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COMPARISON OF 13 EQUATIONS FOR DETERMINING EVAPOTRANSPIRATION FROM A PRAIRIE WETLAND, COTTONWOOD LAKE AREA, NORTH DAKOTA, USA

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Abstract: Evapotranspiration determined using the energy-budget method at a semi-permanent prairie-pothole wetland in east-central North Dakota, USA was compared with 12 other commonly used methods. The Priestley-Taylor and deBruin-Keijman methods compared best with the energy-budget values; mean differences were less than 0.1 mm d^{-1}, and standard deviations were less than 0.3 mm d^{-1}. Both methods require measurement of air temperature, net radiation, and heat storage in the wetland water. The Penman, Jensen-Haise, and Brutsaert-Stricker methods provided the next-best values for evapotranspiration relative to the energy-budget method. The mass-transfer, deBruin, and Stephens-Stewart methods provided the worst comparisons; the mass-transfer and deBruin comparisons with energy-budget values indicated a large standard deviation, and the deBruin and Stephens-Stewart comparisons indicated a large bias. The Jensen-Haise method proved to be cost effective, providing relatively accurate comparisons with the energy-budget method (mean difference = 0.44 mm d^{-1}, standard deviation = 0.42 mm d^{-1}) and requiring only measurements of air temperature and solar radiation. The Mather (Thornthwaite) method is the simplest, requiring only measurement of air temperature, and it provided values that compared relatively well with energy-budget values (mean difference = 0.47 mm d^{-1}, standard deviation = 0.56 mm d^{-1}). Modifications were made to several of the methods to make them more suitable for use in prairie wetlands. The modified Makkink, Jensen-Haise, and Stephens-Stewart methods all provided results that were nearly as close to energy-budget values as were the Priestley-Taylor and deBruin-Keijman methods, and all three of these modified methods only require measurements of air temperature and solar radiation. The modified Hamon method provided values that were within 20 percent of energy-budget values during 95 percent of the comparison periods, and it only requires measurement of air temperature. The mass-transfer coefficient, associated with the commonly used mass-transfer method, varied seasonally, with the largest values occurring during summer.

Key Words: evapotranspiration, evaporation, potential, energy budget, wetlands, prairie potholes, methods comparison

INTRODUCTION

Evapotranspiration (*ET*) is the single largest loss of water from most prairie wetlands. Loss of water to *ET* greatly impacts the stage and salinity of these wetlands, yet few studies have quantified this term adequately in a wetland setting (Meyboom 1967, Eisenlohr 1972, Hayashi et al. 1998, Parkhurst et al. 1998, Burba et al. 1999). Of these, two (Meyboom 1967, Eisenlohr 1972) used a mass-transfer method, and three used a Bowen-ratio energy budget method (Hayashi et al. 1998, Parkhurst et al. 1998, Burba et al. 1999). Hayashi et al. (1998) also used a pan evaporimeter to quantify open-water evaporation.

Parkhurst et al. (1998) measured *ET* from a prairie wetland in North Dakota, USA over a 5-year period. They compared rates determined using the energy-budget method with rates determined using the mass-transfer method. Mass-transfer rates commonly differed from energy-budget rates by 0.7 to 1.4 mm d^{-1} (rates averaged over 2-week periods), and the greatest difference between the two methods was 4 mm d^{-1}.

Winter et al. (1995) compared 11 different methods for obtaining lake evaporation with the Bowen ratio energy-budget method, which they considered their standard. They found that differences from the energy-balance method often were large; mean differences ranged from 0 to 0.7 mm d^{-1} (averages of 22 monthly periods), but maximum monthly differences were as large as 1.5 mm d^{-1}. Differences were even larger if data were not measured on site and over the evaporating surface. These comparisons were made using evaporation data collected over and adjacent to an open-water lake. Similar comparisons have not been made for prairie wetlands, where additional complications exist related to temporal variations in cover by emergent vegetation, wetland surface area, and wetland water volume.

Inter-site comparisons of rates of *ET* between wetlands often are complicated because different methods commonly are used to obtain *ET* values, resulting in errors and bias related to methodology. To address the severity of methodology-related errors and bias, multiple methods for measuring *ET* need to be evaluated at a single site. This paper applies the approach used by Winter et al. (1995) to data collected at wetland P1, a prairie wetland in east-central North Dakota. The energy-budget method, long considered to be one of the most accurate methods for long-term, continuous monitoring of *ET* (Harbeck et al. 1958, Gunaji 1968, Sturrock et al. 1992), is used as a standard, and 12 other methods for determining *ET* are compared to the energy-budget method using monthly averaged data. Many of the alternate methods were then modified to produce results that compare better with the energy-budget values, making those alternate methods more suitable for use in a prairie-wetland setting. *ET* differences determined for wetland P1 were compared to *ET* differences determined at a lake in Minnesota to provide a relative indication of methods that might work well in other wetland settings. Lastly, because many studies do not have the resources to accomplish an energy-budget analysis, we then present discussion comparing accuracy of the alternate methods with materials and labor costs associated with each of those methods.

Evaporation and transpiration both contribute to the loss of water from wetland P1, and the energy-budget method is used primarily to measure open-water evaporation. Nevertheless, variables measured for the energy-budget method also are affected and modified by the influence of transpiration from emergent vegetation that covered a significant and variable percentage of wetland P1. The flux measured by the energy-budget method therefore is referred to as *ET* in this paper. Data were collected during the open-water seasons of 1982–1987 excluding 1986, as reported in Parkhurst et al. (1998).

METHODS

ET originally was measured using the Bowen-ratio energy-budget method at a semi-permanent wetland (1.5–3 ha during 1982–1987) situated near the center of a U.S. Fish and Wildlife Service Waterfowl Protection Area in east central North Dakota (Figure 1) (Parkhurst et al., 1998). Those values are considered the standard for this report, to which results from all other *ET* equations are compared.

The energy-budget equation can be written as

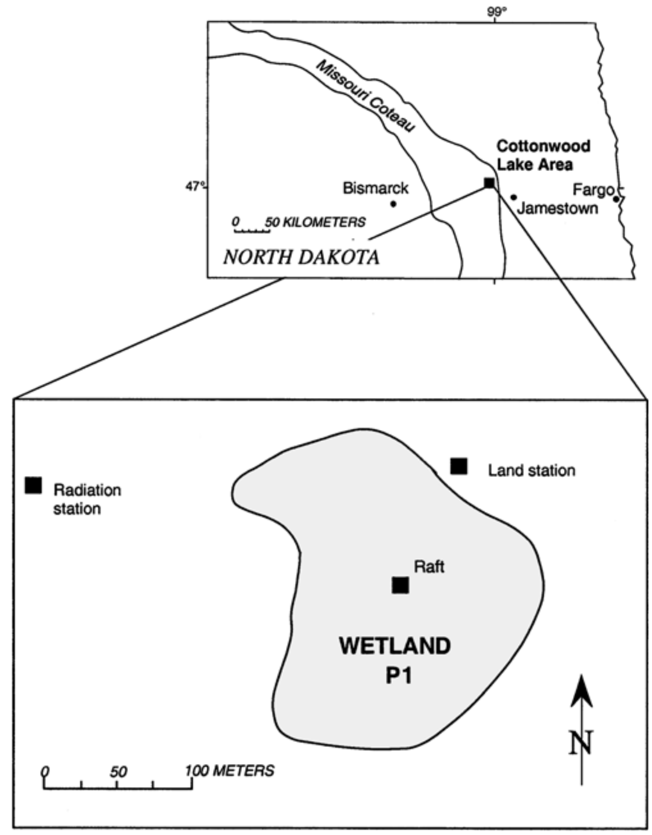

Figure 1. Location of the Cottonwood Lake area and data-collection stations in and adjacent to wetland P1.

$$ET_{eb} = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_x + Q_b}{\rho[L(1 + R) + cT_o]} \tag{1}$$

where

ET_{eb} evapotranspiration determined with the energy-budget method (cm d^{-1}),
Q_s incoming solar shortwave radiation (cal cm^{-2} d^{-1}),
Q_r reflected solar shortwave radiation (cal cm^{-2} d^{-1}),
Q_a incoming atmospheric longwave radiation (cal cm^{-2} d^{-1}),
Q_{ar} reflected atmospheric longwave radiation (cal cm^{-2} d^{-1}),
Q_{bs} longwave atmospheric radiation emitted from the wetland surface (cal cm^{-2} d^{-1}),
Q_v net energy advected to the wetland from precipitation and ground water (cal cm^{-2} d^{-1}),
Q_x change in heat stored in the wetland water body (cal cm^{-2} d^{-1}),
Q_b heat transferred to the water from the wetland sediments (cal cm^{-2} d^{-1}),
ρ density of water (1g cm^{-3}),
L latent heat of vaporization (cal g^{-1}),

R	Bowen ratio, which is the ratio of sensible to latent heat (dimensionless),
c	specific heat capacity of water (1 cal g^{-1} $°C^{-1}$)
T_o	wetland surface-water temperature (°C).

