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Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA

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Summary Few detailed evaporation studies exist for small lakes or reservoirs in mountainous settings. A detailed evaporation study was conducted at Mirror Lake, a 0.15 km^2 lake in New Hampshire, northeastern USA, as part of a long-term investigation of lake hydrology. Evaporation was determined using 14 alternate evaporation methods during six open-water seasons and compared with values from the Bowen-ratio energy-budget (BREB) method, considered the standard. Values from the Priestley–Taylor, deBruin–Keijman, and Penman methods compared most favorably with BREB-determined values. Differences from BREB values averaged 0.19, 0.27, and 0.20 mm d^{-1}, respectively, and results were within 20% of BREB values during more than 90% of the 37 monthly comparison periods. All three methods require measurement of net radiation, air temperature, change in heat stored in the lake, and vapor pressure, making them relatively data intensive. Several of the methods had substantial bias when compared with BREB values and were subsequently modified to eliminate bias. Methods that rely only on measurement of air temperature, or air temperature and solar radiation, were relatively cost-effective options for measuring evaporation at this small New England lake, outperforming some methods that require measurement of a greater number of variables. It is likely that the atmosphere above Mirror Lake was affected by occasional formation of separation eddies on the lee side of nearby high terrain, although those influences do not appear to be significant to measured evaporation from the lake when averaged over monthly periods.

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Introduction

Studies of open-water evaporation from fresh-water systems are biased toward the larger end of the size spectrum. Most have been conducted for reservoirs and larger lakes and relatively few have been conducted for smaller lakes and ponds. Most lakes, ponds, and wetlands are focal points for the hydrologic processes that occur over their drainage basins and in many parts of the world, where fresh-water resources are becoming limited, water managers need to quantify these hydrologic fluxes for increasingly smaller water bodies. Quantification of hydrologic fluxes, including evaporation, also is required to address issues related to water quality, recreation, and ecological processes. Recent estimates indicate that the world contains over 300 million lakes and ponds having an area of 0.1 km^2 or less (Downing et al., 2006). Given this large number, it is imperative that we understand and quantify evaporation over small lakes, ponds and reservoirs where special considerations, such as insufficient fetch (Heilman et al., 1989; Condie and Webster, 1997; Horst, 1999; Stannard et al., 2004) and abrupt changes in surface slope and roughness length (Arya and Shipman, 1981; Taylor et al., 1987), exert a greater influence. Unfortunately, determination of evaporation from small or undeveloped lakes is rarely done because interest or funding is not sufficient to warrant the time and expense. When an estimate of evaporation is made, frequently it is based on sparse or remotely collected data. Thorough investigation into evaporative loss is even less frequent, precluding analysis of the suitability of various evaporation methods in small-lake settings.

Accurate measurements of evaporation were required as part of a long-term study of hydrological and ecological processes at Mirror Lake, a small (0.15 km^2) kettle-hole lake in the southern portion of the White Mountains of New Hampshire, USA (Winter, 1985). Mirror Lake is one of the most studied lakes in the world (Likens, 1985) and has undergone the scrutiny of a broad range of scientific disciplines. Although earlier estimates of evaporation had been made for Mirror Lake using an evaporation pan (Likens, 1985), the Bowen-ratio energy-budget (BREB) method subsequently was used to provide more accurate estimates as part of a detailed water-budget study of the lake (Winter et al., 2003). Generally considered to be among the most robust and most accurate methods for determining evaporation (Harbeck et al., 1958; Gunaji, 1968; Sturrock et al., 1992; Lenters et al., 2005), BREB-determined evaporation estimates are assumed to be within 10% of true values when averaged over a season and within 15% when averaged over a month (Winter, 1981). Evaporation rates were determined for weekly to biweekly energy-budget periods during the open-water periods of 1982–1987 (Winter et al., 2003). Given their complexity and expense, BREB studies of this duration are uncommon for small lakes and reservoirs. This six-year record presents the opportunity to compare those best estimates with evaporation determined with other, often less expensive or less labor-intensive, methods for the purpose of providing guidance for obtaining best evaporation estimates depending on the data or resources available for a particular lake. To provide the best possible BREB evaporation rates as a standard to which others are compared, values from the energy-budget periods were time weighted and averaged over monthly periods for this study.

