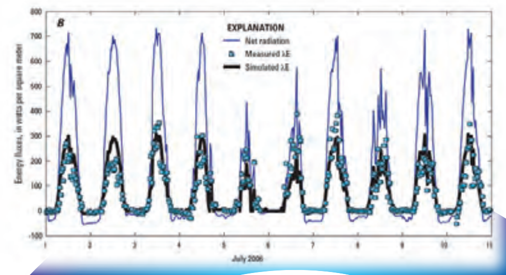
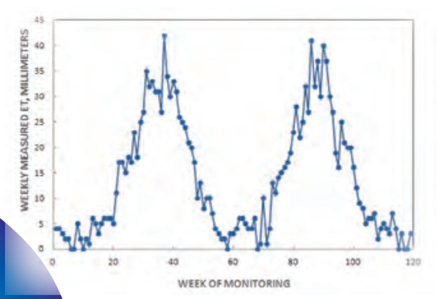
Prepared in Cooperation with the
New Jersey Pinelands Commission

Measurement and Simulation of Evapotranspiration at a Wetland Site in the New Jersey Pinelands

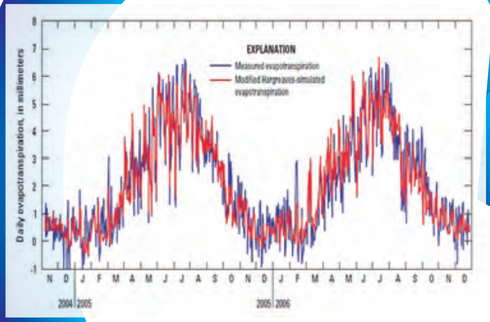


Daily energy fluxes



Weekly evapotranspiration

Data logging



Daily measured and simulated evapotranspiration

Sensor arrays

Evapotranspiration flux tower

Scientific Investigations Report 2012–5118

U.S. Department of the Interior
U.S. Geological Survey

Measurement and Simulation of Evapotranspiration at a Wetland Site in the New Jersey Pinelands

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U.S. Department of the Interior
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Acknowledgments

Access to the evapotranspiration (ET) monitoring site was arranged by Christian Bethman, Superintendent of Brendan T. Byrne State Forest, whose assistance in clearing the site and providing road improvements to this previously inaccessible area is gratefully acknowledged. The authors gratefully acknowledge U.S. Geological Survey (USGS) colleagues Amanda Garcia and Amy Swancar for providing helpful comments that greatly improved this report, and William Ellis, Ruth Larkins and Gregory Simpson for their assistance with report preparation and illustrations. Special thanks are extended to Richard W. Edwards, USGS Electronics Technician, whose technical organization, skill, and resourcefulness ensured a successful ET monitoring campaign at this remote location.

Contents

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Tables

Conversion Factors and Vertical Datum

Multiply	By	To obtain
	Length	
millimeter (mm)	0.039	inch (in.)
centimeter (cm)	0.394	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.386	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flux	
millimeter per day (mm/d)	0.03937	inch per day (in/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
watt per square meter (W/m^2)	0.0342 at 0 °C	millimeter per day (mm/d)
watt per square meter (W/m^2)	0.0354 at 25 °C	millimeter per day (mm/d)
watt per square meter (W/m^2)	0.0359 at 50 °C	millimeter per day (mm/d)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Energy	
joule (J)	0.239	calorie
joule (J)	0.0000002	kilowatt-hour (kWh)
	Mass	
gram (g)	0.035	ounce, avoirdupois (oz)
kilogram (kg)	2.294	pound (lb)
	Pressure	
kilopascal (kPa)	0.010	atmosphere, standard (atm)
kilopascal (kPa)	0.296	inch of mercury at 60°F (in Hg)
kilopascal (kPa)	0.145	pound-force per inch (lbf/in)
	Density	
gram per cubic centimeter (g/cm^3)	62.422	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

List of Symbols

a	An empirical coefficient equal to a value of 0.0135
b	An empirical coefficient equal to a value of 17.8
B	Bowen ratio, equal to the ratio of sensible and latent heat fluxes
C_p	Specific heat capacity of air, in J/(g·C)
d	Momentum displacement height of vegetation, in m
e	Vapor pressure, in kPa
e_s	Saturation vapor pressure, in kPa
E	Evapotranspiration rate, in g/(m^2·s)
ET	Evapotranspiration rate, in mm/yr
ET_a	Reference ET, in the same water evaporation units as R_a
F	Factor used in krypton hygrometer correction that accounts for molecular weights of air and atmospheric abundance of oxygen, equal to 0.229 g·°C/J
G	Soil heat flux at land surface, in W/m^2
h	Canopy height, in m
H	Sensible heat flux, in W/m^2
H_{BREB}	Sensible heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method, in W/m^2
K_o	Extinction coefficient of hygrometer for oxygen, in m^3/(g·cm)
K_{RS}	An empirical coefficient usually estimated as 0.16 and 0.19 for inland and coastal areas, respectively
K_w	Extinction coefficient of hygrometer for water, in m^3/(g·cm)
P_a	Atmospheric pressure, in Pa

q	Specific humidity, in g water/g moist air
r_h	Aerodynamic resistance, in seconds per meter
R_a	Extraterrestrial radiation, in the same water evaporation units as ET_a
R_d	Gas constant for dry air, equal to 0.28704 J/°C/g
R_n	Net radiation, in W/m^2
R_s	Incoming solar radiation on land surface, in the same water evaporation units as ET_a
S	Change in storage of energy in the biomass, air, and any standing water, in W/m^2
T_a	Air temperature, in °C
TC	Daily air temperature, in °C
TR	Daily temperature range, in °C
T_s	Sonic temperature, in °C
u	Lateral wind speed along coordinate x-direction, in m/s
v	Lateral wind speed along coordinate y-direction, in m/s
w	Wind speed along coordinate z-direction, in m/s
x	One of two orthogonal coordinate directions within a plane parallel to canopy surface
y	One of two orthogonal coordinate directions within a plane parallel to canopy surface
z	Coordinate direction perpendicular to canopy surface
z_s	Height of sensors above land surface, in m
z_m	Roughness length of canopy for momentum, in m
α	Priestley-Taylor coefficient, dimensionless
Δ	Slope of the saturation vapor pressure curve, in kPa/°C
η	Angle of rotation about the z-axis to align u into the x-direction on the x-y plane, in radians
γ	Psychrometric constant, in kPa/°C
λ	Latent heat of vaporization, in J/g
λE	Latent heat flux, in W/m^2

λE_{BREB}	Latent heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method, in W/m^2
λE_{REB}	Latent heat flux as estimated by the residual energy-budget variant of the eddy-covariance method, in W/m^2
θ	Angle of rotation in the y-direction to align w along the z-direction, in radians
ρ	Air density, in g/m^3
ρ_v	Vapor density, in g/m^3
μ	Ratio of molecular weight of air to molecular weight of water
σ	Ratio of vapor density (ρ_v) to air density (ρ)

Measurement and Simulation of Evapotranspiration at a Wetland Site in the New Jersey Pinelands

By David M. Sumner[1], Robert S. Nicholson[1], and Kenneth L. Clark[2]

Abstract

Evapotranspiration (ET) was monitored above a wetland forest canopy dominated by pitch-pine in the New Jersey Pinelands during November 10, 2004–February 20, 2007, using an eddy-covariance method. Twelve-month ET totals ranged from 786 to 821 millimeters (mm). Minimum and maximum ET rates occurred during December–February and in July, respectively. Relations between ET and several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) were explored. Net radiation ($r^2 = 0.72$) and air temperature ($r^2 = 0.73$) were the dominant explanatory variables for daily ET. Air temperature was the dominant control on evaporative fraction with relatively more radiant energy used for ET at higher temperatures. Soil moisture was shown to limit ET during extended dry periods. With volumetric soil moisture below a threshold of about 0.15, the evaporative fraction decreased until rain ended the dry period, and the evaporative fraction sharply recovered. A modified Hargreaves ET model, requiring only easily obtainable daily temperature data, was shown to be effective at simulating measured ET values and has the potential for estimating historical or real-time ET at the wetland site. The average annual ET measured at the wetland site during 2005–06 (801 mm/yr) is about 32 percent higher than previously reported ET for three nearby upland sites during 2005–09. Periodic disturbance by fire and insect defoliation at the upland sites reduced ET. When only undisturbed periods were considered, the wetland ET was 17 percent higher than the undisturbed upland ET. Interannual variability in wetlands ET may be lower than that of uplands ET because the upland stands are more susceptible to periodic drought conditions, disturbance by fire, and insect defoliation. Precipitation during the study period at the nearby Indian Mills weather station was slightly higher than the long-term (1902–2011) annual mean of 1,173 millimeters (mm), with 1,325 and 1,396 mm of precipitation in 2005 and 2006, respectively.

Introduction

Water budgets are fundamental to the understanding of hydrologic systems. If the various components of the water budget can be quantified, including inflows, outflows, and changes in stored water, then a more complete understanding and evaluation of a hydrologic system becomes possible. In the New Jersey Pinelands area (fig. 1), wetlands and aquatic habitats are supported by discharge from the Kirkwood-Cohansey aquifer system, and detailed water budgets of the area are needed in order to develop a quantitative understanding of aquifer-wetland-stream interactions at the watershed scale. As described by Rhodehamel (1970), groundwater flow in the Pinelands is initiated as aquifer recharge, primarily in upland areas, and follows regional and local subsurface flow paths, with local flow paths terminating as aquifer discharge to wetlands and streams. Temporal variations in recharge affect aquifer interactions with wetlands and streams, as demonstrated by investigations in the New Jersey Pinelands by Modica (1998) and Walker and others (2011). Quantification of aquifer recharge on a seasonal basis, therefore, is needed to understand the dynamics of aquifer interactions with wetlands and streams.

Evapotranspiration (ET) is an important component of the hydrologic budget in the Pinelands, and ET variability exerts considerable control over the amount of water available seasonally for aquifer recharge. On an average annual basis, ET from the Pinelands has been estimated to exceed recent Statewide public water use in New Jersey by more than a factor of two (based on data presented in Rhodehamel, 1979, and Hutson and others, 2004). In spite of its significance, the seasonal variability of ET and the relations between ET and other environmental factors in this ecologically important region are poorly quantified. Methods for direct measurement of ET have been developed (Dyer, 1961; Tanner and Greene, 1989) and used in a number of settings (Moore, 1976; Sumner, 1996; Stannard, 1993). Estimating seasonally variable ET rates for specific time periods at the watershed scale in the Pinelands requires site-specific data.

The U.S. Geological Survey (USGS) conducted a study of ET in the Pinelands, in cooperation with the New Jersey

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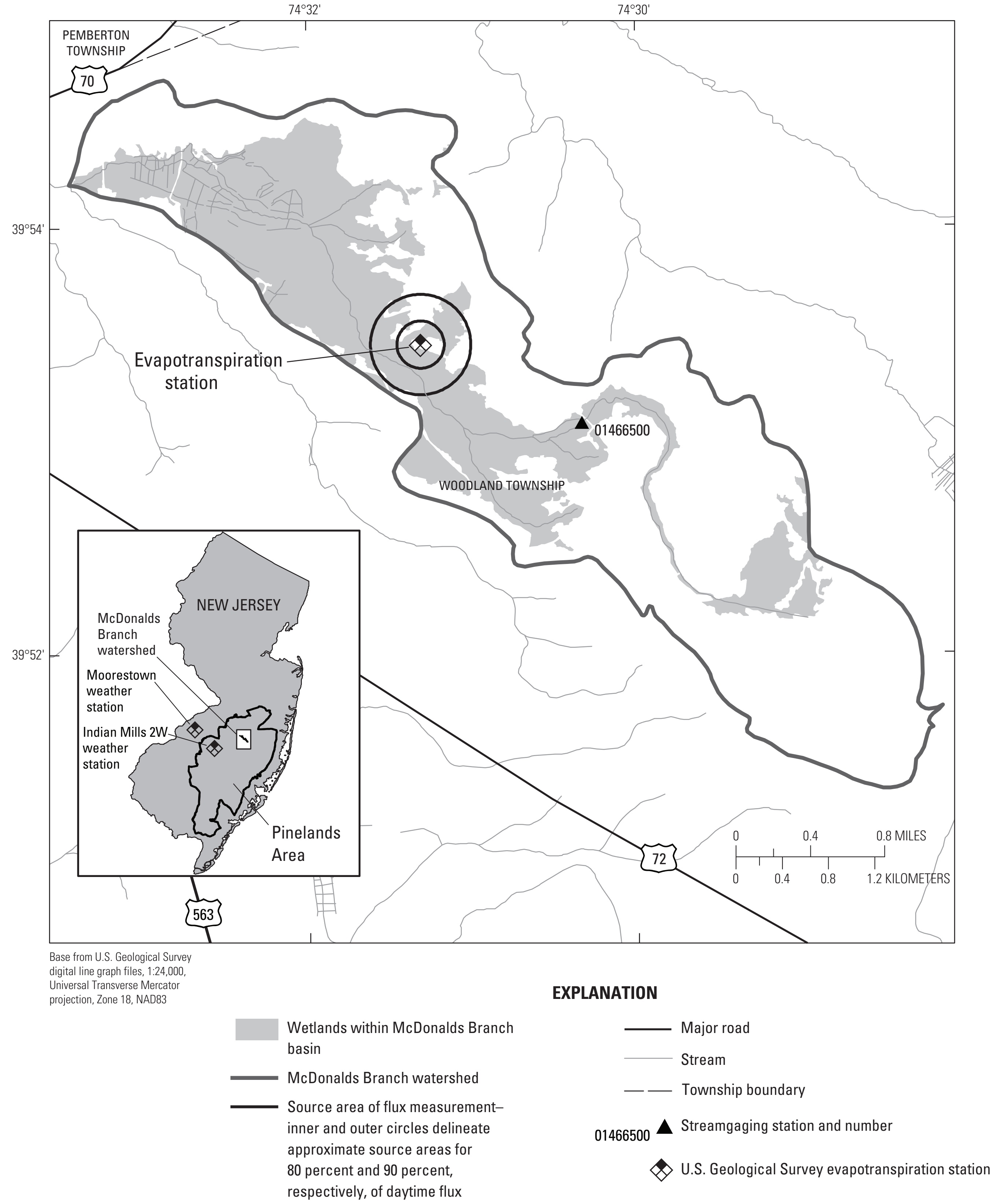
[1] U.S. Geological Survey

[2] U.S. Department of Agriculture, Forest Service, New Lisbon, New Jersey



Base from U.S. Geological Survey digital line graph files, 1:24,000, Universal Transverse Mercator projection, Zone 18, NAD83

Figure 1. Location of McDonalds Branch basin, selected weather stations, and evapotranspiration station, Pinelands area, New Jersey.

Pinelands Commission, to quantify the temporal variability of ET and to examine relations between ET and environmental variables as part of the Kirkwood-Cohansey Project (Pinelands Commission, 2003). During November 10, 2004–February 20, 2007, ET was monitored above a wetland forest canopy in the McDonalds Branch basin in Burlington County, New Jersey (fig. 1). Meteorological and eddy-covariance sensors were deployed on a 24.5-meter (m) tower, and groundwater levels and soil moisture at the site were also monitored. Three models were evaluated for their utility in simulating ET, and a time series of weekly ET rates was developed for the measurement period.

Purpose and Scope

This report presents the results of an ET study at the wetland forest site in the Pinelands area. It includes an explanation of the methods used, an analysis of the flux source area, measured ET rates, relation of these rates to environmental variables, a comparison of wetland ET with ET measured in upland areas in the Pinelands, and a comparison of ET measured during the 27-month monitoring period to ET simulated using selected models. The results of this study can be used in conjunction with information on other components of the water budget to develop an understanding of temporal variations in water exchange among different compartments of the Pinelands hydrologic system. Results can also be extended to formulate approaches for estimating ET in the Pinelands during other time periods using commonly measured environmental variables. Values for ET are shown in figures and are listed in tables.

Previous Investigations

ET in the New Jersey Pinelands has been the subject of published investigations for more than 115 years. The following summary of previous investigations provides context for the present study. Determination of ET played a key role in early water-supply planning in the region. Vermeule (1894) approximated monthly and annual ET for southern New Jersey watersheds on the basis of calculations made using empirical relations between precipitation and runoff in other East Coast watersheds. These calculations were used to estimate the safe yield for Joseph Wharton's 1891 proposal to divert flow from more than 1,191 square kilometers of "the great pine belt" of southern New Jersey and deliver it to the cities of Camden and Philadelphia (City of Philadelphia, 1892). Wood (1937) quantified interception (the amount of rain or snow stored on leaves and branches and eventually evaporated back to the atmosphere), an important component of the hydrologic cycle that contributes to evapotranspiration, in an oak-pine forest in the Pinelands. A number of studies were conducted during the 1950s and 1960s to understand the effects of forest management practices on water resources in the Pinelands as part of a research initiative referred to as the "Pine Region Hydrological Research Project" (Buell, 1955); related research continued into the 1970s. Lull and Axley (1958) studied ET in different upland vegetative communities in the Pinelands by measuring soil moisture changes, but significant differences were not found among the communities. Barksdale (1958) concluded that ET in the lower Delaware River Basin accounted for about 50 percent of precipitation. Rhodehamel (1970) found this 50-percent value applicable to the Pinelands area and estimated the mean annual ET rate in the Pinelands on the basis of the long-term difference between precipitation and runoff to be 572 millimeters per year (mm/yr), or about 50 percent of precipitation. Rhodehamel (1979) found reasonable agreement between this ET rate and estimated ET rates from other investigations in the Pinelands and vicinity. Summer ET rates in hardwood-dominated and cedar-dominated wetlands in the Pinelands were estimated from water-table fluctuations, and no differences in the ET rates of these communities were detected (Ballard, 1971; Buell and Ballard, 1972). ET rates in lowland shrub communities were found to be lower than those of lowland tree communities (Buell and Ballard, 1972). ET rates were shown to be greater in lowland (wetland) areas of the Pinelands, where water is more available to plants, than in upland areas (Ballard and Buell, 1975). Ballard (1979) examined these differences in an energy flux context and concluded that in wetland tree areas, the net summer loss of groundwater discharge through ET was 250 millimeters (mm).

