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EVAPOTRANSPIRATION IN THE EVERGLADES; COMPARISON OF BOWEN RATIO MEASUREMENTS AND MODEL ESTIMATIONS

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EVAPOTRANSPIRATION IN THE EVERGLADES: COMPARISON OF BOWEN RATIO MEASUREMENTS AND MODEL ESTIMATIONS

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Abstract: The Everglades in south Florida is a marsh system where most of the time wet vegetated marshes and open water features prevail. Rainfall and evapotranspiration (ET) are the main parameters in the hydrology of the Everglades. The delicate balance between rainfall and evapotranspiration maintains the hydrology system in either a wet condition or dry condition. Based on a literature review of both measurement and estimate of evapotranspiration in south Florida, 134.5 cm is an average estimate of annual potential evapotranspiration or evapotranspiration from wetlands and open water in south Florida. In this study, comparisons are made between Bowen ratio-energy balance measured ET at nine sites in the Everglades and wetland ET estimations with a Simple Model (also cited as Abtew Equation or Simple Abtew equation) that is based on solar radiation. The results of this study cross-validate model estimates and Bowen ratio measurements of ET in marshes because the Simple Model was calibrated independently from a previous lysimeter ET study. The area is warm, humid, wet, high solar radiation and low wind speed with prevalent wind direction of north-north-east, east-north-east and east-south-east.

Key Words: Bowen ratio, evapotranspiration, evaporation, Everglades, South Florida, wetland evapotranspiration.

Introduction

Evapotranspiration is one of the major parameters of wetland hydrology. As a major component of the hydrologic cycle, there is a need for reasonably accurate estimates of evaporation from water bodies and evapotranspiration from vegetation. Evapotranspiration depends on the availability of energy, the mechanism of mass transfer, energy transfer, and the availability of water. Evaporation and evapotranspiration are functions of solar radiation, temperature, wind speed, vapor pressure deficit, atmospheric pressure, characteristics of the surrounding environment and type and condition of vegetation. The actual evapotranspiration of wetlands that do not dryout, can be estimated as the theoretical atmospheric demand or potential ET of wetlands (Mitsch and Gosselink, 1993; Abtew et al., 2003). In dry out conditions, roots of macrophytes will increase ET compared to no vegetation cover. Takagi et al. (1999) reported that invasion of vascular plants in a northern Japanese bog increased ET where water level was always below ground level at both test sites. Souch et al. (1998) compared measured and model estimated evapotranspiration from disturbed (drained) and undisturbed wetland sites and concluded that there was no substantial difference between the two sites. The drained site water levels rarely dropped below the root zone.

Through the years, various measurements and estimates of evapotranspiration from wetland vegetation have been reported for many locations. Figure 1 depicts the chronological presentation of past studies comparing wetland macrophyte ET to evaporation from shallow water surface. Recent studies clearly show the trend of reporting where wetland ET is not markedly higher or lower than shallow open water evaporation. Isohyetal map of estimated average annual potential evapotranspiration or evaporation from wetlands ranging from 122 cm at the north (Orlando) to 137 cm in the south (Everglades National Park) is shown in Abtew et al., 2003.

