small differences between the ET approximations are directly transmitted to a change in water level, after being magnified by specific yield. For example, when converting a flow rate to

Table 7. Comparison of flows simulated by the calibrated water-balance models using measured evapotranspiration and two evapotranspiration approximations.

[SD, standard deviation; ME, mean error; MAE, mean absolute error; RMSE, root-mean-square error; RM%, root-mean-square error as a percentage of the mean; E_1 , modified coefficient of efficiency; --, not applicable; all values, except RM%, are in millimeters per day]

Station name and statistics	ET statistic values			Runoff statistic values			Recharge statistic values			Ground-water flow statistic values		
	Measured	Hargreaves	Priestley-Taylor	Measured	Hargreaves	Priestley-Taylor	Measured	Hargreaves	Priestley-Taylor	Measured	Hargreaves	Priestley-Taylor
Lake Wales Ridge Station, site 4												
Mean	1.82	1.82	1.82	--	--	--	1.69	1.69	1.69	--	--	--
SD	1.05	.97	1.06	--	--	--	10.20	10.16	10.26	--	--	--
ME	--	.00	.00	--	--	--	--	.00	.00	--	--	--
MAE	--	.26	.12	--	--	--	--	.26	.12	--	--	--
RMSE	--	.35	.17	--	--	--	--	.35	.17	--	--	--
RM%	--	19	9	--	--	--	--	20	10	--	--	--
E_1	--	.71	.86	--	--	--	--	.95	.98	--	--	--
Tiger Bay Station, site 2												
Mean	2.72	2.72	2.72	.86	.83	.83	-.35	-.32	-.33	--	--	--
SD	1.11	.86	1.15	5.46	5.41	5.47	7.93	7.83	8.09	--	--	--
ME	--	.00	.00	--	.03	.02	--	-.03	-.02	--	--	--
MAE	--	.58	.31	--	.23	.14	--	.76	.43	--	--	--
RMSE	--	.76	.43	--	1.87	1.06	--	2.00	1.15	--	--	--
RM%	--	28	16	--	226	127	--	-629	-352	--	--	--
E_1	--	.34	.65	--	.86	.91	--	.81	.89	--	--	--
Blue Cypress Marsh Station, sites 8, 9, 10, 11, 12, and 14												
Mean	3.55	3.55	3.55	.23	.23	.23	-.20	-.20	-.20	-.11	-.08	-.09
SD	1.49	1.24	1.49	2.42	2.14	2.41	9.50	9.23	9.51	.75	.76	.76
ME	--	.00	.00	--	.00	.00	--	.00	.00	--	--	-.02
MAE	--	.63	.21	--	.11	.06	--	.64	.21	--	.08	.06
RMSE	--	.79	.30	--	1.28	.96	--	.94	.49	--	.12	.09
RM%	--	22	8	--	558	414	--	-476	-247	--	-147	-95
E_1	--	.50	.84	--	.76	.87	--	.88	.96	--	.85	.90
Disney Wilderness Preserve Station, site 5												
Mean	2.63	2.63	2.63	.34	.38	.37	.90	.86	.87	.75	.71	.72
SD	1.16	.97	1.17	3.63	3.43	3.50	9.83	9.60	9.74	.29	.37	.36
ME	--	.00	.00	--	-.04	-.03	--	.04	.03	--	.04	.03
MAE	--	.54	.36	--	.24	.18	--	.76	.53	--	.12	.10
RMSE	--	.65	.45	--	2.34	1.84	--	2.41	1.90	--	.16	.13
RM%	--	25	17	--	611	491	--	279	217	--	22	18
E_1	--	.46	.64	--	.65	.73	--	.86	.90	--	.51	.59
Lyonia Preserve Station, site 3												
Mean	2.83	2.84	2.84	--	--	--	2.71	2.70	2.70	.60	.59	.59
SD	1.27	1.05	1.29	--	--	--	14.16	13.94	14.21	.20	.19	.20
ME	--	-.01	-.01	--	--	--	--	.01	.01	--	.01	.01
MAE	--	.52	.26	--	--	--	--	.52	.26	--	.01	.01
RMSE	--	.67	.35	--	--	--	--	.67	.35	--	.01	.01
RM%	--	23	12	--	--	--	--	25	13	--	2	1
E_1	--	.48	.74	--	--	--	--	.94	.97	--	.94	.96

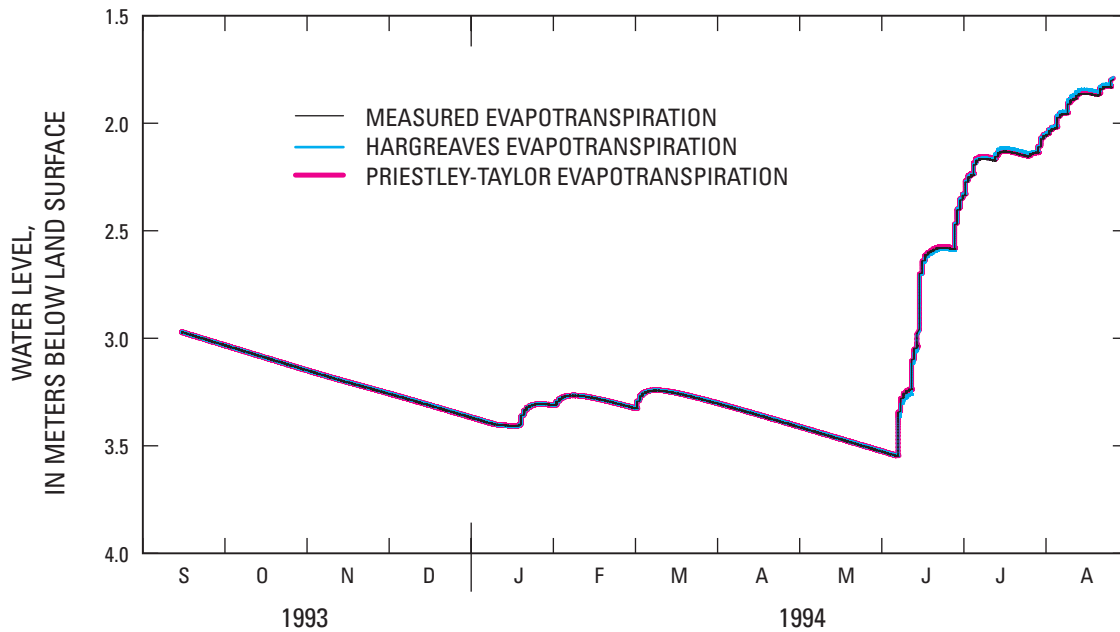


Figure 13. Water-table depth simulated by the calibrated VS2DT model using measured and approximated evapotranspiration at the Lake Wales Ridge, site 4.