ET has been estimated as part of water-supply and availability studies in the New Jersey Coastal Plain. Mean ET rates in the major drainage areas of the New Jersey Coastal Plain were estimated by Vowinkel and Foster (1981) as the long-term difference between mean precipitation and mean runoff. Estimates of ET (presented as "water loss") for basins partly within the Pinelands ranged from 414 to 653 mm/yr (Vowinkel and Foster, 1981). More detailed examinations of water budgets that include ET in selected drainage areas that are within the New Jersey Coastal Plain and at least partly within the Pinelands are presented in a series of reports by Watt and Johnson (1992), Johnsson and Barringer (1993), Watt and others (1994), Johnson and Watt (1996), Watt and others (2003), and Gordon (2004). Although the methods used to estimate ET in these studies vary somewhat, the ET estimates were all based on the concept of water-budget closure and are, therefore, consistent with estimates of other water-budget components. The ET estimates from the previously mentioned series of reports range from 563 to 658 mm/yr. As part of the Kirkwood-Cohansey Project, the USGS assessed hydrologic conditions in three basins in the Pinelands during 2004–06, including the McDonalds Branch basin where the present ET study site is located (Walker and others, 2011). Results of the hydrologic assessment of the McDonalds Branch basin include estimates of water-budget components that can be used to evaluate the veracity of ET measurements presented in this report.

Other recent investigations have examined the physiological responses of a variety of Pinelands shrub and tree species to hydrologic stress, fire, and insect defoliation. As part of their research on carbon and fire dynamics in the Pinelands, Clark and others (2010, 2011) measured ET flux using an eddy covariance method at an oak-dominated upland site and two pine-dominated upland sites in the Pinelands. They observed that ET at the oak-dominated upland site was slightly greater in summer and lower in winter than ET at the pitch pine-dominated upland site and that ET averaged 51 to 62 percent of annual precipitation at the sites when they were undisturbed. Additional flux monitoring demonstrated the effects of fire and insect defoliation on ET and water-use efficiency at the three sites; annual ET at one of the defoliated sites was as low as 419 mm/yr, 37 percent of incident precipitation (Clark and others, 2011). When all years were considered, maximum seasonal leaf area index at these sites explained 82 and 80 percent of the variation in daily ET during the summer at the oak- and pine-dominated sites, respectively. Results of the study by Clark and others (2011) indicate that gypsy moth defoliation disturbance in 2007 may have resulted in a temporary increase in aquifer recharge of approximately 9 percent in upland forests throughout the Pinelands. Schafer (2011) examined changes in stomatal conductance in response to drought, defoliation, and mortality in an upland oak/pine forest in the Pinelands. Drought caused reductions in canopy-level conductance, and corresponding reductions in ET, with the magnitude of the effect varying by species.

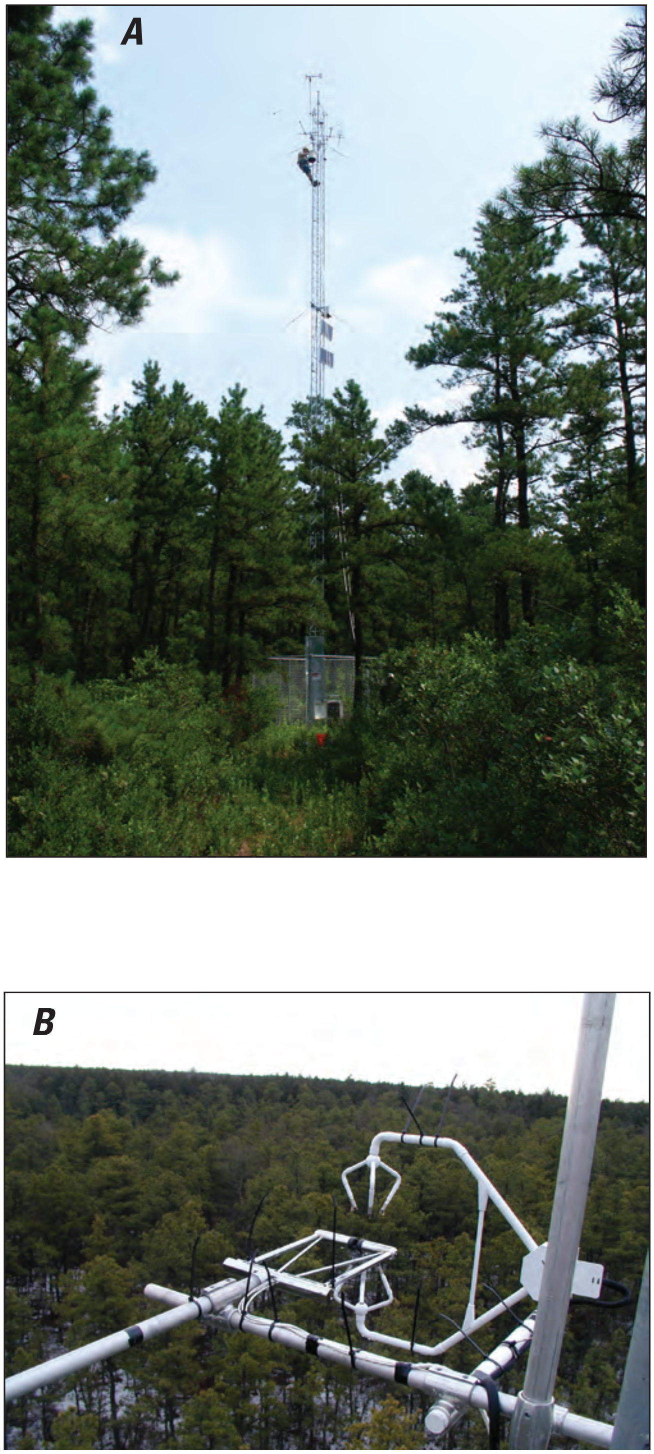


Figure 2. Evapotranspiration station at a pitch-pine lowland site in the McDonalds Branch basin, Pinelands area, New Jersey: A, tower with instrumentation (Photograph by Anthony S. Navoy, USGS) and B, krypton hygrometer (foreground) and sonic anemometer (background) mounted at top of tower at evapotranspiration station (Photograph by Robert S. Nicholson, USGS).

Methods for Measurement and Simulation of Evapotranspiration

ET was measured at a site within McDonalds Branch basin (fig. 1) using the eddy-covariance method (Dyer, 1961; Baldocchi and others, 1988; and Tanner and Greene, 1989). The site chosen for the ET station is within a pitch-pine lowland stand. Canopy vegetation at the site is dominated by *Pinus rigida* (pitch pine) that reaches a maximum height of about 15 m. Understory vegetation is dominated by *Gaylussacia frondosa* (dangleberry), *Kalmia angustifolia* (sheep laurel), *Eubotrys racemosa* (fetterbush), and *Xerophyllum asphdeloides* (turkeybeard). Vegetation types in nearby areas of cedar swamp are dominated by *Chamaecyparis thyroides* (Atlantic white cedar) and *Shagnum spp* (shagnum moss); nearby areas of hardwood swamp are dominated by *Acer rubrum* (red maple) and *Nyssa silvatica* (blackgum). Depth to the water table at the site fluctuates between about 0.5 to 1.5 meters (m) below land surface although parts of the surrounding area exhibit standing water during wet periods. The site of the ET station is adjacent to one of the vegetation plots used by Laidig and others (2010a, 2010b) to develop models for predicting the distribution of wetland vegetation on the basis of hydrologic conditions. Eddy-covariance instrumentation was deployed on a 24.5 m tall Rohn 45G communications-type tower at the site (fig. 2), and 30-minute data were collected for an 833-day period from November 10, 2004, to February 20, 2007. Other meteorological and hydrologic instrumentation also was deployed on or around the tower to collect data for ET models and to provide ancillary data for the eddy-covariance analysis. The instrumentation used in the study is described in table 1. Measured values of ET were used to calibrate ET models or for comparison with model results.

Measurement of Evapotranspiration

Evapotranspiration can be measured above a forest canopy by using a variety of methods. The method selected for this study is the eddy-covariance method.

Eddy-Covariance Method

The eddy-covariance method (Dyer, 1961; Tanner and Greene, 1989) was used to measure two components of the energy budget of the plant canopy: latent and sensible heat fluxes. Latent heat flux (λE) is the energy removed from the canopy in the liquid-to-vapor phase change of water and is the product of the heat of vaporization of water (λ) and the ET rate (E). Sensible heat flux (H) is the heat energy removed from/added to the canopy as a result convective transport along a temperature gradient between the canopy and the air. Both latent and sensible heat fluxes are transported by turbulent eddies in the air that are generated by a combination of frictional and convective forces. The energy available to generate turbulent fluxes of vapor and heat is equal to the net radiation (R_n) less the sum of the heat flux into the soil surface (G) and the change in storage (S) of energy in the biomass, air, and any standing water. The energy involved in fixation of carbon dioxide is usually negligible (Brutsaert, 1982, p. 144). Net radiation is the difference between incoming radiation (shortwave solar radiation and longwave atmospheric radiation) and outgoing radiation (reflected shortwave and surface-emitted longwave radiation). Energy is transported to and from the base of the canopy by conduction through the soil. Assuming that net horizontal advection of energy is negligible, the energy-budget equation, for a control volume extending from land surface to a height z_s at which the turbulent fluxes are measured, takes the following form:

$$R_n - G - S = H + \lambda E \quad , \tag{1}$$

where
the left-hand side of equation 1 represents the available energy, the right-hand side represents the turbulent fluxes, and

R_n is net radiation to/from plant canopy, in watts per square meter;
G is soil heat flux at land surface, in watts per square meter;
S is change in storage of energy in the biomass, air, and in any standing water, in watts per square meter;
H is sensible heat flux at height z_s above land surface, in watts per square meter;

Table 1. Description of study instrumentation.

[CSI, Campbell Scientific, Inc.; HS, Hydrological Services Pty Ltd; REBS, Radiation and Energy Balance Systems, Inc.; RMY, R.M. Young, Inc.; psi, pounds per square inch; negative height is depth below land surface; number of instruments listed in parentheses]

Characteristic	Instrument	Height above land surface (meters)
Evapotranspiration	CSI eddy-covariance system including Model CSAT3 three-dimensional sonic anemometer and Model KH2O krypton hygrometer (1)	22.1
Air temperature/relative humidity	CSI Model HMP45 temperature and relative humidity probe (1)	22.3
Solar radiation	LI-COR, Inc., Model LI200 pyranometer (1)	22
Net radiation	REBS Model Q-7.1 net radiometers (2)	22
Soil moisture	CSI Model CS615 Water content reflectometer (1)	0 – -0.3
Precipitation	HS Model TB3 tipping bucket rain gage (1)	14.2
Water level in well	In-Situ Model MiniTROLL 5 pounds per square inch pressure sensor and datalogger unit (1)	-2
Wind speed and direction	RMY Model 05305VM Wind Monitor (1)	24.7
Data logging	CSI Model 10X data loggers (2), 12-volt 100 amp-hour deep-cycle batteries (2), 50 watt solar panels (2)	0–1, 0–1, 10–13

λE is latent heat flux at height z_s above land surface, in watts per square meter; and the sign convention is such that R_n and G are positive downwards and H and λE are positive upwards.

The eddy-covariance method is a conceptually simple, one-dimensional approach for measuring the turbulent fluxes of vapor and heat above a surface. For the case of vapor transport above a flat, level landscape, the time-averaged product of measured values of vertical wind speed (w) and vapor density (ρ_v) is the estimated vapor flux (ET rate) during the averaging period, assuming that the net lateral advection of vapor is negligible. Because of the insufficient accuracy of instrumentation available for measurement of actual values of wind speed and vapor density, this procedure generally is performed by monitoring the fluctuations of wind speed and vapor density about their means, rather than monitoring their actual values. This formulation is represented by the following equations:

$$E = \overline{w\rho_v} = \overline{(\overline{w} + w')(\overline{\rho_v} + \rho_v')} \quad , \tag{2}$$

$$= \overline{\overline{w}\,\overline{\rho_v}} + \overline{\overline{w}\rho_v'} + \overline{w'\overline{\rho_v}} + \overline{w'\rho_v'} \quad , \tag{3}$$

and

$$\overline{w'\rho_v'} = covariance\,(w, \rho_v) \quad , \tag{4}$$

where

E is ET rate, in grams per square meter per second;

w is vertical wind speed, in meters per second;

ρ_v is vapor density, in grams per cubic meter; and overbars and primes indicate means over the averaging period and deviations from means, respectively.

The first term of equation 3 is approximately zero because mass-balance considerations dictate that mean vertical wind speed perpendicular to the surface is zero; this conclusion is based on an assumption of constant air density (correction for air-density fluctuations are noted later in this report). The second and third terms are zero based on the definition that the mean fluctuation of a variable is zero. Therefore, it is apparent from equation 4 that vertical wind speed and vapor density have to be correlated for a non-zero vapor flux to exist. The turbulent eddies that transport water vapor (and sensible heat) produce fluctuations in both the direction and magnitude of vertical wind speed. The ascending eddies must on average be moister than the descending eddies for ET to occur; that is, upward air movement has to be positively correlated with vapor density, and downward air movement must be negatively correlated with vapor density.

Source Area of Measurements

The source area for a turbulent flux measurement is defined as the area (upwind of the measurement location) contributing to the measurement. The source area can consist of a single vegetative cover if that cover is adequately extensive. This condition is met if the given cover extends sufficiently far upwind such that the atmospheric boundary layer has equilibrated with the cover from ground surface to at least the height of the instrumentation. If this condition is not met, the flux measurement is a composite of fluxes from two or more covers within the source area.

Schuepp and others (1990) provide an estimate of the source area for turbulent flux measurements and the relative contributions within the source area on the basis of an analytical solution of a one-dimensional (upwind) diffusion equation for a uniform surface cover. In this approach, source area varies with instrument height (z_s), zero displacement height (d), roughness length for momentum (z_m), and atmospheric stability. The instrument height for the turbulent flux measurements in this study was 22.1 m. Campbell and Norman (1998, p. 71) proposed empirical relations for zero displacement height (d~0.65h) and roughness length for momentum (z_m~0.10h), where h is the canopy height. A uniform canopy height of 15 m was assumed in this analysis. The source area estimates were made assuming mildly unstable conditions typical of daytime conditions when heat and vapor fluxes are highest; the Obukhov stability length (Businger and Yaglom, 1971) was set equal to -10 m. About 80 percent and 90 percent of the source area for the daytime turbulent flux measurements were estimated to be within upwind distances of about 205 and 435 m, respectively, as shown in figures 1 and 3. The source area during the generally more stable nighttime conditions could extend considerably further, but turbulent fluxes are relatively small in the absence of sunlight. The source area is forested throughout, but includes wetlands with pitch pine and cedar swamps and uplands covered by oak and pine (fig. 1). Because the measured turbulent fluxes are representative of upwind

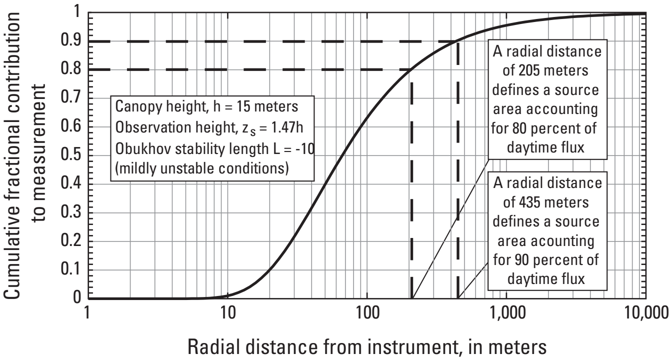


Figure 3. Radial extent of source area for daytime turbulent flux measurements. (Produced using the method of Schuepp and others, 1990)

land covers, the vegetative composition of the source area will change with varying wind direction. For example, wind directions ranging clockwise from southeast to west would provide flux measurements almost exclusively representative of forested wetland; other wind directions provide flux measurements representative of varying mixtures of wetland and upland forests. In this study, discrepancies between measured ET and simulated ET from models that are invariant with wind direction are examined as a function of wind direction. This comparison will show the degree to which differences in ET between the two forest communities can be discerned with the available measurements.