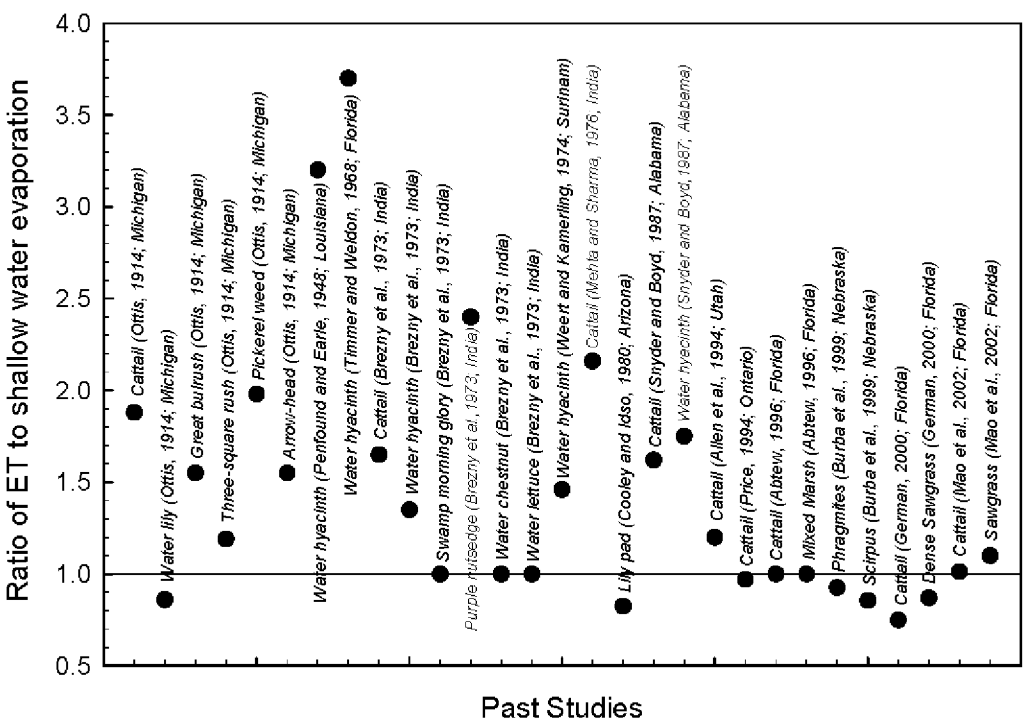

Figure 1. Past studies comparing wetland macrophyte ET to shallow water evaporation.

Rainfall. South Florida is a sub-tropical region that is relatively wet, warm, and humid. The wet season runs from June through October and accounts for 66 percent of the annual rainfall. Typically, the driest month is December, followed by January. Runoff generated by wet-season rainfall and dry-season high-rainfall events is stored in ponds, lakes, impoundments, wetlands, and aquifers resulting in potential evaporation and evapotranspiration over large areas. The average annual rainfall for the South Florida Water Management District area is 134 cm (Ali and Abtew, 1999).

Meteorology. At Sites 1 and 2, Stormwater Treatment Area 1 West (formerly the Everglades Nutrient Removal Project), the annual average air temperature is 23.1 ^{o}C with a monthly average temperature increasing from 17.3 ^{o}C in January to 27.2 ^{o}C in July and August. The average wind speed at 10-meter height is 3.1 m s^{-1}. The annual average relative humidity is 85 percent. This area has significant sunshine with an annual average solar radiation flux rate of 0.195 kw m^{-2}. Table 1 depicts monthly average meteorological parameters from a weather station at a constructed wetland. The annual average wetland evapotranspiration at the site was 131.7 cm.

Table 1. Mean monthly weather parameters at Stormwater Treatment Area 1 West (1994 to 2003).

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Tmean (oC)	17.3	19.1	20.9	22.5	25.1	26.4	27.2	27.2	26.7	24.8	21.4	18.8
Tmax (oC)	23.2	23.4	25.0	25.8	27.3	28.3	28.8	28.9	28.4	27.4	25.3	23.4
Tmin (oC)	8.5	12.1	15.1	17.8	22.0	24.0	24.9	24.8	24.2	21.0	16.1	10.3
Rhmin (%)	70.9	71.9	71.3	67.2	74.0	79.5	80.6	81.1	80.8	75.8	76.0	74.3
Rhmax(%)	96.1	94.8	96.0	94.0	94.1	95.0	93.9	95.8	96.9	95.2	96.9	97.1
WS at 10m (m s^{-1})	3.52	3.60	3.84	3.45	2.91	2.66	2.49	2.44	2.56	3.11	3.39	3.35
Rs (MJ M^2 d^{-1})	12.51	14.60	18.18	20.03	21.70	19.54	19.95	18.33	15.97	16.11	13.69	11.59
ET (mm d^{-1})	2.69	2.99	3.80	4.41	4.84	4.35	4.41	4.06	3.52	3.31	2.75	2.40
Rainfall (cm)	3.40	4.77	8.86	6.05	7.95	18.50	16.42	18.13	18.01	14.03	7.87	6.01

Wetland Evapotranspiration

A two-year lysimeter study of evapotranspiration in three wetland environments (cattails, mixed vegetation marsh, and open water/algae) was conducted in the Everglades Nutrient Removal Project, a constructed wetland in south Florida (26° 38' N, 80° 25' W). The study was conducted between 1993 and 1996 and the sites were adjacent to sites 1 and 2 (Figure 3). An average rate of 3.6 mm day^{-1} evapotranspiration was reported (Abtew and Obeysekera, 1995; Abtew, 1996). Figure 2 depicts cattail, mixed vegetation, and open water lysimeters in the Everglades Nutrient Removal constructed wetland. The results of the study were applied to test and calibrate six evapotranspiration estimation models: Penman-Monteith, Penman-Combination, Priestly-Taylor, Modified Turc, Radiation/Tmax, and Radiation (Simple) methods. The performance of each method was compared.

Figure 2. Cattail, mixed vegetation, and open water lysimeters in the Everglades Nutrient Removal constructed wetland.

