REGIONAL EVALUATION OF EVAPOTRANSPIRATION IN THE EVERGLADES

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ABSTRACT

One of the most important components of the Everglades (south Florida) water budget is evapotranspiration (ET). In this area, most rainfall is likely returned to the atmosphere by ET. A study to quantify and model ET in the Everglades was begun in 1995. A network of nine ET-evaluation sites was established that represents the varied hydrologic conditions and vegetative characteristics of the Everglades. Data from continuous measurements of parameters for evaluation of ET at the sites for the period January 1996 through December 1997 were used to develop regional models that can be used to simulate ET at other times and places throughout the Everglades.

The Bowen-ratio energy budget method was selected for the ET evaluation. After careful screening to eliminate erroneous data, site and regional models of ET were calibrated for the nine sites. A modified Priestley-Taylor model of ET was calibrated for each site. In these models the Priestley-Taylor coefficient (α) was expressed as a function of incoming solar energy and water level. The individual site models were then combined into two regional models: one is applicable to vegetated wet-prairie and sawgrass-marsh sites in the natural Everglades system, and the other is applicable to freshwater sloughs and other open areas with little or no emergent vegetation.

Computed ET totals for all nine sites ranged from 42.78 inches per year at a sometimes-dry sparse-sawgrass site to 55.54 inches per year at an open-water site. Differences in annual ET relate to water availability and perhaps to density of vegetation.

The annual total ET values simulated by the regional models generally are in relatively close agreement with the computed values. The difference between computed and simulated ET generally was less than 3 inches per year. The median difference was about 1.4 inches per year.

1. INTRODUCTION

Knowledge of the water budget of the Everglades (south Florida) system is crucial to the success of restoration and management actions. Although the water budget is simple in concept, it is difficult to assess quantitatively. Models used to simulate changes in water levels and vegetation that might result from various management actions need to account for all components of the water budget accurately.

One of the most important components of the Everglades water budget is evapotranspiration (ET). ET is water removed from the land or water surface and soils by direct evaporation and plant transpiration. In south Florida, ET rates may exceed 40 in/yr (inches per year) on average; during dry years, the ET could exceed rainfall (average rainfall is about 50 in/yr). Thus, most rainfall is returned to the atmosphere locally by ET. Despite the importance of ET in the Everglades water budget, knowledge of ET rates is, at present, only semi-quantitative. Recent advances in instrumentation and measurement techniques have made it possible to compute ET continuously, so that an accurate evaluation of ET rates in the Everglades can be made.

In 1995, a study to quantify and model ET in the Everglades was begun as part of the South Florida Ecosystem Program (McPherson and others, 1995). The principal objective of the study was to develop an understanding of how ET functions in the Everglades, excluding agricultural and brackish environments. To achieve this, a network of nine ET-evaluation sites was established that represents the varied hydrologic conditions and vegetative characteristics of the Everglades. Data from continuous measurements of parameters to evaluate ET at the sites for a 2-year period (January 1996 through December 1997) supported the development of regional models that can be used to simulate ET at other times and places throughout the Everglades.

2. SITE CHARACTERISTICS AND LOCATIONS

The main consideration in selecting ET sites was to provide representative coverage of the Everglades system in terms of plant communities, duration of water inundation, and geographic features. Other considerations were security and logistics. Although it is impossible to represent all of the varied Everglades ecosystems and areas with just nine sites, the sites that were selected represent a wide range of conditions in the natural system. The ET sites are shown on the location map of figure 1 and the site characteristics are identified in table 1. Eight of these sites were operational throughout 1996 and 1997. A ninth site (site 9 in fig. 1) was added in January 1997 to increase coverage of relatively dry areas.

3. STUDY METHOD

The Bowen-ratio energy budget method (Bowen, 1926) was selected for use in the Everglades. The method has been used at other locations in Florida (Bidlake and others, 1993).