Instrumentation

Instrumentation capable of high-frequency resolution is used in applications of the eddy-covariance method because of the relatively high frequency of the turbulent eddies that transport water vapor. Instrumentation included a three-axis sonic anemometer and a krypton hygrometer to measure or infer variations in wind speed and vapor density, respectively (fig. 2; table 1). The sonic anemometer relies on three pairs of sonic transducers to detect wind-induced changes in the transit time of emitted sound waves and to infer fluctuations in wind speed in three orthogonal directions. The measurement path length between transducer pairs is 10.0 centimeter (cm) (vertical) and 5.8 cm (horizontal); the transducer path angle from the horizontal is 60 degrees. In contrast to some sonic anemometers used previously (Sumner, 1996), the transducers of this improved anemometer are not permanently destroyed by exposure to moisture and thus are suitable for long-term deployment. Operation of the anemometer used in this study ceases when moisture on the transducer disrupts the sonic signal but recommences upon drying of the transducers.

The hygrometer relies on the attenuation of ultraviolet radiation, emitted from a source tube, by water vapor in the air along the 1-cm path to the detector tube. The instrument pathline was laterally displaced 10 cm from the midpoint of the sonic-transducer pathlines (fig. 2B). Hygrometer voltage output is proportional to the attenuated radiation signal, and fluctuations in this signal can be related to fluctuations in vapor density by Beer's Law (Weeks and others, 1987). Similar to the anemometer, the hygrometer ceases data collection when moisture obscures the windows on the source or detector tubes. Also, the tube windows become "scaled" with exposure to the atmosphere, resulting in a loss of signal strength. The hygrometer is designed such that vapor density fluctuations are accurately measured in spite of variable signal strength; however, if signal strength declines to near-zero values, the fluctuations cannot be discerned. Periodic cleaning of the sensor windows (performed monthly in this study) with a cotton swab and distilled water restores signal strength. Eddy-covariance instrument-sampling frequency was 8 Hertz (Hz) with 30-minute averaging periods. The eddy-covariance instrumentation was placed about 7.1 m above the tree canopy. The 8-Hz data were processed into 30-minute composites and stored in a data logger near ground level.

Flux measurements are made in the constant-flux inertial sublayer, in which lateral variations in vertical flux are negligible, to be representative of the surface cover. Measurements made in the underlying roughness sublayer can reflect individual roughness elements (for example, individual trees or gaps between trees) rather than the composite surface cover (Monteith and Unsworth, 1990). Garratt (1980) defines the lower boundary of the inertial sublayer to occur where the difference of the instrument height (z_s) and the zero displacement height (d) is much greater than the roughness length for momentum (z_m). Employing the empirical relations of Campbell and Norman (1998) for zero displacement height and roughness length for momentum, and assuming that "much greater than" implies greater by a factor of eight (8), leads to an instrument height requirement of z_s greater than 1.45h. A factor of about 1.47 was used in the present study.

Calculation of Turbulent Fluxes

Latent heat flux was estimated based on a modified form of equation 4:

$$\lambda E = \lambda \left((1 + \mu\sigma)(\overline{w'\rho'_v} + \frac{\rho_v H}{\rho C_p (T_a + 273.15)}) + \frac{F K_0 H}{K_w (T_a + 273.15)} \right) \quad , (5)$$

where

λE is latent heat flux, in watts per square meter;
λ is latent heat of vaporization of water, estimated as a function of temperature (Stull, 1988), in joules per gram;
μ is ratio of molecular weight of air to molecular weight of water;
σ is ratio of vapor density (ρ_v) to air density (ρ);
ρ is air density, estimated as a function of air temperature, total air pressure, and vapor pressure (Monteith and Unsworth, 1990), in grams per cubic meter;
H is sensible heat flux, in watts per square meter;
C_p is specific heat capacity of air, estimated as a function of temperature and relative humidity (Stull, 1988), in joules per gram per degree Celsius;
T_a is air temperature, in degrees Celsius;
F is a factor that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen, equal to 0.229 gram-degree Celsius per joule;
K_o is extinction coefficient of hygrometer for oxygen, estimated as -0.0045 cubic meters per gram per centimeter (Tanner and others, 1993);
K_w is extinction coefficient of hygrometer for water, equal to the manufacturer-calibrated

value, in cubic meters per gram per centimeter; and overbars and primes indicate means over the averaging period and deviations from the means, respectively.

The $(1 + \mu\sigma)$ multiplier and the second term of the right-hand side of equation 5 account for temperature-induced fluctuations in air density (Webb and others, 1980), and the third term accounts for the sensitivity of the hygrometer to oxygen (Tanner and Greene, 1989).

Similar to vapor transport, sensible heat can be estimated by:

$$H = \rho C_p \overline{w' T_a'} \quad . \tag{6}$$

The sonic anemometer is capable of measuring "sonic" temperature on the basis of the dependence of the speed of sound on this variable (Kaimal and Businger, 1963; Kaimal and Gaynor, 1991). Schotanus and others (1983) related the sonic sensible heat, based on measurement of sonic temperature fluctuations, to the true sensible heat given in equation 6. Those researchers included a correction for the effect of wind blowing normal to the sonic acoustic path that has been incorporated directly into the anemometer measurement by the manufacturer (E. Swiatek, Campbell Scientific, Inc., written commun., 1998), leading to a simplified form of the Schotanus and others (1983) formulation given by

$$\overline{w' T_a'} = \overline{w' T_s'} - 0.51 \ \overline{(T_a + 273.15)} \ \overline{w'q'} \quad , \tag{7}$$

where

T_s is the sonic temperature, in degrees Celsius; and

q is specific humidity, in grams of water vapor per gram of moist air.

On the basis of the relation between specific humidity and vapor density (Fleagle and Businger,1980),

$$q \approx \frac{\rho_v R_d (T_a + 273.15)}{P_a} \quad , \tag{8}$$

where

$R_{d,}$ is the gas constant for dry air (0.28704 joules per degree Celsius per gram) and

$P_{a,}$ is atmospheric pressure, in pascals (assumed to remain constant at 100,534 pascals at top of tower about 58 meters above sea level).

Equation 7 can be expressed in terms of fluctuations in the hygrometer-measured water vapor density rather than fluctuations in specific humidity as

$$\overline{w'T_a'} = \frac{\overline{(T_a + 273.15)}}{\overline{(T_s + 273.15)}} \ (\overline{w'T_s'} - 0.51 R_d \overline{(T_a + 273.15)}^2 \ \overline{w'\rho_v'} \ / \ P_a) \quad . \tag{9}$$

Estimation of turbulent fluxes (eqs. 5 and 6) relies on an accurate measurement of velocity fluctuations perpendicular to the lateral airstream. The study area is relatively flat and level, indicating that the airstream is approximately perpendicular to gravity and the sonic anemometer was oriented with respect to gravity with a bubble level. Measurement of wind speed in three orthogonal directions with the sonic anemometer used in this investigation allowed for a more refined orientation of the collected data with the natural coordinate system through mathematical coordinate rotations. The magnitude of the coordinate rotations are determined by the components of the wind vector in each 30-minute averaging period. The wind vector is composed of three time-averaged components (*u, v, w*) in the three coordinate directions (*x, y, z*). Direction z initially was approximately oriented vertically (with respect to gravity) and the other two directions were arbitrary. Tanner and Thurtell (1969) and Baldocchi and others (1988) outline a procedure in which measurements made in the initial coordinate system are transformed into values consistent with the natural coordinate system. First, the coordinate system is rotated by an angle η about the z-axis to align *u* into the *x*-direction on the *x-y* plane. Next, rotation by an angle θ is performed about the y-direction to align w along the *z*-direction. These rotations force *v* and *w* equal to zero; therefore, u is pointed directly into the airstream. A third rotation is sometimes used in complex situations (such as a curving airstream around a mountain) to force $\overline{v'w'}$ equal to zero, although Baldocchi and others (1988) indicate that two rotations generally are adequate, and two rotations were used in the current study.

Consistency of Measurements with Energy Budget

Previous investigators (Moore, 1976; Lee and Black, 1993; Bidlake and others, 1996; Goulden and others, 1996; Sumner, 1996; Twine and others, 2000; German, 2000; and Foken, 2008) have described a recurring problem with the eddy-covariance method: a frequent discrepancy of the measured latent and sensible heat fluxes with the energy-budget equation (eq. 1). The usual case is that measured turbulent fluxes ($H + \lambda E$) are less than the measured available energy (R_n - G - S). Turbulent fluxes measured above a coniferous forest by Lee and Black (1993) accounted for only 83 percent of available energy. Possible explanations for the observed discrepancy in the measured turbulent fluxes include a sensor frequency response that is insufficient to capture high-frequency eddies; an averaging period insufficient to capture low-frequency eddies; drift in the absolute values of anemometer and hygrometer measurements, resulting in statistical non-stationarity within the averaging period; lateral advection of energy; a discrepancy in the measurement points for the wind and vapor density sensors; and overestimation of available energy. Several researchers (Moore, 1976; Goulden and others, 1996; German, 2000) have shown that the eddy-covariance method obtains better energy-budget closure in windy conditions than during calm conditions.

Twine and others (2000) performed an experiment using multiple models of eddy-covariance sensors and net radiometers to measure energy fluxes from a grassland and observed a systematic energy closure discrepancy (turbulent fluxes less than available energy) of 10 to 30 percent. Their conclusion was that eddy-covariance measurements should be adjusted for energy-budget closure. Two common alternatives to adjust turbulent flux measurements for energy-budget closure are to (1) preserve the Bowen ratio or (2) preserve the measured sensible heat flux. Twine and others (2000) indicate a preference for the Bowen ratio approach but state that “the method for obtaining closure appears to be less important than assuring that eddy-covariance measurements are consistent with conservation of energy.” The Bowen ratio alternative assumes that the ratio of turbulent fluxes is adequately measured by the eddy-covariance method. The energy-budget equation (eq. 1), along with turbulent fluxes (H and λE) measured using the standard eddy-covariance method are used to produce corrected (H_{BREB} and λE_{BREB}) turbulent fluxes in this “Bowen ratio energy-budget variant” of the eddy-covariance method as indicated in equations 10 to 12. On the basis of equation 12, this variant fails when the Bowen ratio is close to -1 and the denominator approaches zero.

$$R_n - G - S = H_{BREB} + \lambda E_{BREB} = \lambda E_{BREB}(1 + B) \quad , \qquad (10)$$

where the Bowen ratio (B) is given by

$$B = \frac{H}{\lambda E} \quad , \qquad (11)$$

Rearranging eq. 10,

$$\lambda E_{BREB} = \frac{R_n - G - S}{1 + B} \quad , \qquad (12)$$

$$H_{BREB} = R_n - G - S - \lambda E_{BREB} \quad . \qquad (13)$$

The second alternative for adjustment of fluxes for energy-budget closure used in this study assumes that the sensible heat flux measured by the standard eddy-covariance method is correct but that latent heat flux is underestimated. Therefore, the corrected latent heat flux is computed as a residual of the energy budget (eq. 1). This “residual energy-budget” variant of the eddy-covariance method is

$$\lambda E_{REB} = R_n - G - S - H \quad . \qquad (14)$$

Energy generally enters the soil surface and (or) any standing water and is stored in the biomass and air during the day and released at night. Implementation of equations 10 to 14 was facilitated by using daily composites of terms in these equations and assuming that soil heat flux and changes in energy storage in the biomass, air, and any standing water were negligible at this site over a diurnal cycle. Therefore, although eddy-covariance flux measurements were made at 30-minute resolution, only daily or coarser ET estimates incorporate energy-budget closure considerations. Use of a daily compositing interval of flux values in this study allowed for neglect of those terms of the energy budget that were not measured (soil heat flux and biomass/air/standing water energy storage). However, during periods of rapid temperature changes (for example, cold front passage), the net soil heat flux and the net change in energy stored in the biomass/air/standing water over a diurnal cycle may not be negligible.

As mentioned previously, missing 30-minute turbulent flux data can result from scaling of hygrometer windows and from moisture on the anemometer or hygrometer. These data need to be estimated prior to construction of daily composites of turbulent fluxes. In the present study, regression analysis of measured 30-minute turbulent flux and net radiation data was used to estimate unmeasured values of 30-minute turbulent fluxes. Additionally, both H and λE were set to zero during periods of rainfall when rainwater on eddy-covariance and net radiation sensors resulted in missing or corrupted data. An assumption of negligible turbulent fluxes during rainfall events was considered reasonable because of the cloudy and, therefore, low net radiation conditions generally prevalent during rain.

Simulation of Evapotranspiration

Several models were evaluated for their utility in estimating ET. The eddy-covariance instrumentation can have extended periods of non-operation, as discussed previously. However, more robust meteorological and hydrologic instrumentation (sensors for measurement of net radiation, air temperature, relative humidity, solar radiation, wind speed, soil moisture, and water-table depth) provide nearly uninterrupted data. ET models, calibrated to measured turbulent flux data and based on continuous meteorological and hydrologic data, can be used to fill gaps in measured data, providing continuous estimates of ET. Additionally, ET models can provide insight into the cause-and-effect relation between the environment and ET— in particular, relations among water-table depth, soil moisture, and ET. Finally, some ET models can provide estimates of maximum (potential or reference) ET under conditions of optimal moisture availability.

Measurement of ET using the eddy-covariance method is resource intensive, so it is practical to use the results of short-term studies to develop and verify ET models that can then be used to estimate ET for other time periods and to understand the cause-and-effect nature of evaporative processes. The utility of different models is related to the model assumptions or the data used by the models. For example, results of a model that is indifferent to wind direction can be compared with measurements to help determine if ET is related to wind direction. A model that requires only temperature data can be used to estimate historical variability in ET using readily available long-term temperature records. The three ET models explored are described below.

Priestley-Taylor Equation

Physics-based ET models generally rely on the work of Penman (1948), who developed an equation for evaporation from wet surfaces that is based on energy budget and aerodynamic principles. That equation has been applied to estimate ET from well-watered, dense agricultural crops (reference or potential ET). In Penman's equation, the transport of latent and sensible heat fluxes from a "big leaf" to the sensor height is subject to an aerodynamic resistance. The big leaf assumption implies that the plant canopy can be conceptualized as a single source of both latent and sensible heat at a given height and temperature. Inherent in the Penman approach is the assumption of a net one-dimensional, vertical transport of vapor and heat from the canopy. The Penman equation is

$$\lambda E = \frac{\Delta(R_n - S) + \dfrac{\rho C_p (e_s - e)}{r_h}}{\Delta + \gamma} , \qquad (15)$$

where

Δ is slope of the saturation vapor-pressure curve, in kilopascals per degree Celsius;
e_s is saturation vapor pressure, in kilopascals;
e is vapor pressure, in kilopascals;
r_h is aerodynamic resistance, in seconds per meter;
γ is the psychrometric "constant", equal to approximately 0.067 kilopascals per degree Celsius but varying slightly with atmospheric pressure and temperature; and other terms are as previously defined.

The first term is known as the energy term; the second term is known as the aerodynamic term.

Priestley and Taylor (1972) proposed a simplification of the Penman equation for the case of saturated atmosphere ($e = e_s$), for which the aerodynamic term is zero, leaving

$$\lambda E = \frac{\Delta(R_n - S)}{\Delta + \gamma} . \qquad (16)$$

However, Priestley and Taylor (1972) noted that empirical evidence indicates that evaporation from extensive wet surfaces is greater than this amount, presumably because the atmosphere generally does not attain saturation. Therefore, the Priestley-Taylor coefficient, α, was introduced as an empirical correction to the theoretical expression

$$\lambda E = \alpha \frac{\Delta(R_n - S)}{\Delta + \gamma} . \qquad (17)$$

This formulation assumes that the energy and aerodynamic terms of the Penman equation are proportional to each other. The value of α has been estimated to be 1.26, which indicates that under potential ET conditions, where there is no moisture limitation, the aerodynamic term of the Penman equation is about 21 percent of the total latent heat flux. Eichinger and others (1996) have shown that the empirical value of α has a theoretical basis; a nearly constant value of α is expected under the existing range of Earth-atmospheric conditions.

Previous studies (Flint and Childs, 1991; Stannard, 1993; Sumner, 1996) have applied a modified form of the Priestley-Taylor equation. The approach in these studies relaxes the Penman assumption of a free-water surface or a dense, well-watered canopy by allowing α to be less than 1.26 and to vary as a function of environmental factors. The Penman-Monteith equation (Monteith, 1965) is a more theoretically rigorous generalization of the Penman equation that also accounts for a relaxation of the Penman assumptions. However, Stannard (1993) noted that the modified Priestley-Taylor approach to simulation of observed ET rates was superior to the Penman-Monteith approach for a sparsely vegetated site in the semi-arid rangeland of Colorado. Similarly, Sumner (1996) found the modified Priestley-Taylor approach performed better than the Penman-Monteith for a site of herbaceous, successional vegetation in central Florida. The modified Priestley-Taylor approach was evaluated in the present investigation to simulate daily ET. The selected form of α as a function of environmental variables was determined in this study through trial-and-error exploratory data analysis, and the parameterization of a particular form of α was determined using regression with measured daily values of ET.