Input data requirements increase from the Radiation method to the Penman-Monteith method. In south Florida, most of the variance (73 percent) in daily evapotranspiration is explained by solar radiation alone (Abtew, 1996). The effect of humidity and wind speed is relatively minimal. The Simple method (Eq. 1) requires a single measured parameter, solar radiation, and is less subject to local variations (Abtew, 1996). The Simple method is also cited as Abtew equation and Simple Abtew equation in published literature.

$$ET = K_1 \frac{Rs}{\lambda} \tag{1}$$

Where ET is daily evapotranspiration from wetland or shallow open water (mm d^{-1}), Rs is solar radiation (MJ m^{-2} d^{-1}), λ is latent heat of vaporization (MJ kg^{-1}), and K_1 is a coefficient (0.53). Mean monthly weather parameters at Stormwater Treatment Area 1 West are depicted in Table 1. The weather station is close to Site 1 shown in Figure 3.

Bowen Ratio-Energy Balance Method

In a U.S. Geological Survey (USGS) study, nine sites in the Everglades were instrumented with sensors to determine evapotranspiration from different features using the Bowen ratio-energy balance method (German, 2000). Figure 3 shows the nine USGS sites and site characteristics where evapotranspiration was measured with the Bowen ratio-energy balance method. Field data with varying lengths of record, from 1996 to 2000, is available on the USGS web site (http://sofia.usgs.gov/people/german.html). A picture of the Bowen ratio-energy balance instrumentation at Site 3 is shown in Figure 4 (German, 2000). The instrumentation has net radiometer, pyranometer, wind speed and direction sensors, air temperature and humidity sensors, rain gauge, storage battery, solar panel, data logger and cellular phone. The Bowen ratio-energy balance method is a micrometeorological method for measurement of evaporation (latent heat) with an approximate accuracy of 10 percent (Dugas et al., 1991). The following equation (Eq. 2) represents the Bowen ratio-energy balance.

$$LE = \frac{Rn - G}{1 + \beta} \tag{2}$$

Where LE is latent energy, Rn is net radiation, G is soil heat flux, and β is Bowen ratio which is the ratio of sensible heat (H) to latent heat (λE).

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} \tag{3}$$

Where γ is psychrometric constant, and ΔT and Δe are finite difference of above-canopy potential temperature and vapor pressure.