Equation 1 then is multiplied by 10 to convert ET_{eb} from cm d^{-1} to mm d^{-1}.

Atmospheric data were collected from a land station next to the shoreline and from a raft situated over open water in the center of wetland P1. Air temperature, relative humidity, wind speed, and water-surface temperature were collected at the raft; atmospheric sensors were kept at 2 m above the wetland water surface. Incoming solar shortwave (Q_s) and atmospheric longwave (Q_a) radiation were collected from a land station at 3 m above the ground. Sensors were sampled each minute, and hourly and daily averages and totals were calculated and stored by digital dataloggers that were connected to the sensors. Q_b was determined using thermistors installed in the wetland sediments. Q_v from rainfall was determined based on wet-bulb temperatures during rainfall; Q_v due to exchange with ground water was determined based on applying the temperature of shallow ground water to the mass of ground water that entered the wetland. In the cases where wetland water was moving to ground water, the temperature of the wetland water was used. Q_x was determined approximately biweekly by measuring change in temperature from the beginning to the end of each energy-budget period at seven locations in the wetland and at four depths at each location. Maximum water depth in the wetland varied from 0.2 m to 1.1 m during the study period.

Additional terms necessary for comparing evaporation methods were calculated from measured variables. Q_r, Q_{ar}, and Q_{bs} were calculated using incoming radiation data, and Q_{bs} also required T_o data (Parkhurst et al. 1998). Atmospheric vapor pressure (e_a) was determined using relative humidity and air-temperature data. Saturated vapor pressure at the water-surface temperature (e_o) was determined using the water-surface temperature data. Saturated vapor density (*SVD*), the slope of the curve of saturated vapor pressure vs air temperature (s), and hours of daylight were obtained from tables in Campbell (1977) and the Smithsonian Meteorological Tables (List 1966). Values for the psychrometric constant (γ) were obtained from an empirical relationship presented in Fritschen and Gay (1979).

Alternate methods for determining *ET* at wetland P1 are listed in Table 1. The eleven alternate methods for determining evaporation used by Winter et al. (1995) for Williams Lake in Minnesota are evaluated here. In addition, the Mather (1978) method, which was used to estimate *ET* from wetland P1 for simulations that related vegetation response to climate change (Poiani 1990, Poiani and Johnson 1993), is evaluated here. Mather (1978) referred to this equation as the Thornthwaite (1948) method, but to be consistent with results published previously, it is referred to here as the Mather method. The methods are organized based on type: (1) a group based on the Penman equation, (2) a solar radiation-temperature group, (3) a temperature group, and (4) the mass-transfer method.

RESULTS

Daily ET_{eb} averaged by month is shown in Figure 2 (from Parkhurst et al. 1998). During four of the five years, maximum evaporation occurred during July. Interannual monthly variability was smallest during July (4.3–5.2 mm d^{-1}); rates varied considerably more from year to year during June (3.5–6.0 mm d^{-1}) and August (2.9–4.2 mm d^{-1}).

ET_{eb} values shown in Figure 2 were subtracted from alternate estimates of *ET*, and differences for each alternate method are shown in Figure 3. Three of the twelve methods presented in Figure 3 (deBruin-Keijman, Priestley-Taylor, and Penman) provided results that were within 1 mm d^{-1} of the ET_{eb} values for all comparison periods. With the exception of July 1985 comparisons, the Priestley-Taylor and deBruin-Keijman methods provided results that were within 0.5 mm d^{-1} of the ET_{eb} values for all comparison periods. The Jensen-Haise method provided values that were within 1 mm d^{-1} of the ET_{eb} values during 19 of 20 monthly comparison periods. Three of these four methods that compare best with ET_{eb} show little bias; the Jensen-Haise method indicated the largest average bias of 0.44 mm d^{-1}. The methods that compared least well relative to ET_{eb} estimates were deBruin, Stephens-Stewart, Papadakis, and mass-transfer. The deBruin and Stephens-Stewart methods both indicated significant overall bias; the bias was particularly uniform with the Stephens-Stewart method. Most of the alternate methods indicated a negative bias shift during 1987 relative to the first four years of comparisons. The only methods that did not indicate a negative bias shift during 1987 were Priestley-Taylor, deBruin-Keijman, and Brutsaert-Stricker.

Some of the *ET* methods indicate a slight seasonal bias relative to the ET_{eb} values. The mass-transfer method has been reported to overestimate *ET* during spring and fall and underestimate *ET* during summer for small water bodies (Eisenlohr 1972, Ficke 1972). This pattern appears to hold at wetland P1 during 1987, the only year when data collection extended into spring and fall. The deBruin method would indicate a similar seasonal bias if the larger, annual-scale bias were removed. The Papadakis method tends to over-

Table 1. Equations for calculation of potential evapotranspiration (*PET*) or actual evapotranspiration (*AET*), the results from which are compared to results from the energy-budget equation, in mm/d.

Method	Reference	Equation	Devel. for
Penman group			
Priestley-Taylor	Stewart and Rouse, 1976	$PET = \alpha \frac{s}{s+\gamma} \frac{Q_n - Q_x}{L} \times 10$	*PET* for periods of 10 days or more
deBruin-Keijman	deBruin and Keijman, 1979	$PET = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_n - Q_x)}{L} \times 10$	*PET,* daily
Penman	Brutsaert, 1982	$PET = \frac{s}{s+\gamma}\left(\frac{Q_n - Q_x}{L}\right) \times 10 + \frac{\gamma}{s+\gamma}[0.26(0.5 + 0.54U_2)(e_s - e_a)]$	*PET,* for periods greater than 10 days
Brutsaert-Stricker	Brutsaert and Stricker, 1979	$AET = (2\alpha - 1)\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_n - Q_x}{L}\right)(10) - \left(\frac{\gamma}{s+\gamma}\right) \times [0.26(0.5 + 0.54U_2)(e_s - e_a)]$	*AET,* daily
deBruin	deBruin, 1978	$PET = 1.625\left(\frac{\alpha}{\alpha - 1}\right)\left(\frac{\gamma}{s+\gamma}\right)\frac{(2.9 + 2.1U_2)(e_s - e_a)}{L} \times 2.0635 \times 10$	*PET,* for periods of 10 days or greater
Solar radiation/temperature group			
Jensen-Haise	McGuinness and Bordne, 1972	$PET = (0.014T_a - 0.37)(Q_s \times 0.000673) \times 25.4$	*PET* for periods greater than 5 days
Makkink	McGuinness and Bordne, 1972	$PET = \left[\left(0.61\frac{s}{s+\gamma}\frac{Q_s}{L}\right) - 0.012\right] \times 10$	*PET,* monthly (Holland)
Hamon	Hamon, 1961	$PET = 0.55\left(\frac{D}{12}\right)^2 \frac{SVD}{100}(25.4)$	*PET,* daily
Stephens-Stewart	McGuinness and Bordne, 1972	$PET = (0.0082T_a - 0.19)\left(\frac{Q_s}{1500}\right) \times 25.4$	*PET,* monthly (Florida)
Temperature			
Mather	Mather, 1978	$PET = \left[1.6\left(\frac{10T_a}{I}\right)^{6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 + 1.79\times10^{-2}I + 0.49}\right]\left(\frac{10}{d}\right)$	*PET,* daily
Papadakis	McGuinness and Bordne, 1972	$PET = 0.5625[e_s\max - (e_s\min - 2)]\left(\frac{10}{d}\right)$	*PET,* monthly
Mass transfer	Harbeck and others, 1958	$ET = [NU_2(e_o - e_a)] \times 10$	*ET,* depends on calibration of *N*

α = 1.26 = Priestley-Taylor empirically derived constant, dimensionless
s = slope of the saturated vapor pressure-temperature curve at the mean air temperature (mb °C^{-1})
γ = psychrometric "constant" (depends on temperature and atmospheric pressure) (mb °C^{-1})
Q_n = net radiation ($Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_b$), in cal cm^{-2} day^{-1}
Q_s = solar radiation, in cal cm^{-2} day^{-1}
Q_x = change in heat stored in the water body, in cal cm^{-2} day^{-1}
L = latent heat of vaporization, in cal cm^{-3} (assumes 1 g H_2O = 1 cm^3)
N = mass-transfer coefficient (used 0.00547 from Parkhurst et al. (1998))
I = annual heat index ($I = \Sigma_i$, $i = (T_a/5)^{1.514}$)
U_2 = wind speed at 2 m above surface, in m s^{-1}
e_o = saturated vapor pressure at temperature of the water surface, in millibars
e_s = saturated vapor pressure at temperature of the air, in millibars
e_a = vapor pressure at temperature and relative humidity of the air, in millibars
SVD = saturated vapor density at mean air temperature, in g m^{-3}
T_a = air temperature, in °F for the Jensen-Haise and Stephens-Stewart equations, °C for the Mather equation
D = hours of daylight
d = number of days in month
$e_s$max and
$e_s$min = saturated vapor pressures at daily maximum and minimum air temperatures, in millibars