The components of the energy budget and other data necessary for application of the Bowen-ratio method were measured at 15-minute intervals. Net radiation (R_n), the difference between incoming shortwave (solar) radiation and outgoing shortwave and longwave radiation, was measured by using a net

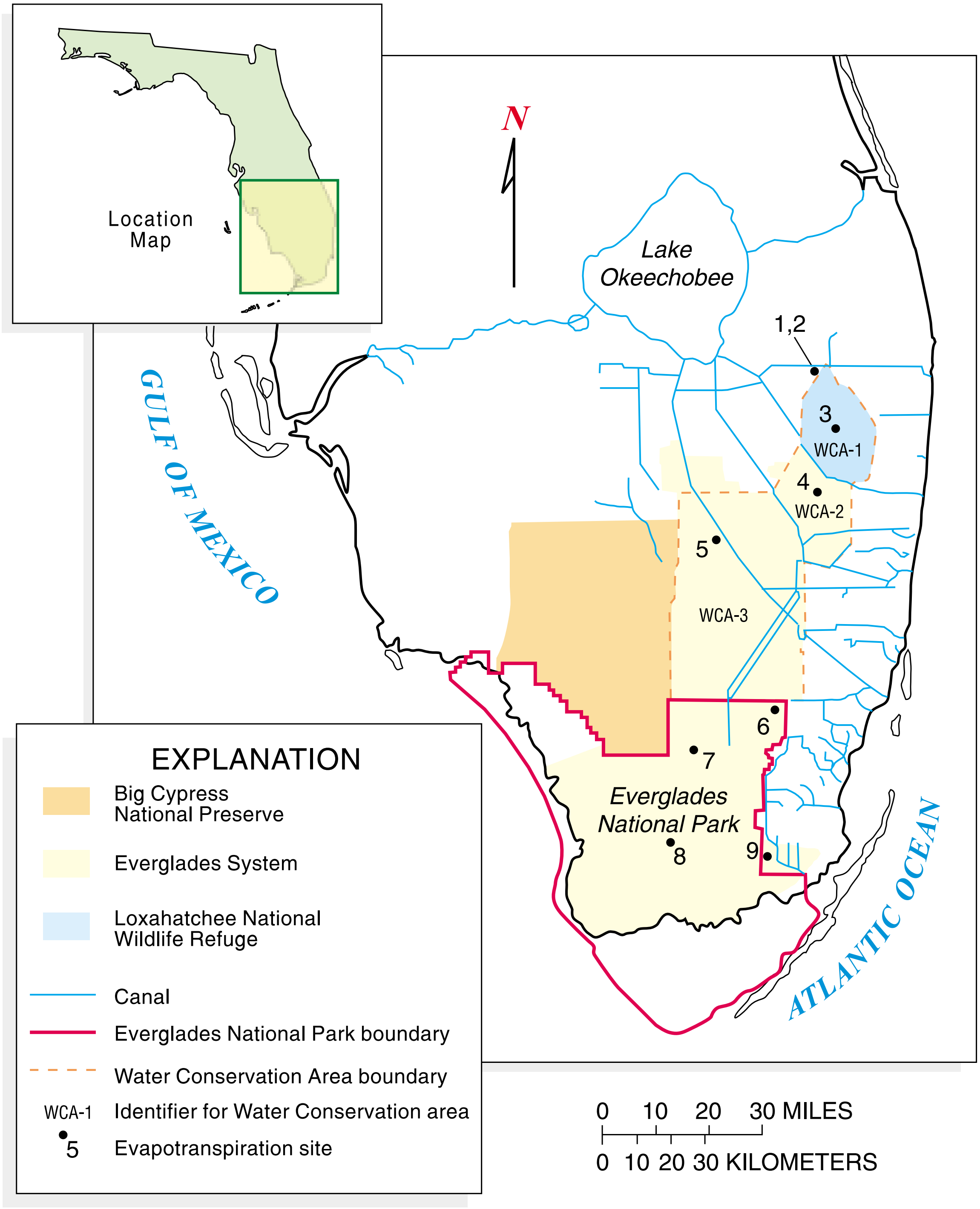

Figure 1. The Everglades and locations of evapotranspiration (ET) stations.

Table 1. ET evaluation site numbers, locations, and characteristics

Site number	Community	Latitude-Longitude	Comments
1	Cattails	263910 0802432	Never dry
2	Open water	263740 0802612	Never dry
3	Open water	263120 0802013	Never dry
4	Dense sawgrass	261900 0802307	Dry part of most years
5	Medium sawgrass	261541 0804356	Dry part of some years
6	Medium sawgrass	254450 0803007	Never dry
7	Sparse sawgrass	253655 0804211	Never dry
8	Sparse rushes	252112 0803807	Dry part of every year
9	Sparse sawgrass	252135 0804600	Dry part of every year

