Chapter 7
Wetland Evapotranspiration

Abstract Wetland, marsh, bog, and fen evapotranspiration (ET) rates historically were estimated far higher than open water evaporation. Recent studies have shown that wetland evapotranspiration is not higher than open water evaporation. Lysimeter studies in south Florida show that there is no significant difference in evapotranspiration between cattails, mixed marsh, and open water. Bowen ratio evapotranspiration measurements also showed wetland evapotranspiration being not more than open water evaporation. Simple equations based on solar radiation and temperature can provide estimates of evaporation and ET in regions where most of the variation in ET is explained by one or two parameters.

Keywords Wetland evapotranspiration • Lysimeter measurements • Wetland evapotranspiration estimation methods

7.1 Introduction

Wetlands are ecosystems with open water and wetland vegetation features and periodic variation in the type and density of vegetation cover and water levels. Wetlands are subject to hydrologic variation, but mostly surface or subsurface water is available for evaporation and evapotranspiration except in regions that experience periodic severe droughts. Historically, wetlands were not of great economic interest, which might have contributed to the relatively limited study of their hydrology. Evapotranspiration is one of the major parameters of wetland hydrology. There has been lack of consensus on rates of evaporation losses from wetland features. 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

W. Abtew and A. Melesse, *Evaporation and Evapotranspiration: Measurements and Estimations*, DOI 10.1007/978-94-007-4737-1_7,

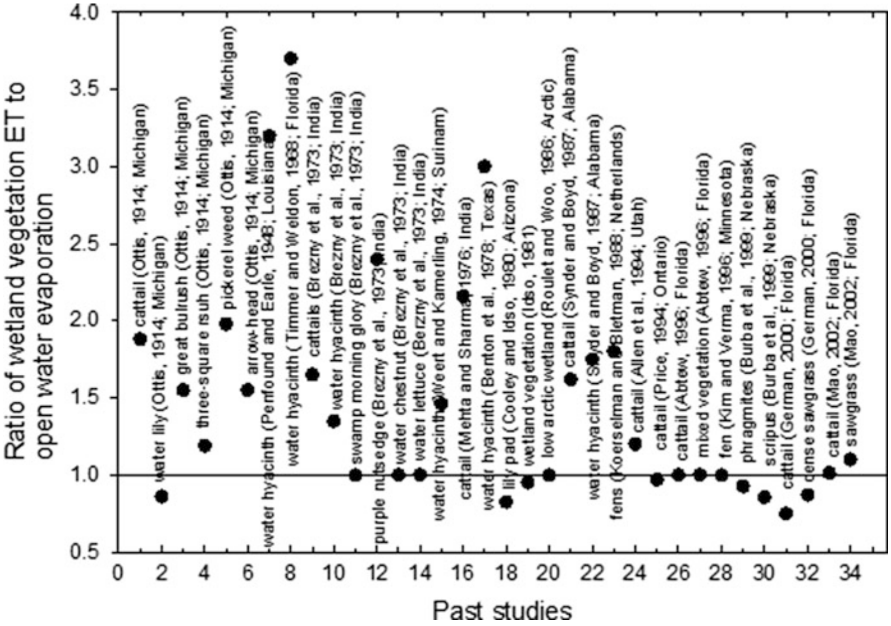

Fig. 7.1 Reported ratios of wetland evapotranspiration to open water evaporation (Abtew 2005; Abtew and Obeysekera 1995)

type and condition of vegetation. The existence of both open water and wetland vegetation in one environment has resulted in different views of what the rate of evapotranspiration could be from such systems. A shallow lake drying out due to hydrological drought could be observed invaded with vegetation, and the drying could be mistakenly attributed to an increased wetland vegetation ET.

In the past, there has been a general belief supported by small-scale experiments that wetland vegetation evapotranspiration is far higher than open water evaporation. There were cases where small pot studies were influenced by the surrounding environment. Estimated rates of wetland evapotranspiration as high as three times open water evaporation have been reported. A literature review of studies of evapotranspiration of wetland vegetation indicated that there are diverse opinions on the ratio of wetland vegetation evapotranspiration to evaporation from shallow open water surfaces. Figure 7.1 chronologically depicts various measurements and estimates of ratio of evapotranspiration from wetland vegetation to open water evaporation for many locations through the years. The reported ratios of wetland vegetation evapotranspiration to open water evaporation range from 0.75 for cattails (German 2000) in Florida to 3.7 for water hyacinth (Timmer and Weldon 1968) in Florida. Recent studies generally show the trend of reporting where wetland ET is not markedly higher or lower than shallow open water evaporation. In India, after conducting tests in 0.36 m^2 and 0.6 m deep concrete tanks, Mehta and Sharma (1976) reported a 2.16 ratio for *Typha angustata* evapotranspiration and open water evaporation. Weert and Kamerling (1974) discuss the experiment of Penfound and Earle stating that the experimental containers were placed on a laboratory balcony making clear that border effects influenced the reported rate of water hyacinth ET in Louisiana being over three times that of open water. Lafleur and Roulet (1992) studied evapotranspiration from a sedge-covered mineral-rich fen and sphagnum carpet mineral-poor fen in the southern part of the Hudson Bay in Canada. They concluded that both fen surfaces evaporate less than open water in contradiction to much of the previous literature.