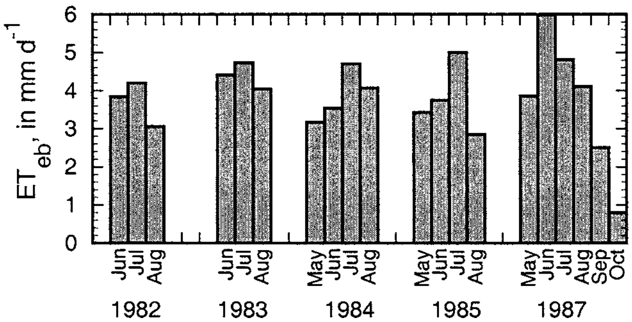

Figure 2. Daily *ET* from wetland P1 averaged per month, as determined by the energy-budget method, 1982–85 and 1987 (data from Parhkurst et al. 1998).

estimate ET during the fall and underestimate ET during spring and late summer. Some of these overestimates during the fall can be significant departures from ET_{eb} values when *ET* rates decrease in the fall. For example, the approximately 1.1 mm d^{-1} overestimate of *ET* during October 1997 by the Papadakis method was 2.4 times the ET_{eb} value.

Results from alternate *ET* methods are ranked based on the percent of time that the alternate *ET* values were within 5, 10, and 20 percent of ET_{eb} values (Table 2). Methods are presented in Table 2 from best to worst, based on the number of times the alternate methods provided results that were within 20 percent of the ET_{eb} values (ties were decided using the performance in the ''within 10%'' column). The Priestley-Taylor and deBruin-Keijman methods compared remarkably well with the ET_{eb} results; they provided results that were within 20 percent of ET_{eb} 100 percent of the time. Values from the Priestley-Taylor and deBruin-Keijman methods were within 5 percent of ET_{eb} values during half or more of the comparison periods. The Brutsaert-Stricker and Jensen-Haise methods also provided values that compared well with ET_{eb} values, based on the ''within 5%'' percent-difference comparisons.

Average bias and standard deviation during the study period of each alternate method are presented in Figure 4. Average differences relative to ET_{eb} values were very small for the Priestley-Taylor (0.07 mm d^{-1}) and deBruin-Keijman methods (0.15 mm d^{-1}). The Penman, Brutsaert-Stricker, Jensen-Haise, Mather, and mass-transfer methods also showed relatively small overall bias (less than 0.5 mm d^{-1} average difference). Average differences were greatest for the Stephens-Stewart and deBruin methods. Most methods underestimated *ET* relative to ET_{eb} values; only 5 of the 12 unmodified methods provided mean differences that were greater than ET_{eb} values (Figure 4). The deBruin method provided the greatest overestimates of *ET* relative to the ET_{eb} estimates, with a mean overestimate of 0.67 mm d^{-1}.

The five smallest standard deviations of differences between alternate methods and ET_{eb} values were deBruin-Keijman (0.26 mm d^{-1}), Priestley-Taylor (0.27 mm d^{-1}), Penman (0.37 mm d^{-1}), Jensen-Haise (0.42 mm d^{-1}), and Stephens-Stewart (0.43 mm d^{-1}). The Makkink, Hamon, and Mather methods all provided results with intermediate standard deviations (0.44–0.55 mm d^{-1}). Results were much more variable relative to ET_{eb} estimates for the deBruin, Papadakis, and Mass-transfer methods (0.75–1.99 mm d^{-1}).

DISCUSSION

Four of the alternate methods that performed quite well are in the Penman group (Figure 4). The Penman equation is theoretically derivable from energy-budget and aerodynamic principles (except for the empirical wind function) and, in an ideal setting, is very accurate. The equation is comprised of an available energy term and an aerodynamic term (Table 1). Four of the five methods within the Penman group contain an available energy term (Priestley-Taylor, deBruin-Keijman, Penman, and Brutsaert-Stricker), which distinguishes them from the fifth member of the Penman group, the deBruin method. The impressive performance (both mean bias and standard deviation) of the available energy sub-group emphasizes the importance of energy in determining *PET*. Priestley and Taylor (1972) first introduced this importance by demonstrating that, on average, the available energy term is about 79 percent of the total *PET*. The relatively poor performance (especially the large standard deviation, Figures 3E and 4) of the deBruin method is a consequence of attempting to reconstruct the full Penman equation from the small aerodynamic term (Table 1), which is only 21 percent of the total, on average. Any noise in the relation between the aerodynamic term and the total is amplified almost five times using this method.

Overall, the performance of the solar radiation-temperature group and the temperature group were roughly comparable (Figure 4). The bias magnitudes of the solar-radiation-temperature group are, on average, slightly greater than of the temperature group, but the standard deviations are smaller. The equations in both groups were empirically derived and probably perform best in the specific climate and setting for which they were developed. Solar radiation is highly correlated with available energy, and inclusion of solar radiation usually constitutes an improvement over a strictly temperature-based estimate. However, when applied to this specific site, other empirical aspects of the equations may compromise the improvement. The smaller standard deviation indicates a greater correlation with ET_{eb}, and if the methods are modified and calibrated to wetland P1, the solar radiation-temperature group

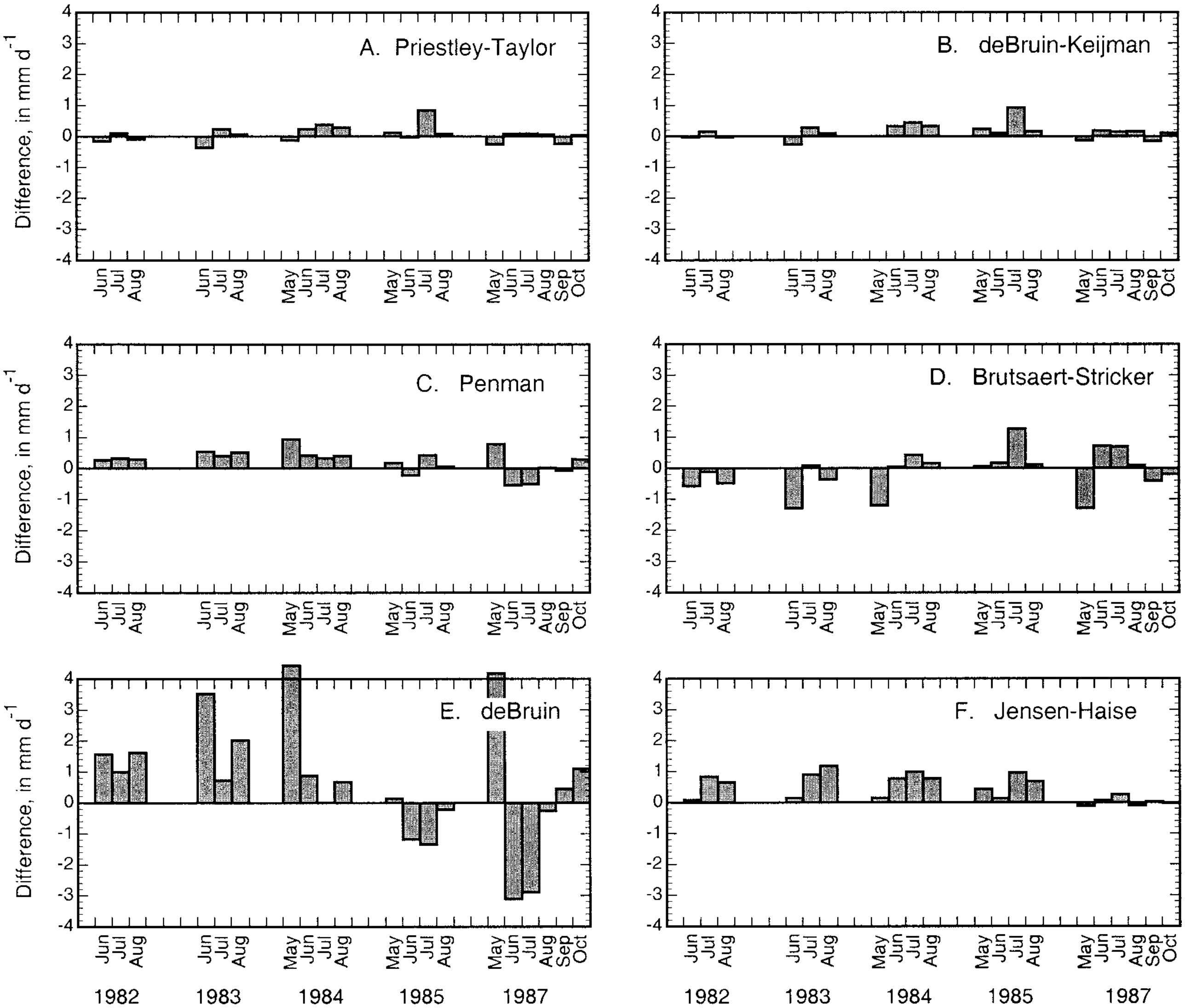

Figure 3. Difference in calculated *ET* between values determined with the energy-budget method and values determined with the 12 equations presented in Table 1, in mm d^{-1}).

performs significantly better than the temperature group.