radiometer. Soil heat storage (G) was estimated by using measured values of heat flux, soil temperature, and soil moisture, together with estimated values of soil bulk density and particle heat capacity. Storage of heat in water (W), which must be considered when the water level is above land surface, was estimated from measurements of water level and water temperature. The difference between the net radiation (R_n) and the energy adsorbed by the water and soil gives the total amount of energy available for sensible heat transport (H) and latent heat transport (λE), where λ is the latent heat of vaporization of water and E is the mass evaporation rate. Sensible heat is the heat associated with convective transport; latent heat is the heat required for changing water from a liquid to a vapor state. The energy budget, given by the following equation, is also illustrated in fig. 2:

$$R_n - G - W = H + \lambda E \quad (1)$$

The Bowen ratio (B) is the ratio of H to λE. Bowen (1926) showed that B can be approximated as a function of vertical differences of temperature and vapor pressure in the air, or

$$B = \gamma \; (t_2 - t_1) / (e_2 - e_1) \quad (2)$$

where γ is a function of air temperature and barometric pressure (roughly a constant), t_2 and t_1 are air temperatures measured at two points at different heights above the land surface, and e_2 and e_1 are vapor pressures measured at the same two points. The energy budget can then be solved for λE:

$$\lambda E = (R_n - G - W) / (1 + B) \quad (3)$$

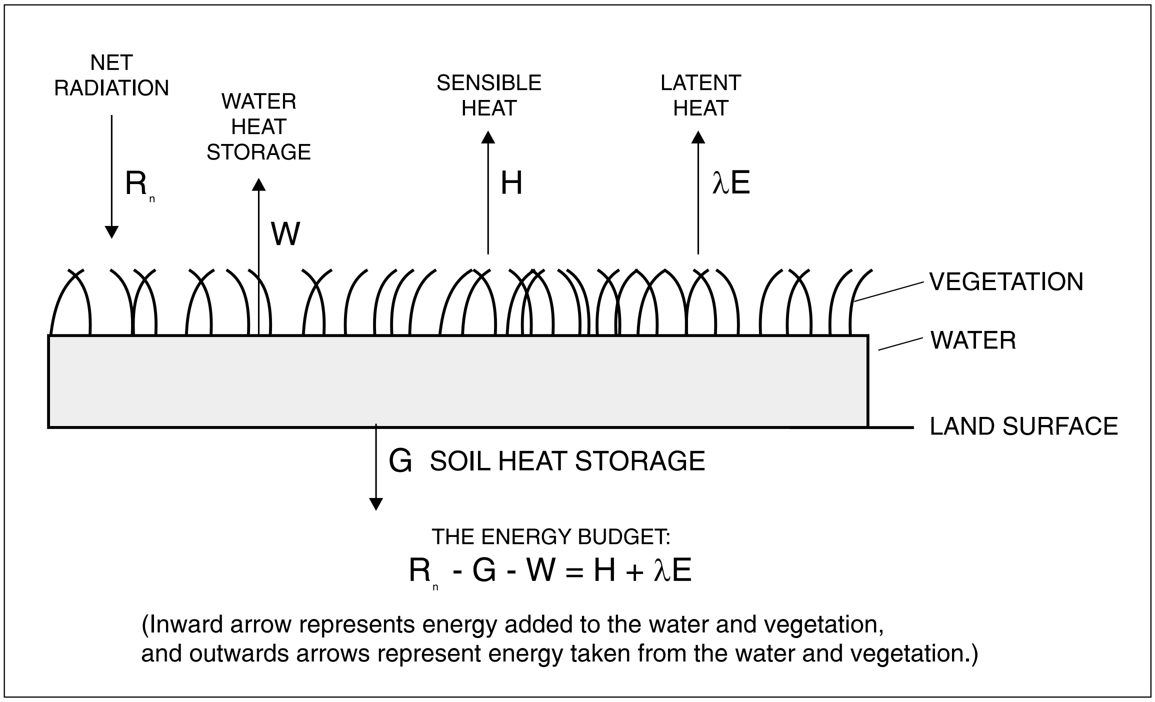

Figure 2. Energy budget during daytime heating.

At vegetated sites, air temperature and vapor-pressure measurements are made simultaneously every 30 seconds at two points that are several feet above the land surface and separated vertically by 3 to 5 feet (ft). Because the temperature and vapor-pressure differentials generally are small in comparison to sensor calibration bias, the upper and lower sensors are reversed in position every 15 minutes. This reversal of position makes it possible to eliminate the effect of sensor bias by averaging the differences in the mean measured air temperature and vapor-pressure differentials during two successive 15-minute intervals, and by using the resultant average differentials to compute λE at 1/2-hour intervals.