a water-level change, a specific yield of 0.25 yields a four-fold magnification. Converting the RMSE values for approximated ET to equivalent water-level changes yields 1.4 mm for Hargreaves ET (RMSE of 0.35 divided by S_{y1} of 0.25, tables 7 and 3, respectively) and 0.68 mm for Priestley-Taylor ET (RMSE of 0.17 divided by S_{y1} of 0.25, tables 7 and 3, respectively). These errors are small and are less than the accuracy of the water-level measurements; however, small errors can accumulate over time. Error accumulation did not occur, because the vegetation coefficients (fig. 5) were computed such that total ET was equal over the period of record among the measured, Hargreaves, and Priestley-Taylor values. (Note that the mean values of ET are equal, table 7.)

E_1 values for recharge were considerably greater than the corresponding values for each ET approximation even though RMSE values are the same (table 7). Because E_1 (as well as E_1') is a relative measure of model fit, the variability inherent in the quantity of interest directly affects the value of the statistic. This is apparent from examination of equation 11 by noting that E_1 is the ratio of MAE and mean absolute deviation (MAD) subtracted from 1. For the Lake Wales Ridge site, MAE values are identical but MAD values are substantially greater for recharge than ET, as can be inferred from the large differences in standard deviation. Therefore, the values of E_1 near 1.0 indicate that the error in recharge is small relative to the variability in recharge, yet the same error is larger relative to the variability in ET (E_1 values of 0.71 and 0.86 for the Hargreaves and Priestley-Taylor ET, respectively, table 7).

Tiger Bay

The water-table depth simulated using each ET approximation method was compared to that of the baseline simulation at the Tiger Bay site (fig. 14). During January–June 1998 the water levels simulated using the ET approximations closely match the baseline simulation. However, there is substantial disagreement among the water levels simulated using the two ET approximations and the baseline simulation during the period July 1998–July 1999. This probably is due to fires that radically changed the natural vegetation. Brush fires burned 40 percent of the Tiger Bay watershed in June 1998, moving through the area of the ET station on June 25, 1998; damaged trees were logged during November–December 1998 (Sumner, 2001, p. 4). Actual ET was lower than average during the later half of 1998 through early spring 1999, after which time actual ET was higher than average because the vegetation had re-grown considerably. The computed vegetation coefficients follow this pattern, with the largest differences occurring from June–December 1998 (fig. 4b). Consequently, application of the average vegetation coefficient (fig. 4b) results in the overprediction of ET during June–December, thus causing the underprediction of water level.

Periods of overprediction (or underprediction) can affect future water levels as a result of serial correlation. Serial correlation causes present-day water levels to “remember” and, consequently, to be influenced by previous water levels.

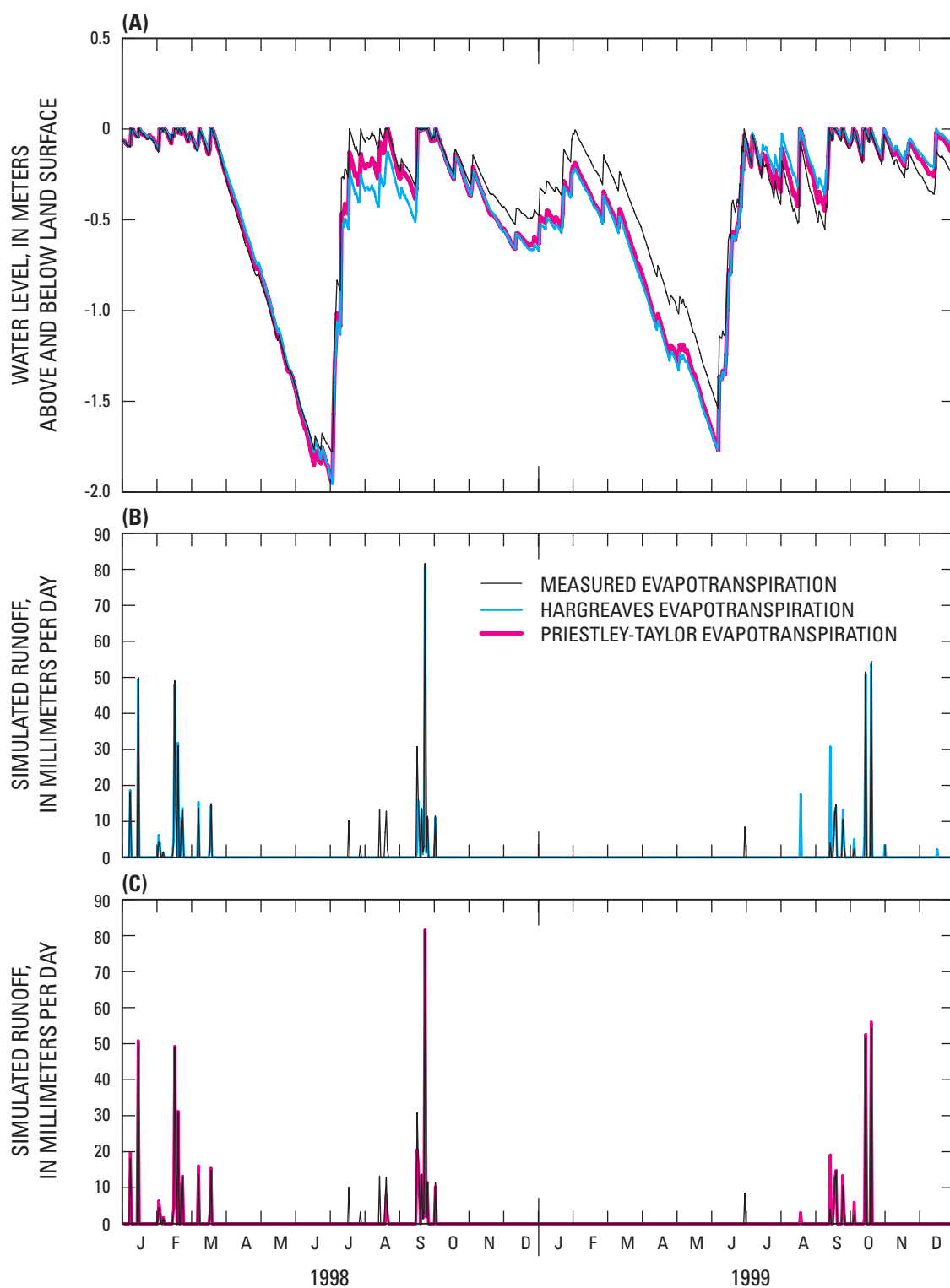


Figure 14. Simulated data using measured and approximated evapotranspiration at the Tiger Bay, site 2: (A) daily water-table depth, and (B and C) daily runoff at evapotranspiration station.