Idso (1981), after reviewing literature and conducting experiments, concluded that evapotranspiration from an expansive water body does not increase measurably by the introduction of wetland vegetation. Based on experimental study in 0.6 m^2 and 0.75 m deep tanks in Fort Pierce, Florida, Debusk et al. (1983) concluded that ET rates of water hyacinth increased with plant density. They also pointed out wetland vegetation ET was correlated with open water evaporation, solar radiation, and mean daily temperature. Snyder and Boyd (1987) studied evapotranspiration of water hyacinth and *Typha latifolia* in Alabama using 5.8 m^2 and 0.41 m deep tanks. They concluded that the ratio of evapotranspiration to open water evaporation was 1.75 and 1.62 for water hyacinth and *Typha latifolia*, respectively. They remarked that evapotranspiration of Typha was highly correlated with solar radiation and leaf area index. After reviewing Snyder and Boyd's results, Idso and Anderson (1988) indicated that the high ratio of emergent macrophyte ET to open water evaporation is due to the contribution of the peripheral or side area of the experimental vegetation clump.

Actual evapotranspiration of wetlands that do not dry out 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.

7.2 Wetland Evapotranspiration Measurement and Modeling

7.2.1 Lysimeters

The use of constructed wetlands for storage and water quality improvements has become a developing technology. A fully automated lysimeter system was designed and installed at the Everglades Constructed Wetland Project site in south Florida (Abtew and Hardee 1993; Abtew and Obeysekera 1995). A 2-year lysimeter study of evapotranspiration in three wetland environments (cattails, mixed marsh vegetation, and open water) was conducted in the Everglades Nutrient Removal Project, a

Fig. 7.2 (**a**) Cattails, (**b**) mixed marsh, and (**c**) open water lysimeters in a multiple cell-constructed wetland (Abtew 2005, photograph provided by South Florida Water Management District)

constructed wetland in south Florida (26° 38′ N, 80° 25′ W). Two types of three fully automated lysimeters were designed to measure in situ evapotranspiration losses from three types of wetland features. One lysimeter simulated cattails (*Typha domingensis*) in cattail marsh, the second lysimeter simulated mixed marsh vegetation (spike rush, duck potato, arrowhead, maiden cane, and saw grass) in a mixed vegetation marsh, and the third simulated open water in an open water cell of the constructed wetland. Figure 7.2 depicts cattail, mixed vegetation, and open water lysimeters. The purpose of the lysimeter study was to provide ET measurements for water budget computation for the wetland and also to calibrate ET models from high-resolution meteorology data measured at the site.

The main component of each lysimeter system is a circular polyethylene tank, 3.53 m in diameter and 91 cm deep, analog depth gage, inflow and outflow pumps, flow meters, data loggers, battery, solar panel, and a complete weather station. The tank was placed on a frame at an elevation to maintain the rim of the tank a few inches above water of the surrounding wetland with fluctuating water levels. Soils from the surrounding marsh were filled in the tank to a depth of 60 cm. Cattails or mixed marsh vegetation was planted in the two respective lysimeters from the surrounding wetland. The third lysimeter was filled with water imitating the surrounding wetland. 15-min, hourly, or daily evapotranspiration (ET) was derived from the system based on Eq. 7.1:

$$\mathrm{ET} = D_t - D_{t-1} + R_\mathrm{f} + I - O \tag{7.1}$$

where D_t and D_{t-1} are depth of water level at time t and $t-1$ measured from the bottom, R_f is rainfall, I is inflow pumping, and O is outflow pumping.

The lysimeters started and stopped operating at different dates with 688 common days of observations. An average rate of 3.7 mm day^{-1} evaporation from open water, 3.5 mm day^{-1} evapotranspiration from mixed marsh, and 3.6 mm day^{-1} evapotranspiration from cattails was reported (Abtew 1996). Figure 7.3a depicts open water evaporation; Fig. 7.3b, c depicts mixed marsh and cattail evapotranspiration, respectively, from the respective lysimeters. A conclusion from the study was that there is no significant difference between evapotranspiration of wetland vegetation and evaporation from a shallow water body. The design of the lysimeters is discussed in Chap. 3.