At open-water sites with little or no emergent vegetation, the air temperature and vapor-pressure differentials are determined from measurements of water temperature at the water surface and air temperature and vapor pressure at a point 3 to 4 ft above the water surface. The water-surface temperature is measured by using a float-mounted thermocouple and is assumed to represent the air temperature at the water-air interface. The vapor pressure at that point is assumed to be equivalent to 100 percent relative humidity. Because the water-surface to air differences are much greater than differences in the air over similar distances, the effect of air and vapor pressure sensor bias is negligible. Therefore, the sensor exchange mechanism is not required and only one vapor pressure sensor is needed at such sites.

4. SITE AND REGIONAL MODELS OF ET

A modified Priestley-Taylor model of ET was calibrated for each site. These individual site models were then combined into two regional models: one applicable to vegetated wet-prairie and sawgrass-marsh sites, and the other applicable to freshwater sloughs and other open areas with little or no emergent vegetation.

4. 1 The Modified Priestley-Taylor Model

The Priestley-Taylor model of evaporation (Priestley and Taylor, 1972) is a relatively simple model that has been successfully applied in many areas. This model is a semi-empirical model, derived from the physics-based Penman-Monteith model (Monteith, 1965) that expresses ET as a function of aerodynamic resistance (a function of wind speed, canopy characteristics, and atmospheric stability) and canopy resistance (a measure of stomatal resistance to vapor transport from plants). In the Priestley-Taylor model, the atmosphere is assumed to be saturated and an empirical term is added (the Priestley-Taylor coefficient) to account for the fact that the atmosphere does not generally attain saturation.

The form of the Priestley-Taylor equation is:

$$\lambda E = \alpha \Delta A / (\Delta+\gamma) \quad (4)$$

where

λ is the latent heat of vaporization of water, in joules/g,
E is the evaporation rate, in g/m^2-s,
the product λE is the latent heat energy, in $watts/m^2$,
α is the Priestley-Taylor coefficient (dimensionless),
Δ is the slope of the saturation vapor-pressure curve, in pascals/deg. C,
A is the available energy (R_n - G - W), in $watts/m^2$, and
γ is the psychrometric constant computed from atmospheric pressure and air temperature (Fritschen and Gay, 1979), in pascals/deg. C. The dependency of γ on atmospheric pressure is small and a constant value of 101 kilopascals (kPa) was used to calculate γ.

Priestley and Taylor (1972) estimated that the value of α is 1.26 over a free-water surface or a dense, well-watered canopy. Other studies examined use of a modified form of the Priestley-Taylor equation, in which the value of α is varied according to soil water availability (Davies and Allen, 1973), sensible heat flux (Pereira and Villa Nova, 1992), or solar radiation (DeBruin, 1983). DeBruin noted that the diurnal variation in α is related primarily to solar radiation. Sumner (1996) studied ET in a ridge area of central Florida and developed a Priestley-Taylor model in which he expressed α as a function of solar radiation, vapor-pressure deficit, soil moisture, and a sinusoidal function of Julian date to take into account seasonal factors such as plant cycles. The fit of this model to computed ET was as good as the fit obtained by using the more rigorous Penman-Monteith model. Knowles (1996), in a study of ET in the Rainbow Springs and Silver Springs basins in north-central Florida, used a function relating α to net radiation, air temperature, and leaf-area index.

Priestley-Taylor models were developed for the nine ET sites, in which α was expressed as a function of incoming solar energy and water level. This resulted in the following model:

$$\lambda E = (C_0+C_1 S + C_2 P)\, \Delta A / (\Delta+\gamma) \quad (5)$$

where

λ, E, Δ, A, and γ are the same as in equation (4),
C_0, C_1, and C_2 are constants for each site,
S is depth of water above land surface (negative if below land surface) in ft, and
P is incoming solar radiation, in watts/m^2.

The values for C_0, C_1, and C_2 were determined by expanding equation (4) and by using least-squares regression to determine the best expression for λE as a function of the quantity $\Delta A / (\Delta+\gamma)$.