Other evaporation methods may better serve as a standard of comparison (Drexler et al., 2004). The eddy-covariance method is a more direct means of measuring evaporation, but it requires more expensive instruments that, at the time these data were collected, were ill-suited for long term, continuous deployment. The surface-renewal method requires fewer instruments than the eddy-covariance method but, like the eddy-covariance method, it requires frequent (on the order of 10 Hz) measurement of air temperature, data that were not available at Mirror Lake nor at many other locations in the world. An adaptation of LIDAR (light detection and ranging) technology called the Raman LIDAR has been used to measure water-vapor flux in several locations (Drexler et al., 2004), but those data also did not exist for Mirror Lake, making the BREB method the best available standard of comparison.

This approach for investigating the suitability of various evaporation methods has been used in other physical and climatic settings, none of which were in a mountainous, setting. For example, Rosenberry et al. (2004) compared evapotranspiration rates determined with several empirical methods for a wetland in semi-arid North Dakota. Winter et al. (1995) compared a nearly identical suite of evaporation methods applied to a medium-sized lake in the continental climate of northern Minnesota. Rasmussen et al. (1995) used seven empirical methods to estimate evaporation from nine lakes in Minnesota. Singh and Xu (1997) compared thirteen mass-transfer methods applied to four sites in Ontario, Canada. Dalton et al. (2004) compared evaporation rates determined with several methods for Lake Seminole, a large reservoir that borders Georgia and Florida. The three studies that used BREB as the standard (Rosenberry et al., Winter et al., Dalton et al.) found that empirical methods that emphasize an assessment of energy fluxes provide the best estimates of water loss to the atmosphere. Rankings of alternate methods for estimating evaporation varied among the three above-mentioned studies. In some cases, the robustness of a particular empirical method depended on the ambient climate.

The present study of evaporation methodology was designed to be similar to those conducted at Williams Lake, Minnesota (Winter et al., 1995), Sparkling Lake, Wisconsin (Lenters et al., 2005), Lake Lucerne, Florida (Lee and Swancar, 1997), and at the Cottonwood wetlands in North Dakota (Rosenberry et al., 2004), and is part of a long-term effort to evaluate hydrological processes and measurement techniques in different environments through inter-site comparisons. Such an effort requires a common conceptual framework and common field and analytical techniques at all sites. Mirror Lake was chosen to represent a small lake in a mountainous setting in a humid continental (Dfb Köppen classification) climate, typical of the mountainous regions of New England (Likens, 1985).

Evaporation determined using the BREB method (Winter et al., 2003) is compared with five ''combination'' methods that quantify both energy and advective terms; three methods that rely on measurement of solar radiation and air temperature; two methods that require measurement of air temperature and humidity, water-surface temperature, and windspeed; two methods that require measurement of air temperature and day length; and two methods that require only measurement of air temperature. Seasonal and interannual variability of output from alternate methods are compared to BREB values with the goal of determining the relative significance of evaporation drivers in a small, mountainous lake basin. The suitability of the use of less robust and less expensive evaporation methods that require fewer data also is discussed and, where appropriate, some methods are modified to generate better evaporation estimates for settings similar to Mirror Lake.

As mentioned earlier, this study is relevant to millions of small lakes located throughout the world. Locally, in New England and the Adirondack and Catskill Mountains, approximately 3500 lakes exist of a size between 0.04 and 0.2 km^2 (Brakke et al., 1988). Many of these lakes are in a climatic and mountainous setting very similar to that of Mirror Lake, making results of this study of particular relevance to thousands of lakes within 300 km of Mirror Lake.