That is, the simulated water level is the sum of net daily flow, which is converted to a water level by S_{y1} , and the previous day's water level, resulting in a dependence of water level on previous values (eq. 3). Therefore, the overprediction of water level that results from underestimating ET for some time period generally will be offset by the underprediction of water level that results from overestimating ET during some other time period. This memory is "reset" when the water table rises above H_R (equal to land surface at this site, table 3), because the runoff component of the water-balance model (eq. 6) forces the water table to be equal to H_R regardless of previous values. As a result of the memory imparted by serial correlation, the simulated water level remained low from April–July 1999 even though the average vegetation coefficients had dropped below the actual 1999 values, resulting in the underprediction of ET after April 1999 (fig. 4b). Vegetation growth was vigorous and water was amply available during the summer rainy season, leading to above-average ET values (vegetation coefficients greater than average, fig. 4b), and water levels simulated using the ET approximations were greater than the baseline simulation using actual ET (fig. 14).

Simulated flows at the Tiger Bay site—surface runoff and ground-water recharge—were also affected by error in the ET approximations. Even though the RMSE values for runoff and recharge are more than double those for the respective ET approximations, the E_1 values are much closer to 1.0, indicating that the errors imparted by the ET approximations are relatively small compared to the variability of runoff and recharge (table 7). However, some differences exist in the timing and magnitude of runoff events. The water table simulated using Hargreaves and Priestley-Taylor approximations was consistently underpredicted during July–August 1998 and did not rise above land surface, thus no runoff was simulated during this period (fig. 14b).

Blue Cypress Marsh

Each of the water-balance models developed for the six sites in the Blue Cypress Marsh Conservation Area was used with each time series of approximated ET. For calculation of the statistics in tables 4 and 7, results from all models were combined and a single value for each statistic was computed for the pooled data. RMSE values between simulated and measured water levels are the same for the three simulations, and values of E_1 near 0.0 indicate little difference compared to the baseline simulation (table 4). Individually, each model predicted similar water levels when compared to its respective baseline simulation (fig. 15), even though differences between actual ET and Hargreaves and Priestley-Taylor ET approximations are fairly large (RM% is 22 and 8 percent, respectively, table 7).

Simulated flows at the Blue Cypress Marsh sites—surface runoff, ground-water recharge, and ground-water flow—were affected by error in the ET approximations. RMSE values for runoff and recharge were greater than those

for the respective ET approximations, but the E_1 values are closer to 1.0, indicating that the errors imparted by the ET approximations are small compared to the variability of runoff and recharge (table 7). For ground-water flow, RMSE values were less than those for the respective ET approximations, although this might be expected because the standard deviation of ground-water flow is smaller (table 7). E_1 values for ground-water flow are closer to 1.0, indicating that the errors imparted by the ET approximations are relatively small even when compared to the lesser variability of ground-water flow (table 7).

The relatively low sensitivity of water levels and flows at the Blue Cypress Marsh sites to temporal variations in ET is partly due to the generally ample availability of water, so that actual ET often is near potential ET rates. As discussed previously, the vegetation coefficient will equal 1.0 under potential conditions where water is freely available, as is often the case at Blue Cypress Marsh (fig. 5). In general, as a site becomes increasingly moisture deficient the vegetation coefficient will drop further below a value of 1.0 and vary over a greater range during the year (for example, Lake Wales Ridge site, fig. 5). Also, because the water level in the marsh generally is above land surface, the magnifying effects of specific yield on water-table fluctuations is minimized. That is, when the water table is above land surface, a specific yield of 1.0 is used (S_{y2} , table 3), resulting in a one-to-one correspondence between flows and rates of water-level change.

Disney Wilderness Preserve

The water-table depth simulated using each ET approximation method was compared to that of the baseline simulation at the Disney Wilderness Preserve site (fig. 16). During September 2001–September 2003 the water levels simulated using ET approximations closely match the baseline simulation. However, there is substantial disagreement among the water levels simulated using the two ET approximations and the baseline simulation during October 2000–August 2001, resulting in E_1 values substantially less than 1.0 and E_1' values substantially less than 0.0 (table 4). This probably is due to the drought conditions that prevailed during much of this time period (note the large water-level decline, fig. 16). The vegetation coefficients from September 2000–May 2001 are as little as half those during corresponding months in 2002 and 2003 (fig. 4d). Consequently, application of the average vegetation coefficient (fig. 4d) results in the overprediction of ET during September 2000–May 2001, thus causing the underprediction of water level during October 2000–August 2001 (fig. 16).

Simulated flows at the Disney Preserve site—surface runoff, ground-water recharge, and ground-water flow—were affected by error in the ET approximations. RMSE values for runoff and recharge were greater than those for the respective ET approximations, but the E_1 values are closer to 1.0, indicating that the errors imparted by the ET approximations