Modifications of *ET* Methods

Comparisons of different methods for determining *ET* to the energy-budget method assume that ET_{eb} values are best estimates and are unbiased. If this assumption is valid, alternate methods can be modified to provide values that more closely match ET_{eb} values. Since these modifications were made based on conditions measured at wetland P1, caution should be exercised in extending their use beyond a prairie wetland setting. Many of the alternate *ET* methods presented in this paper contain coefficients that were developed for specific locations. Numerous modifications of coefficients, and wind functions in particular, appear in the literature for some of these methods. However, in most cases, the original versions of these equations were used for this paper. The exceptions include the use of an area-correction factor (Sweers 1976) with the deBruin method appropriate for wetland P1 (a value of 1.625 was used for a 2.8-ha wetland area) and the Penman and Brutsaert-Stricker methods, where a modified wind function suggested by Penman (1956) was used. Numerous versions of the empirical wind function in the Penman equation have been reported in the literature, although most of these modifications are associated with use of different units in measurement of wind speed and vapor pressure. Penman (1948) originally used the wind function

$$f(U_2) = 0.26(1 + 0.54U_2) \tag{2}$$

where U_2 is the wind speed at 2 m above the surface

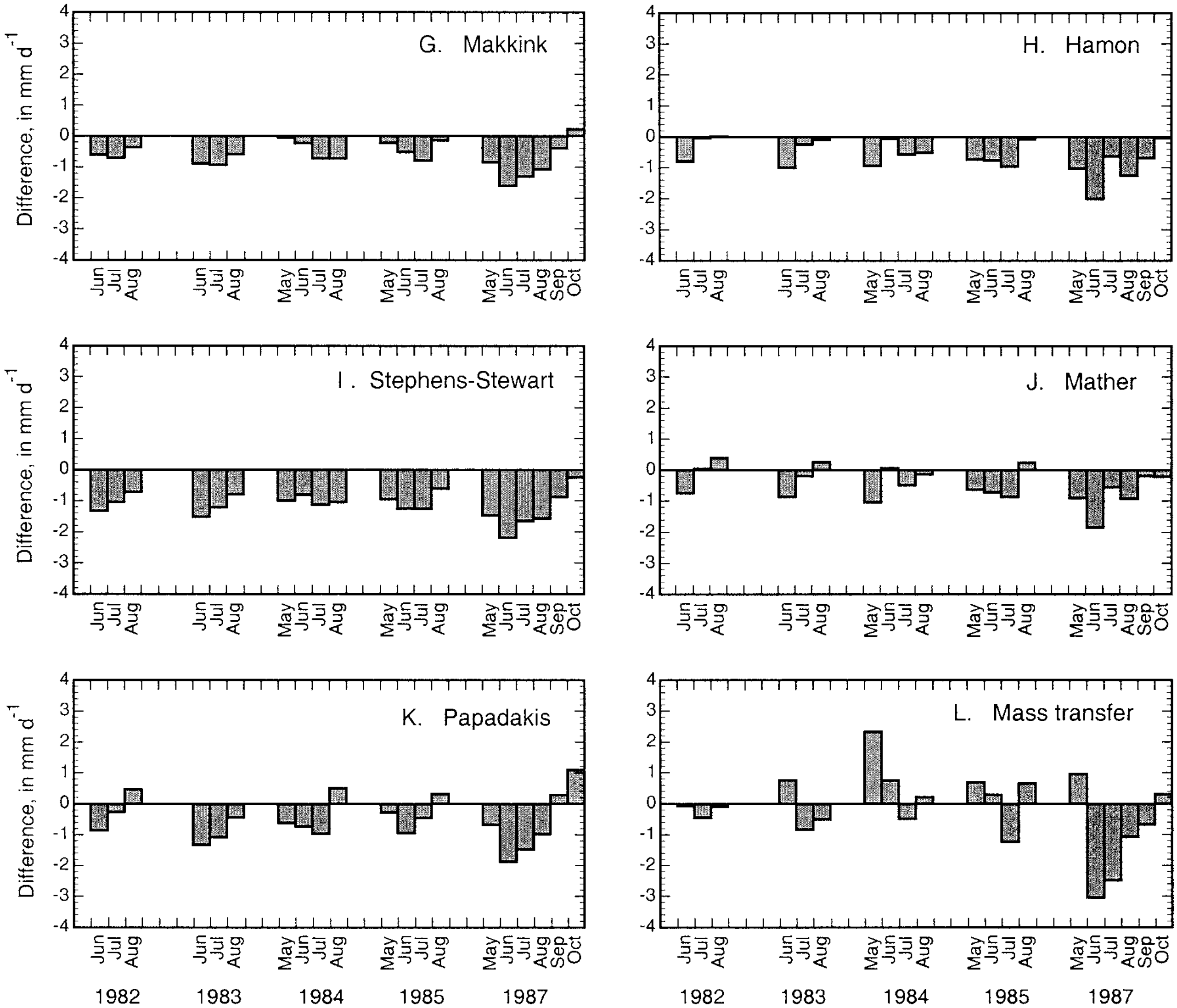

Figure 3. Continued.

in m s^{-1}. Penman (1956) later proposed a modification for use over large lakes:

$$f(U_2) = 0.26(0.5 + 0.54U_2) \quad (3).$$

This latter wind function was used for this paper, even though wetland P1 certainly is not a ''large lake,'' in part to be consistent with the equation used in Winter et al. (1995). However, the use of (2) instead of (3) at wetland P1 would have made the positive bias associated with use of the Penman method even larger.

Obvious biases exist for some of the comparison methods presented in this paper that could be eliminated with a simple adjustment of a coefficient if one had an error-free value of *ET* to which coefficients could be calibrated. For *ET* comparisons presented here, there is no need to adjust the Priestley-Taylor or deBruin-Keijman methods because they compared very well with the ET_{eb} values. However, six of the remaining ten methods (deBruin, Jensen-Haise, Makkink, Hamon, Stephens-Stewart, and Papadakis) were modified to obtain better comparisons with ET_{eb} values. The Penman and Brutsaert-Stricker methods were not modified to avoid changing fairly standard wind functions, the Mather method was not adjusted because the form used for this paper is so widely used, and the mass-transfer method was not adjusted because the mass-transfer coefficient already was calibrated for use at wetland P1. The Jensen-Haise method would not have needed adjustment, but it is nearly identical in form to the Stephens-Stewart method so it also was modified for consistency. Modified methods are presented in Table 3 and the results of comparisons with ET_{eb} values are shown in Figure 5.

The deBruin method was modified several ways in an attempt to improve the results. The best modification was obtained by using multiple regression (forced

Table 2. Percent of energy-budget periods that alternate ET values are within 5, 10, and 20 percent of ET_{eb} values. Number of monthly comparison periods = 20.