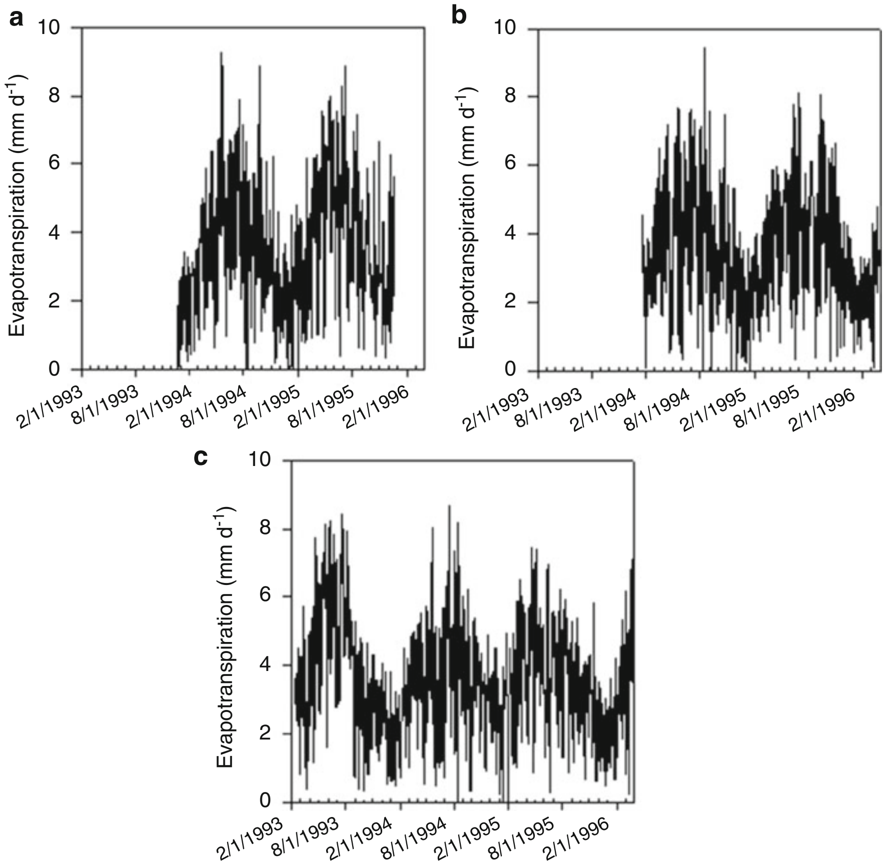

Fig. 7.3 (**a**) Daily open water evaporation, (**b**) daily mixed marsh evapotranspiration, and (**c**) daily cattails evapotranspiration

7.2.2 Wetland ET Modeling from Lysimeter Observations

Since the lysimeters were not designed for long-term ET monitoring, there was the need to calibrate and test ET models for long-term data acquisition. The results of the lysimeter study were applied to test and calibrate six evaporation and evapotranspiration estimation models, from simple to complex, using data acquired from weather stations at the lysimeter sites. The methods include two newly developed methods: the simple Abtew method and a radiation–temperature method. The Turc method was modified and applied by substituting daily maximum air temperature for daily average air temperature in the original equation. The Penman combination and the Penman–Monteith methods were also calibrated and applied. The simple method required a single-measured parameter and achieved comparable performance to the complex methods with numerous input requirements, as shown in Abtew (1996) and Chaps. 6 and 8.

Lysimeter-measured daily ET and weather parameters showed that ET was correlated with solar radiation ($r = 0.73$), vapor pressure deficit (0.59), minimum relative humidity ($r = 0.46$), and maximum air temperature ($r = 0.36$). Most of the variance is explained by solar radiation.

Since solar radiation explains much of the variation in wetland evapotranspiration and open water evaporation in south Florida, the potential exists to calibrate a simple solar radiation-based estimation equation. An additional advantage of solar radiation-based equations is that it eliminates the need for net solar radiation, which is more challenging to collect good quality data. Equation 7.2, which is referred to the simple Abtew method or equation, was developed from the three lysimeters' daily evapotranspiration and evaporation data and radiation measurements at the site:

$$\mathrm{ET} = K_1 \frac{R_\mathrm{s}}{\lambda} \tag{7.2}$$

where ET is daily evapotranspiration from wetland or shallow open water or potential evapotranspiration (mm day^{-1}), R_s is solar radiation (MJ m^{-2} day^{-1}), λ is latent heat of vaporization of water (MJ kg^{-1}), and K_1 is a coefficient (0.53). The mm day^{-1} unit is derived from the fact that a kilogram of water is 1,000 cc (10^6 mm^3) and a square meter is 10^6 mm^2. Equation 7.2 estimates correlated to the average of the three lysimeters' observations with a regression coefficient of 0.7 and standard error of estimate less than 1 mm day^{-1}. The simple Abtew equation is cited, and applications in many regions are published (Abtew 1996; Xu and Singh 2000; Abtew et al. 2003; Delclaux and Coudrain 2005; Oudin et al. 2005; Shoemaker and Sumner 2006; Melesse et al. 2009; Zhai et al. 2009; Setegn et al. 2011; Enku et al. 2011).