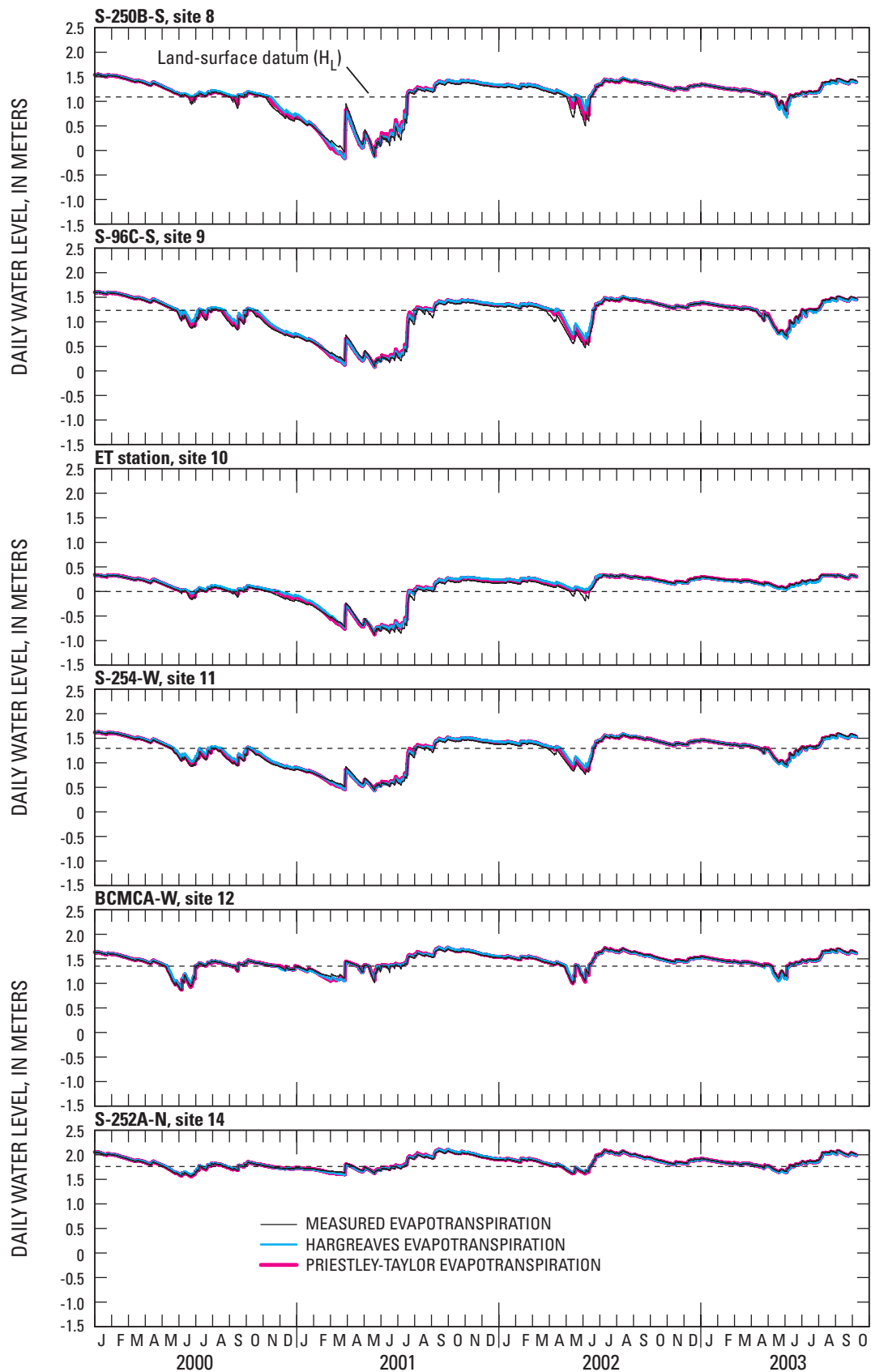


Figure 15. Simulated daily water level in Blue Cypress Marsh Conservation Area using measured and approximated evapotranspiration at six sites.

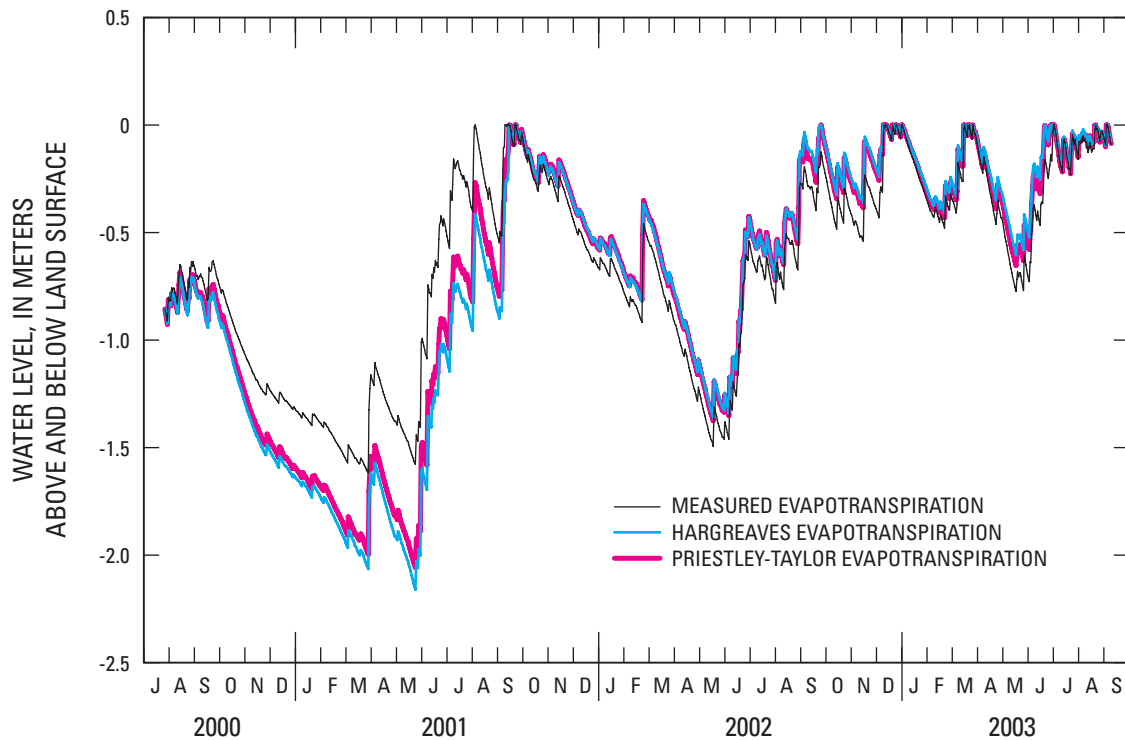


Figure 16. Simulated daily water-table depth using measured and approximated evapotranspiration at the Disney Wilderness Preserve, site 5.

are small compared to the variability of runoff and recharge (table 7). For ground-water flow, RMSE values were less than those for the respective ET approximations, although this might be expected because the standard deviation of ground-water flow is smaller (table 7). E_1 values for ground-water flow (0.51 for Hargreaves ET and 0.59 for Priestley-Taylor ET, table 7) were relatively low compared to other simulated flows at this site as well as other sites, indicating that errors imparted by the ET approximations are significant even when compared to the lesser variability of ground-water flow.