Alternate Method	Results within 5% of ET_{eb}	Results within 10% of ET_{eb}	Results within 20% of ET_{eb}
Priestley-Taylor	55%	95%	100%
deBruin-Keijman	50%	90%	100%
Penman	15%	65%	85%
Brutsaert-Stricker	40%	50%	75%
Mather	20%	35%	75%
Jensen-Haise	45%	50%	70%
Makkink	10%	20%	70%
Hamon	30%	35%	55%
Papadakis	0%	15%	50%
Mass Transfer	10%	20%	45%
deBruin	10%	20%	35%
Stephens-Stewart	0%	0%	5%

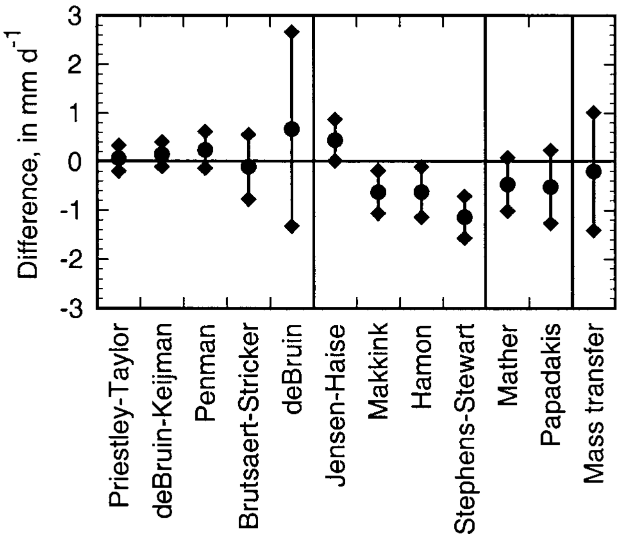

Figure 4. Differences between alternate ET estimates and ET_{eb}. Symbols show mean difference plus or minus standard deviation from mean difference, in mm d^{-1}.

through the origin) to obtain slope and offset terms for a calibrated wind function, but this resulted in a nonsensical wind function where wind speed was negatively correlated with ET. The area factor also was adjusted to reduce the bias, but the new area factor related to a wetland area of 150 m^2, an area far too small for the approximately 30,000 m^2 area of wetland P1. Therefore, no modified forms of the deBruin method are presented.

The Stephens-Stewart method originally was developed for use in humid Florida, whereas the similar Jensen-Haise method was developed for use in the more arid portions of the western United States. The two methods are identical in form and differ only in their empirical coefficients. Specifically, the solar radiation coefficients are virtually identical, and the lin-

Table 3. Equations for calculating PET, modified for best fit with ET_{eb} measurements at wetland P1.

Modified Method	Modification	Equation
Jensen-Haise	Regressed temp. function	$PET = (0.016T_a + 0.186)(Q_s \times 0.000673) \times 25.4$
Stephens-Stewart	Regressed temp. function	$PET = (0.016T_a + 0.188)\left(\frac{Q_s}{1500}\right) \times 25.4$
Makkink	Regressed Q_s/L function	$PET = \left(8.671\frac{s}{s + \gamma}\frac{Q_s}{L}\right) - 0.904$
Hamon	Adjusted coefficient	$PET = 0.656\left(\frac{D}{12}\right)^2\frac{SVD}{100}(25.4)$
Papadakis	Adjusted coefficient	$PET = 0.65[e_s\max - (e_s\min - 2)]\left(\frac{10}{d}\right)$

α = 1.26 × Priestley-Taylor empirically derived constant, dimensionless
s = slope of the saturated vapor pressure-temperature curve at the mean air temperature (mb °C^{-1})
γ = psychrometric "constant" (depends on temperature and atmospheric pressure) (mb °C^{-1})
Q_s = solar radiation, in cal cm^{-2} day^{-1}
L = latent heat of vaporization, in cal cm^{-3}
U_2 = wind speed at 2 m above surface, in m s^{-1}
e_s = saturated vapor pressure at temperature of the air, in millibars
e_a = vapor pressure at temperature and relative humidity of the air, in millibars
SVD = saturated vapor density at mean air temperature, in g m^{-3}
T_a = air temperature, formerly in °F for the Jensen-Haise and Stephens-Stewart equations, now is in °C
D = hours of daylight
d = number of days in month
$e_s$max and
$e_s$min = saturated vapor pressures at daily maximum and minimum air temperatures, in millibars
All equations result in units of mm day^{-1}.

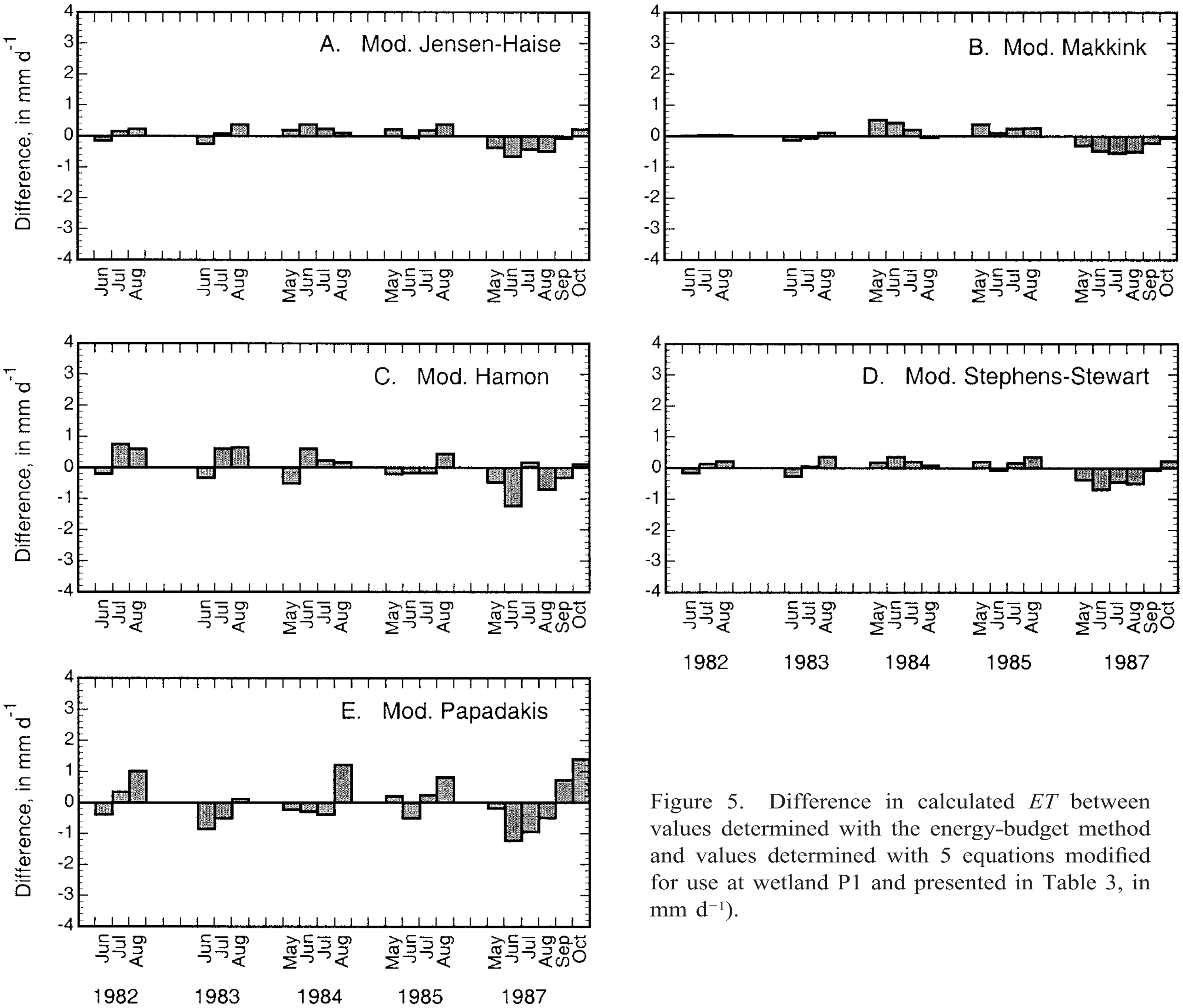

Figure 5. Difference in calculated *ET* between values determined with the energy-budget method and values determined with 5 equations modified for use at wetland P1 and presented in Table 3, in mm d^{-1}).

ear temperature functions differ. At 31°F (−0.5°C), the two methods yield identical results, but at 60°F (16°C), the ratio of the Jensen-Haise to Stephens-Stewart results is 1.57, and at 90°F (32°C), the ratio is 1.62. The closer agreement with the Jensen-Haise than the Stephens-Stewart method probably results from conditions in central North Dakota being closer to the arid western United States than to humid Florida. Neither method explicitly accounts for the influence of vapor pressure deficit on *ET*. Since the Stephens-Stewart method was calibrated for Florida conditions, where vapor pressure deficits are small, it tends to underestimate *ET* in settings with larger vapor pressure deficits (more arid). The Jensen-Haise method empirically compensates for the effect of vapor pressure deficit in more arid settings through the greater temperature function. Therefore, it works well in arid and semi-arid regions but probably would overestimate *ET* in humid regions.