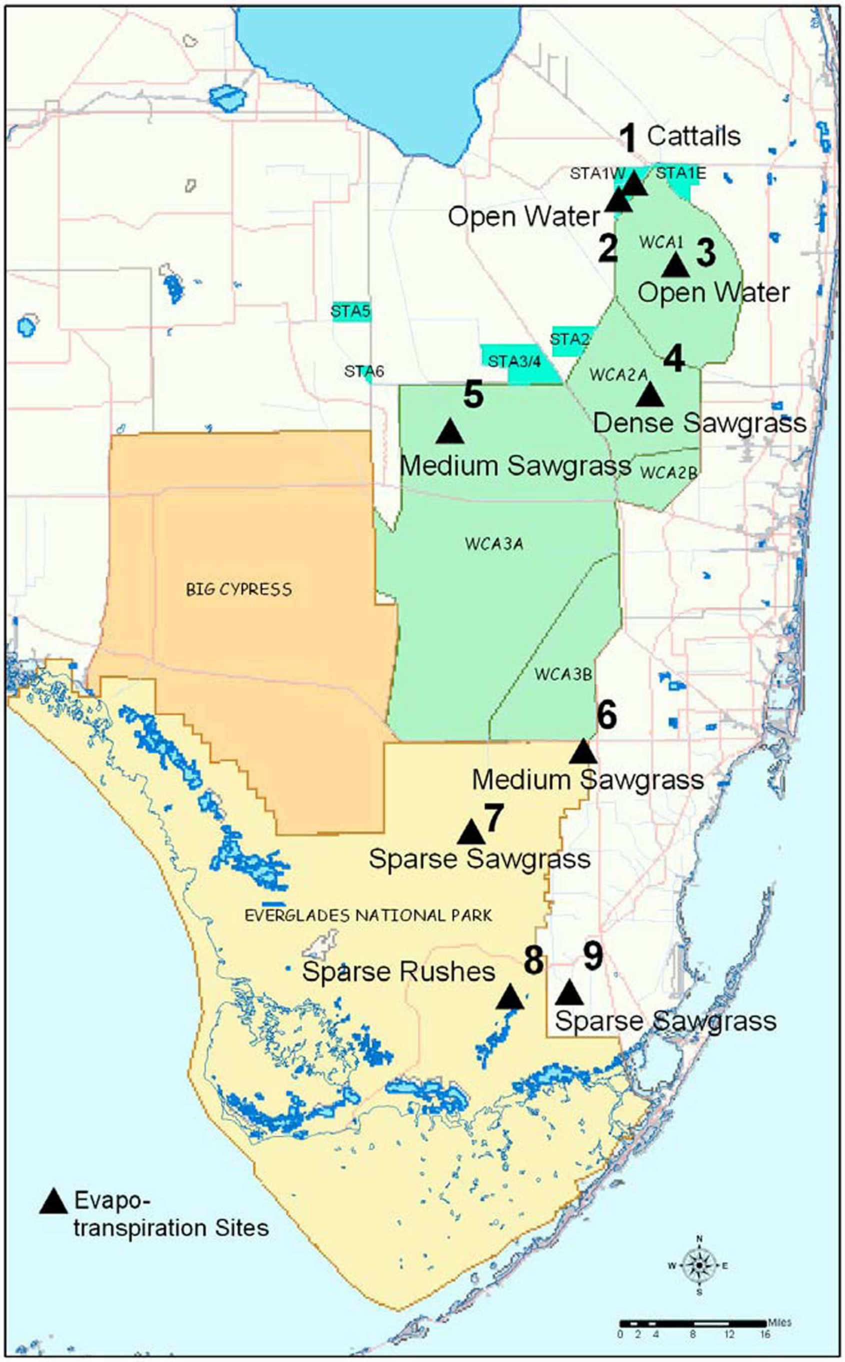

Figure 3. Bowen ratio-energy balance ET measurement sites.

Figure 4. Bowen ratio-energy balance instrumentation in Loxahatchee National Wildlife Refugee, Site 3 (German, 2000).

The Bowen ratio instrumentation includes temperature and humidity differentials with height measurements. At the Bowen ratio-energy balance ET measurement sites, sensor measurements were collected every 30 seconds and averaged to 15 or 30 minutes. Comparison of measured and model estimates of a parameter provides cross validation when the model is calibrated independently. In this case, the Simple method (Abtew method) was calibrated with lysimeter ET measurements from a separate study. Graphical comparisons of Bowen ratio-energy balance measured and Simple method (Abtew equation) estimated average daily wetland ET for each month is shown in Figures 5a-5i. Solar radiation data used by the Simple method (Abtew equation) was obtained from the instrumentation at each of the Bowen ratio site except Site 2 where solar radiation data was used from a nearby SFWMD weather station, ENR308.

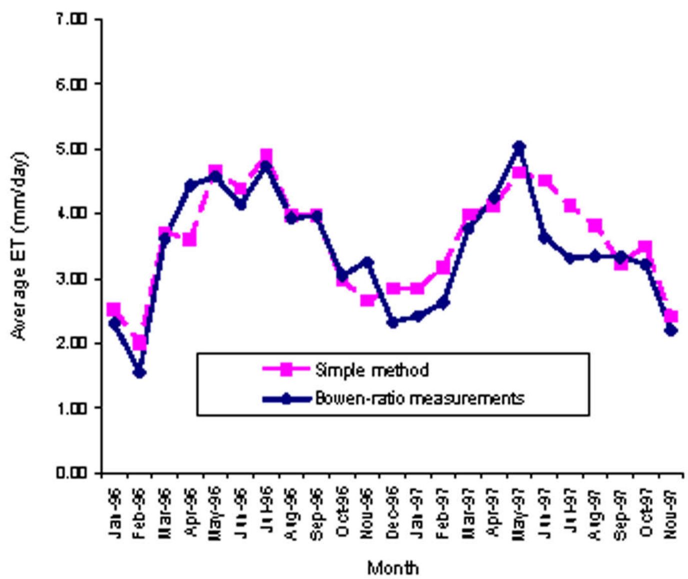

Figure 5a. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Everglades Nutrient Removal Project cattail site (Site 1).

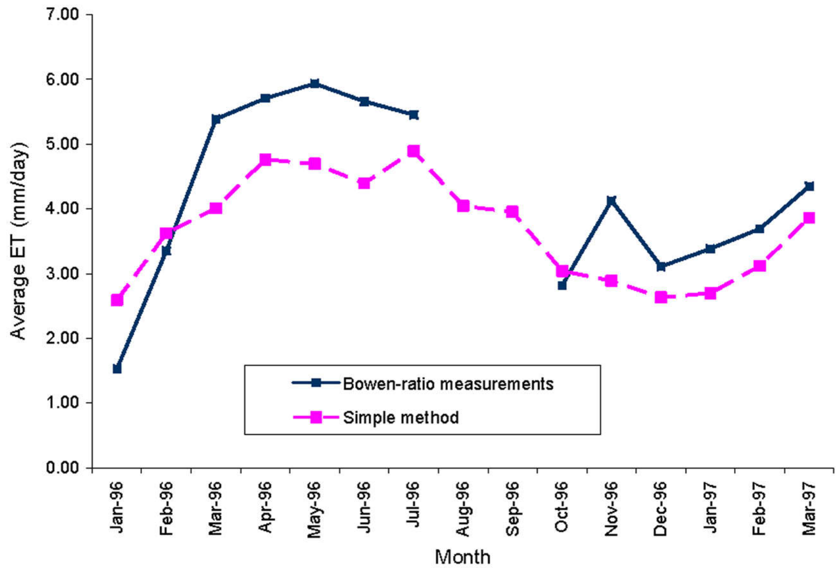

Figure 5b. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Everglades Nutrient Removal Project open water site (Site 2).