Equation 7.3 was calibrated to estimate ET from solar radiation (R_s) and daily maximum temperature. K_3 is constant with a unit (56°C). T_max is daily maximum air temperature in °C. Equation 7.3 daily ET estimates correlated to the average of the three lysimeters' observations with a regression coefficient of 0.7 and standard error of estimate less than 1 mm:

$$\mathrm{ET} = \frac{1}{K_3} \frac{R_\mathrm{s}}{\lambda} T_\mathrm{max} \tag{7.3}$$

Equation 7.4 is a modified Turc equation where maximum evaporation was estimated from solar radiation and air temperature. In the original Turc equation, average air temperature is used while here maximum air temperature was applied as it showed more correlation to evapotranspiration in south Florida than average air temperature. The coefficient K_2 has similar value of 0.013 as in Turc equation for computing potential evapotranspiration in a humid region:

$$\mathrm{ET_P} = K_2 \frac{(23.89 R_\mathrm{s} + 50) T_\mathrm{max}}{(T_\mathrm{max} + 15)} \tag{7.4}$$

where ET is maximum evapotranspiration (mm day^{-1}), K_2 is a dimensionless coefficient, R_s is solar radiation (MJ m^{-2} day^{-1}), and T_{max} is maximum daily air temperature (°C). Equation 7.4 estimates correlated to the average of the three lysimeters' observations with a regression coefficient of 0.7 and standard error of estimate less than 1 mm day^{-1}.

The Priestley–Taylor equation (Eq. 7.5) is also a relatively simpler method except that it requires net solar radiation data as input. Good quality net solar radiation data acquisition requires intensive maintenance and calibration of the radiometer sensor. Experience has shown that solar radiation measurements with pyranometers are better quality than net solar radiation measurement with radiometers:

$$\mathrm{ET} = \alpha \frac{\Delta}{(\Delta + \gamma)\lambda}(R_n - G) \tag{7.5}$$

where ET is in mm day^{-1}, is slope of the vapor pressure curve (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}) , R_n is net radiation (MJ m^{-2} day^{-1}) , and G is heat flux (MJ m^{-2} day^{-1}). The coefficient (α) in the Priestley–Taylor equation was modified from 1.26 to 1.18 to fit the model with least error of estimation and regression coefficient of 0.7 (Abtew and Obeysekera 1995).

The Penman combination equation for estimating reference evapotranspiration from grass or alfalfa in SI units is given in Eq. 7.6 (Allen et al. 1989):

$$\mathrm{ET} = \frac{1}{\lambda} \frac{\Delta(R_n - G) + \gamma 6.43(a_w + b_w u_2)(e_a - e_d)}{\Delta + \gamma} \tag{7.6}$$

where ET is in mm day^{-1}, e_a is saturation vapor pressure, e_d is actual vapor pressure, u_2 is wind speed at 2-m height in m s^{-1}, and a_w and b_w are empirical coefficients, also referred as wind coefficients, estimated as a function of day of the year. Since all other parameters in the Penman combination equation are measured or derived from measured parameters, the coefficients a_w and b_w were used as calibration coefficients to fit the model to the three lysimeters' observations with a regression coefficient of 0.7. In doing so, the regional values of the two coefficients were developed based on the normal probability density function equation applied by J.W. Wright (Allen et al. 1989). Equations 7.7 and 7.8 were calibrated and used to estimate the wind coefficients where J is day of the year (Abtew and Obeysekera 1995):

$$a_w = 0.10 + 0.2 \exp\left\{-\left[\frac{J - 173}{58}\right]^2\right\} \tag{7.7}$$

$$b_w = 0.04 + 0.2 \exp\left\{-\left[\frac{J - 243}{80}\right]^2\right\} \tag{7.8}$$

The performance of ET estimation models is dependent on the temporal distribution of weather parameters. Characteristic of south Florida weather is that there is sunshine due to the lower latitude and prevalent clear skies, high humidity, high temperatures, and low wind speed. Air temperature and solar radiation increase from north to south. Data from a weather station at the middle of the region is presented to display mean temporal variation of the main variables that determine the rate of evapotranspiration. Figure 7.4a depicts monthly mean of daily mean, minimum, and maximum air temperatures (1994–2010). Mean daily air temperature is 22.9°C with mean daily minimums and maximums of 18.7 and 28.2°C, respectively.