To calibrate these methods for use at wetland P1, the temperature function was isolated from the rest of the equation. Multiple regression was forced through the origin, with ET_{eb} as the dependent variable, to solve for the slope and offset coefficients of the modified temperature function. Temperature in °C rather than °F was used in the modified equations. The resulting equations for the prairie-wetland-calibrated Jensen-Haise and Stephens-Stewart methods are nearly identical (Table 3); the modified equations eliminated the bias and reduced the standard deviation compared to the unmodified Jensen-Haise and Stephens-Stewart methods (Figure 6 compared with Figure 4).

The Makkink method also was modified using multiple linear regression to solve for slope and offset (Ta-

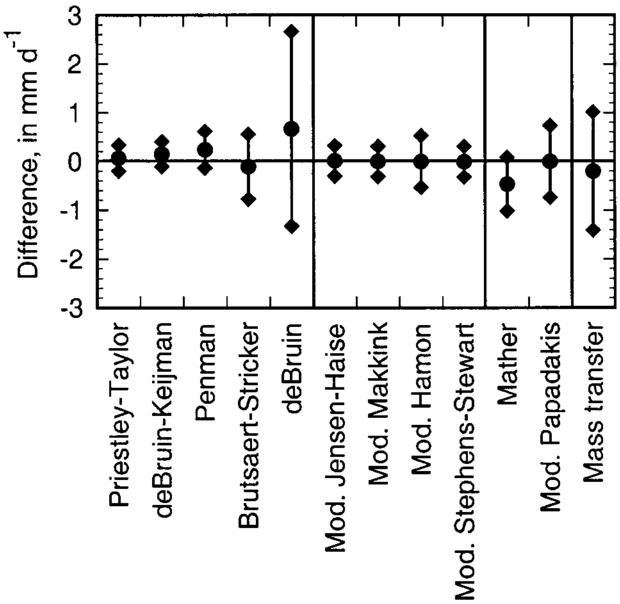

Figure 6. Differences between alternate ET estimates (including several methods modified for use at wetland P1) and ET_{eb}. Symbols show mean difference plus or minus standard deviation from mean difference, in mm d^{-1}.

Table 4. Percent of energy-budget periods that alternate ET values (including several methods modified for use at wetland P1) are within 5, 10, and 20 percent of ET_{eb} values. Number of monthly comparison periods = 20. Modified methods are underlined.

Alternate Method	Results within 5% of ET_{eb}	Results within 10% of ET_{eb}	Results within 20% of ET_{eb}
Priestley-Taylor	55%	95%	100%
deBruin-Keijman	50%	90%	100%
Makkink	50%	75%	100%
Jensen-Haise	40%	75%	95%
Stephens-Stewart	40%	70%	95%
Hamon	25%	40%	95%
Penman	15%	65%	85%
Brutsaert-Stricker	40%	50%	75%
Mather	20%	35%	75%
Papadakis	10%	40%	70%
Mass Transfer	10%	20%	45%
deBruin	10%	20%	35%

ble 3). The modified coefficients solve for ET in mm d^{-1} and do not require multiplication by 10 as did the original Makkink method. The Hamon and Papadakis methods were modified by adjusting the coefficient until bias was eliminated.

Modified ET methods compared much better with ET_{eb} values when re-ranked according to the percent of time that alternate ET values were within 5, 10, and 20 percent of ET_{eb} values (Table 4). The modified Makkink method provided values that were nearly as close to ET_{eb} values as the Priestley-Taylor and deBruin-Keijman methods, but the Makkink method only requires measurement of Q_s and T_a. The modified Jensen-Haise, Stephens-Stewart, and Hamon methods also provided values that were remarkably close to ET_{eb} values and also required measurement of only Q_s and T_a or, in the case of the Hamon method, only T_a.

Seasonality of the Mass Transfer Coefficient

Many of the previous studies of water loss from prairie pothole wetlands used the mass-transfer method (Eisenlohr 1966, Meyboom 1967, Allred et al. 1971). In those studies, the mass-transfer coefficient (N) was determined by plotting the mass-transfer product ($U(e_o - e_a)$) against change in stage of the water body (Langbein et al. 1951). This was deemed to be an acceptable approach for periods when there are no fluxes, other than evaporation, to and from the water body. The method also was deemed appropriate as long as any fluxes to or from ground water were constant during the change in stage. In fact, the mass-transfer versus stage-change plot could be used to estimate fluxes to or from ground water, as indicated by the y-axis intercept value of the regression line. It was noted in the studies mentioned above that N varied according to season. Eisenlohr (1966) attributed the variability in N to the changing growth stages of hydrophytes during the course of a summer. Meyboom (1967) noted that N varied exponentially with evaporative power and that N decreased throughout the summer by about 50 percent.

The study of wetland P1 provided the opportunity to examine the seasonality of the mass-transfer coefficient when calibrated using an independent estimate of evaporation. Data were summarized during each energy-budget period from 1982 to 1987 (including five periods during 1986). Plots of the mass-transfer product ($U_2(e_o - e_a)$) against ET_{eb} for different seasons are shown in Figure 7. For easier comparison with earlier studies (e.g., Meyboom 1967, Eisenlohr 1972), the mass-transfer product was calculated using miles per hour (instead of meters per second) and millibars. As with previous studies, the regression line was forced through the origin; therefore, the goodness-of-fit indicators for the plots in Figure 7 are not shown. The regression slope using all of the data is 0.00514 (Figure 7A). The regressions using spring (April–June), summer (July–August), and fall (September–October) data are presented in Figure 7 panels B-D. Similar to the results of Eisenlohr (1972), N was largest during the summer for wetland P1. However, Eisenlohr indicated that N was next largest in the fall, whereas for wetland P1, the next largest N value was in spring. N decreased markedly from summer to fall (Figure 7). A

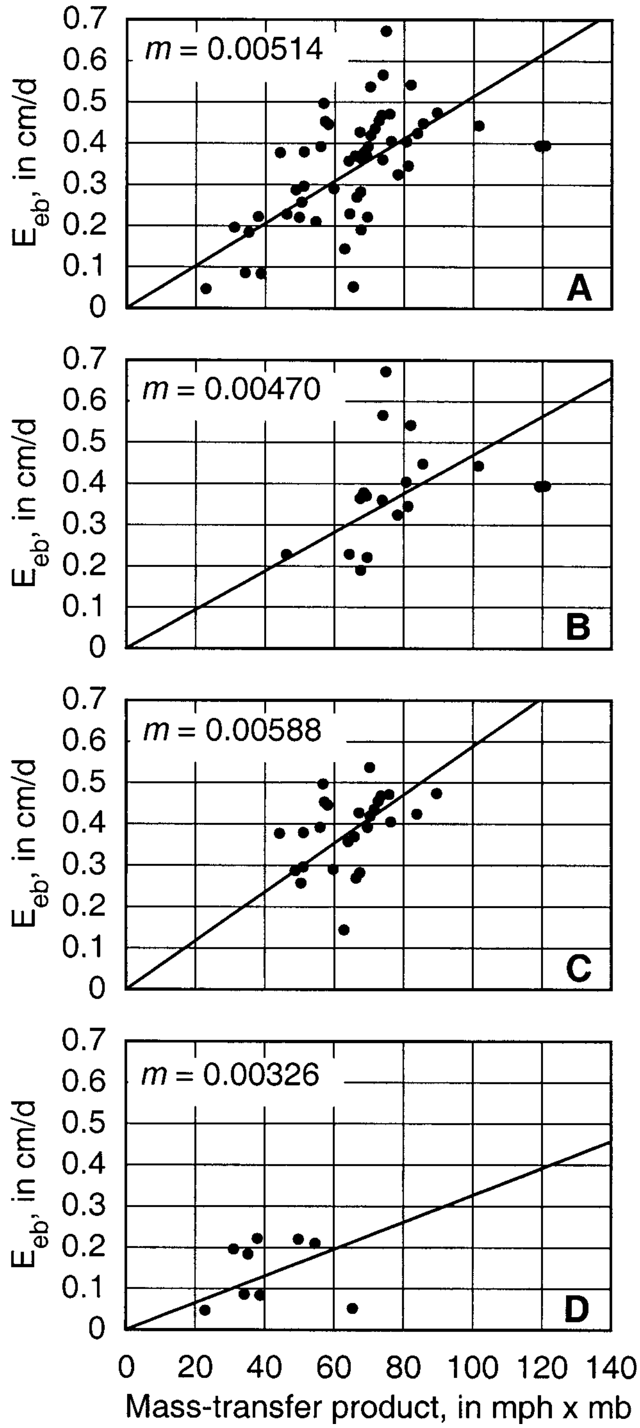

Figure 7. Mass-transfer coefficient determined by least-squares linear regression (forced through the origin) of the mass-transfer product (mi hr^{-1} x mb) vs ET_{eb}. Panel A includes all approximately biweekly energy-budget periods; Panel B includes only spring (April–June) data; Panel C includes only summer (July–August) data; Panel D includes only fall (September–October) data.

similar decrease in N for a Canadian prairie wetland was reported by Meyboom (1967), although Meyboom reported largest values in spring that then decreased steadily throughout the summer. Meyboom reported that N determined from fall data was only 50 percent of N determined using summer data. At wetland P1, N during the fall was 55 percent of N during summer.