Hargreaves Equation

The Hargreaves equation (Hargreaves and Allen, 2003) is widely used in agricultural studies in the United States and globally to estimate reference ET. Reference ET is defined as the evapotranspiration from an actively growing, well-watered grass or alfalfa vegetative cover of a specific height range (Allen and others, 2005). The Hargreaves equation is appealing because of the sparse data requirements; only minimum and maximum daily air temperature are required, and these are typically measured at most weather stations. The coefficients and form of the equation are empirical and were developed based on a comparison with ET data from precision weighing lysimeters used with grass land covers. The Hargreaves equation is based on an empirical relation between ET and the two most important explanatory variables for this term—incoming solar radiation and air temperature (eq. 18). Another empirical relation (eq. 19) is used to relate incoming solar radiation to extraterrestrial radiation and a variable highly correlated with cloud cover (daily temperature range). Combining equations 18 and 19 leads to the Hargreaves equation (eq. 20).

$$ET_a = aR_s\,(TC + b) \quad , \tag{18}$$

$$R_s = K_{RS} R_a TR^{0.50} \quad , \tag{19}$$

$$ET_a = aK_{RS} R_a\,(TC + b)\,TR^{0.50} \quad , \tag{20}$$

where

ET_a is reference ET, in the same water evaporation units as R_a (for example, millimeters per day);

R_s is incoming solar radiation on land surface, in the same water evaporation units as ET_a;

R_a is extraterrestrial radiation, in the same water evaporation units as ET_a;

TC is average daily air temperature, in degrees Celsius;

TR is daily temperature range, in degrees Celsius;

a is an empirical coefficient equal to a value of 0.0135;

b is an empirical coefficient equal to a value of 17.8; and

K_{RS} is an empirical coefficient usually estimated as 0.16 and 0.19 for inland and coastal areas, respectively.

Hargreaves and Samani (1985) suggest that the product aK_{RS} be set equal to 0.0023 for reference conditions. R_a can be estimated using an analytical expression of latitude and day of year (Allen and others, 2005). *TC* and *TR* are usually estimated as the average and difference of maximum and minimum daily air temperature, respectively.

In this study, a modified form of the Hargreaves equation was considered to allow for the non-reference conditions. The modification allows the empirical coefficients *a* and *b* of eq. 18 to vary in a regression analysis to best replicate measured daily values of ET and incoming solar radiation. The necessary daily temperature data for this analysis were obtained from measurements at the ET station and also from nearby National Weather Service stations in New Jersey (Moorestown and Indian Mills; National Climatic Data Center, 2012).

North American Regional Reanalysis

The National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) is an effort to create a long-term set of consistent climate data for North America (Mitchell and others, 2004; North American Regional Reanalysis, 2012). NARR is based on a coupled approach to simulation of atmospheric and land-surface processes of energy and mass transfer that assimilates weather data. The period of record of NARR is from 1979 to 2012, and the resolution is 32 kilometers (km) and 3 hours. In the present study, NARR estimates of latent heat flux (at NARR grid centered at 39.75° N. and 74.5° W.) were compared to the values measured at the ET station (39.89° N. and 74.52° W.).

Measurement of Environmental Variables

Meteorological, hydrologic, and vegetative data were collected in the study area as ancillary data required by the energy-budget variant of the eddy-covariance method and as independent variables within an ET model. Meteorological variables monitored included net radiation, air temperature, relative humidity, wind speed, and incoming solar radiation. These data were monitored by data loggers at 15-second intervals, using instrumentation summarized in table 1; the resulting 30-minute means were stored.

Two net radiometers, deployed at a height of 22 m, provided redundant measurement of net radiation at the ET station. Measured values of net radiation were corrected for wind-speed effects as instructed by the instrument manual. About 90 percent of the source area of the net radiation measurement is contained within a radius of three times the height of the sensor above the canopy (Stannard, 1994). Therefore, the measurement of net radiation had a much smaller source area (radius of about 21 m) than did the turbulent flux measurement (about 90 percent of source area within upwind distance of about 450 m during typical daytime conditions). The source area for measured net radiation is composed exclusively of the pitch pine lowlands/cedar swamp typical of forested wetlands in the Pinelands area.

Air temperature and relative humidity were monitored at the ET station at a height of 22.3 m. The slope of the saturation vapor pressure curve (a function of air temperature) was computed in the manner of Lowe (1977), using the measured air temperature. A propeller-type anemometer to monitor wind speed and direction and an upward-facing pyranometer to measure incoming solar radiation were deployed at heights of 24.7 and 22 m, respectively, at the ET station (table 1).

Hydrologic variables that were monitored include precipitation, water-table depth, stream discharge, and soil moisture. Precipitation records were obtained from a tipping-bucket rain gage deployed at a height of 14.2 m at the ET station. Soil moisture at a location at the ET station was monitored using a water content reflectometer probe installed to provide an averaged volumetric soil moisture content within the upper 30 cm of the soil profile. The measured soil moisture values at this single location are not necessarily representative of the watershed or of the source area of the turbulent flux measurements but are presumed to be correlated with generalized wetting and drying conditions. Soil-moisture measurements were made and recorded on the data logger every 30 minutes (table 1).

Water levels in a shallow (3-m depth) observation well at the ET station (USGS well number 051604) were measured at 60-minute intervals using a pressure transducer and recorded. The well is situated 5 m from the ET flux tower. Stream discharge of the McDonalds Branch was measured at 15-minute intervals at an upstream site 1.4 km east of the ET station (USGS station number 01466500; fig. 1). Well-construction data, water-level and stream-discharge data collection methods, water-level data, and stream-discharge data are presented in Walker and others (2011).

Results of Evapotranspiration Measurement and Simulation

Most (73 percent) of the 30-minute resolution eddy-covariance measurements made during the 833-day study period were acceptable and could be used to develop ET models to estimate missing data and discern the effect of environmental variables on ET. Unacceptable measurements resulted from failure of the krypton hygrometer or sonic anemometer and were most extensive (81 percent of missing data) during nighttime hours because dew formation at night is common in this humid climate. This diurnal pattern of missing data was less of a problem than it might appear initially because turbulent fluxes are relatively small during the evening to early-morning hours when solar radiation is zero or low, so errors associated with gap filling do not translate into substantial errors in total ET. The environmental variable that provided the best explanatory value for 30-minute turbulent flux values was net radiation; missing flux data were estimated on the basis of linear regressions between the turbulent fluxes and net radiation for each month of the study (eqs. 21 and 22). This approach reproduced measured 30-minute values of λE and H with r^2 values of 0.80 and 0.84, respectively, and standard errors of 34 and 46 watts per square meter (W/m^2), respectively. The R_n-to-turbulent flux regression coefficients showed considerable consistency for a given month from year to year (fig. 4). Although 27 percent of the 30-minute turbulent flux measurements were gap filled using equations 21 and 22, the fraction of energy flux gap filled was small (5 and 7 percent of λE and H, respectively) because missing data generally occurred during periods of low energy flux.

$$\lambda E = a_i R_n + b_i \quad , \qquad (21)$$

$$H = c_i R_n + d_i \quad , \qquad (22)$$

where

a_i, b_i, c_i, and d_i are coefficients for a given year-month i,
a_i and c_i are unitless, and
b_i and d_i are in watts per square meter.

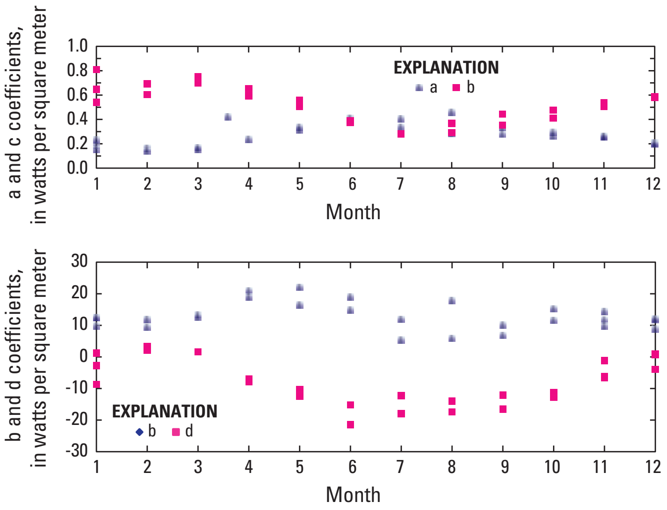


Figure 4. Monthly values of regression coefficients used in equations 21 and 22.

Examples of measured and regression-simulated energy fluxes are shown for July 1–10, 2006, in figure 5. The prominence of daytime over nighttime turbulent fluxes is evident. Also, a strong correspondence between the diurnal and cloudiness-related variations in net radiation and the turbulent fluxes is apparent. The simple linear relations of eqs. 21 and 22 also reproduced the variations in measured turbulent fluxes reasonably. The mean, diurnal pattern of turbulent fluxes and net radiation (fig. 6) indicates that the vast majority of ET occurs during daytime, driven by incoming solar radiation. During average daytime conditions, both latent and sensible heat flux are upward. At night, the surface cools below air temperature, producing a reversal in the direction of sensible heat flux. Although the average, nighttime latent heat flux was slightly upward, dew formation (downward latent heat flux) commonly occurred.

Daytime wind was predominantly from wetland source areas (fig. 1 and fig. 7). The two wind arcs most representative of uplands (350° clockwise to 20° and 90° clockwise to 120°) represent only 15 percent of measured wind directions; other wind directions were primarily representative of wetlands, although to varying degrees. From this analysis and the analysis of the source area (figs. 1 and 3), it is concluded that the source of measured evaporative flux is primarily wetlands.

Energy-budget closure of turbulent fluxes relative to net radiation was examined using weekly, gap-filled composites of the sum of λE and H. As previously discussed, for this analysis, net radiation is equivalent to available energy because it has been assumed that the storage and soil heat flux energy-budget terms are negligible over daily or greater time scales. Energy-budget closure was generally better during relatively windy periods, as indicated in figure 8. Measured and gap-filled 30-minute turbulent fluxes accounted for 77 and 83 percent of mean net radiation values of 101 and 100 W/m^2 for

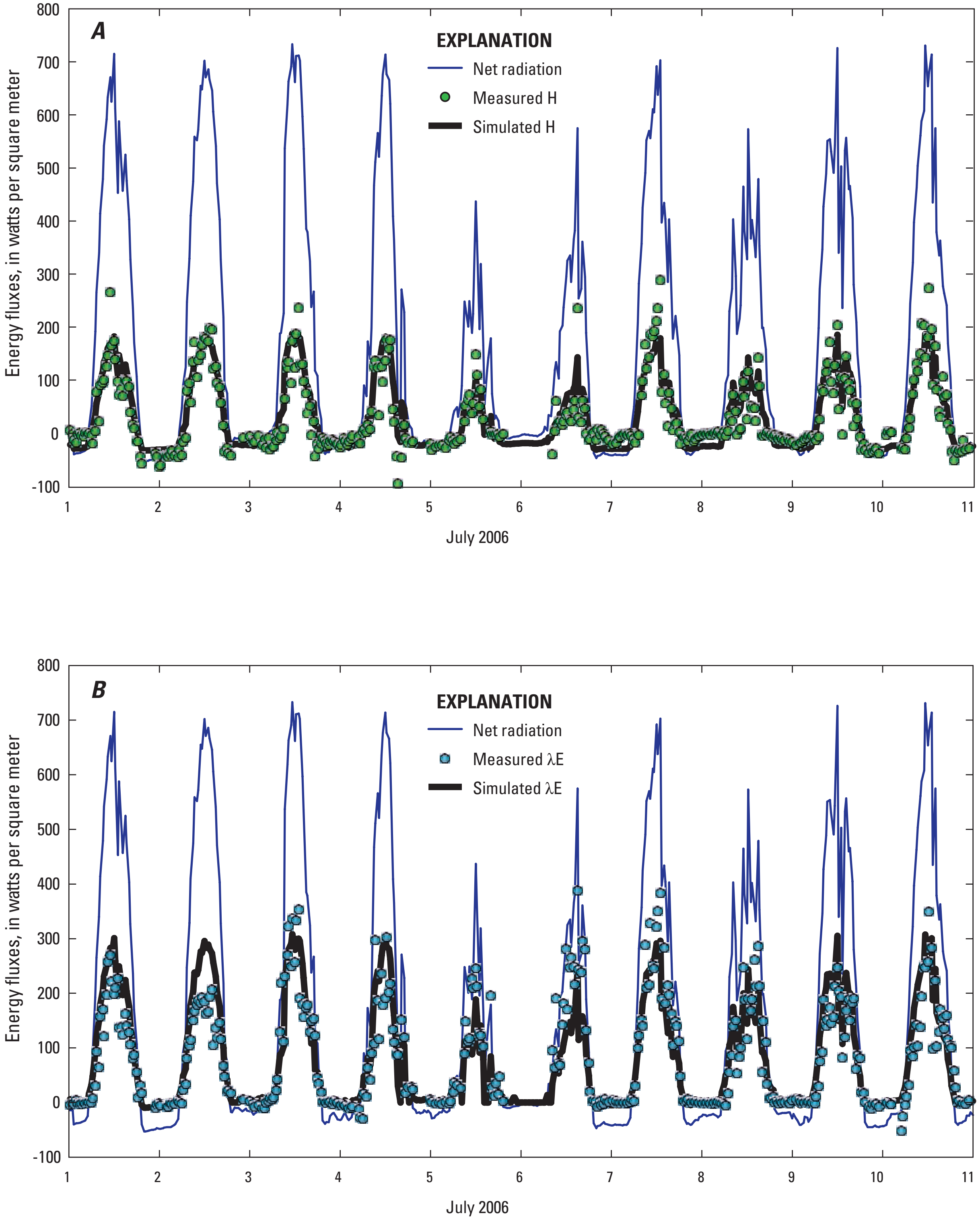


Figure 5. Measured and simulated energy fluxes: A, sensible heat flux and B, latent heat flux at the wetland site in the Pinelands area, New Jersey, July 1–10, 2006. (H, sensible heat flux; λE, latent heat flux)

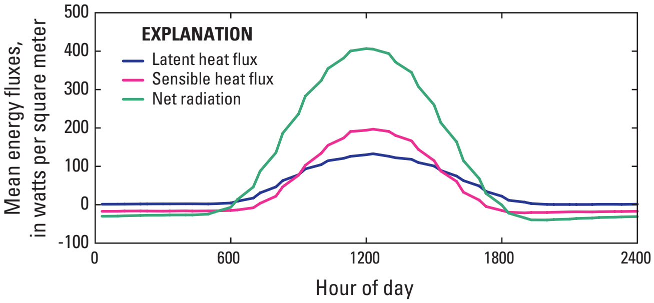


Figure 6. Mean diurnal pattern of energy fluxes at the wetland site in the Pinelands area, New Jersey, 2005–06.

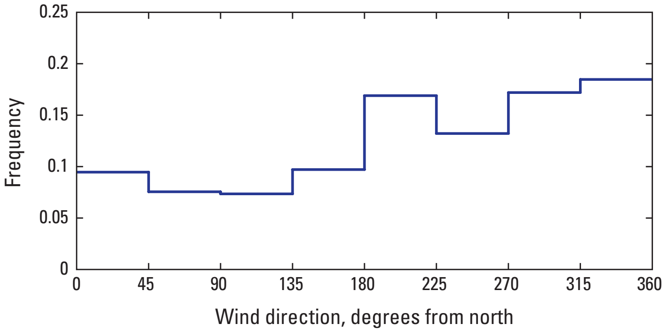


Figure 7. Relative frequency of measured wind direction at the wetland site in the Pinelands area, New Jersey, 2005–06.

2005 and 2006, respectively. The relatively large energy-budget discrepancy from early June 2005 to mid-October 2005 led to an exchange of krypton hygrometers on October 19, 2005, and to subsequently improved energy-budget closure. The hygrometer used in the early part of the study was returned to the manufacturer for evaluation and was diagnosed as exhibiting an unstable voltage output. For this reason, daily values of λE computed using either the standard eddy-covariance method or the Bowen ratio variant are considered unreliable for the period June 1, 2005, to October 19, 2005. After the conclusion of the study, the hygrometer used subsequent to October 19, 2005, was returned to the manufacturer for evaluation and was deemed to be stable with a drift in calibration of less than 1 percent. Daily values of ET are shown in figure 9 for the standard eddy-covariance method and the Bowen ratio and residual variants, excluding the standard and Bowen ratio methods for the period in 2005 when a hygrometer readings were suspect. For 2006, average ET was 1.66, 2.10, and 2.25 millimeters per day (mm/d) for the standard, Bowen ratio, and residual eddy-covariance methods, respectively; this comparison was restricted to the 343 days when the Bowen ratio was not close to -1 and equation 12 did not have a denominator near zero. As indicated by Twine and others (2000), energy-budget-closure methods are preferable to the standard eddy-covariance method. The discrepancy in estimated ET between the Bowen ratio and the residual energy-budget methods averaged 7 percent in 2006 with the Bowen ratio variant producing consistently lower ET estimates than the residual variant. The residual variant was selected in this study as the final method to quantify ET and will be used from here on, primarily because of the loss of data continuity in the Bowen ratio method associated with the suspected failure of the hygrometer during June–October 2005. However, the 7 percent overestimation of ET by the residual method relative to the Bowen ratio method can serve as an estimate of possible bias or uncertainty in estimated ET related to the method of energy-budget closure.