Compared to the other four sites, the hydrologic system at the Disney Wilderness Preserve site is the most sensitive to temporal variations in ET, both in terms of water levels and flows. The primary factors contributing to this sensitivity probably are the combination of shallow rooted vegetation, well-drained soils, and a prolonged drought from October 2000 through May 2001. These factors increase the variability of ET.

Lyonia Preserve

The water-table depth simulated using each ET approximation method was compared to the baseline simulation at the Lyonia Preserve site (fig. 17). Each simulation using a different ET time series produced similar water-level results when compared to their respective baseline (E_1' values

near 0.0, table 4), even though differences between actual ET and Hargreaves and Priestley-Taylor ET approximations are fairly large (RM% is 23 and 12 percent, respectively, table 7). The water levels simulated using Hargreaves and Priestley-Taylor ET approximations were nearly identical (fig. 17).

Simulated flows at the Lyonia Preserve site—ground-water recharge and ground-water flow—were affected by error in the ET approximations. RMSE values for recharge were equal to those for the respective ET approximations because there is no surface runoff at this site, thus recharge is simply equal to available water (precipitation minus ET). E_1 values for recharge are close to 1.0, indicating that the errors imparted by the ET approximations are relatively small compared to the variability of recharge (table 7). For ground-water flow, RMSE values were much less than those for the respective ET approximations. This might be expected because ground-water flow was simulated with a combined specified-flux and head-dependent flux boundary condition (eq. 8). The specified flux of 1.68 mm/d (G_{con} , table 3) is more than double the average head-dependent flux of 0.60 mm/d. Of course, G_{con} remains unchanged among different simulations, thus the standard deviation of ground-water flow is smaller (table 7). E_1 values for ground-water flow are close to 1.0, indicating that the errors imparted by the ET approximations are relatively small even when compared to the lesser variability of ground-water flow (table 7).

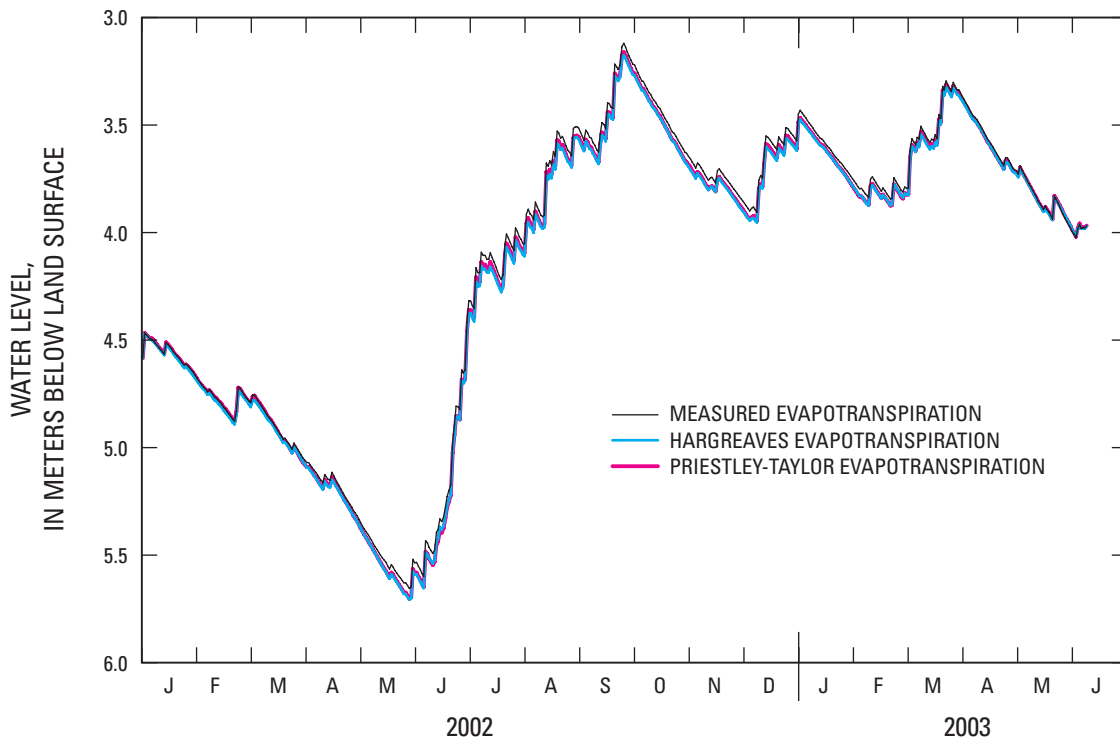


Figure 17. Simulated daily water-table depth using measured and approximated evapotranspiration at the Lyonia Preserve, site 3.

The insensitivity of water levels and flows at the Lyonia Preserve site to temporal variations in ET probably is due in large part to the unusual precipitation pattern during the period of data collection. A large amount of precipitation occurred during 2002, totaling 2,300 mm (91 in.)—63 percent greater than the long-term average (Knowles and others, 2005, p. 32). Precipitation at Lyonia Preserve was more variable than at the other four sites (figs. 6 and 7). Vegetation at this site included pine and oak trees, probably having deep roots tapping soil moisture in the lower unsaturated zone or the saturated zone, which would tend to mediate fluctuations in ET. However, during periods of average to below-average precipitation, the Lyonia Preserve site might exhibit greater sensitivity to temporal variations in ET because the well-drained sandy soils would tend to subject the vegetation to moisture stress more frequently, thereby causing a greater range of fluctuations in ET.

Factors Influencing the Adequacy of Evapotranspiration Approximations

Two primary factors that influence how the temporal variability of ET affects hydrologic simulation in central Florida are: (1) stochastic character of precipitation and ET and (2) the ability of the local hydrologic system to attenuate variability of input stresses. Statistical analyses of time series of measured

precipitation and ET show: (1) precipitation is much more variable than ET over a wide range of time scales and in a variety of hydrologic settings in central Florida (figs. 6 and 7); and (2) differences in the median and mean values of precipitation and ET at individual sites vary considerably among sites (fig. 7). These differences in the stochastic character of precipitation and ET, both the central location and spread of the data, result in substantial influence of precipitation, and a relatively small influence of ET, on the quantity and timing of water available to the hydrologic system (table 2). For hydrologic simulation, when precipitation and ET are of similar magnitude, small errors in ET can produce relatively large errors in available water, and accurate estimates of actual ET are more important. In contrast, when precipitation is larger and more variable than ET, small errors in ET have little effect on available water, and less accurate estimates of ET can be used. Similar results were reported by Sumner (2006a) for a site in a bahia grass pasture with a shallow water table (generally less than 1 m deep) in central Brevard County.