The mass-transfer method would compare much more favorably with ET_{eb} values if a term for atmospheric stability were included. The lack of such a term is the major reason N is seasonally variable. The greater the instability of the boundary layer over the water (air cooler than water surface), the greater the ET for a given vapor pressure difference and windspeed. For the case of wetland P1 (and the similarly small wetlands reported in Meyboom (1967), Eisenlohr (1966) and Allred (1971)), maximum instability occurs during mid-summer, which would result in the greatest underestimate of ET using the mass-transfer method. Maximum stability would occur during winter (or spring and fall during the open-water season), which would result in the greatest overestimate of ET using the mass-transfer method. This general pattern is apparent in the monthly comparison of the mass-transfer ET with ET_{eb} (Figure 3L).

Effect of Emergent Aquatic Vegetation on Evaporation

Prairie pothole wetlands commonly have emergent aquatic plants present over part of their surface area. The plant communities generally form concentric rings around areas of open water. In the case of wetland P1, a zone of deep-marsh plants (largely cattail and bulrush) surrounds the open water, and a zone of shallow-marsh plants (largely whitetop, *Stachus*, and *Lycopus*) are present between the deep-marsh plants and the shoreline. The effect of these plant communities on estimates of ET from the water body as a whole has been the subject of considerable controversy (Eisenlohr 1966, Burba et al. 1999, Mitsch and Gosselink 2000). The basic question is whether more water is lost to the atmosphere from the vegetated part of the wetland or from the open-water part. We restrict our interest here to that portion of the wetland that is covered by standing water, and we assume that ET is occurring at the potential rate. The problem of determining the influence of plant type and plant density on rates of ET is even more complex when the water table is below land surface (Lott and Hunt 2001). To compare evaporation rates from the open-water areas of a wetland with ET from the vegetated areas, it is necessary to place instruments in each of the areas. This was not done for this study of wetland P1, where the instruments were placed only in the open-water area, and it was assumed that sensors represented an integrated flux from both areas. However, it is useful to review other studies of similar types of wetlands to determine if there might be some transfer value to wetland P1.

In prairie pothole terrain similar to the Cottonwood Lake area, Eisenlohr (1966) tried to determine the differences between open-water evaporation and *ET* from vegetated areas by using the mass-transfer method. The rationale for trying this method is that the mass-transfer coefficient (*N*) is affected by the amount of vegetation present. By assuming that *N* during the dormant season represents evaporation only and that *N* determined during the growing season represents *ET*, transpiration alone can be determined by subtracting evaporation from *ET*. Using this method, Eisenlohr indicated that evaporation from open water was 50 percent to more than 100 percent greater than transpiration. However, because of the difficulty and uncertainty in determining the different mass-transfer coefficients for the various stages of seasonal plant growth, Eisenlohr also indicated that his approach was quite crude and subject to considerable uncertainty.

A recent study of *ET* from wetlands in Nebraska was conducted specifically to measure and compare open-water evaporation rates with *ET* rates from vegetated areas (Burba et al. 1999). In that study, instruments to determine *ET* by the Bowen ratio-energy balance method were placed in two different plant communities (reedgrass (*Phragmites australis* (cav.) Trin. ex Steud.) and bulrush (*Scirpus acutus* Muhl. Ex Bigelow)) and in open water. Results of the study indicated that daily evaporation from the open water area was 8 percent more than daily *ET* from the *Phragmites*-covered area, and 17 percent more than daily *ET* from the *Scirpus*-covered area.

The energy-budget evaporation study of wetland P1 reported by Parkhurst et al. (1998) and the differences from those values reported in this paper do not distinguish between evaporation from the open water and *ET* from the vegetated parts of the wetland. However, results of the study by Burba et al. (1999) could be used to address qualitatively the issue of evaporation versus *ET* for wetland P1. For five years of this study (1982–1986), wetland P1 had about 35 to 40 percent open water. The exception was 1987, when open water covered only about 25 percent of the wetland (Figure 8). For all years, deep-marsh emergent aquatic species, largely cattail and bulrush, covered the largest area of the wetland. These species are the most similar to the aquatic plants (bulrush) reported by Burba et al. (1999) to transpire about 17 percent less water than open-water evaporation. Therefore, using a very rough estimate of 60 percent emergent plant coverage and 17 percent less water loss by transpiration for that area,

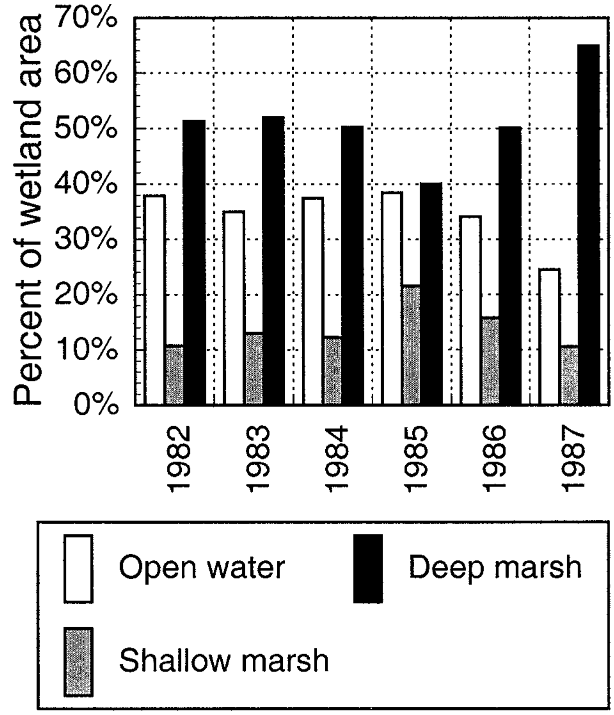

Figure 8. Percent of wetland P1 surface area that is open water, covered by shallow-marsh vegetation, and covered by deep-marsh vegetation, 1982–87.

it is conceivable that the water lost by the total of evaporation and transpiration might be about 10 percent less than the values reported by Parkhurst et al. (1998) and those calculated for the comparisons presented in this report.

Impact of Fetch on Measured *ET* Rates

Measurements of air temperature and vapor pressure were made at 2 m above the wetland surface with the assumption that the air flowing past the sensors was equilibrated with the wetland surface before it reached the sensors. For a wetland as small as wetland P1 (~1.5–3 ha during 1982–87), this assumption may not be valid. If the airmass is not in equilibrium with the wetland surface when it reaches the *ET* sensors then the energy-budget values for *ET*, the standard to which the other methods are compared, may be incorrect. Furthermore, the effect of an inadequate fetch may not be consistent among various other *ET* methods.

The energy-budget method potentially is sensitive to an improper fetch because it requires determinations of air-temperature and vapor-pressure differences over the evaporating surface. Therefore, analyses were done to test the effect that fetch would have on the energy-budget measurements of *ET* at wetland P1. Those results are reported in Stannard et al. (2004). For wetland P1, fetch-induced error in ET_{eb} rates was less than 2 percent. The error is relatively small, largely because the lower sensor was floating on the water surface and, therefore, was fully equilibrated to the surface (see Stannard et al. (2004)).

The alternate methods tested here are more likely to be affected by fetch-induced errors than is the energy-budget method because they do not make use of the sensor floating on the water surface (except for the mass transfer method). Because of the short fetch at wetland P1, the vapor pressure measured at 2 m above the water surface was smaller than if fetch had been adequate due to the drier air over the upland advecting over the wetland. Within the Penman group of methods, this lack of equilibration produces some interesting and predictable results, seen in Figure 4. The Penman equation over-predicts *ET* at wetland P1 because the vapor pressure deficit ($e_s - e_a$), and therefore the aerodynamic term, is greater than if equilibration were complete. However, since the available energy term is unaffected by the short fetch, the mean over-prediction is fairly small, equal to 0.24 mm d^{-1}. The Priestley-Taylor equation is an abbreviated form of the Penman equation, based on the assumption that the aerodynamic term is 26 percent of the available energy term (this assumption leads to $\alpha = 1.26$). It does not explicitly contain an aerodynamic term and is therefore unaffected by short fetch. In the wetland P1 setting, it performs better than the Penman equation, over-predicting *ET* by only 0.07 mm d^{-1}. The deBruin-Keijman equation is a slight revision of the Priestley-Taylor equation. It uses coefficients of 0.85 and 0.63 for s and γ, respectively, in the denominator, whereas the Priestley-Taylor equation uses 0.794 (the inverse of α) for both. This results in slightly different sensitivities of the two equations to temperature. Not surprisingly, the two methods perform similarly, both in terms of mean bias and standard deviation. The Brutsaert-Stricker equation is a linear combination of the Penman and Priestley-Taylor equations. Based on the complementary relationship, it predicts that actual *ET* (which in this study also happens to be potential *ET*) is equal to two times the Priestley-Taylor equation minus the Penman equation (Table 1). Therefore, the mean bias of the Brutsaert-Stricker equation is -0.11 mm d^{-1}, which is equal to two times the Priestley-Taylor bias minus the Penman bias. The deBruin equation is an exception within this group because it does not contain an available energy term. Because the deBruin equation relies entirely on the aerodynamic term to estimate *PET*, it is particularly susceptible to the short fetch at wetland P1 and over-predicts *ET* by 0.67 mm d^{-1}.