Weekly, monthly, and 12-month totals of measured rainfall and ET estimated with the residual energy-budget variant of the eddy-covariance method are summarized in tables 2 and 3. Annual ET was a remarkably consistent fraction of annual precipitation (0.62 and 0.58 in 2005 and 2006, respectively) and of net radiation (0.62 in 2005 and 2006) as shown in table 4. An examination of long-term (1902–2011) precipitation data at the nearby National Weather Service Indian Mills weather station indicates that the study period was slightly wetter than mean annual total of 1,173 mm; annual precipitation totals at Indian Mills were 1,325 and 1,396 mm for 2005 and 2006, respectively. The Indian Mills precipitation totals are within 30 mm (about 2 percent) of the precipitation measured at the study site during 2005 and 2006 (table 4). Streamflow measurements during 2005–06 indicate average conditions; mean annual streamflow measured at USGS streamgaging station 01466500 (fig. 1) during 2005–06 was 0.0593 cubic meters per second (m^3/s), which is nearly identical to the long-term mean annual flow of 0.0592 m^3/s for the 1954–2011 period of record. Streamflow, water-table altitude, and soil moisture all fluctuated with similar responses to precipitation and no precipitation. Soil moisture and water-table altitude were highly correlated (r^2=0.91). Minimum and maximum ET occurred during December to February and July, respectively (table 3). Twelve-month ET totals were in a relatively narrow range (786 to 821 mm) over the period of record compared to the range in 12-month rainfall totals (1,124 to 1,452 mm). A first-order data analysis consisting of linear regressions between several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) indicated that net radiation ($r^2 = 0.72$) and air temperature ($r^2 = 0.73$) were the dominant explanatory variables for daily ET. Cross correlation was noted between net radiation and air temperature ($r^2 = 0.41$), and cross correlations are expected between these variables and forest phenological changes, precluding a unique determination of the role of each variable in determining ET. Variations in the evaporative fraction (ratio of latent heat flux to net radiation) indicate that air temperature is the strongest explanatory variable in the partitioning of available energy for ET (fig. 10A). The evaporative fraction was seemingly unaffected by decreased soil moisture during the April to September 2005 and the July to August 2006 dry periods,

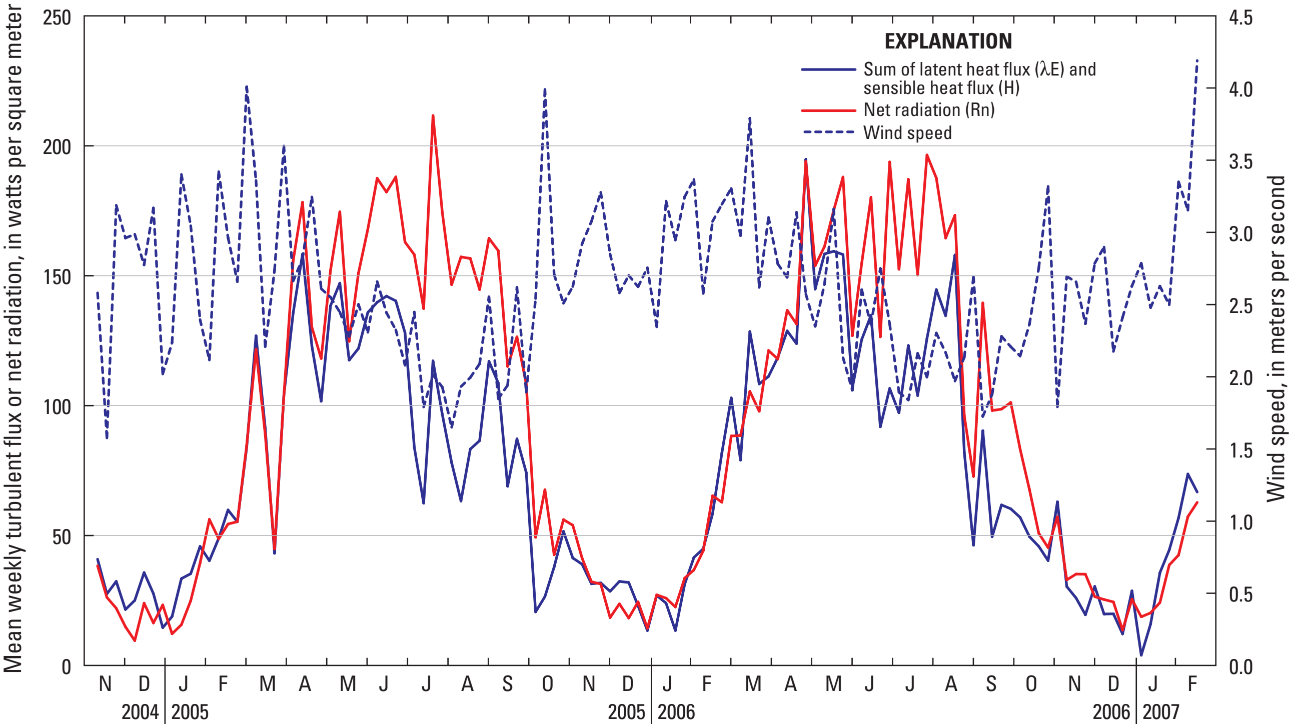


Figure 8. Mean weekly values of net radiation, turbulent fluxes, and wind speed at the wetland site in the Pinelands area, New Jersey, November 2004–February 2007.

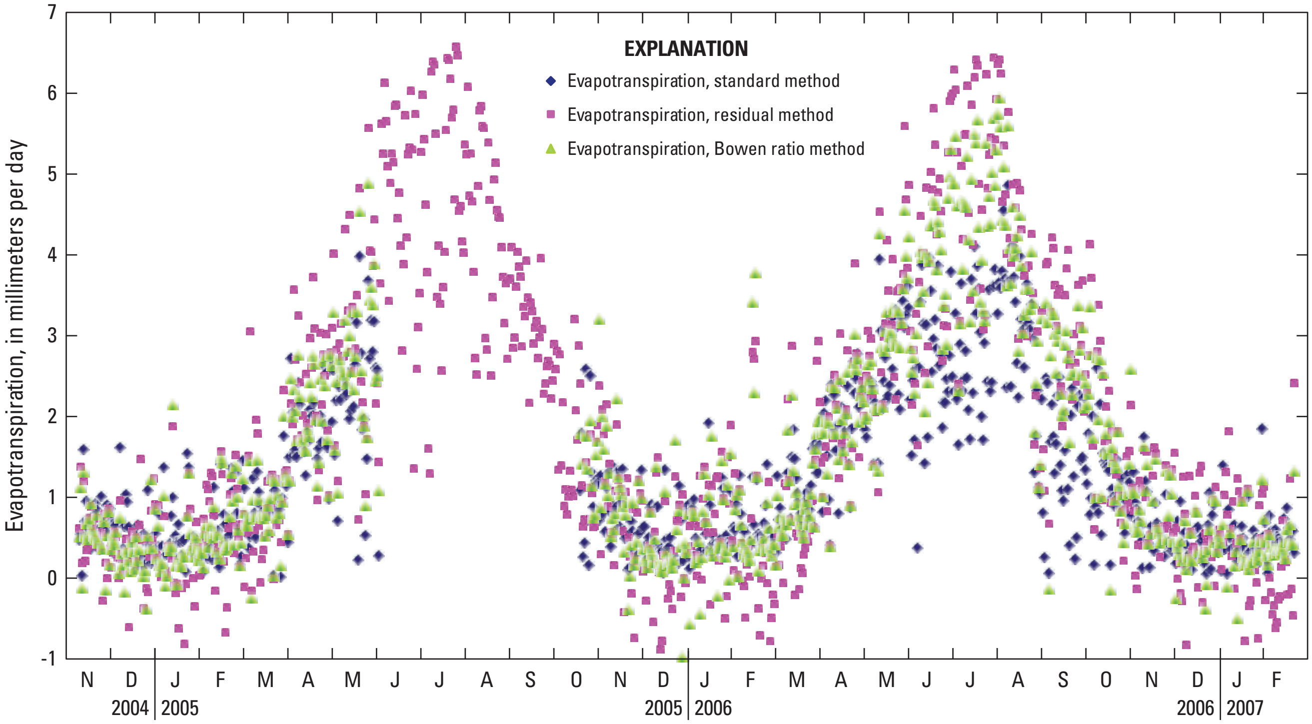


Figure 9. Daily evapotranspiration measured using the standard eddy-covariance method, the Bowen ratio method, and the residual energy-budget variant method, at the wetland site in the Pinelands area, New Jersey, November 2004–February 2007.

Table 2. Weekly measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy covariance method at the wetland site, Pinelands area, New Jersey, November 2004–February 2007.

[mm, millimeter]

First day of week	Rainfall (mm)	Evapotranspiration (mm)
11/10/2004	37	4
11/17/2004	3	4
11/24/2004	39	3
12/1/2004	33	2
12/8/2004	19	2
12/15/2004	2	0
12/22/2004	26	0
12/29/2004	2	5
1/5/2005	38	2
1/12/2005	31	0
1/19/2005	6	2
1/26/2005	11	1
2/2/2005	9	6
2/9/2005	30	5
2/16/2005	14	3
2/23/2005	21	5
3/2/2005	14	6
3/9/2005	2	6
3/16/2005	3	6
3/23/2005	64	5
3/30/2005	44	11
4/6/2005	35	17
4/13/2005	0	17
4/20/2005	10	15
4/27/2005	30	18
5/4/2005	5	17
5/11/2005	0	23
5/18/2005	43	18
5/25/2005	17	25
6/1/2005	34	27
6/8/2005	0	35
6/15/2005	0	32
6/22/2005	51	33
6/29/2005	53	31
7/6/2005	31	31
7/13/2005	47	27
7/20/2005	1	42
7/27/2005	7	34
8/3/2005	29	30
8/10/2005	16	33
8/17/2005	1	31
8/24/2005	1	26
8/31/2005	0	25
9/7/2005	0	24
9/14/2005	8	21
9/21/2005	2	20
9/28/2005	3	17
10/5/2005	92	10
10/12/2005	135	13
10/19/2005	68	8
10/26/2005	1	10
11/2/2005	0	10
11/9/2005	6	7
11/16/2005	70	4
11/23/2005	26	3
11/30/2005	34	2
12/7/2005	17	2
12/14/2005	27	0
12/21/2005	16	3
12/28/2005	67	3
1/4/2006	1	4
1/11/2006	31	6
1/18/2006	52	6
1/25/2006	6	5
2/1/2006	17	4
2/8/2006	14	4
2/15/2006	1	6
2/22/2006	2	0
3/1/2006	7	1
3/8/2006	4	10
3/15/2006	0	1
3/22/2006	2	4
3/29/2006	3	13
4/5/2006	24	11
4/12/2006	0	14
4/19/2006	46	15
4/26/2006	1	16
5/3/2006	0	17
5/10/2006	66	19
5/17/2006	9	23
5/24/2006	0	28
5/31/2006	43	22
6/7/2006	26	25
6/14/2006	0	32

Table 2. Weekly measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy covariance method at the wetland site, Pinelands area, New Jersey, November 2004–February 2007.—Continued

[mm, millimeter]

First day of week	Rainfall (mm)	Evapotranspiration (mm)
6/21/2006	82	27
6/28/2006	28	41
7/5/2006	78	32
7/12/2006	3	37
7/19/2006	13	30
7/26/2006	26	40
8/2/2006	5	37
8/9/2006	0	30
8/16/2006	0	27
8/23/2006	90	19
8/30/2006	127	16
9/6/2006	0	25
9/13/2006	68	21
9/20/2006	15	20
9/27/2006	11	20
10/4/2006	26	16
10/11/2006	76	12
10/18/2006	15	9
10/25/2006	40	8
11/1/2006	5	5
11/8/2006	117	6
11/15/2006	11	6
11/22/2006	44	7
11/29/2006	5	2
12/6/2006	0	4
12/13/2006	4	5
12/20/2006	44	4
12/27/2006	39	3
1/3/2007	51	7
1/10/2007	3	4
1/17/2007	7	0
1/24/2007	3	3
1/31/2007	5	0
2/7/2007	0	0
2/14/2007	34	3

Table 3. Monthly and 12-month measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy-covariance method at the wetland site, Pinelands area, New Jersey, December 2004–January 2007.

[mm, millimeter; -, no data]

Year-Month	Monthly measured evapotranspiration (mm)	12-month moving sum evapotranspiration (mm)	Monthly measured rainfall (mm)	12-month moving sum rainfall (mm)
04-Dec	7	-	79	-
05-Jan	7	-	88	-
05-Feb	18	-	60	-
05-Mar	27	-	97	-
05-Apr	66	-	111	-
05-May	94	-	73	-
05-June	133	-	115	-
05-July	148	-	108	-
05-Aug	134	-	48	-
05-Sep	94	-	13	-
05-Oct	49	-	296	-
05-Nov	27	804	120	1,208
05-Dec	8	805	96	1,225
06-Jan	22	821	136	1,273
06-Feb	14	816	33	1,245
06-Mar	24	814	13	1,161
06-Apr	58	806	74	1,124
06-May	94	807	76	1,127
06-June	119	794	171	1,183
06-July	157	802	125	1,201
06-Aug	124	792	99	1,252
06-Sep	88	786	213	1,452
06-Oct	55	792	163	1,319
06-Nov	26	790	176	1,375
06-Dec	15	797	53	1,332
07-Jan	14	789	104	1,299

Table 4. Summary of selected characteristics measured or simulated annually and dates of spring and fall freezes at the wetland site, Pinelands area, New Jersey, 2005–06.

Characteristic	Year 2005	Year 2006
Measured evapotranspiration at McDonalds Branch (AET_m), in millimeters	805	797
Priestley-Taylor potential evapotranspiration (PET), in millimeters	1,022	1,013
Hargreaves reference evapotranspiration (RET), in millimeters	986	1,008
North American Regional Reanalysis (NARR) actual evapotranspiration (AET_{NARR}), in millimeters	831	930
Rainfall (R) at McDonalds Branch, in millimeters	1,225	1,332
Snow (S) at Indian Mills, in millimeters	749	343
Estimated precipitation ($P = R + 0.1S$), in millimeters	1,300	1,366
Measured latent heat flux, in watts per square meter	63	62
Incoming solar radiation, in watts per square meter	159	163
Net radiation (R_n), in watts per square meter	101	100
Average daily minimum temperature, in °C	6.64	7.62
Average daily maximum temperature, in °C	16.75	17.83
Last spring freeze	17-April	24-March
First fall freeze	11-November	27-October
Priestley-Taylor vegetation factor (AET_m /PET)	0.79	0.82
Hargreaves vegetation factor (AET_m /RET)	0.79	0.79
Measured to NARR evapotranspiration ratio (AET_m / AET_{NARR})	0.97	0.86
Evapotranspiration to precipitation ratio (AET_m /P)	0.62	0.58
Evaporative fraction (ratio of mean latent heat flux to mean net radiation)	0.62	0.62

until soil moisture fell below a critical threshold of about 0.15, and evaporative fraction decreased. When rains ended the dry period and soil moisture rose above this threshold again, the evaporative fraction recovered (fig. 10B). A similar drop in evaporative fraction during a dry period in early July 2004 was observed at a nearby upland oak-pine site and attributed to apparent stomatal closure (Kenneth Clark, U.S. Forest Service, written commun., 2010). Schafer (2011) measured a reduction in sap-flux scaled canopy conductance at the upland site during drought conditions in 2006. The observed decrease in the evaporative fraction during the extreme dry periods is an important indication that lower water availability can result in lower rates of ET.