4.2 The Site Models

Only data for 1996-97 that passed screening tests for accuracy were used to develop the site models using equation 5. The screening tests were based on range limits, visual inspection of plotted net radiation, temperature and humidity readings to eliminate periods when sensors were obviously malfunctioning, and on criteria given by Ohmura (1982). Ohmura specified that flux calculations (equation 3) are inappropriate if the calculated latent heat flux is not in the opposite direction from the observed vapor-pressure gradient. Such a situation would indicate an error in determination of either the energy budget or the vapor-pressure or temperature gradient. Ohmura also recommended that Bowen-ratio calculations be rejected if temperature or vapor-pressure gradients are at or less than sensor resolution limits. Resolution limits for this study are 0.013 degree Celsius for vertical temperature differences and 0.003 kPa for vapor-pressure differences. These screening criteria eliminated about one-half of the available data from model development, mostly because of sensor failure and resolution limits. Most of the data rejected because of resolution limits or flux directions were for night-time hours, when energy inputs, air-temperature gradients, and vapor-pressure gradients are all relatively low.

Regression statistics and values for the coefficients shown in table 2 indicate goodness-of-fit characteristics and some common attributes among the nine site models. In all cases, site model coefficients of determination were 0.91 or greater. The model coefficients of variation ranged from 23 percent at site 9 to 39 percent at site 1. Although this variation indicates a somewhat imprecise fitting of 30-minute latent-heat-flux data, the precision of daily means or sums would be much better because random errors associated with the individual measurements would tend to cancel over a long period.

Table 2. Summary of regression coefficients and goodness of fit for Priestley-Taylor site models

(N is the number of records used in the regression; C_0, C_1, and C_2 are the regression coefficients in the relation $\lambda E = (C_0 + C_1 S + C_2 P) \Delta A / (\Delta + \gamma)$; R^2 is the coefficient of determination; and C.V. is the coefficient of variation)

Site	N	C_0	C_1	C_2	R^2	C.V., percent
1	6,957	1.061	0.0123	-0.003500	0.91	39
2	12,255	1.158	0.0151	0.0000634	0.93	34
3	30,671	1.078	0.0432	0.0000806	0.98	20
4	15,254	1.149	0.0650	-0.000545	0.95	32
5	16,104	1.000	0.1200	-0.000333	0.95	28
6	15,182	0.860	0.1070	-0.000222	0.95	31
7	15,794	1.022	0.0849	-0.000304	0.96	24
8	21,205	1.054	0.1900	-0.000374	0.95	33
9	10,323	0.975	0.2050	-0.000316	0.98	23

Both water level and incoming solar radiation were significant at the 95-percent level in explaining variation in latent heat flux at all sites. The sign of the regression coefficient C_1 is positive for all sites, indicating that α increases as water depth increases. The coefficient C_2 indicates that, at vegetated sites, α decreases as incoming solar radiation increases. At open-water sites (2 and 3), α increases as incoming solar radiation increases.

The effect of water depth on α when the water surface is above the land surface might be related to the presence of dead plant debris on the land surface. The dead plant material that is above the water surface intercepts some of the incoming solar energy, thereby preventing it from heating the water surface and enhancing evaporation. Instead, the dead plant debris is heated, which enhances convective heat transport. During periods of high water when some dead plant debris is submerged, lesser amounts of the debris are exposed to solar heating, and the water surface receives a greater portion of the solar energy than during periods of lower water. As a result, the portion of solar energy that is transformed into latent heat could be directly proportional to the water level, as is indicated by the positive value of the water-level coefficient (C_1 in table 2) at all sites. When water level is below land surface, as occurred occasionally at sites 8 and 9, α is still related directly to water level. This might be because moisture availability at the land surface decreases as the water level declines.

The inverse relation of α to incoming solar energy at vegetated sites (all sites except 2 and 3) also could be an effect of the non-transpiring dead plant debris. Solar heating of this dead plant debris would be proportional to the quantity of incoming solar energy. This solar heating could result in an increased portion of the available energy being converted into sensible heat, at the expense of latent heat. Incoming solar energy and α are directly related at both open-water sites (2 and 3). At these two sites, there is little or no emergent vegetation or debris subject to solar heating.

4.3 The Regional Models

The presence of some common attributes among the individual Priestley-Taylor models (table 2) indicates that a generalized form of the model could provide a reasonable estimate of ET at all sites. This indicates that a generalized (regional) model would be appropriate for evaluating ET at other areas in the Everglades with similar hydrologic and vegetation characteristics to the sites modeled in this study.