The peak months for temperature are May through October with relatively cooler temperatures from November through April. Relative humidity and wind speed are also main variables in determining the rate of ET. South Florida is a humid region with the daily maximum relative humidity averaging 96% and showing little variation from month to month. The mean and minimum relative humidity shows a pattern with the minimum in April and May. Minimum daily humidity declines from December through April and starts rising in the summer months. Figure 7.4a depicts mean monthly average air temperature (mean, minimum, and maximum). Figure 7.4b depicts mean monthly average relative humidity (mean, minimum, and maximum).

Air temperature and humidity determine saturation and actual vapor pressure. The difference between saturation and actual vapor pressure is the vapor pressure deficit which indicates available capacity of the air to hold moisture when available.

Figure 7.5a depicts solar radiation, vapor pressure deficit (×15), and wetland ET (×2). May is the peak solar radiation and peak ET month increasing from the preceding months and receding to the following months through December. An almost similar pattern is shown by vapor pressure deficit.

Generally, the region has low wind speed averaging 3.2 $\mathrm{m\,s^{-1}}$. Peak wind speed is in March with minimum wind speed in July and August. The seasonal variation of wind speed is depicted in Fig. 7.5b. In south Florida, rare events such as tropical storms as hurricanes can generate wind speed as high as 50 $\mathrm{m\,s^{-1}}$ for several hours; ET is not so important on those days as continuous rain and no sunshine conditions prevail (Abtew and Iricanin 2008). For the purpose of ET estimation, those extraordinary wind speeds need to be excluded from mean wind speed calculation to avoid bias in ET estimation.

7.2.3 Bowen Ratio–Energy Balance Method

In a U.S. Geological Survey (USGS) study, nine sites in the marshes of the Everglades in south Florida were instrumented with sensors to determine evapotranspiration from different wetland features using the Bowen ratio–energy balance method (German 2000). Field data with varying lengths of record, from 1996 to 2000, is available on the USGS web site (http://fl.water.usgs.gov/Abstracts/wri00_4217_german.html, accessed 12 December 2011). Pictures of Bowen ratio–energy

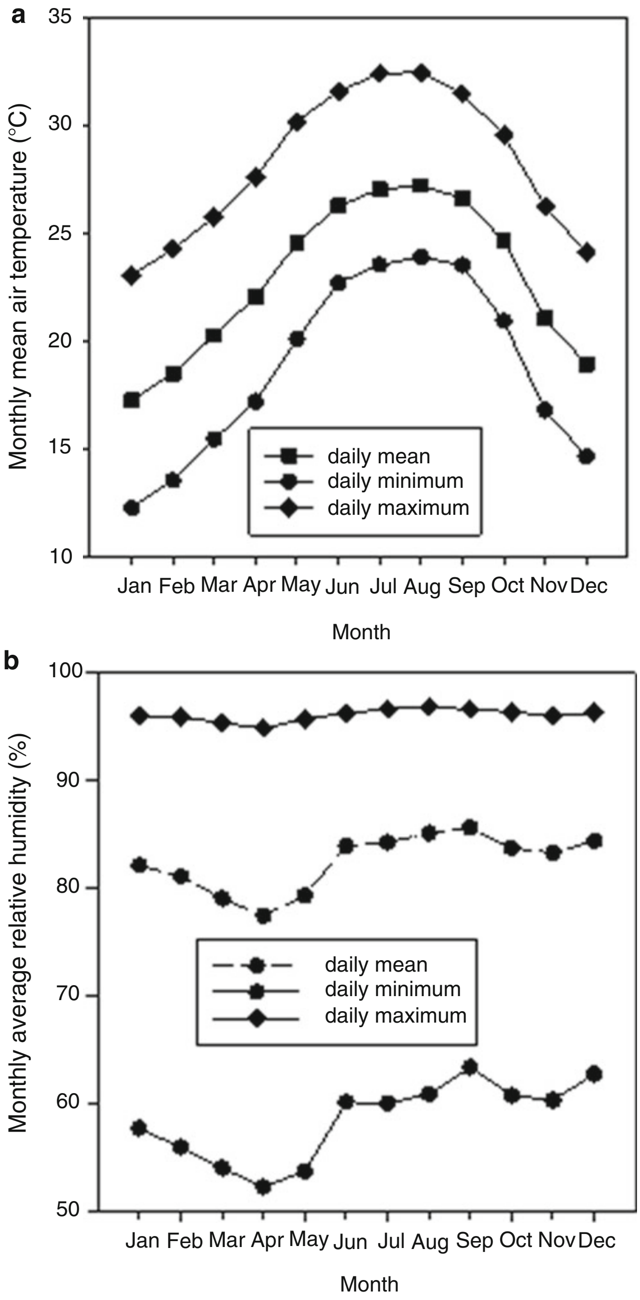

Fig. 7.4 Mean, minimum, and maximum (**a**) air temperature and (**b**) relative humidity