The hydrologic models presented and discussed herein are simple representations of site-specific conditions. As such, the models do not incorporate the more complex hydrologic processes that attenuate the variability of meteorological inputs. In general, different locations in a hydrologic system respond differently to temporal variations in ET. Soil-moisture contents in the root zone are sensitive to daily variations in ET, whereas spring flow responds to only longer term variations in ET.

A hydrologic system can be conceptualized as a series of filters. “Signals” (such as precipitation or ET) at land surface are attenuated, and increasingly lower frequency variations propagate deeper into the ground-water flow system. Higher frequency variations are attenuated by the water transmission and storage characteristics of the hydrologic system, as demonstrated by comparison of water-balance and VS2DT model results at the Lake Wales Ridge site (fig. 8). Negative feedback from other flow components also attenuate variations. For example, consider a case where ground-water flow from the surficial aquifer system discharges laterally and vertically as controlled by a constant boundary head, such as simulated at the Disney Wilderness Preserve site. The overprediction of ET during the drought period (October 2000–May 2001) results in an underprediction of water level (fig. 16). However, this water-level discrepancy is offset to some degree by decreased ground-water flow because of the smaller head difference between the simulated and boundary heads.

The data and hydrologic model simulations presented demonstrate that both the Hargreaves and Priestley-Taylor equations for potential ET, when applied with an annually invariant monthly vegetation coefficient derived from comparison of measured ET with computed potential ET values, can be used with a hydrologic model to produce reasonable predictions of water levels and flows. Baseline-adjusted modified coefficients of efficiency for simulated water levels ranged from 0.0, indicating that water levels were simulated equally as well with approximated ET as with actual ET values (Lake Wales Ridge and Blue Cypress Marsh sites; tables 4 and 6), to -0.6, indicating that water levels were simulated better with actual ET values (Tiger Bay, Disney Wilderness Preserve, and Lyonia Preserve; table 4). Model bias is small for water levels and flows for all models (note mean errors, tables 4, 6, and 7). Consequently, if the errors in ET approximations are roughly random with a mean error of zero, then errors in simulated water levels and flows will tend to average out. This demonstrates the importance of using an ET model that produces a mean value equal to the best available estimate of the actual mean ET.

Simulations using the Hargreaves approximation consistently yield larger absolute and relative errors; that is, larger MAE and RMSE values; E_1 values further from 1.0; and E_1' values further from 0.0 (tables 4, 6, and 7). These discrepancies notwithstanding, the differences between the Hargreaves and Priestley-Taylor simulations generally were much smaller than differences between these simulations and the simulations using actual ET (figs. 13–17). This suggests that the simpler Hargreaves equation, which requires only commonly available measurements of air temperature, may be an adequate substitute for the more complex Priestley-Taylor equation. Of course, it is incumbent upon the model user to ascertain the level of adequacy required to satisfy the particular objectives of the modeling effort in the most efficient manner. In any modeling effort, a balance must be maintained between model simplicity and model accuracy.

Summary

The difference of precipitation and evapotranspiration (ET) provides the “available water” to a hydrologic system for stream flow and aquifer recharge. The relative timing and magnitude of the temporal variations in precipitation and ET determine the temporal variability of available water, therefore determining the degree of influence each has on the transient response of the hydrologic system. The transient response of the hydrologic system can be of great concern to water-resource managers, and models are frequently used to quantify and predict the effects of natural processes or management activities on a hydrologic system. Because considerable effort is directed toward quantifying stresses acting on a hydrologic system, it is prudent to investigate the relative importance of these stresses on the hydrologic response of interest (typically water levels and flows) to ascertain the appropriate effort to expend in obtaining estimates of each stress.

Meteorological, ET, and hydrologic data collected from 1993 to 2003 and spanning 1- to 3²/₃-year periods were presented for five sites in central Florida. Site specific hydrologic models were developed and calibrated to measured water levels at each site. The sensitivities of water levels and flows simulated by these hydrologic models to simple approximations of ET were quantified and the adequacy of each ET approximation was assessed.

ET was approximated by computing potential ET and multiplying by vegetation coefficients to adjust the potential ET values to actual ET. Two simple models were used for computation of potential ET: (1) Hargreaves and Samani (1985) temperature-based model; and (2) Priestley and Taylor (1972) radiation-based model. Measured and potential ET were plotted and a positive correlation was noted for each site. Coefficients of determination indicate that Priestley-Taylor potential ET explains much of the variability in measured ET—ranging from 71 to 96 percent. Hargreaves potential ET is not as good an explanatory variable for measured ET, although Hargreaves equation does explain 45 to 73 percent of the variability in measured ET and requires only commonly available measurements of air temperature.

A strong temporal variation in ET is due primarily to meteorological variables (such as precipitation, solar radiation, windspeed, and humidity) and the plant/hydrologic system response to these variables. The temporal variability of ET in central Florida, however, is considerably less than that of precipitation over a wide range of timescales (from daily to annual). A comparison of the standard deviations of precipitation and ET at time scales of 1 to 91 days indicates that this disparity in variability between precipitation and ET exists at the five sites. Precipitation data generally follow an extreme-event distribution and ET is more smoothly varying, as a result of differing hydroclimatic processes and interactions. A further examination of the correlation between available water and its

two components, precipitation and ET, indicates that precipitation strongly influences available water. Precipitation explains 98-99 percent of the variability in available water, whereas ET explains only 1-12 percent.

Hydrologic models were developed for each ET site using a simple water-balance approach. Additionally, at one site having a relatively deep water table, a one-dimensional variably saturated flow model was developed using the USGS model code VS2DT (Lappala and others, 1987; Healy, 1990). All models were calibrated to ground-water or surface-water levels measured at each site. Simulated water levels generally matched measured water levels closely, with root-mean-square errors of 0.06 to 0.35 meters and coefficients of efficiency of 0.69 to 0.91.