The relation of α to water level for solar intensities of 200 and 800 watts per square meter (watts/m^2) is plotted for all sites in figure 3. The plots indicate that, at 200 watts/m^2, the relations of α to water level are similar but not identical among the sites. For the five wet vegetated sites (1, 4, 5, 6, and 7), sites 4 and 6 define the upper and lower boundaries of the relation. Sites 4 and 6 are characterized by dense or medium sawgrass, and the reasons for the resultant differences in the α to water-level relation are not obvious.

At higher solar-energy levels (800 watts/m^2), the plots of α as a function of water level define two obvious groups: open-water sites (2 and 3) and vegetated sites (all others). The large separation between the two site types (open water and vegetated) at the higher energy level indicates that a significant portion of the incoming solar energy at vegetated sites is used in heating plants and plant debris, with a resultant relative increase in sensible heat transport compared to latent heat transport.

A generalized relation of α to water level and incoming solar energy was developed for vegetated and open-water sites by using least-squares regression to fit a data set of α generated by the individual site models. The values of α were generated over a range of water level from -1 to 2 ft in 0.1-ft intervals and a range of incoming solar radiation from 0 to 1200 watts/m^2 in 100-watts/m^2 intervals. These two generalized relations are shown in figure 3 for incoming solar energy levels of 200 and 800 watts/m^2. The goodness of fit of the generalized vegetated-site model to specific sites depends on the incoming energy level. For example, the generalized vegetated-site model underestimates α for site 4 at 200 watts/m^2, but overestimates α for the same site at 800 watts/m^2. The generalized open-water site model appears to fit both sites (2 and 3) at all incoming energy levels.