Comparison of Measured Evapotranspiration at Wetland and Upland Sites

Basin-scale hydrologic analysis requires estimates of ET over large areas, and therefore, an accounting of variability in ET rates across the landscape is needed. Previous investigations have indicated a substantial difference in ET between wetlands and uplands in the Pinelands area. Plot-scale studies using lysimeters concluded that ET from wetland areas in the Pinelands is expected to be greater than ET from upland areas because wetland soils are wetter and water is more readily available for ET (Ballard and Buell, 1975; Ballard, 1979). Evaluation of this difference over larger areas is possible by comparing ET measurements collected at the wetland station with those collected at three nearby upland stations operated by the U.S. Forest Service (USFS). The locations of evapotranspiration measurement stations for the wetland stand and the three upland USFS stands are shown in figure 11. The

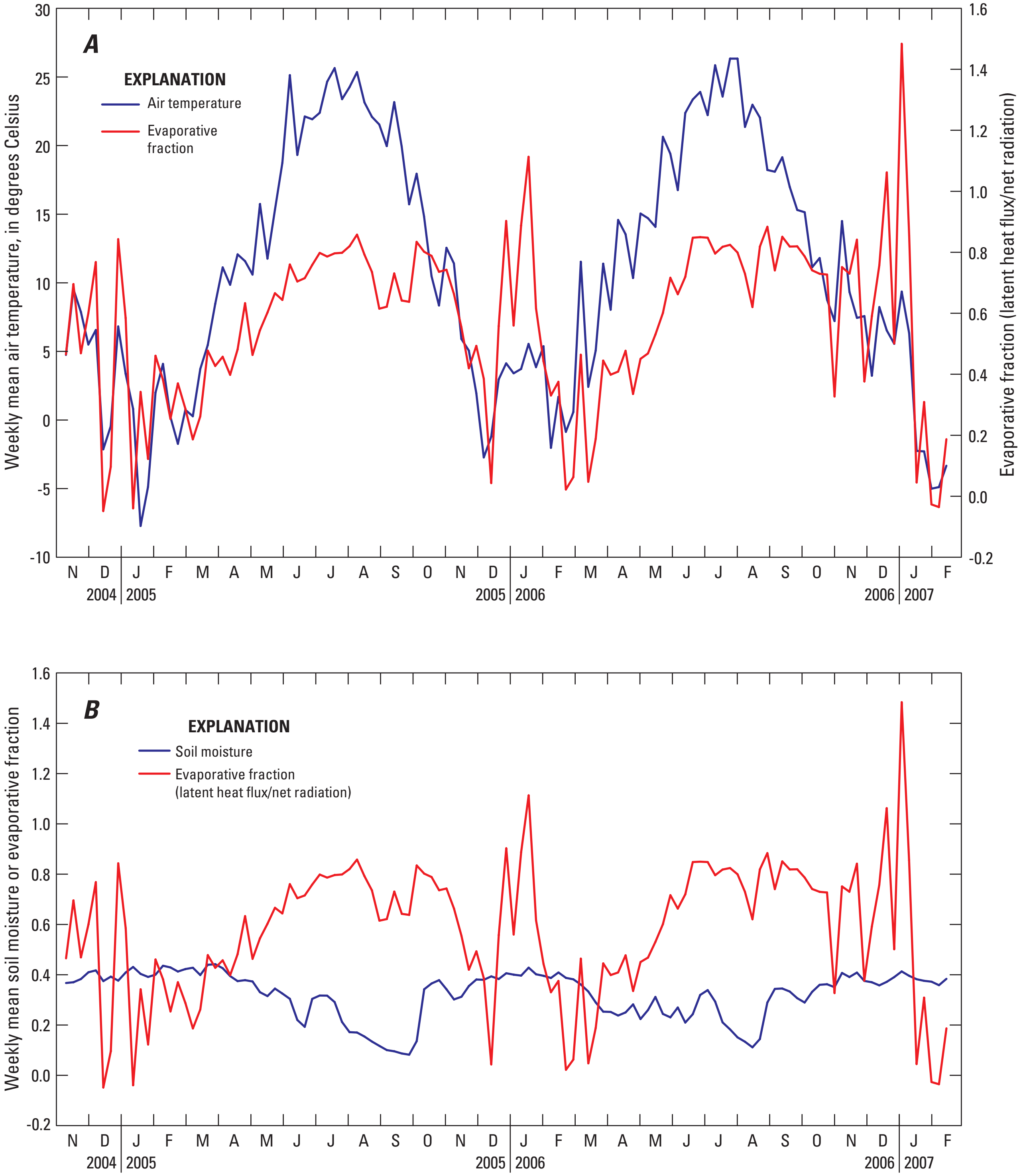


Figure 10. Relation of A, weekly mean air temperature and B, weekly mean soil moisture to evaporative fraction, at a wetland site in the Pinelands area, New Jersey, November 2004–February 2007.

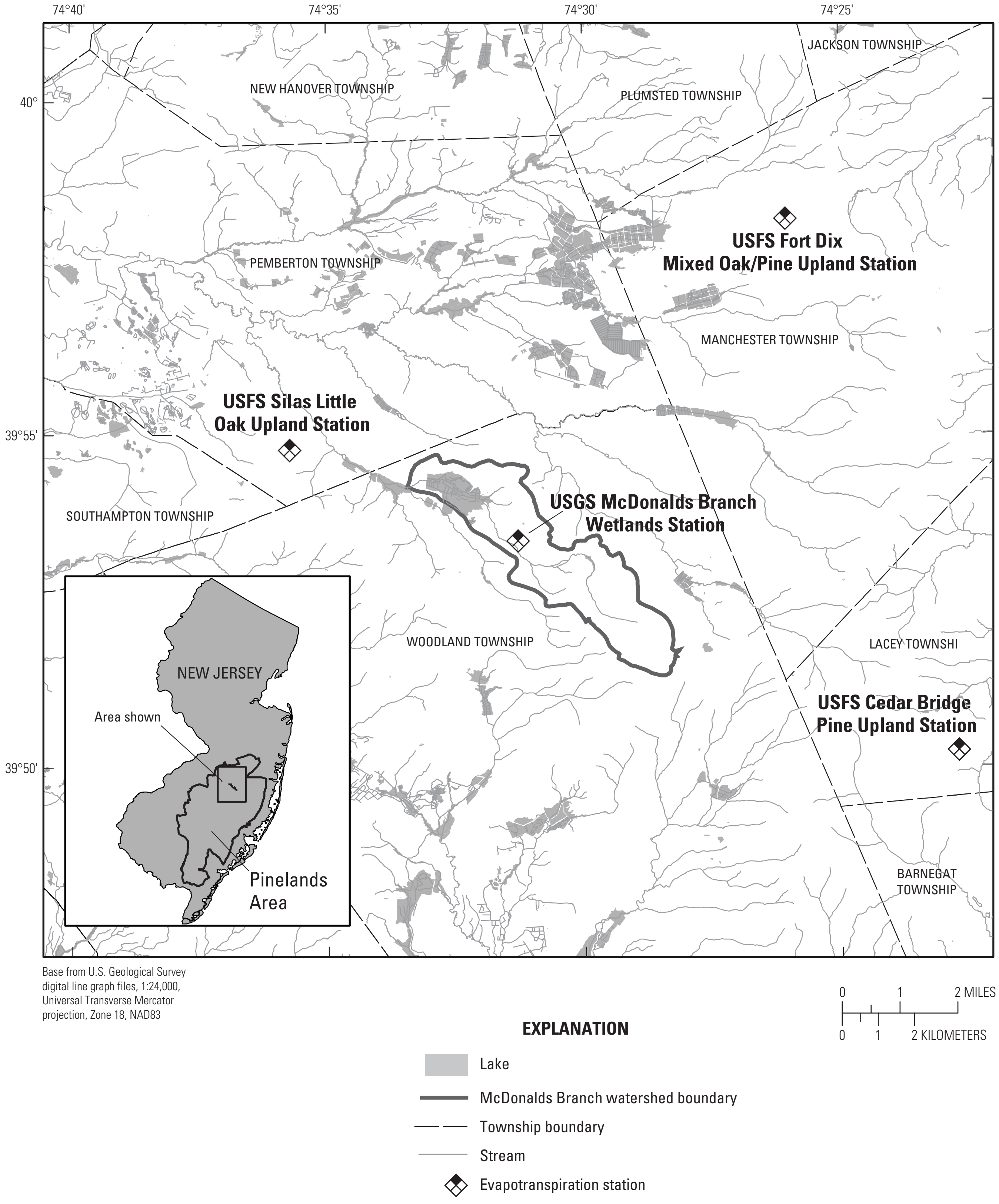


Figure 11. Location of the wetland and upland evapotranspiration measurement stations, Pinelands area, New Jersey. (USGS, U.S. Geological Survey; USFS, U.S. Forest Service)

three upland stations are located within 14 km of the wetland station, and fluxes were monitored using eddy-covariance techniques similar to those used at the wetland station. The specific ET measurement methods used at the three upland sites are described by Clark and others (2010, 2011, 2012). The three upland forest stands are dominated by oak, pine, and mixed oak and pine, respectively. ET was measured at the upland stations during 2005–09, which included periods of disturbance by fire and insect defoliation that had a significant effect in reducing ET. Annual precipitation and ET measured at the three upland stations and the wetland station are listed in table 5. Clark and others (2012) showed that, when averaged across all upland stations for all years of measurement (2005–09), annual ET was 606 mm/yr. The average annual ET measured at the wetland station during 2005–06 (801 mm/yr) is about 32 percent higher than this upland average. When ET at the upland stations is averaged over years without disturbance (685 mm/yr), the average annual wetland ET is about 17 percent higher. As a percentage of precipitation, ET at the wetland station was higher than that of the undisturbed oak and mixed oak/pine upland stations in 2005 and was similar to that of the undisturbed oak and pine upland stations in 2006.

Several factors are likely contributing to differences in ET rates among different stations and among different years. These factors include water availability, dominant plant species, and leaf area. Water availability varies year to year with precipitation and evapotranspiration, and it also varies site to site with depth to the water table and other site conditions. Water availability is less variable in wetlands because the water table is close to or at land surface, whereas in uplands the water table is deeper. Also, upland soils are more susceptible to drought conditions. Phenological and physiological differences among plant species result in different seasonal patterns of ET and different responses to stress and disturbance in the Pinelands, as described by Clark and others (2012). Leaf area is a function of several site characteristics, including plant species, successional stage, and response to disturbance (including by fire and defoliation). The results presented in table 5 and figure 12 indicate that interannual variability in wetland ET may be less than that of upland ET because the

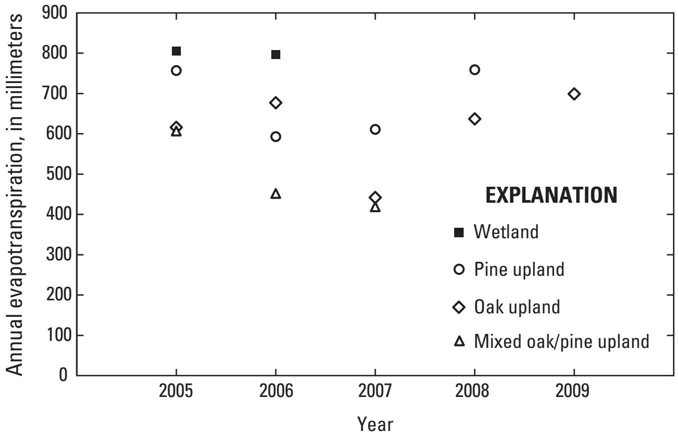


Figure 12. Annual evapotranspiration measured at the wetland, pine upland, oak upland, and mixed oak/pine upland sites in the Pinelands area, New Jersey, 2005–09.

Table 5. Annual evapotranspiration at the wetland site and three upland forest sites, Pinelands area, New Jersey, 2005–09.

[Data for upland sites are from Clark and others (2012). mm, millimeters; ET, evapotranspiration]

Site	Year	Disturbance (if any)	Annual precipitation (mm)	Annual ET (mm)	Annual ET as a percentage of precipitation
Wetland (this study)	2005		1,225	805	66
	2006		1,332	797	60
Oak upland	2005		1,092	616	56
	2006		1,108	677	61
	2007	Complete defoliation	934	442	47
	2008	Partial defoliation	936	637	68
	2009		1,173	699	60
Mixed upland	2005		1,184	607	51
	2006	Burn and defoliation	1,163	452	39
	2007	Partial defoliation	1,135	419	37
Pine upland	2006		1,230	757	62
	2007	Partial defoliation	1,052	593	56
	2008	Prescribed burn	1,163	611	54
	2009		1,382	759	55

wetland sites are less susceptible to periodic drought conditions, disturbance by fire (Foreman and Boerner, 1981), and insect defoliation (Houston and Valentine, 1985; Whitmire and Tobin, 2006). Higher ET in wetlands is probably attributable to greater water availability and differences in canopy plant species and leaf area.

A useful approach for validating ET measurements is to use them in a watershed-scale analysis of the water budget, along with other hydrologic measurements. A balanced water budget is an indication that the various measurements are internally consistent. Walker and others (2011) describe the water balance in the McDonalds Branch basin for 2005–06. The analysis includes an estimate of basin-wide, spatially weighted ET that was based on the respective ET rates for the wetland and upland sites described previously. The analysis included a land-surface water budget and a groundwater budget. Both budgets were used to estimate aquifer recharge independently as a residual. The comparability of the independent recharge estimates for the McDonalds Branch basin indicate that the ET measurements presented in this report are reasonably consistent with other hydrologic measurements.

Utility of Models to Simulate Evapotranspiration

The utility of three models—Priestley-Taylor, Hargreaves, and North American Regional Reanalysis (NARR)—were evaluated through a comparison of model-simulated ET with ET measured at the wetland site using the residual energy-budget variant method. Models that successfully replicated measured ET offer the potential to transfer the results of the site measurements to other locations or to other time periods outside the study period.

Priestley-Taylor Equation

The environmental variables considered as possible predictors of modified Priestley-Taylor α included soil moisture, solar radiation, air temperature, vapor-pressure deficit, and wind speed. Exploratory data analysis revealed that the greatest explanatory value for the Priestley-Taylor α was related to air temperature, followed by solar radiation, soil moisture, wind speed, and finally vapor-pressure deficit. A Priestley-Taylor α function composed of a second order polynomial of air temperature (fig. 13) was optimized to successfully reproduce daily values of latent heat flux measured with the energy-budget residual variant ($r^2 = 0.90$; standard error = 0.65 mm or 19 W/m^2; and bias = 0; table 6).

Comparison of modeled latent heat flux residuals with possible explanatory variables other than air temperature revealed little relation, supporting the use of the simple temperature-dependent Priestley-Taylor α function. This function shows an increase in α with air temperature, with the rate of increase decreasing with increasing air temperature. This relation for α probably represents a combination of direct plant stomatal response to air temperature but also a response to phenological changes in the forest plant species that are associated with seasonal temperature changes. A comparison of residuals with vector-averaged daily mean wind direction (fig. 14) provides a means of evaluating the effects of non-homogeneous surface covers (wetlands and uplands) within the source area of the latent heat flux measurement. No obvious relation was apparent between ET residuals and wind direction that was consistent with the patterns of wetlands and uplands in the source area, indicating that wind direction, a surrogate for source areas with different vegetation, was not responsible for variability in ET not already accounted for by the temperature relation.

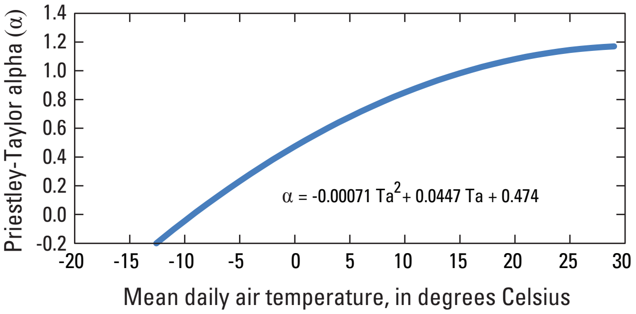


Figure 13. Optimized relation between Priestley-Taylor *α* and mean daily air temperature for the wetland site in the Pinelands area, New Jersey.

Figure 15 shows a good relation between daily measured (energy-budget residual variant) and modified Priestley-Taylor simulated latent heat flux, without noticeable temporal bias. The simulated values of latent heat flux generally are less erratic in the winter than are the measured values; this phenomenon may be more a consequence of violation of one

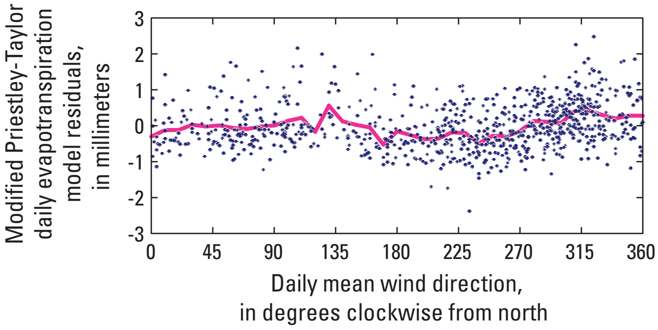


Figure 14. Relation of residuals using the modified Priestley-Taylor model to daily mean wind direction, wetland site, Pinelands area, New Jersey, 2004–07. Residual is simulated evapotranspiration minus measured evapotranspiration: The two wind arcs most representative of uplands are 350 degrees clockwise to 20 degrees and 90 degrees clockwise to 120 degrees. The red line is mean residual for a given wind direction.

Table 6. Error statistics relating evapotranspiration measured at the wetland site to evapotranspiration simulated using alternative models, Pinelands area, New Jersey.