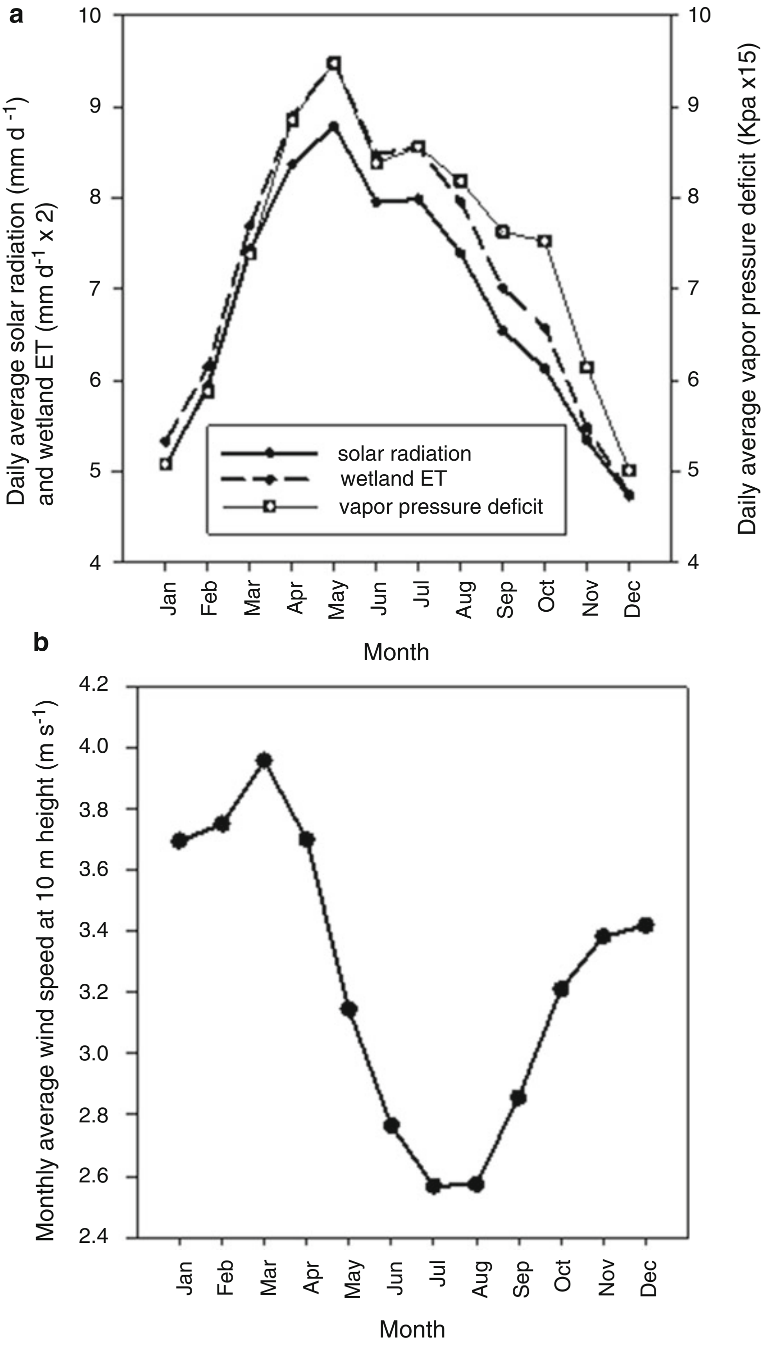

Fig. 7.5 (**a**) Solar radiation, vapor pressure deficit (×15), wetland ET (×2), and (**b**) mean wind speed