Transferability of *ET* Comparisons to Other Wetland Settings

The ability to transfer results from site-specific studies to other locations is one of the most asked questions in science. The default response typically is to extend the results to other physical settings ''similar'' to the site studied. However, since the comparison methods used for this study were identical to comparisons made for a 39-ha open-water lake in northern Minnesota (Winter et al. 1995, Winter and Rosenberry 1997) located 335 km east of wetland P1, it is possible to make a relative comparison of transferability regarding the use of various *ET* methods in other wetland settings that range from 3 to about 40 ha.

The three best alternate methods for determining *ET* at a small wetland containing significant emergent vegetation in a relatively dry (440 mm yr^{-1}), continental setting were also the three best alternate methods for determing *ET* at a much larger open-water lake in a more humid (640 mm yr^{-1}) continental setting (Figure 9). The Priestley-Taylor, deBruin-Keijman, and Penman methods were the three methods that compared most favorably with ET_{eb} at both study sites. With the exception of the Brutsaert-Stricker method, all of the other methods compared more favorably with ET_{eb} rates at the open-water lake site than at wetland P1. Standard deviations were larger for the deBruin and mass-transfer methods when applied to wetland P1 data. Both of these methods rely heavily on relative humidity measured above the water surface, and the larger standard deviations using wetland P1 data may be an indication that the effect of insufficient fetch may be temporally variable depending on the contrast in temperature and vapor pressure between the upland and the wetland. Furthermore, the large inter-site change in bias associated with the deBruin method underscores the instability of a method that relies totally on the aerodynamic term to approximate *ET*.

It is reasonable to expect that errors associated with use of many of the alternate methods for determining *ET* for wetland P1 would be larger than when using data from the 39-ha open-water lake. Wetland P1 is small, which increases the potential for advection-induced error, and emergent vegetation covers a relatively large and temporally variable portion of the surface area of wetland P1. While certainly not an exhaustive test of transferability of results, this comparison between a small prairie-pothole wetland and a larger open-water lake in a forested setting would indicate that these results are applicable to wetlands larger than P1 and to wetlands where emergent vegetation covers a smaller portion of the surface area.

Cost and Effort Versus Accuracy

Many studies do not have the human or financial resources to measure *ET* using the energy-budget method. Comparisons between *ET* methods presented here can be used to indicate the relative sacrifice in

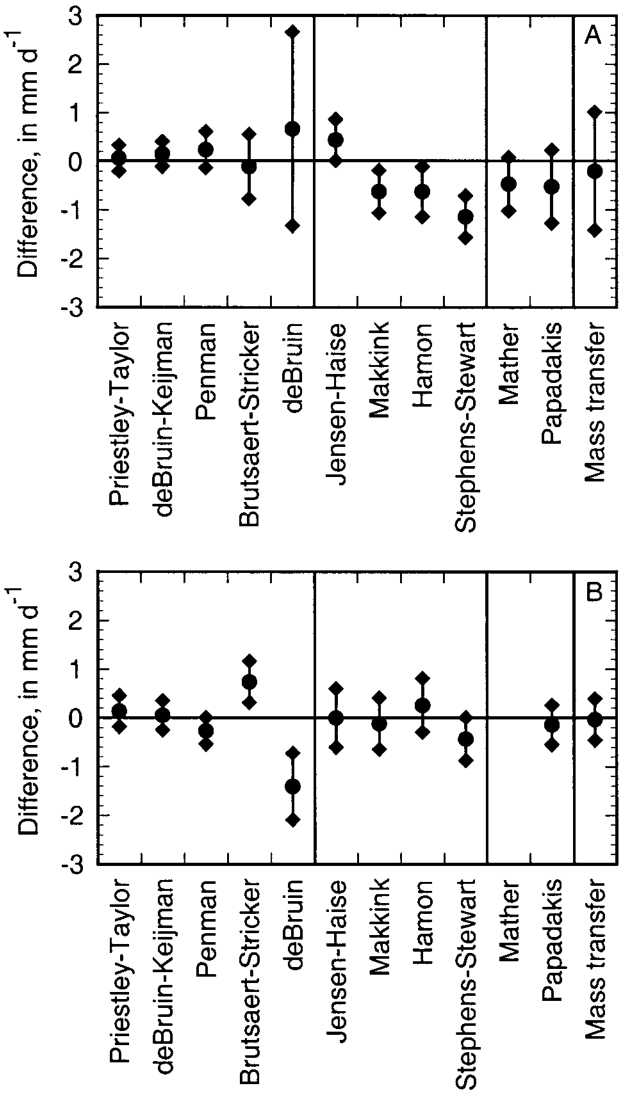

Figure 9. Differences between alternate *ET* estimates and ET_{eb} at (A) wetland P1 and (B) Williams Lake in northern Minnesota. Symbols show mean difference plus or minus standard deviation from mean difference, in mm d^{-1}.

accuracy compared to cost savings resulting from reduced instrumentation and labor associated with an alternate *ET* method.

The Priestley-Taylor and deBruin-Keijman methods provided the best results when compared to ET_{eb} values. Both methods require measurement of T_a, Q_n, and Q_x. Of these three variables, Q_x is the most labor-intensive and costly to acquire. However, obtaining data from one station rather than many in a wetland may result in very little loss of accuracy. Parkhurst et al. (1998) indicated that measurement of Q_x at one location in wetland P1, rather than using data from all seven stations, resulted in a median change in estimated evaporation of only 1.3 percent. Rosenberry et al. (1993) indicated a similarly small effect of measuring Q_x at one station rather than 16 at Williams Lake in northern Minnesota; the values were less than 5 percent different from best estimates 96 percent of the time.

The Penman method provided the next best comparison data, but it (along with the Brutsaert-Stricker method) requires the greatest number of measurements (T_a, Q_n, Q_x, U, E_a) and nearly the same level of effort as does the energy-budget method. The Jensen-Haise and Stephens-Stewart methods yielded results that tied for the fourth smallest standard deviation compared to ET_{eb} values. These methods require measurement of only Q_s and T_a, providing, perhaps, the greatest accuracy-to-effort ratio. If the temperature-function coefficients modified for use at wetland P1 are used, the Jensen-Haise and Stephens-Stewart methods rank 4th and 5th in the alternate-method heirarchy, nearly as good as the two best methods. Because of its original large bias, modifying the Stephens-Stewart temperature function changed the method from being one of the worst to one of the best (Figure 4, Figure 6).

The Makkink method also requires measurement of only Q_s and T_a, and determinations of s, γ, and L are made based on measurements of T_a. The Makkink method compared moderately well with ET_{eb} methods in its unmodified form, but following modifications of the slope and offset coefficients, the modified Makkink method became one of the best alternate approaches for estimating *ET* at wetland P1 (Figure 6).

The Hamon method requires only measurement of T_a, which is used in determining saturation vapor density. The number of hours of daylight also is needed, but that can easily be obtained from various published sources. Result were within 20 percent of ET_{eb} values 55 percent of the time. However, when the method was modified to remove bias, results were within 20 percent of ET_{eb} values 95 percent of the time and within 5 percent of ET_{eb} values 25 percent of the time.

The Mather (Thornthwaite) method provided results that compared relatively well with ET_{eb} values, and it also requires measurement of only T_a. It is the simplest method of all those compared in this report and works relatively well for estimation of *ET* at wetland P1.

The mass transfer and deBruin methods both require measurement of T_a, e_a, and U. In addition, the mass-transfer method requires calibration of the mass-transfer coefficient (N). However, neither of these methods worked particularly well at estimating *ET* at wetland P1 when compared to the ET_{eb} method.

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