Physical and climatic setting

Mirror Lake is situated near the lower end of the Hubbard Brook Valley in the southern portion of the White Mountains of New Hampshire (Fig. 1). The lake is oligotrophic, 0.15 km^2 in area, has a mean depth of 5.75 m, a maximum depth of 11 m, and is at an elevation of 213 m above mean sea level (Winter, 1985). It is situated in a crystalline-bedrock basin that is partially covered with glacial drift, where land surface rises over 250 m above the lake surface within 1 km of the lake. Three small streams drain into the lake and a dam controls the outlet and maintains the lake at a higher and more stable stage than would naturally occur. More water flows from the lake to ground water than leaves the lake via the surface-water outlet (Rosenberry et al., 1999). Annual precipitation (1969–2000) averages 1220 mm (Bailey et al., 2002) and is about 2.5 times the long-term average annual evaporation of 490 mm (Likens, 1985). Average monthly temperature (1957–1997) ranges from 19.3 °C during July to −7.6 °C during January (Bailey et al., 2002).

Methods

The BREB method for calculating open-water evaporation can be stated as

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_x + Q_v - Q_b}{\rho(L(1+R) + cT_0)} \quad (1)$$

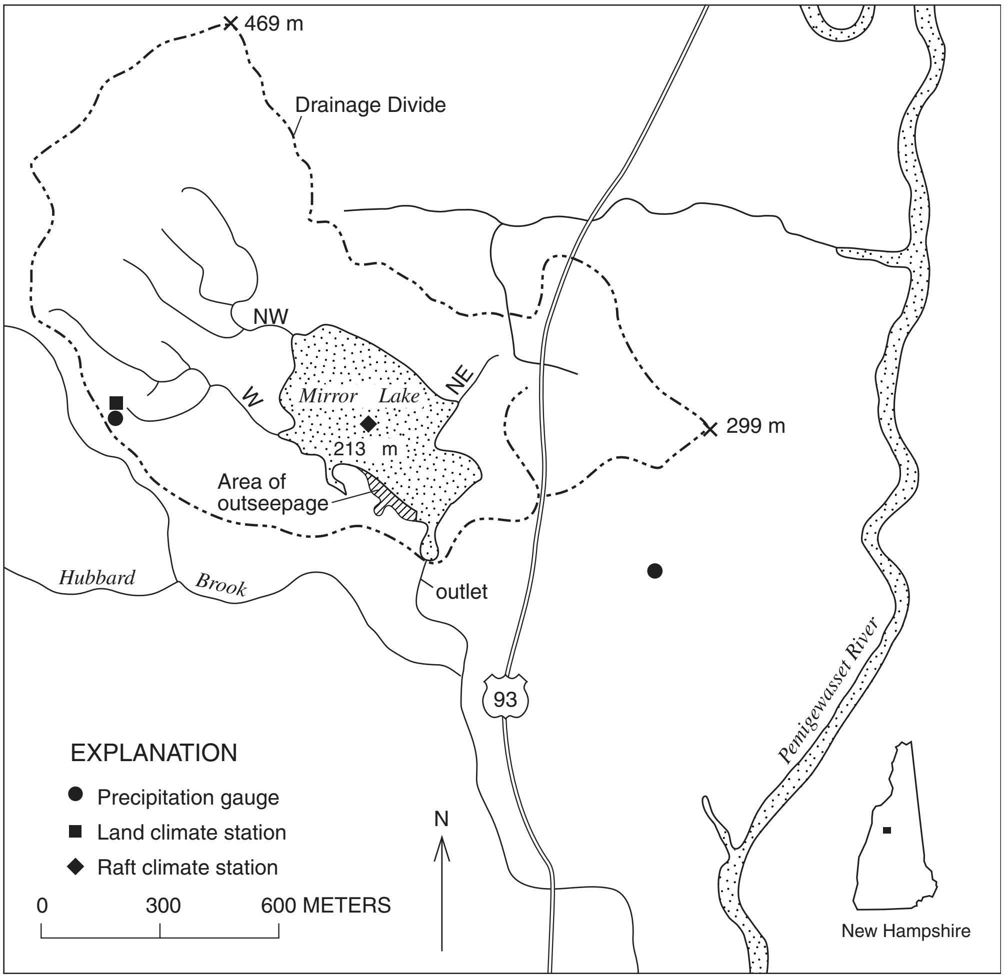

Figure 1 Location of Mirror Lake, including instrumentation sites and major physical features of the Mirror Lake drainage basin.