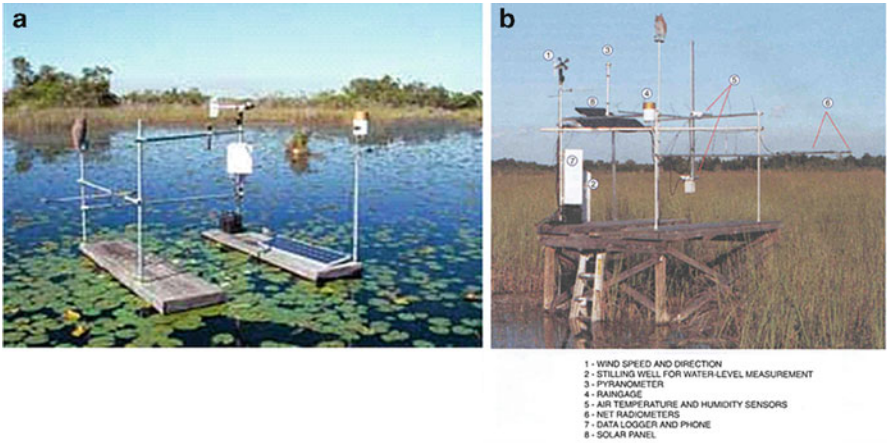

Fig. 7.6 Bowen ratio–energy balance instrumentation at (**a**) water-dominated marsh (**b**) vegetation-dominated marsh (German 2000; U.S. Geological Survey)

balance instrumentation at open water and vegetated sites are shown in Fig. 7.6 (German 2000). A location map for the sites is shown in Chap. 6. 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% (Dugas et al. 1991). The following equation (Eq. 7.9) represents the Bowen ratio–energy balance:

$$\lambda E = \frac{R_\mathrm{n} - G}{1 + \beta} \tag{7.9}$$

where λ is latent heat of vaporization of water, E is evaporation rate, R_n is net radiation flux, G is soil heat flux, and β is Bowen ratio, which is the ratio of sensible heat (H) to latent heat (E) and derived from Eq. 7.10.

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} \tag{7.10}$$

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

The Bowen ratio instrumentation includes temperature and humidity differential with height measurements. At the Bowen ratio–energy balance ET measurement sites, sensor measurements were collected every 30 s and averaged to 15 or 30 min. Comparison of measured and model estimates of a parameter provides cross validation when the model is calibrated independently. In this case, the simple Abtew equation was calibrated with lysimeter ET measurements from a separate

Table 7.1 Comparison of Bowen ratio-measured ET and simple Abtew equation model-estimated wetland ET (Abtew 2005)

Site	No. of months	r	MSE mm^2	Bowen ratio-measured ET mm day^{-1}	Model-estimated ET mm day^{-1}	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 saw grass
5	24	0.83	0.76	3.91	3.77	Medium saw grass; dry part of some years
6	32	0.80	0.50	3.63	3.80	Medium saw grass
7	58	0.82	0.99	4.19	3.97	Sparse saw grass
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 saw grass; dry part of each year

study. Statistical comparisons of Bowen ratio–energy balance measured at each of the nine sites and the simple Abtew method-estimated average daily wetland ET for each month are presented in Table 7.1. Solar radiation data used by the simple Abtew equation was obtained from the instrumentation at each of the Bowen ratio sites, except site 2 where solar radiation data was used from a nearby weather station.

Table 7.1 presents the number of months with data (n), correlation coefficient (r), mean square error (MSE), and mean daily ET. The statistics provide a comparison between the Bowen ratio–energy balance-measured ET and the simple Abtew equation-estimated wetland ET. Site 1, the cattail marsh site, showed the smallest mean square error. The two sites with the largest difference in measured and estimated ET were sites 2 and 3. The Bowen ratio instrumentation at these open water-dominated marshes was different. While at the other seven sites, air temperature and humidity differentials were measured between two points in the air, 91–152 cm apart; at sites 2 and 3, air temperature and humidity differentials were measured 91–121 cm above the water surface. The mean estimated daily ET from all nine sites by Eq. 7.2 (3.79 mm day^{-1}) has a difference of less than 2% from the mean measured ET (3.85 mm day^{-1}) for all nine sites.

7.2.4 Penman–Monteith Method

The Penman–Monteith equation (Eq. 7.11) for evapotranspiration estimation from vegetation surfaces has numerous measured, derived, and estimated inputs, as shown in Table 6.3 and Chap. 3 (Monteith 1965):