The adequacy of each ET approximation was evaluated by examining the sensitivities of water levels and flows simulated by the hydrologic models. The time series of approximated ET computed using the Hargreaves and Priestley-Taylor equations were input into each calibrated hydrologic model. All other model characteristics and parameter values were left unchanged to ascertain the simulated response of the hydrologic system to variability in ET only. Two primary factors that influence how the temporal variability of ET affects hydrologic simulation in central Florida were identified: (1) stochastic character of precipitation and ET and (2) the ability of the local hydrologic system to attenuate variability in input stresses. Differences in the stochastic character of precipitation and ET—both the central location and spread of the data—result in substantial influence of precipitation on the quantity and timing of water available to the hydrologic system and a relatively small influence of ET. For hydrologic simulation, when precipitation and ET are of similar magnitude, small errors in ET can produce relatively large errors in available water, and accurate estimates of actual ET are more important. In contrast, when precipitation is larger and more variable than ET, small errors in ET have little effect on available water, and less accurate estimates of ET can be used. Local hydrologic conditions can also be an important factor influencing the hydrologic response to ET variability. Various points along a flow path in a hydrologic system respond differently to temporal variations in ET. For example, soil-moisture contents in the root zone are sensitive to daily variations in ET, whereas spring flow responds to only longer term variations in ET.

Both the Hargreaves and Priestley-Taylor equations for potential ET, when applied with an annually invariant monthly vegetation coefficient derived from comparison of measured ET with computed potential ET values, can be used with a hydrologic model to produce reasonable predictions of water levels and flows. Baseline-adjusted modified coefficients of efficiency for simulated water levels ranged from 0.0, indicating that water levels were simulated equally as well with approximated ET as with actual ET values, to -0.6, indicating that water levels were simulated better with actual ET values. Simulations using the Hargreaves approximation consistently yield larger absolute and relative errors than the Priestley-

Taylor approximation. However, the differences between the Hargreaves and Priestley-Taylor simulations generally were much smaller than differences between these simulations and the simulations using actual ET. This suggests that the simpler Hargreaves equation may be an adequate substitute for the more complex Priestley-Taylor equation. Of course, it is incumbent upon the model user to ascertain the level of adequacy required to satisfy the particular objectives of the modeling effort.

References

- Allen, R.G., Pereira, L.S., Raes, Dirk, and Smith, Martin, 1998, Crop evapotranspiration—Guidelines for computing crop water requirements: Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56.
- Amatya, D.M., Skaggs, R.W., and Gregory, J.D., 1995, Comparison of methods for estimating REF-ET: *Journal of Irrigation and Drainage Engineering*, v. 121, no. 6, p. 427-435.
- Andréassian, Vazken, Perrin, Charles, and Michel, Claude, 2004, Impact of imperfect potential evapotranspiration knowledge on the efficiency and parameters of watershed models: *Journal of Hydrology*, v. 286, p. 19-35.
- Baldwin, Robert, Bush, C.L., Hinton, R.B., Huckle, H.F., Nichols, Paul, Watts, F.C., and Wolfe, J.A., 1980, Soil survey of Volusia County, Florida: United States Department of Agriculture, Soil Conservation Service, 207 p.
- Brenner, Mark, and Schelske, C.L., 1995, Historical sedimentation and nutrient storage rates in the Blue Cypress Marsh Conservation Area: Palatka, Fla., St. Johns River Water Management District Special Publication SJ95-SP3, 177 p.
- Calder, I.R., Harding, R.J., and Rosier, P.T.W., 1983, An objective assessment of soil-moisture deficit models: *Journal of Hydrology*, v. 60, p. 329-355.
- Choi, Jungyill, Harvey, J.W., and Newlin, J.T., 2003, Significance of microtopography as a control on surface-water flow in wetlands, in *Proceedings of the Joint Conference on the Science and Restoration of the Greater Everglades and Florida Bay Ecosystem*, Palm Harbor, Florida, April 13-18, 2003, p. 251-253.
- Dausmann, Alyssa, and Langevin, C.D., 2005, Movement of the saltwater interface in the surficial aquifer system in response to hydrologic stresses and water-management practices, Broward County, Florida: U.S. Geological Survey Scientific Investigations Report 2004-5256, 73 p.
- Doolittle, J.A., and Schellentrager, Gregg, 1989, Soil survey of Orange County, Florida: U.S. Department of Agriculture, Soil Conservation Service, 175 p.