[mm, millimeter]

Alternative model	Coefficient of determination (r^2) with measured actual evapotranspiration	Root mean square error (mm/day)	Bias relative to measured evapotranspiration (mm/year)
Priestley-Taylor potential evapotranspiration (PET)	0.85	1.08	+216
Hargreaves reference evapotranspiration (RET)	0.87	0.85	+196
Modified Priestley-Taylor actual evapotranspiration (AET_{PT})	0.9	0.65	0
Modified Hargreaves actual evapotranspiration (AET_H)			
McDonalds Branch wetland site	0.89	0.61	0
Indian Mills weather station	0.84	0.73	0
Moorestown weather station	0.83	0.76	0
North American Regional Reanalysis (NARR) actual evapotranspiration (AET_{NARR})	0.6	1.21	+80

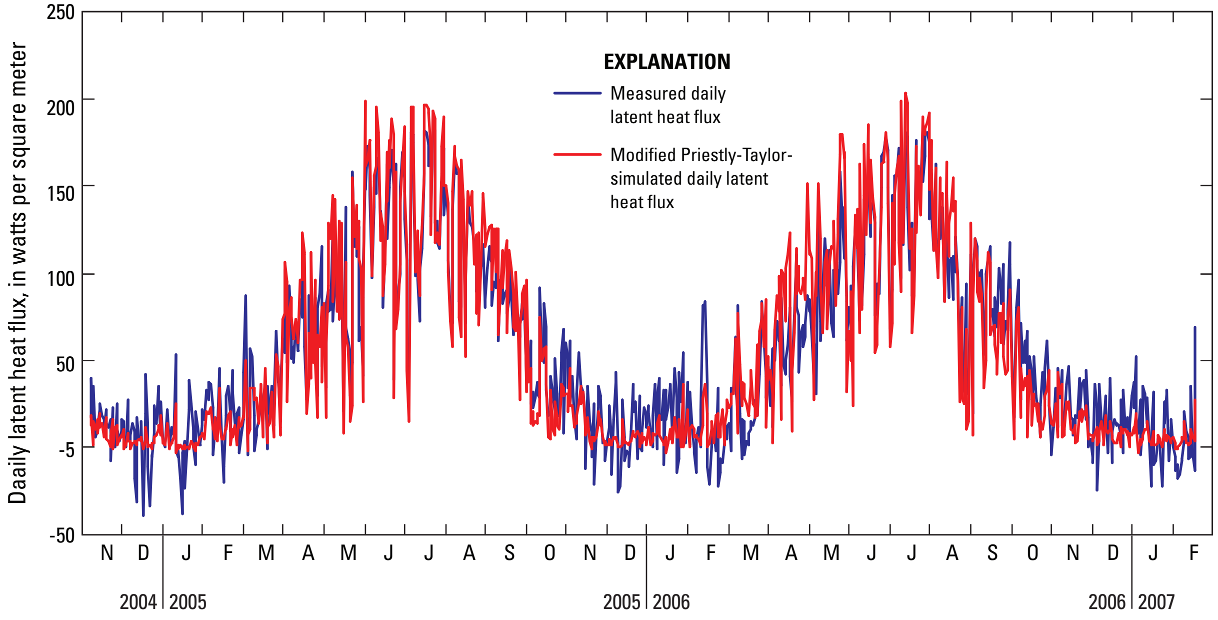


Figure 15. Measured and modified Priestly-Taylor-simulated daily latent heat flux for the wetland site, Pinelands area, New Jersey, 2005–06.

of the assumptions of latent heat flux measurement—negligible changes in canopy heat storage during rapid winter-time temperature changes— than an error in the model.

The modified Priestley-Taylor model developed in this study is subject to several qualifications. The form of the equation developed for α was empirical rather than physics based and was simply designed to reproduce measured values of ET as accurately as possible. The covariance between environmental variables confounds a unique parameterization. The model was developed for a limited range of environmental conditions, and therefore, extrapolation of the model to conditions not encountered in this study are best done with caution. As noted earlier, deficit soil moisture appeared to play a role in restricting ET during particularly dry periods, but this effect was not considerable enough to be discerned clearly in the identification of the appropriate Priestley-Taylor α function.

Annual measured ET at the wetland site was a relatively constant fraction of potential ET as estimated by the standard Priestley-Taylor method with an α of 1.26 (0.79 and 0.82 in 2005 and 2006, respectively; table 4). However, potential ET was highly correlated with measured ET ($r^2 = 0.85$), indicating that a constant vegetation factor applied to potential ET also can replicate actual ET rather well at this wetland site, where moisture availability was not often a constraint.

Hargreaves Equation

The modified Hargreaves equation performed remarkably well at reproducing measured values of daily ET (table 6; fig 16.) with relatively low error and little temporal bias. Additionally, measurements of daily incoming solar radiation were also well replicated ($r^2 = 0.70$; coefficient of variation = 31 percent; and bias = 3 percent) using the preferred value of $K_{RS} = 0.16$ for inland areas. The values of *a* and *b* identified by the regression analysis to most closely replicate measured daily ET for each source of temperature data are shown in table 7. As might be expected, use of temperature data from the ET station at the McDonalds Branch site provides better explanatory values within the modified Hargreaves equation for ET ($r^2 = 0.89$; standard error = 0.61 mm/d; and bias = 0 mm/year) than does use of remote temperature data from either of the National Weather Service stations (Indian Mills and Moorestown; table 6). However, Hargreaves models adjusted for temperature data from either of the remote temperature stations can be considered successful at

Table 7. Parameters for the standard Hargreaves reference evapotranspiration equation and optimized parameters for the modified Hargreaves actual evapotranspiration equation for alternative sources of daily temperature data.

[a, b, K_{RS}, and aK_{RS} are empirical coefficients]

Parameter	Standard Hargreaves	McDonalds Branch wetland site	Moorestown weather station	Indian Mills weather station
a	0.0148	0.0198	0.0167	0.0169
b	17.8	4.1	3.1	3.2
K_{RS} (inland)	0.16	0.16	0.16	0.16
aK_{RS}	0.0023	0.0032	0.0027	0.0027

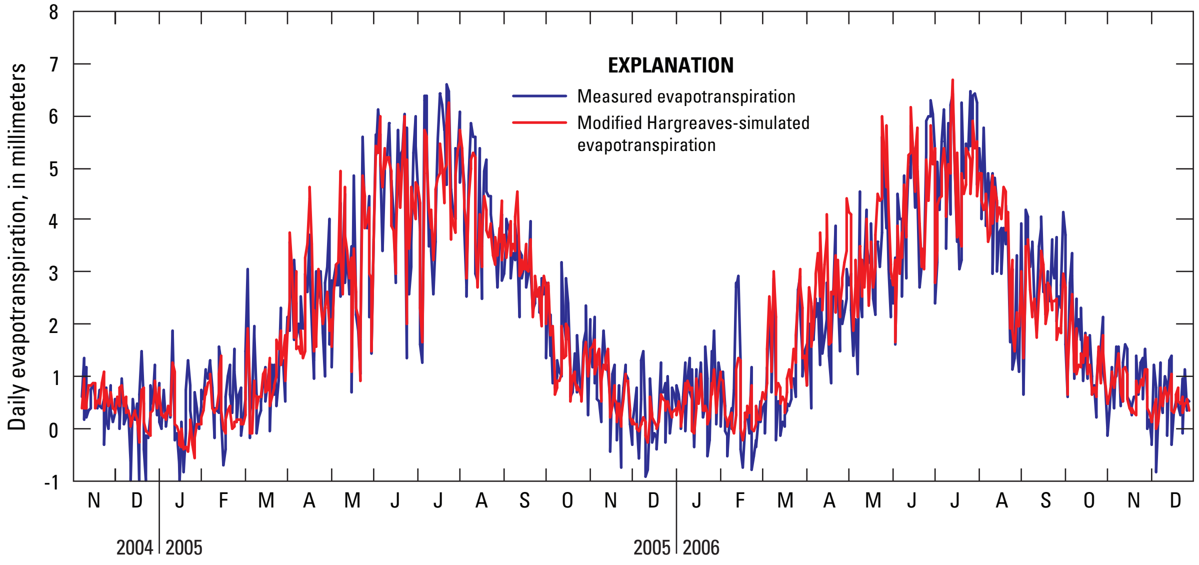


Figure 16. Daily measured and modified Hargreaves-simulated evapotranspiration for the wetland site, Pinelands area, New Jersey, 2005–06.

ET estimation, although the models performed slightly better using values from the closer Indian Mills station ($r^2 = 0.84$; standard error = 0.73 mm/d; and bias = 0 mm/year) than using values from the more distant Moorestown station ($r^2 = 0.83$; standard error = 0.76 mm/d; and bias = 0 mm/year). The lower values (3.1 to 4.1) of the temperature offset parameter *b* in the optimized forms of the modified Hargreaves actual ET equation relative to the *b* value of 17.8 in the standard Hargreaves reference evapotranspiration equation imply that actual ET shows greater sensitivity to temperature at this site than does reference ET. Annual ET was a constant fraction of reference ET, as estimated by the standard Hargreaves method (0.79 in 2005 and 2006; table 4). However, daily reference ET was highly correlated ($r^2 = 0.87$) with measured ET, indicating that a constant vegetation factor applied to reference ET can replicate actual ET at the wetland site rather well. Again, no obvious relation was apparent between ET residuals and wind direction that was consistent with the patterns of wetlands and uplands in the source area (fig. 17).

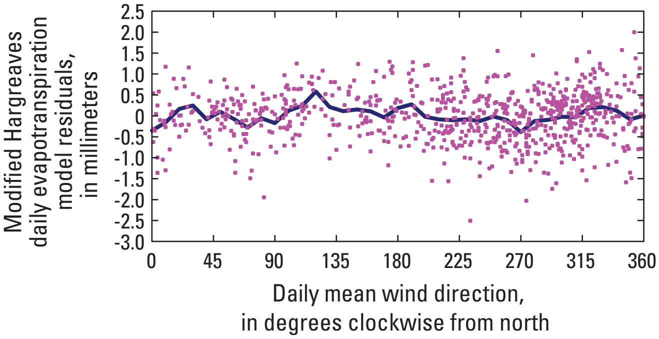


Figure 17. Relation of residuals using the modified Hargreaves daily evapotranspiration model to daily mean wind direction, wetland site, Pinelands area, New Jersey, 2004–07. Residual is simulated evapotranspiration minus measured evapotranspiration: The two wind arcs most representative of uplands are 350 degrees clockwise to 20 degrees and 90 degrees clockwise to 120 degrees. The blue line is mean residual for a given wind direction.

North American Regional Reanalysis (NARR)

The North American Regional Reanalysis performed relatively poorly ($r^2 = 0.60$; standard error = 1.21 mm; and bias = 80 mm/year) at replicating measured values of daily ET relative to the other models considered (table 6). In particular, NARR showed substantial under-prediction of measured ET during the dry periods (fig. 18) that occurred during August–October 2005 and in August 2006 and slight over-prediction during wetter periods. Apparently, the NARR algorithms restrict ET as a result of perceived plant moisture stress during dry periods to a degree that is excessive for the largely wetland environment of the study area. The large spatial resolution of the NARR product (32-km grid) is intended for a more regional estimate of ET than the relatively small-scale measurement described in the present study, and this discrepancy in scale can be expected to account for some of the difference between the two ET estimates. Annual measured ET totals as a fraction of NARR ET were 0.97 and 0.86 in 2005 and 2006, respectively (table 4).

Comparison and Limitations of Evapotranspiration Models

Of the models investigated in the present study, the modified Hargreaves can be considered the best at replicating the measured daily ET values. The error statistics of the modified Hargreaves model were comparable to those of the modified Priestley-Taylor model and superior to those of the North American Regional Reanalysis product. Additionally, the data requirements of the modified Hargreaves model (minimum and maximum daily air temperature) are more easily met than those of the modified Priestley-Taylor model, which requires both mean daily air temperature and the more difficult to obtain net radiation. The data requirements of the modified Hargreaves equation are ideal for retrospective investigations of ET because they are met by standard National Weather Service measurements that extend back over a century in parts of the Nation, including at Moorestown and Indian Mills, New Jersey. Likewise, in the absence of continuing eddy-covariance measurements, historical or real-time estimates of ET in the study area can be obtained through use of air-temperature data (available from the National Climatic Data Center [*http://www.ncdc.noaa.gov/oa/ncdc.html*] or the New Jersey Weather and Climate Network [*http://climate.rutgers.edu/njwxnet*], for example) and the modified Hargreaves equation. Sumner and Nicholson (2010) present historical and future probabilistic estimates of ET at the wetland site using a Hargreaves-based approach.

The ET models described in this report are best applied to estimate ET at locations or during time periods for which the environmental conditions are similar to those prevailing during the period of record for which these models were calibrated. Use of the models outside of these environmental conditions introduces additional uncertainty in the evapotranspiration estimates. For example, under more extreme dry periods than those that occurred during the study period, ET may be overestimated by models that do not explicitly account for plant moisture stress.

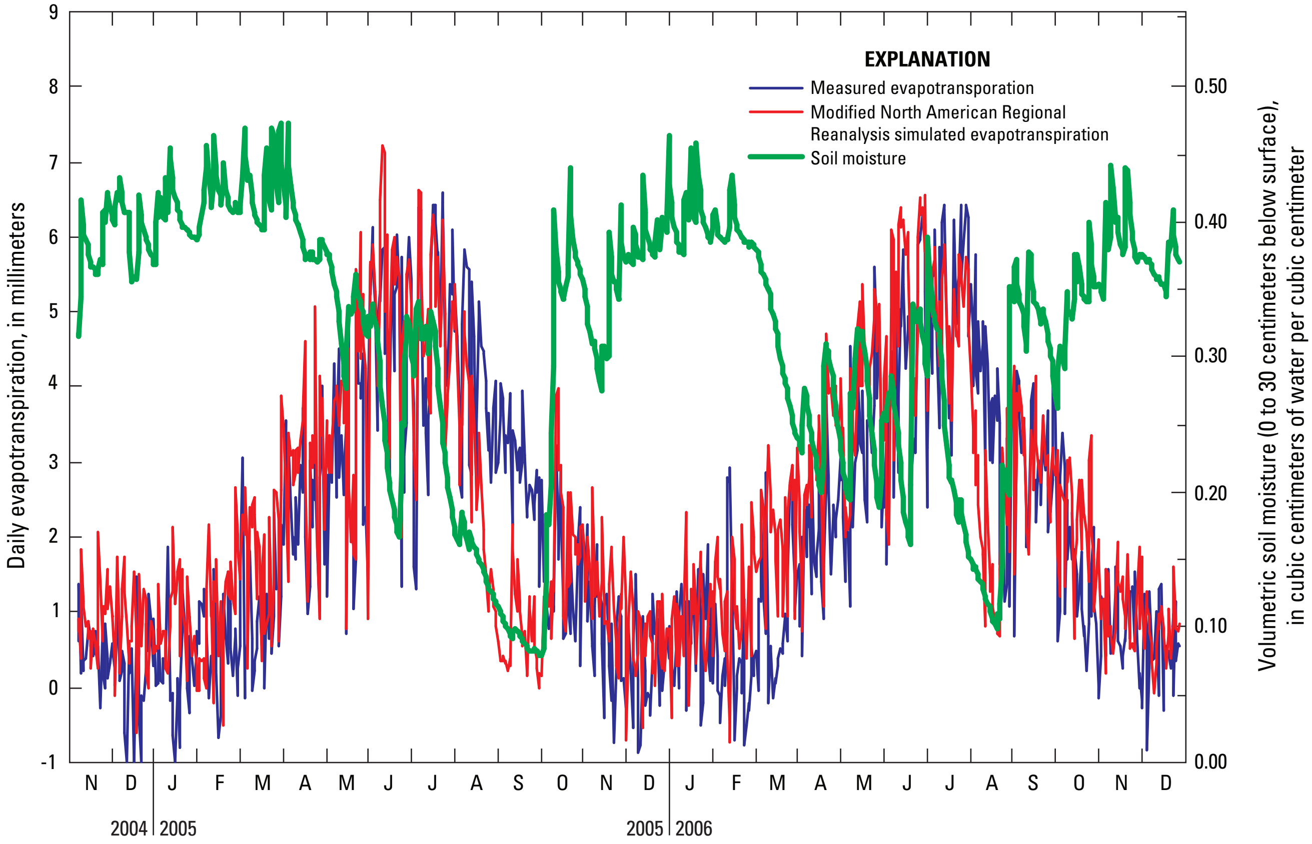


Figure 18. Daily measured and modified North American Regional Reanalysis simulated evapotranspiration, and volumetric soil mositure for the wetland site, Pinelands area, 2005–06.

Summary

Evapotranspiration (ET) was monitored above a wetland forest canopy in the New Jersey Pinelands during November 10, 2004–February 20, 2007. Meteorological, radiation, and eddy-covariance flux measurements were made near the top of a 24.5-meter tower; soil moisture and water-table depth at the site also were monitored. An analysis of the eddy-covariance sensors' source area and predominant wind directions indicated that the source of measured ET was primarily pitch pine/cedar wetlands.

Three methods were evaluated for their utility in estimating ET. The standard eddy-covariance method was used to measure the two turbulent-flux components of the plant-canopy energy budget: latent and sensible heat fluxes. Regression analysis of measured 30-minute turbulent flux and net radiation data was used to estimate missing values of 30-minute turbulent fluxes, which occurred mostly at night and accounted for only 5 percent of the total estimated ET. Two variants of the eddy-covariance method were used to adjust turbulent flux measurements for daily energy-budget closure; one variant preserves the Bowen ratio (Bowen ratio energy-budget variant), and the other preserves the measured sensible heat flux (residual energy-budget variant). Relations between ET and several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) were explored.