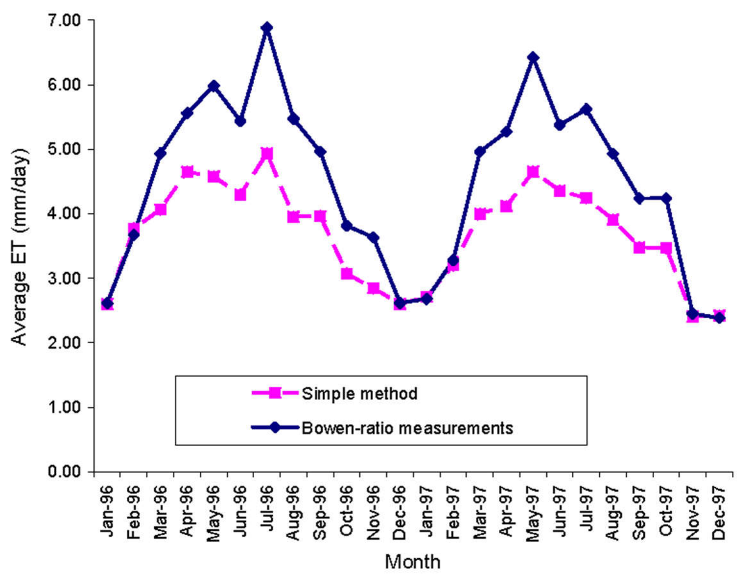

Figure 5c. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Loxahatchee National Wildlife Refuge open water marsh (Site 3).

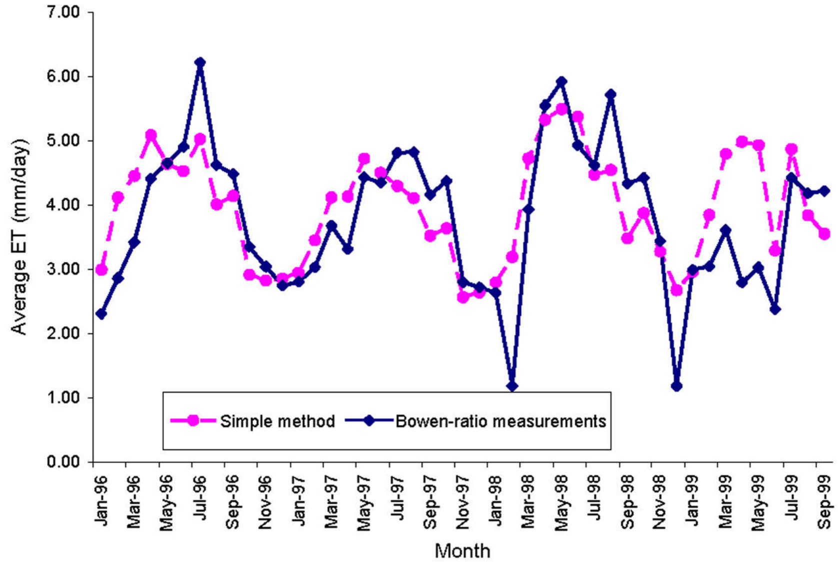

Figure 5d. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Water Conservation Area 2A dense sawgrass marsh site (Site 4).