where

E	evaporation determined with the energy-budget method (m s^{-1})
Q_s	incoming solar shortwave radiation (W m^{-2})
Q_r	reflected solar shortwave radiation (W m^{-2})
Q_a	incoming atmospheric longwave radiation (W m^{-2})
Q_{ar}	reflected atmospheric longwave radiation (W m^{-2})
Q_{bs}	longwave atmospheric radiation emitted from the water surface (W m^{-2})
Q_x	change in heat stored in the lake-water body (positive for an increase in stored heat during an energy-budget period) (W m^{-2})
Q_v	net energy (positive when advected to the lake) from precipitation, surface water, and ground water (W m^{-2})
Q_b	net energy conducted from the lake to the sediments (W m^{-2})
ρ	density of water (assume 998 kg m^{-3})
L	latent heat of vaporization (J kg^{-1})
R	Bowen ratio (dimensionless)
c	specific heat capacity of water (4186 J kg^{-1} °C^{-1})
T_0	water-surface temperature (°C)

Multiply (1) by 8.64×10^7 to convert to mm d^{-1}.

The Bowen ratio is the ratio of sensible to latent heat and is calculated as

$$R = c_B P \frac{T_0 - T_a}{e_0 - e_a} \tag{2}$$

where

c_B	empirical constant determined by Bowen (1926) to be 0.61 (°C^{-1})
P	standard pressure at a specific altitude (kPa) (for the altitude of Mirror Lake, P is 98.8)
T_a	air temperature (°C unless indicated otherwise)
e_0	saturation vapor pressure at the water-surface temperature (Pa)
e_a	atmospheric vapor pressure (Pa)

This formulation of the Bowen ratio ignores any covariance between windspeed and vapor-pressure or temperature differences, which might cause additional errors in BREB calculations. Lenters et al. (2005), in a study of evaporation from a lake in northern Wisconsin, compared the effect of determining a Bowen ratio based on taking daily averages of hourly products of $U(T_0 - T_a)$ and $U(e_0 - e_a)$ versus the standard Bowen-ratio equation in (2), where windspeed in the numerator and denominator is cancelled out. They indicated that neglecting the potential covariance with windspeed resulted in a mean bias of 1% and a standard deviation of 3%. Since these errors were relatively small, and since most Bowen-ratio studies do not consider potential covariance with windspeed, we have chosen, for consistency with previous methods comparisons, to use the traditional Bowen-ratio calculation for this study.

Temperature profiles were measured in the lake-water column at 10 locations (Winter et al., 2003) and energy-budget periods were determined as the time interval between successive thermal surveys. Q_x was determined as the difference in heat stored between the beginning and end of each energy-budget period.

Q_v and Q_b often are very small and are commonly ignored. However, at Mirror Lake, where a large portion of the water balance is seepage of warm, shallow lake water to ground water and flow over the dam, Q_v was occasionally greater than 5% of Q_n. The Q_b term imparts a small but seasonal influence on calculated BREB values (Winter et al., 2003). In the interest of achieving the greatest accuracy, both terms were quantified and included in the numerator of (1).

Air temperature, relative humidity, and windspeed (U_2) were measured at 2 m above the water surface with a precision thermistor psychrometer and RM Young[1] anemometer suspended over the water surface from a raft located near the center of the lake (Fig. 1). Water-surface temperature also was measured at the raft with a precision thermistor that was suspended within the top 1 cm of the lake-water column. All sensors were scanned once a minute by a datalogger that calculated hourly and daily averages. An identical datalogger recorded Q_s and Q_a measured with an Eppley precision spectral pyranometer and an Eppley precision pyrgeometer; both were located in a clearing in the forest 0.5 km west of the lake.

Net radiation ($Q_n = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs}$), a parameter required for many evaporation methods, was calculated based on the measured incident shortwave and longwave radiation. Q_r was calculated using a method described by Koberg (1964) that is based on sun angle, altitude, and cloud cover. Q_{ar} was assumed to be 3% of incoming longwave radiation (Anderson, 1954), and Q_{bs} was calculated from

$$Q_{bs} = \varepsilon \sigma T_0^4 \tag{3}$$

where ε is the emissivity of the water surface, 0.97 was assumed (unitless), σ is the Stephan–Boltzman constant (5.67×10^{-8} W m^{-2} K^{-4} s^{-1}), and T_0 is the water-surface temperature (K).