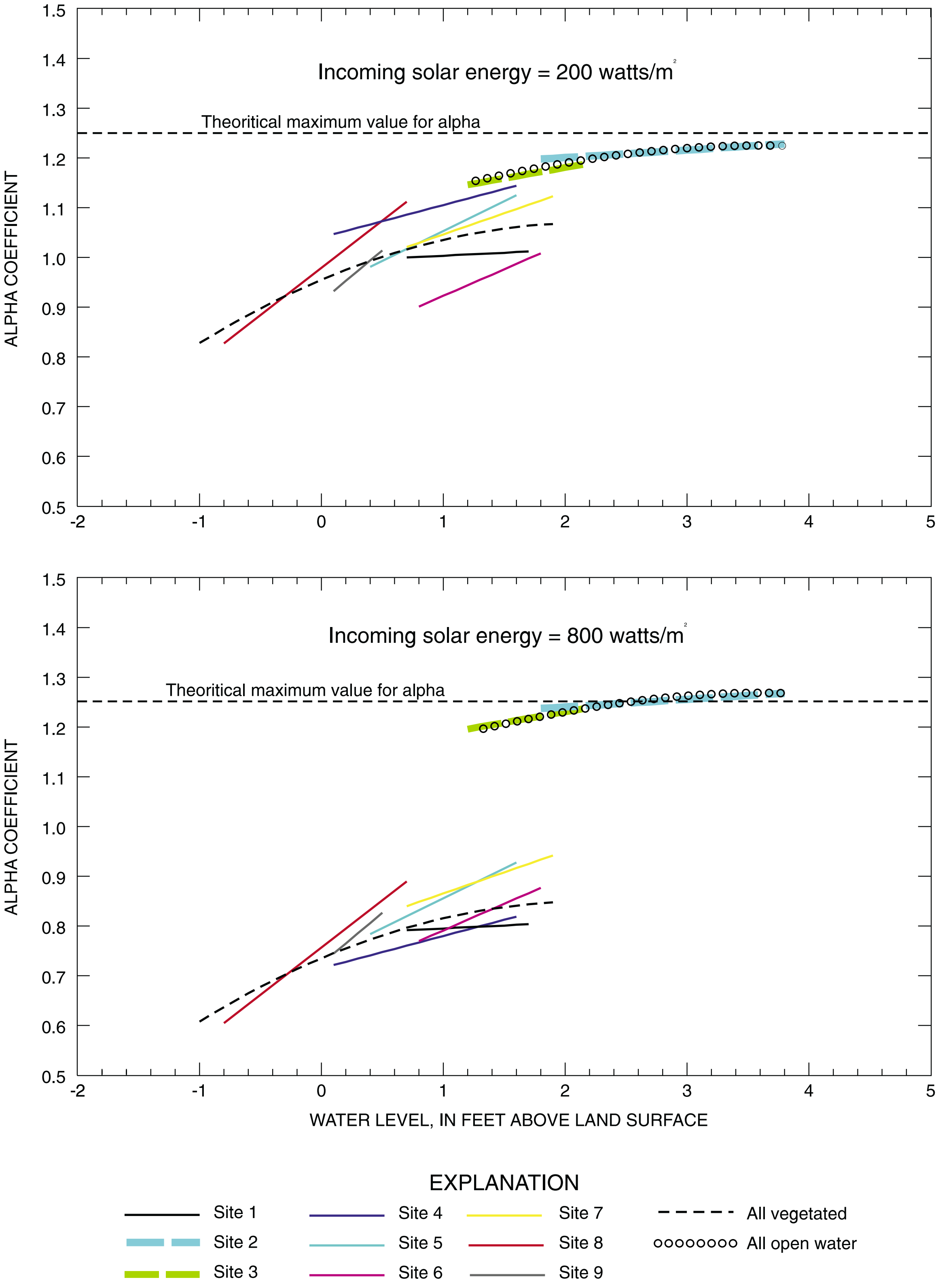

Figure 3. Priestley-Taylor coefficient as a function of water level, at solar intensity of 200 watts/m^2 and 800 watts/m^2.

5. ANNUAL TOTAL ET AT THE SITES

A comparison of total computed annual ET and ET simulated by using regional models for 1996-97 is shown for each site in figure 4. The computed ET totals are a combination of ET values determined from measured data and evaluated from the site model for periods when screening criteria rejected the gradient data needed for an ET measurement.

Computed ET totals for all nine sites ranged from 42.78 in/yr at site 9 to 55.54 in/yr at site 2. The computed ET was greatest at the open-water sites: site 2 (55.54 in/yr) and site 3 (53.22 in/yr). Among the nearly-always wet vegetated sites (1, 4, 5, 6, and 7), ET was lower, ranging from 43.73 in/yr (site 1) to 50.50 in/yr (site 7), with an average value of approximately 47 in/yr. The ET computed at site 1 is low in comparison to the ET at other always-wet vegetated sites. This relatively low ET is due in part to a tendency for more cloud cover at site 1 during the study period, as indicated by comparing the average level of incoming solar radiation at site 1 (192 watts/m^2) with the average for the other sites (201 watts/m^2). This difference in solar energy input could account for about 5 percent of the difference in ET between site 1 and the other vegetated sites, or about 2.3 in/yr. Among the other wet-vegetated sites (4, 5, 6, 7) ET ranged from 45.68 to 50.05 in/yr. The ET differences among these sites could be related to vegetation density. ET at the two sites where the water level was below land surface at least several weeks each year was significantly lower than at all other sites and was 42.78 in/yr at site 9 and 43.44 in/yr at site 8.

The comparison of results in figure 4 indicates that the annual total ET values simulated by the regional models are generally in relatively close agreement with the computed values. The difference between computed and simulated ET was generally less than 3 in/yr, and the median difference was about 1.4 in/yr.

The regional site models could be used to estimate ET at specific sites without the expense of installing and operating the full set of ET-evaluation instrumentation. This would still require a record of incoming solar radiation, net radiation, water level, water temperature, and soil heat storage. At present, the possibility of using regional models to evaluate ET as a function of water depth, air temperature, and incoming solar radiation is being investigated. This approach would greatly reduce the cost of data collection for the purpose of evaluating ET in the Everglades.