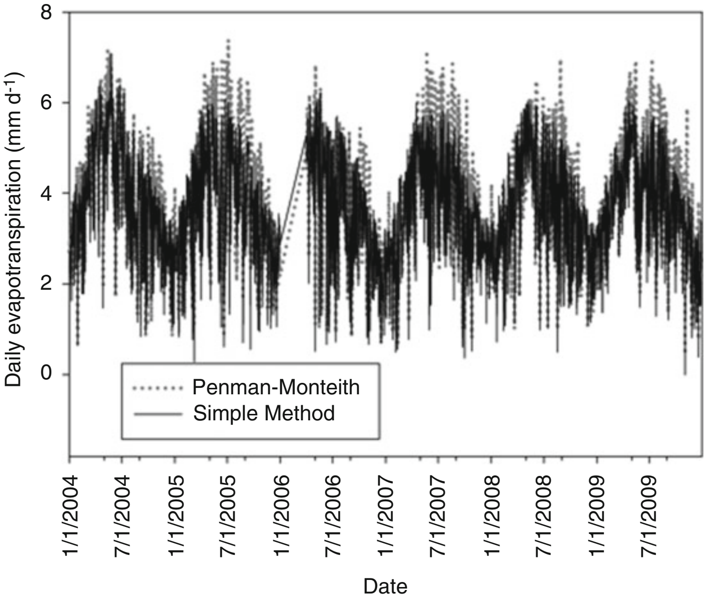

Fig. 7.7 Penman–Monteith and simple Abtew method evapotranspiration estimation from south Florida wetland

$$\mathrm{ET} = \frac{1}{\lambda}\frac{\Delta(R_\mathrm{n} - G) + \rho c_\mathrm{p}(e_\mathrm{a} - e_\mathrm{d})\frac{1}{r_\mathrm{a}}}{\Delta + \gamma\left(1 + \frac{r_\mathrm{c}}{r_\mathrm{a}}\right)} \tag{7.11}$$

where ET is in mm day^{-1}, $e_\mathrm{a} - e_\mathrm{d}$ is vapor pressure deficit in kPa, r_a is aerodynamic resistance in s m^{-1}, and r_c is canopy resistance in s m^{-1}. Details of the input in to the Penman–Monteith equation are given in Chap. 6. Application of this method to a wetland in south Florida is given as illustration of method application. The Penman–Monteith method was applied in south Florida to estimate evapotranspiration from wetlands, and the daily estimates are compared with estimates by the simple Abtew method (Fig. 7.7). The period of analysis is from January 1, 2002, to December 31, 2009, with data missing for the 3 months of January, February, and March of 2006.

The Penman–Monteith method estimates are higher for the hot and wet months of May through October with annual estimates of 1,421 mm compared to 1,335 mm for the simple Abtew method. Monthly analysis clearly displays the difference between the two methods (Fig. 7.8).

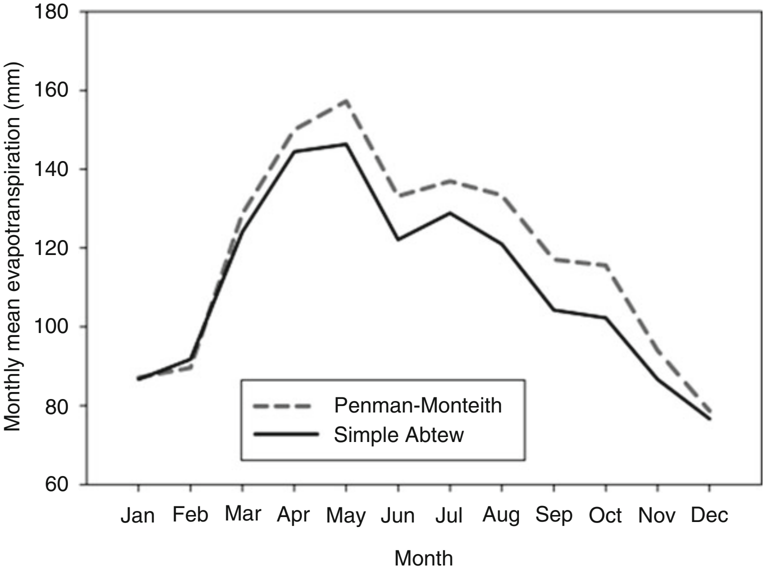

Fig. 7.8 Comparison of mean monthly evapotranspiration estimated by the Penman–Monteith and the simple Abtew method (2004–2009)

7.3 Summary

Mixed wetland vegetation and open water features of wetlands have led to many hypotheses on the rate of evapotranspiration from such features. In the past, many believed the rates are far higher than open water evaporation. Recent studies have shown that wetland evapotranspiration in many regions is not that much different from open water evaporation. The rate of evapotranspiration is controlled not only by the availability of water and the presence of vegetation but also by the availability of energy, by capacity of the air to hold moisture, and by rates of energy and mass transfer. In south Florida and many regions, simple models based on solar radiation and temperature could provide low-cost wetland evapotranspiration, open water evaporation, and potential evapotranspiration estimates. Detail of application of complex methods is presented in Chap. 6. Remote sensing applications for evapotranspiration estimation are presented in Chaps. 10, 11, and 12.

Acknowledgements We would like to acknowledge Ed German from U.S. Geological Survey for taking the photographs shown in Fig. 7.6a, b.

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