Additional terms necessary for the evaporation methods compared here were calculated from measured variables. Relative humidity was used in combination with T_a to obtain e_a. Water-surface temperature data were used to determine e_0. Saturated vapor density (SVD) and hours of daylight were obtained from tables in Campbell (1977) and the Smithsonian Meteorological Tables (List, 1966). The slope of the curve of saturated vapor pressure versus air temperature (s) was obtained from an equation presented in Lowe (1977). Values for the psychrometric constant (γ) were obtained from an empirical relationship dependent on standard atmospheric pressure and water temperature (Fritschen and Gay, 1979).

Estimates of instrument error were obtained from manufacturers and a first-order analysis (e.g., Taylor, 1982) of errors was conducted for the BREB method. Errors were assumed to be Q_s (1%), Q_a (3%), Q_n (10%), Q_x (5%), Q_v (10%), Q_b (10%), T_0 and T_a (0.1 °C), e_a (3%). Monthly errors ranged from 5% to 19% of the calculated monthly evaporation rates and averaged 11.2%.

Several of the most commonly used and widely applied evaporation methods were selected for comparison with

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[1] Use of brand names is for informational purposes only and does not constitute endorsement by the authors or the US Geological Survey.

Table 1 Methods for calculation of evaporation (E), the results from which are compared to results from the BREB method, in mm d^{-1}

Method	Reference	Equation	Developed for
Combination group			
Priestley–Taylor	Stewart and Rouse (1976)	$E = \alpha \frac{s}{s+\gamma} \frac{Q_n - Q_x}{L\rho} \times 86.4$	Periods of 10 d or greater
deBruin–Keijman	deBruin and Keijman (1979)	$E = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_n - Q_x)}{L\rho} \times 86.4$	Daily
Penman	Brutsaert (1982)	$E = \frac{s}{s+\gamma}\left(\frac{Q_n - Q_x}{L\rho}\right) \times 86.4 + \frac{\gamma}{s+\gamma}(0.26(0.5 + 0.54U_2)(e_s - e_a))$	Periods greater than 10 d
Brutsaert–Stricker	Brutsaert and Stricker (1979)	$E = (2\alpha - 1)\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_n - Q_x}{L\rho}\right) \times 86.4 - \frac{\gamma}{s+\gamma} 0.26(0.5 + 0.54U_2)(e_s - e_a)$	Daily
deBruin	deBruin (1978)	$E = 1.192\left(\frac{\alpha}{\alpha - 1}\right)\left(\frac{\gamma}{s+\gamma}\right)\frac{(2.9 + 2.1U_2)(e_s - e_a)}{L\rho} \times 86.4$	Periods of 10 d or greater
Solar radiation, temp. group			
Jensen–Haise	McGuinness and Bordne (1972)	$E = (0.014T_a - 0.37)(Q_s \times 3.523 \times 10^{-2})$	Periods greater than 5 d
Makkink	McGuinness and Bordne (1972)	$E = \left(\left(52.6 \frac{s}{s+\gamma} \frac{Q_s}{L\rho}\right) - 0.12\right)$	Monthly (Holland)
Stephens–Stewart	McGuinness and Bordne (1972)	$E = (0.0082T_a - 0.19)(Q_s \times 3.495 \times 10^{-2})$	Monthly (Florida)
Dalton group			
Mass transfer	Harbeck et al. (1958)	$E = (NU_2(e_0 - e_a)) \times 10$	Depends on calibration of N
Ryan–Harleman	Rasmussen et al. (1995)	$E = \frac{(2.7(T_0 - T_a)^{0.333} + 3.1U_2)(e_0 - e_a)}{L\rho} \times 86.4$	Daily
Temp., day length group			
Blaney–Criddle	McGuinness and Bordne (1972)	$E = (0.0173T_a - 0.314) \times T_a \times (D \div D_{TA}) \times 25.4$	Monthly
Hamon	Hamon (1961)	$E = 0.55\left(\frac{D}{12}\right)^2 \frac{SVD}{100}(25.4)$	Daily
Temperature group			
Papadakis	McGuinness and Bordne (1972)	$E = 0.5625(e_s \max - (e_s \min - 2))\left(\frac{10}{d}\right)$	Monthly
Thornthwaite	Mather (1978)	$E = \left(1.6\left(\frac{10T_a}{I}\right)^{6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 + 1.79\times10^{-2}I + 0.49}\right)\left(\frac{10}{d}\right)$	Monthly