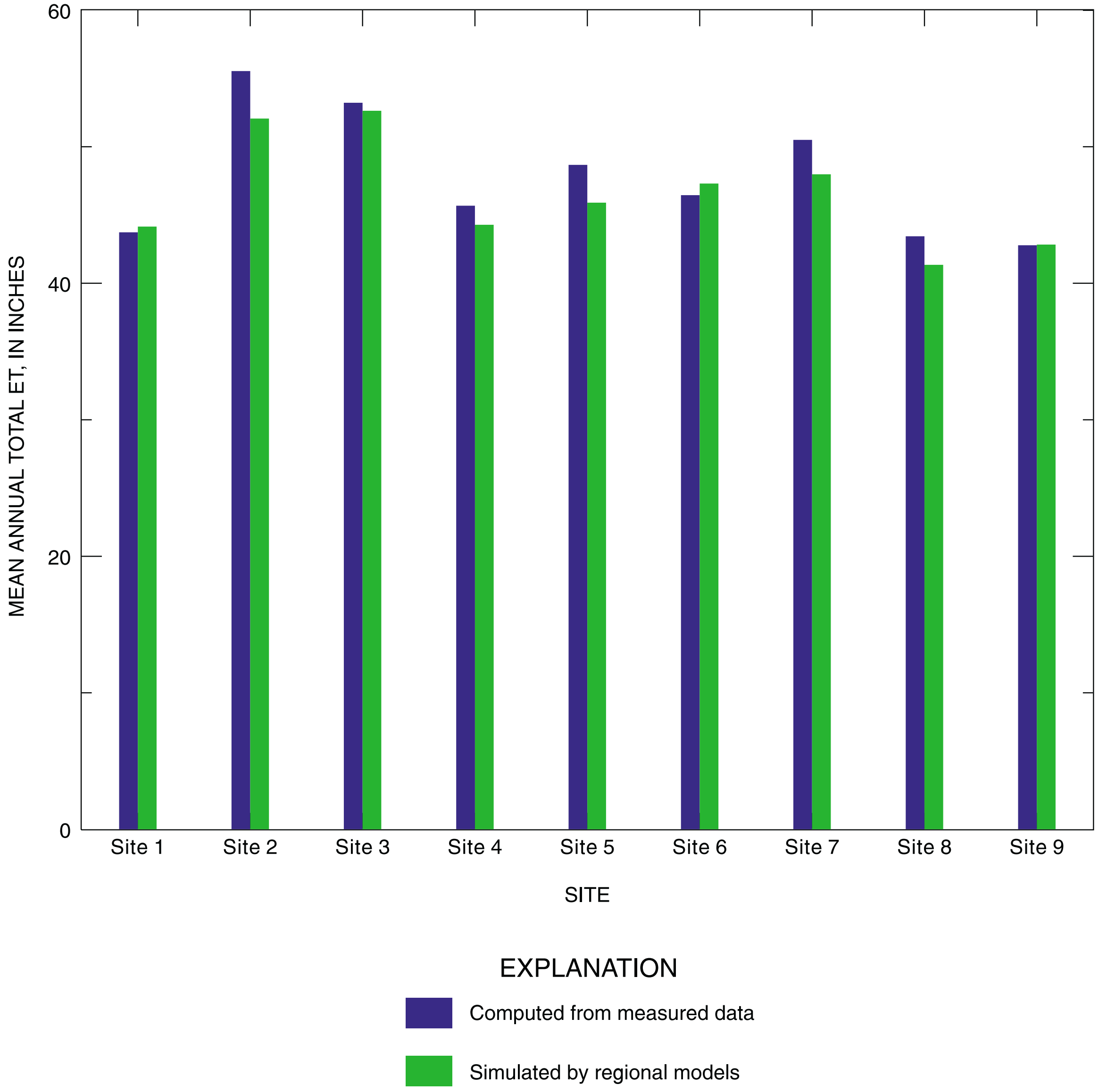

Figure 4. Mean annual total ET for 1996-97.

6. SUMMARY

A study to evaluate and model ET in the Everglades was begun in 1995. A network of nine ET-evaluation sites was established that represents the varied hydrologic conditions and vegetative characteristics of the Everglades. Data from continuous measurements of parameters for evaluation of ET at the sites for a 2-year period (January 1996 through December 1997) were used to develop regional models that can be used to simulate ET at other times and places throughout the Everglades.

A modified Priestley-Taylor model of ET was calibrated for each site. In these models the Priestley-Taylor coefficient (α) was expressed as a function of incoming solar energy and water level. The individual site models were then combined into two regional models: one is applicable to vegetated wet-prairie and sawgrass-marsh sites, and the other is applicable to freshwater sloughs and other open areas with little or no emergent vegetation.

Computed ET totals for all nine sites ranged from 42.78 inches per year at a sometimes-dry sparse-sawgrass site to 55.54 inches per year at an open-water site. Differences in annual ET relate to water-availability and perhaps to density of vegetation.

Comparisons indicate that the total ET values simulated by regional models generally are in relatively close agreement with the values determined from the measured data. The difference between computed and simulated ET generally was less than 3 in/yr. The median difference was about 1.4 in/yr.

The regional site models could be used to evaluate ET at specific sites without the expense of installing and operating a full set of ET-evaluation instrumentation. However, these regional models still depend on measurement of the components of the energy budget, as well as solar intensity and water level.

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