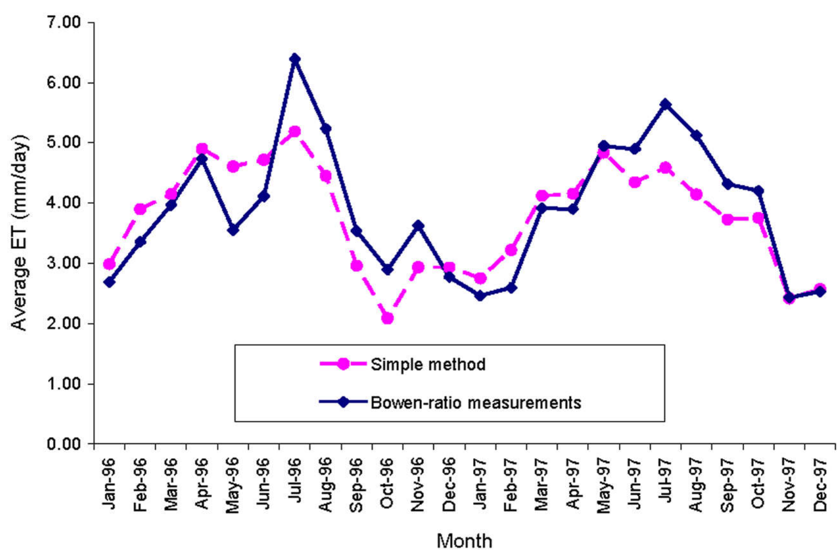

Figure 5e. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Water Conservation Area 3A medium sawgrass marsh site, dry part of some years (Site 5).

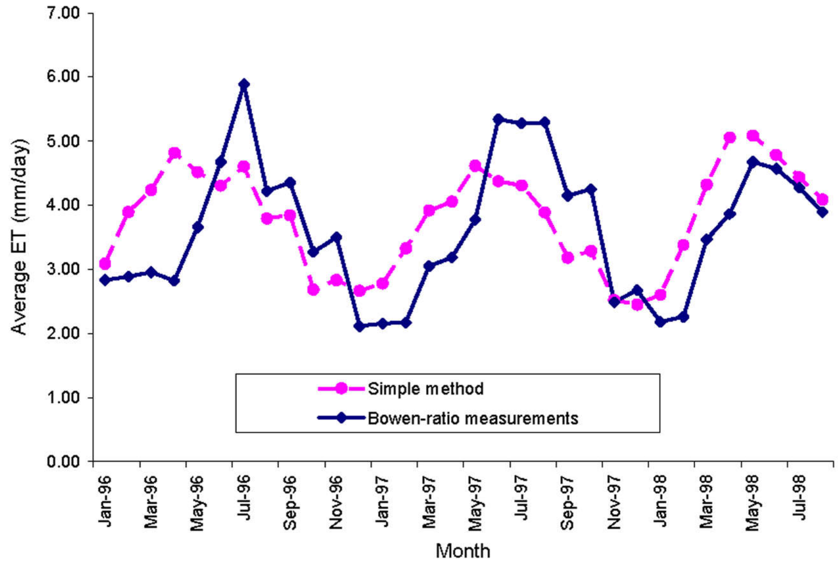

Figure 5f. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Everglades National Park northeast corner medium sawgrass marsh site (Site 6).

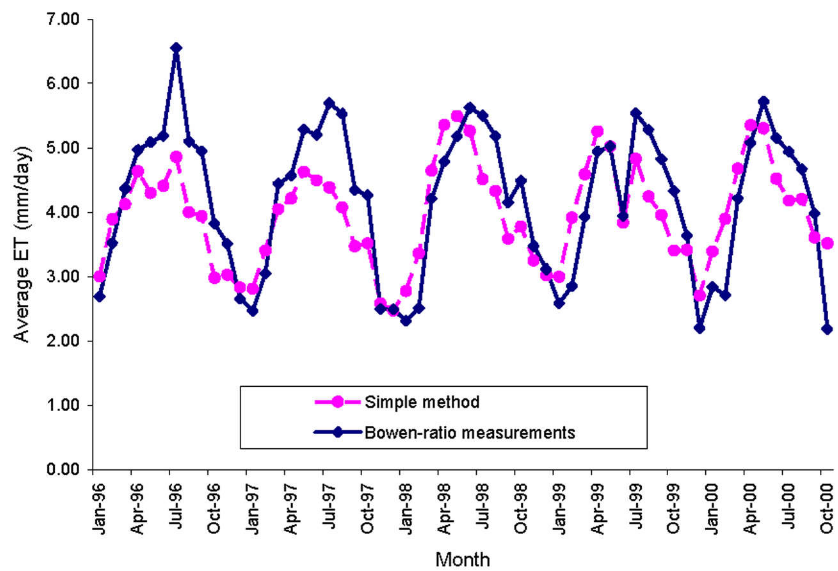

Figure 5g. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Everglades National Park north sparse sawgrass marsh site (Site 7).