- Duke, H.R., 1972, Capillary properties of soils—Influence upon specific yield: *Transactions of the American Society of Agricultural Engineers*, v. 15, no. 4, p. 688-691.
- Fayer, M.J., and Hillel, D., 1986a, Air encapsulation: I. Measurement in a field soil: *Soil Science Society of America Journal*, v. 50, no. 3, p. 568-572.
- Fayer, M.J., and Hillel, D., 1986b, Air encapsulation: II. Profile water storage and shallow water table fluctuations: *Soil Science Society of America Journal*, v. 50, no. 3, p. 572-577.
- Ford, R.D., Robbins, J.M., Jr., Werner, J.T., Cowherd, Dean, Gordon, C.N., Warmack, W.B., Brown, M.M., Monroe, K.W., George, W.G., Sanders, Thomas, and Basch, Phyllis, 1990, Soil survey of Polk County: U.S. Department of Agriculture, Soil Conservation Service, 235 p.
- Fowler, Anthony, 2002, Assessment of the validity of using mean potential evaporation in computations of the long-term soil water balance: *Journal of Hydrology*, v. 256, p. 248-263.
- Hargreaves, G.H., and Allen, R.G., 2003, History and evaluation of Hargreaves evapotranspiration equation: *Journal of Irrigation and Drainage*, v. 129, no. 1, p. 53-63.
- Hargreaves, G.H., and Samani, Z.A., 1985, Reference crop evapotranspiration from temperature: *Applied Engineering in Agriculture*, v. 1, no. 2, p. 96-99.
- Healy, R.W., 1990, Simulation of solute transport in variably saturated porous media with supplemental information on modifications to the U.S. Geological Survey's computer program VS2D: U.S. Geological Survey Water-Resources Investigations Report 90-4025, 125 p.
- Jacobs, J.M., and Satti, S.R., 2001, Evaluation of reference evapotranspiration methodologies and AFSIRS crop water use simulation model: Palatka, Fla., St. Johns River Water Management District Special Publication SJ2001-SP8, 114 p.
- Knowles, Leel, Jr., O'Reilly, A.M., and Adamski, J.C., 2002, Hydrogeology and simulated effects of ground-water withdrawals from the Floridan aquifer system in Lake County and in the Ocala National Forest and vicinity, north-central Florida: U.S. Geological Survey Water-Resources Investigations Report 02-4207, 140 p.
- Knowles, Leel, Jr., Phelps, G.G., Kinnaman, S.L., and German, E.R., 2005, Hydrologic response in karstic-ridge wetlands to rainfall and evapotranspiration: U.S. Geological Survey Scientific Investigations Report 2005-5178, 82 p.
- Lappala, E.G., Healy, R.W., and Weeks, E.P., 1987, Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media: U.S. Geological Survey Water-Resources Investigations Report 83-4099, 184 p.
- Legates, D.R., and McCabe, G.J., Jr., 1999, Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation: *Water Resources Research*, v. 35, no. 1, p. 233-241.
- McGurk, Brian, and Presley, P.F., 2002, Simulation of the effects of ground-water withdrawals on the Floridan aquifer system in east-central Florida: Model expansion and revision: Palatka, Fla., St. Johns River Water Management District Technical Publication SJ2002-3, 196 p.
- Monteith, J.L., and Unsworth, M.H., 1990, Principles of environmental physics (2d ed.): London, Edward Arnold, 291 p.
- O'Reilly, A.M., 2004, A method for simulating transient ground-water recharge in deep water-table settings in central Florida by using a simple water-balance/transfer-function model: U.S. Geological Survey Scientific Investigations Report 2004-5195, 49 p.
- Oudin, Ludovic, Andréassian, Vazken, Perrin, Charles, and Anctil, Francois, 2004, Locating the sources of low-pass behavior within rainfall-runoff models: *Water Resources Research*, v. 40, no. 11, W11101.
- Oudin, Ludovic, Hervieu, Frédéric, Michel, Claude, Perrin, Charles, Andréassian, Vazken, Anctil, Francois, and Loumagne, Cécile, 2005a, Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling: *Journal of Hydrology*, v. 303, p. 290-306.
- Oudin, Ludovic, Michel, Claude, and Anctil, Francois, 2005b, Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 1—Can rainfall-runoff models effectively handle detailed potential evapotranspiration inputs?: *Journal of Hydrology*, v. 303, p. 275-289.
- Parmele, L.H., 1972, Errors in output of hydrologic models due to errors in input potential evapotranspiration: *Water Resources Research*, v. 8, no. 2, p. 348-359.
- Paturel, J.E., Servat, E., and Vassiliadis, A., 1995, Sensitivity of conceptual rainfall-runoff algorithms to errors in input data—case of the GR2M model: *Journal of Hydrology*, v. 168, p. 111-125.
- Penman, H.L., 1948, Natural evaporation from open water, bare soil, and grass: *Proceedings of the Royal Society of London, Series A*, v. 193, p. 120-146.
- Priestley, C.H.B., and Taylor, R.J., 1972, On the assessment of surface heat flux and evaporation using large-scale parameters: *Monthly Weather Review*, v. 100, p. 81-92.
- Rumenik, R.P., 1988, Runoff to streams in Florida: Tallahassee, Florida Geology Survey, Map Series 122, 1 sheet.

- Sepulveda, Nicasio, 2002, Simulation of ground-water flow in the intermediate and Floridan aquifer systems in peninsular Florida: U.S. Geological Survey Water-Resources Investigations Report 02-4009, 130 p.
- Sophocleous, Marios, 1985, The role of specific yield in ground-water recharge estimations: A numerical study: *Ground Water*, v. 23, no. 1. p. 52-58.
- Stull, R.B., 1988, An introduction to boundary layer meteorology: Dordrecht, Netherlands, Kluwer Academic Publishers, 666 p.
- Sumner, D.M., 1996, Evapotranspiration from successional vegetation in a deforested area of the Lake Wales Ridge, Florida: U.S. Geological Survey Water-Resources Investigations Report 96-4244, 37 p.
- Sumner, D.M., 2001, Evapotranspiration from a cypress and pine forest subjected to natural fires, Volusia County, Florida, 1998-99: U.S. Geological Survey Water-Resources Investigations Report 01-4245, 56 p.
- Sumner, D.M., 2006, Adequacy of selected evapotranspiration approximations for hydrologic simulation: *Journal of the American Water Resources Association*, v. 42, no. 3, p. 699-711.
- Sumner, D.M., 2007, Effects of capillarity and microtopography on wetland specific yield: *Wetlands*, v. 27, no. 3, p. 693-701.
- Sumner, D.M., and Belaine, G., 2005, Evaporation, precipitation, and associated salinity changes at a humid, subtropical estuary: *Estuaries*, v. 28, no. 6, p. 844-855.
- Sumner, D.M., and Jacobs, J.M., 2005, Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration: *Journal of Hydrology*, v. 308, p. 81-104.
- Swancar, Amy, 2006, Magnitude and variability of components of a central Florida lake water budget during recent climate extremes, 1996-2005 [abs.]: American Society of Civil Engineers 22nd Annual Water Resources Seminar, April 7, 2006, Orlando, Florida.
- Swancar, Amy, Lee, T.M., and O'Hare, T.M., 2000, Hydrogeologic setting, water budget, and preliminary analysis of ground-water exchange at Lake Starr, Polk County, Florida: U.S. Geological Survey Water-Resources Investigations Report 00-4030, 65 p.
- Tibbals, C.H., 1990, Hydrology of the Floridan aquifer system in east-central Florida: U.S. Geological Survey Professional Paper 1403-E, 98 p.
- University of Florida, 2004, St. Johns River Water Management District (SJRWMD) soil information [cited November 2004] <http://soilpedology.ifas.ufl.edu/>
- van Genuchten, M.T., 1980, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils: *Soil Science Society of America Journal*, v. 44, no. 5, p. 892-898.
- Vázquez, R.F., and Feyen, J., 2003, Effect of potential evapotranspiration estimates on effective parameters and performance of the MIKE SHE-code applied to a medium-size catchment: *Journal of Hydrology*, v. 270, p. 309-327.
- Wanielista, Martin, Kersten, Robert, and Eaglin, Ron, 1997, *Hydrology: Water quantity and quality control* (2d ed): New York, John Wiley, 567 p.
- Wettstein, C.A., Noble, C.V., and Slabaugh, J.D., 1987, Soil survey of Indian River County, Florida: United States Department of Agriculture, Soil Conservation Service, 217 p.
- White, W.A., 1970, The geomorphology of the Florida Peninsula: Tallahassee, Florida Geology Survey, Bulletin 51, 164 p.
- Wilson, D.J., Western, A.W., and Grayson, R.B., 2004, Identifying and quantifying sources of variability in temporal and spatial soil moisture observations: *Water Resources Research*, v. 40, no. 2, W02507.