Suspected hygrometer failure during the early part of the measurement period resulted in unreliable ET measurements determined by using the standard eddy-covariance and Bowen ratio energy-budget variant methods. The residual energy-budget variant was selected for use in estimating a time series of daily ET rates for the measurement period. The range of the 12-month ET totals, based on the residual energy-budget variant, is relatively narrow (786 to 821 millimeters (mm)) for the period of record compared to the range of the 12-month rainfall totals (1,124 to 1,452 mm). Minimum and maximum ET values were measured during December–February and

July, respectively. Net radiation ($r^2 = 0.72$) and air temperature ($r^2 = 0.73$) were the dominant explanatory variables for daily ET. Air temperature was the dominant control on evaporative fraction with relatively more radiant energy used for ET at higher temperatures. During extended dry periods, soil moisture was shown to limit available energy partitioning into ET. As volumetric soil moisture fell below a threshold of 0.15, the evaporative fraction decreased until rain broke the dry period and the evaporative fraction sharply recovered. This observation indicates that lower water availability can result in lower rates of ET at this wetland site.

Annual ET totals measured at the wetland site were compared with those measured at three nearby upland sites dominated by oak, pine, or mixed oak and pine. A previous investigation by the U.S. Forest Service determined that, when averaged across all upland sites for all years of measurement (2005–09), annual upland ET was 606 mm/yr. The average annual ET measured at the wetland site during 2005–06 (801 mm/yr) is about 32 percent higher than the average of that at the upland sites. The average annual ET at the wetland site is about 17 percent higher than ET at the upland sites when averaged over years without disturbance at a particular stand. Factors contributing to differences in ET rates among different sites and among different years include water availability, dominant plant species, and leaf area. Interannual variability of wetlands ET may be less than that of uplands ET because the upland sites are more susceptible to periodic drought conditions, disturbance by fire, and insect defoliation.

Three ET models (Priestley-Taylor, modified Hargreaves, and North American Regional Reanalysis) were evaluated to determine their utility in predicting ET at the wetland site using data that may be more readily available in other areas and for other time periods. Of the three models, the modified Hargreaves may be of the most practical use, as it replicated the measured daily ET values reasonably well, and data requirements were relatively easily met. The ET models described in this report are best applied to estimate ET at locations or during time periods for which the environmental conditions are similar to those prevailing during the period of record for which these models were calibrated. Precipitation during the study period at the nearby National Weather Service Indian Mills weather station was slightly higher than the long-term (1902–2011) annual mean of 1,173 mm, with 1,325 and 1,396 mm of precipitation in 2005 and 2006, respectively.

References Cited

Allen, R.G., Walter, I.A., Elliot, R., Howell, T., Itenfisu, D., and Jensen, M., 2005. The ASCE standardized reference evapotranspiration equation: Reston, Va., American Society of Civil Engineers, 59 p.

Ballard, J.T., 1971, Evapotranspiration from lowland vegetation communities of the New Jersey Pine Barrens: New Brunswick, N.J., Ph.D. Thesis, Rutgers University (pagination unavailable).

Ballard, J.T., 1979, Fluxes of water and energy through the Pine Barrens ecosystems, *in* Forman, R.T.T., ed., Pine Barrens: ecosystem and landscape: New York, Academic Press, revised paperback edition, p.133–145.

Ballard, J.T., and Buell, M.F., 1975, The role of lowland vegetation communities in the evapotranspiration budget of the New Jersey Pine Barrens: Bulletin of the New Jersey Academy of Science, v. 20, no. 1, p. 26–28.

Baldocchi, D.D., Hicks, B.B., and Meyers, T.P., 1988, Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods: Ecology, v. 69, no. 5, p. 1331–1340.

Barksdale, H.C., 1958, Ground-water resources in the tri-state region adjacent to the Lower Delaware River: Special Report, New Jersey State Water Policy Commission, State of New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, issue 10, v. 13, 190 p.

Bidlake, W.R., Woodham, W.M., and Lopez, M.A., 1996, Evapotranspiration from areas of native vegetation in west-central Florida: U. S. Geological Survey Water-Supply Paper 2430, 35 p.

Buell, M.F., 1955, New botanical problems in the New Jersey Pine Barrens: Bulletin of the Torrey Botanical Club, v. 82, no. 3, p. 237–252.

Buell, M.F., and Ballard, J.T., 1972, Evapotranspiration from lowland vegetation in the New Jersey Pine Barrens: New Brunswick, N.J., New Jersey Water Resources Research Institute, Rutgers University (pagination unavailable).

Brutsaert, W., 1982, Evaporation into the atmosphere–Theory, history, and applications: Boston, Kluwer Academic Publishers, 299 p.

Businger, J.A., and Yaglom, A.M., 1971, Introduction to Obukhov's paper "Turbulence in an atmosphere with a non-uniform temperature": Boundary-Layer Meteorology, v. 2, p. 3–6.

Campbell, G.S., and Norman, J.M., 1998, An introduction to environmental biophysics: New York, Springer, 286 p.

City of Philadelphia, 1892, Ninth annual report of the Bureau of Water for the year ending December 31, 1891: Philadelphia, Pa (pagination unavailable).

Clark, K.L., Skowronski, N., and Hom, J., 2010, Invasive insects impact forest carbon dynamics: Global Change Biology, v. 16, p. 88–101.

Clark, K.L., Skowronski, N., Gallagher, M., Renninger, H., and Schäfer, K., 2012, Effects of invasive insects and fire on forest energy exchange and evapotranspiration in the New Jersey Pinelands: Agricultural and Forest Meteorology, v. 166–167, p. 50–61.

Clark, K.L., Skowronski, N., Gallagher, M., Schafer, K.V.R, and Renninger, H.J., 2011, Effects of invasive insects and fire on forest evapotranspiration and water use efficiency [abs.]: 96th Annual Meeting of the Ecological Society of America, Austin, TX, August 7–12, 2011.

Dyer, A.J., 1961, Measurements of evaporation and heat transfer in the lower atmosphere by an automatic eddy-correlation technique: Quarterly Journal of the Royal Meteorological Society, v. 87, p. 401–412.

Eichinger, W.E., Parlange, M.B., and Stricker, H., 1996, On the concept of equilibrium evaporation and the value of the Priestley-Taylor coefficient: Water Resources Research, v. 32, no. 1, p. 161–164.

Fleagle, R.G., and Businger, J.A., 1980, An introduction to atmospheric physics: New York, Academic Press, 432 p.

Flint, A.L., and Childs, S.W., 1991, Use of the Priestley-Taylor evaporation equation for soil water limited conditions in a small forest clearcut: Agricultural and Forest Meteorology, v. 56, p. 247–260.

Foken, T., 2008, The energy balance closure problem: an overview: Ecological Applications, v. 18, no. 6, p. 1351–1367.

Foreman, R.T.T., and Boerner, R.E., 1981, Fire frequency and the pine barrens of New Jersey: Bulletin of the Torrey Botanical Club, v. 108, no. 1, p. 34–50.

Garratt, J.R., 1980, Surface influence upon vertical profiles in the atmospheric near-surface layer: Quarterly Journal of the Royal Meteorological Society, v. 106, p. 803–819.

German, E.R., 2000, Regional evaluation of evapotranspiration in the Everglades: U. S. Geological Survey Water-Resources Investigations Report 00–4217, 48 p.

Gordon, A.D., 2004, Hydrology of the unconfined Kirkwood-Cohansey aquifer system, Forked River and Cedar, Oyster, Mill, Westecunk, and Tuckerton Creek basins and adjacent basins in the southern Ocean County area, New Jersey, 1998–99: U.S. Geological Survey Water-Resources Investigations Report 03–4337, 5 pls.

Goulden, M.L., Munger, J.W., Fan, S-M, Daube, B.C., and Wofsy, S.C., 1996, Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy: Global Change Biology, v. 2, p. 169–182.

Hargreaves, G.H., and Allen, R.G., 2003, History and evaluation of Hargreaves evapotranspiration equation: American Society of Civil Engineers Journal of Irrigation and Drainage Engineering, v. 129, no. 1, p. 53–63.

Hargreaves, G.H., and Samani, Z.A., 1985, Estimating potential evapotranspiration: American Society of Civil Engineers Journal of Irrigation and Drainage Engineering, v. 108, no. 3, p. 225–230.

Houston, D.R., and Valentine, H.T., 1985, Classifying forest susceptibility to gypsy moth defoliation: U.S. Department of Agriculture, Agriculture Handbook No. 542, 19 p.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Johnson, M.L., and Watt, M.K., 1996, Hydrology of the unconfined aquifer system, Mullica River Basin, New Jersey, 1991-92: U.S. Geological Survey Water-Resources Investigations Report 94–4234, 6 sheets.

Johnsson, P.A., and Barringer, J.L., 1993, Water quality and hydrogeochemical processes in McDonalds Branch basin, New Jersey Pinelands, 1984–88: U.S. Geological Survey Water-Resources Investigations Report 91–4081, 111 p.

Kaimal, J.C., and Businger, J.A., 1963, A continuous wave sonic anemometer-thermometer: Journal of Applied Meteorology, v. 2, p. 156–164.

Kaimal, J.C., and Gaynor, J.E., 1991, Another look at sonic thermometry: Boundary-Layer Meteorology, v. 56, p. 401–410.

Laidig, K.J., Zampella, R.A., Brown, A.M., and Procopio, N.A., 2010a, Development of vegetation models to predict the potential effect of groundwater withdrawals on forested wetlands: New Lisbon, N.J., Pinelands Commission, 30 p.

Laidig, K.J., Zampella, R.A., Brown, A.M., and Procopio, N.A., 2010b, Development of vegetation models to predict the potential effect of groundwater withdrawals on forested wetlands: Wetlands, v. 30, p.489–500.

Lee, X., and Black, T.A., 1993, Atmospheric turbulence within and above a Douglas-fir stand, Part II: Eddy fluxes of sensible heat and water vapor: Boundary-Layer Meteorology, v. 64, p. 369–389.

Lowe, P.R., 1977, An approximating polynomial for the computation of saturation vapor pressure: Journal of Applied Meteorology, v. 16, no. 1, p. 100–103.

Lull, H.W., and Axley, J.H., 1958. Forest soil-moisture relations in the coastal plain sands of southern New Jersey: Forest Science, v. 4, no. 1, p. 2–18.

Mitchell, K., Ek, M., Lin, Y., Mesinger, F., DiMego, G., Shafran, P., Jovic, D., Ebisuzaki, W., Shi, W., Fan, Y., Janowiak, J., and Schaake, J., 2004, NCEP completes 25-year North American Reanalysis: precipitation assimilation and land surface are two hallmarks: Global Energy and Water Cycle Experiment (GEWEX) News, v. 14, no. 2, p. 9–12.

Modica, E. 1998, Analytical methods, numerical modeling, and monitoring strategies for evaluating the effects of ground-water withdrawals on unconfined aquifers in the New Jersey Coastal Plain: U.S. Geological Survey Water-Resources Investigations Report 98–4003, 66 p.

Monteith, J.L., 1965, Evaporation and environment, *in* Fogg, G.E., ed., the state and movement of water in living organisms, Symposium of the Society of Experimental Biology, San Diego, California: New York, Academic Press, p. 205–234.

Monteith, J.L., and Unsworth, M.H., 1990, Principles of environmental physics (2d ed.): London, Edward Arnold, 291 p.

Moore, C.J., 1976, Eddy flux measurements above a pine forest: Quarterly Journal of the Royal Meteorological Society, v. 102, p. 913–918.

National Climatic Data Center, 2012, National Oceanic and Atmospheric Administration (NOAA) Satellite and Information Service–National Environmental Satellite, Data and Information Service (NESDIS), accessed May 22, 2012, at *http://www.ncdc.noaa.gov/oa/ncdc.html*.

North American Regional Reanalysis, 2012, North American Regional Reanalysis (NARR) Homepage, accessed May 15, 2012, at *http://www.emc.ncep.noaa.gov/mmb/rreanl/*.

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.

Pinelands Commission, 2003, Kirkwood-Cohansey Project Work Plan: New Lisbon, N.J.: New Jersey Pinelands Commission, 37 p.

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.

Rhodehamel, E.C., 1970, A hydrologic analysis of the New Jersey Pine Barrens region: New Jersey Division of Water Policy Water Resources Circular 22, 35 p.

Rhodehamel, E.C. 1979, Hydrology of the Pine Barrens of New Jersey, *in* Forman, R.T.T., ed., Pine Barrens: ecosystem and landscape: New York, Academic Press, revised paperback edition, p. 147–167.

Schafer, V.R., 2011, Canopy stomatal conductance following drought, disturbance, and death in an upland oak/pine forest of the New Jersey Pine Barrens, USA: Frontiers in Plant Science, v. 2, article 15, 7 p.

Schotanus, P., Nieuwstadt, F.T.M., and de Bruin, H.A.R., 1983, Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes: Boundary-Layer Meteorology, v. 50, p. 81–93.

Schuepp, P.H., Leclerc, M.Y., MacPherson, J.I., and Desjardins, R.L., 1990, Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation: Boundary-Layer Meteorology v. 50, p. 355–373.

Stannard, D.I., 1993, Comparison of Penman-Monteith, Shuttleworth-Wallace, and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland: Water Resources Research, v. 29, no. 5, p. 1379–1392.

Stannard, D.I., 1994, Interpretation of surface flux measurements in heterogeneous terrain during the Monsoon ‘90 experiment: Water Resources Research, v. 30, no. 5, p. 1227–1239.

Stull, R.B., 1988, An introduction to boundary layer meteorology: Boston, 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, 38 p.

Sumner, D.M., and Nicholson, R.S., 2010, Estimation of historical and future evapotranspiration: Proceedings of the EWRI of ASCE – 3rd International Perspective on Current & Future State of Water Resources & the Environment, January 2010, Chennai, India.

Tanner, B.D., and Greene, J.P., 1989, Measurement of sensible heat and water vapor fluxes using eddy correlation methods: Final report prepared for U. S. Army Dugway Proving Grounds: Dugway, Utah, 17 p.

Tanner, B.D., Swiatek, E., and Greene, J.P., 1993, Density fluctuations and use of the krypton hygrometer in surface flux measurements: Management of irrigation and drainage systems, Irrigation and Drainage Division: Park City, Utah, American Society of Civil Engineers, July 21–23, 1993, p. 945–952.

Tanner, C.B., and Thurtell, G.W., 1969, Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric boundary layer: Fort Huachuca, Ariz., United States Army Electronics Command, Atmospheric Sciences Laboratory, TR ECOM 66-G22-F, Reports Control Symbol OSD-1366, April 1969, 10 p.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., and Wesely, M.L., 2000, Correcting eddy-covariance flux underestimates over a grassland: Agricultural and Forest Meteorology, v. 103, p. 279–300.

Vermuele, C.C., 1894, Report on water-supply, water power, the flow of streams and attendant phenomena: Final report of the State geologist, v. III: Trenton, N.J., Geological Survey of New Jersey, 352 p.

Vowinkel, E.F., and Foster, W.K., 1981, Hydrogeologic conditions in the Coastal Plain of New Jersey: U.S. Geological Survey Open–File Report 81–405, 39 p.

Walker, R.L., Nicholson, R.S., and Storck, D.A., 2011, Hydrologic assessment of three drainage basins in the Pinelands of southern New Jersey, 2004–06: U.S. Geological Survey Scientific Investigations Report 2011–5056, 145 p.

Watt, M.K., and Johnson, M.L., 1992, Water resources of the unconfined aquifer system of the Great Egg Harbor River Basin, New Jersey, 1989–90: U.S. Geological Survey Water-Resources Investigations Report 91–4126, 5 pls.

Watt, M.K., Johnson, M.L., and Lacombe, P.J., 1994, Hydrology of the unconfined aquifer system, Toms River, Metedeconk River, and Kettle Creek Basins, New Jersey, 1987–90: U.S. Geological Survey Water-Resources Investigations Report 93–4110, 5 pls.

Watt, M.K., Kane, A.C., Charles, E.G., Storck, D.A., 2003, Hydrology of the unconfined aquifer system, Rancocas Creek area: Rancocas, Crosswicks, Assunpink, Assiscunk, Blacks, and Crafts Creek Basins, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 02–4280, 5 sheets.

Webb, E.K., Pearman, G.I., and Leuning, R., 1980, Correction of flux measurements for density effects due to heat and water vapour transfer: Quarterly Journal of the Royal Meteorological Society, v. 106, p. 85–100.

Weeks, E.P., Weaver, H.L., Campbell, G.S., and Tanner, B.D., 1987, Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico: U. S. Geological Survey Professional Paper 491-G, 37 p.

Whitmire, S.L., and Tobin, P.C., 2006, Persistence of invading gypsy moth populations in the United States: Oecologia, 147, p. 230–237.

Wood, O.M., 1937, The interception of precipitation in an oak-pine forest: Ecology, v. 18, no. 2, p. 251–254.

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New Jersey Water Science Center
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