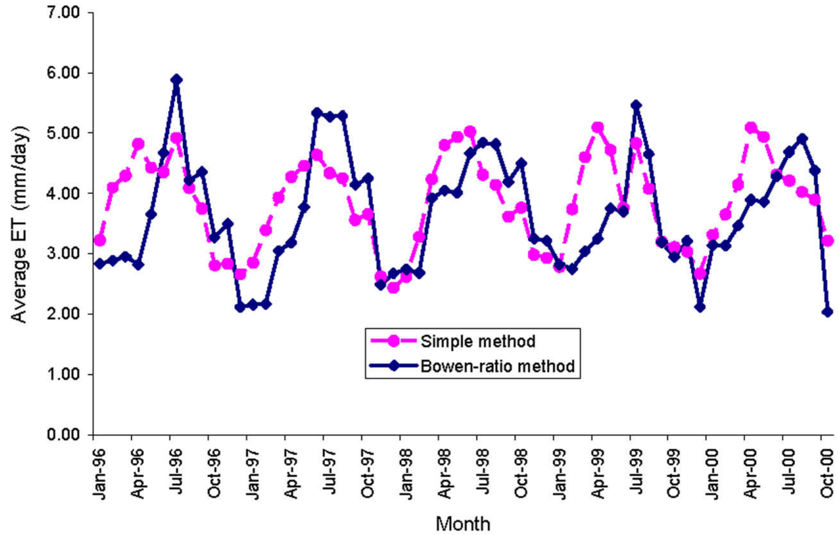

Figure 5h. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at Everglades National Park north sparse sawgrass marsh (Site 8).

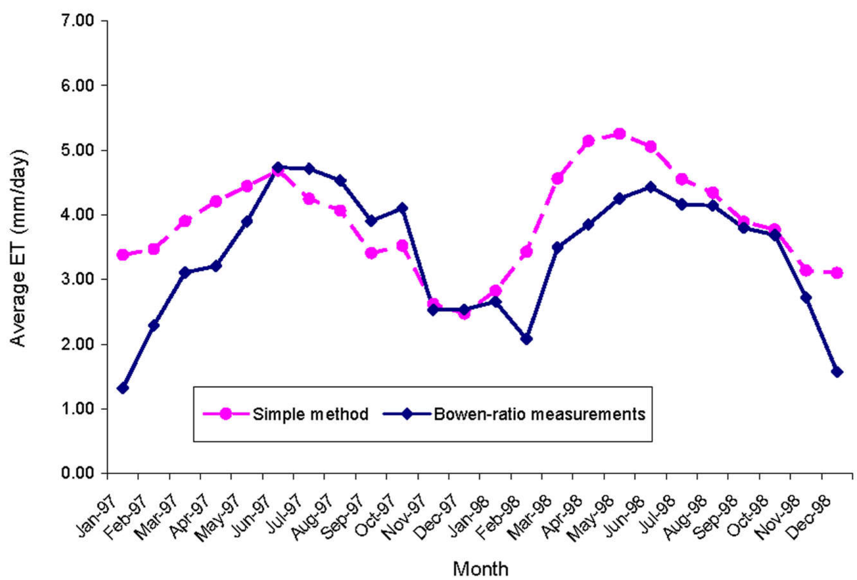

Figure 5i. Comparison of average daily ET measured using the Bowen ratio-energy balance method and wetland ET computed with the Simple method at the Everglades National Park central sparse rushes site, dry part of each year (Site 9).

A site-by-site statistical comparison of Bowen ratio-energy balance measured monthly ET to Simple method (Abtew equation) estimated wetland ET is shown in Table 2. This table presents the number of months with data (n), correlation coefficient (r), mean square error (MSE), and mean daily ET. Both the statistics and visual inspections of Figure 5a-5i provide comparison between the monthly average Bowen ratio-energy balance measured ET and the Simple method (Abtew equation) estimated wetland ET. Site 1, the cattail marsh site and Site 6, the medium sawgrass wet marsh site showed smaller mean square errors and good correlation. The mean estimated daily ET from all nine sites (3.78 mm/day) has a difference of less than 2 percent from the mean measured ET (3.85 mm/day) for all nine sites.

Table 2. Statistical comparison of Bowen ratio-energy balance measured ET and Simple method (Abtew equation) estimated wetland ET.

Site	n	r	MSE (mm^2)	Bowen ratio Measured ET mm/day	Model Estimated ET mm/day	Site Characteristics
1	24	0.90	0.20	3.36	3.54	cattail
2	13	0.89	0.79	4.19	3.63	open water
3	24	0.97	0.99	4.48	3.68	open water
4	45	0.69	0.68	3.79	3.97	dense sawgrass
5	24	0.83	0.76	3.91	3.77	medium sawgrass; dry part of some year
6	32	0.80	0.50	3.63	3.80	medium sawgrass
7	58	0.82	0.99	4.19	3.97	sparse sawgras
8	58	0.61	0.63	3.66	3.86	sparse rushes; dry part of each year
9	24	0.70	0.72	3.40	3.89	sparse sawgrass; dry part of each year

Wind Speed and Direction

The Bowen ratio sites had wind speed and wind direction sensors at eight of the nine sites excluding Site 2 which is close to Site 1. Wind speed was measured at lower heights varying from site to site, with an estimated height of 1 to 1.5 meters. The average wind speed for all the sites was 2.1 m s^{-1}, with a standard deviation of 0.28 m s^{-1}. Average wind speed at 10-meter height for the South Florida Water Management District area is 3.05 m s^{-1}. Based on the power law of wind profile, the 1-meter height wind speed for the District area is 2.2 m s^{-1}. Figure 6 depicts monthly average wind speed for the eight sites in 1996 and 1997. Wind directions at the eight sites showed variations by month and by site. Temporal and spatial average of relative occurrence of wind direction in the eight semi-quadrants is shown in Figure 7. The most prevalent wind directions are north-north-east, east-north-east and east-south-east.

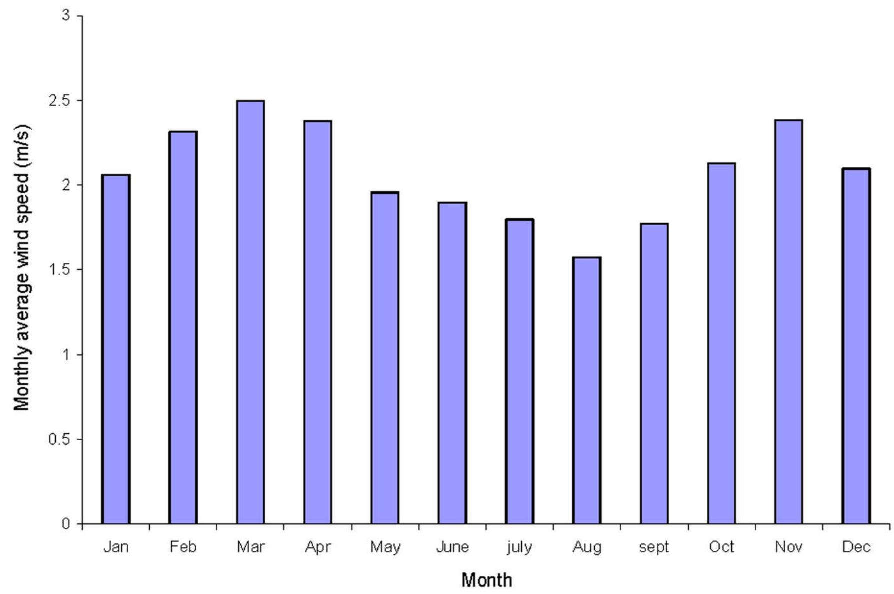

Figure 6. Monthly average wind speed at the Bowen ratio sites.

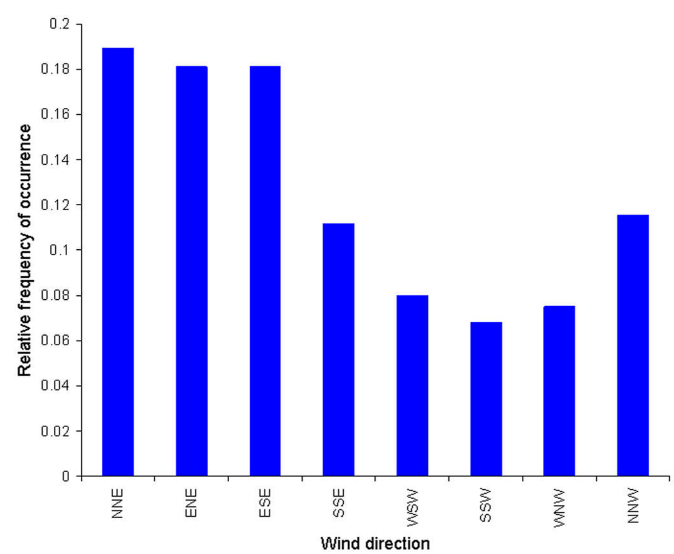

Figure 7. Mean relative frequency of wind directions at the Bowen ratio sites.

Summary

Bowen ratio-energy balance measured evapotranspiration data from nine different sites in south Florida and the Everglades was compared to estimates from a Simple method (Abtew equation) developed for south Florida conditions. Both the graphical presentations of monthly average ET data and comparative statistics show that there is general correspondence in pattern and magnitude between the measured and estimated data. The results of this study cross-validate the model estimates and Bowen ratio measurements of ET since the Simple model (Abtew equation) was calibrated independently from a previous lysimeter ET study. The Simple method (Abtew equation) estimates areal wetland ET from site measurement of a single parameter, solar radiation, which has large spatial coverage. The Bowen ratio method employs site-specific parameters as humidity and temperature differentials and provides actual ET while the Simple method (Abtew equation) provides actual ET for wet surfaces and potential ET for dry surfaces. Areal ET has more widespread application in hydrology.

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