α = 1.26 = Priestley–Taylor empirically derived constant, dimensionless,
s = slope of the saturated vapor pressure–temperature curve at mean air temperature (Pa °C^{-1}),
γ = psychrometric ''constant'' (depends on temperature and atmospheric pressure) (Pa °C^{-1}),
Q_n = net radiation ($Q_s - Q_r + Q_a - Q_{ar} - Q_{bs}$) (W m^{-2}),
Q_s = solar radiation (W m^{-2}),
Q_x = change in heat stored in the water body (W m^{-2}),
L = latent heat of vaporization (MJ kg^{-1}),
ρ = density of water (998 kg m^{-3} at 20 °C),
N = mass-transfer coefficient (used 0.01644 for Mirror Lake),
I = annual heat index ($I = \sum i$, $i = (T_a/5)^{1.514}$),
U_2 = windspeed at 2 m above surface (m s^{-1}),
e_0 = saturated vapor pressure at temperature of the water surface (mb),
e_s = saturated vapor pressure at temperature of the air (mb),
e_a = vapor pressure at temperature and relative humidity of the air (mb),
SVD = saturated vapor density at mean air temperature (g m^{-3}),
T_a = air temperature, °F for the Blaney–Criddle, Jensen–Haise and Stephens–Stewart equations and °C for the Thornthwaite equation,
D = hours of daylight,
D_{TA} = total annual hours of daylight for specific latitude; for Mirror Lake, at 44° N, D_{TA} = 4470,
d = number of days in month,
e_s max and e_s min = saturated vapor pressures at daily maximum and minimum air temperatures (Pa).
The multipliers 10, 25.4, or 86.4 that appear in several equations are to convert output to mm d^{-1}.

BREB values; methods also were selected to represent a range of method complexity with regard to data requirement (Table 1). Although many of these methods were developed to calculate potential evapotranspiration, because the evaporating surface of Mirror Lake is open water, they are assumed here to represent evaporation. Evaporation methods are grouped in Table 1 according to method type. Combination methods include an available-energy term and an aerodynamic term. Combination methods are the most data intensive and require measurement of some or all of the terms Q_n, Q_x, T_a, U_2, and e_a. The three methods in the second group in Table 1 require measurement of Q_s and T_a. Dalton-type methods, two of which are compared here, require measurement of U_2, T_0, T_a, and e_a. The mass-transfer Dalton-type method requires an empirical coefficient that is site dependent. Because BREB data are used to determine the mass-transfer coefficient, another Dalton-type method (Ryan—Harleman) that does not require a site-specific calibration also is compared with BREB values. The last four methods listed in Table 1 require measurement only of T_a. Two of the methods also require a determination of day length for the latitude of the study site.

Fetch considerations

Evaporation from small lakes, especially small lakes in a mountainous setting, present additional measurement challenges. Inherent in any evaporation measurement is the assumption that atmospheric conditions at the point of measurement are representative of those over the rest of the lake. The lake-surface area immediately downwind of the upwind boundary of every lake usually is in violation of this assumption; temperature and vapor-pressure profiles in the near-surface atmosphere of this transition zone are adjusting to conditions presented by the lake surface that often are greatly different from the surrounding landscape. It commonly is assumed that this area of atmospheric transition is small enough relative to the surface area of the entire lake that it can be ignored, but this assumption may not be valid for small lakes. Sensors also need to be situated sufficiently downwind of this area of rapidly evolving atmospheric conditions that the source area of the sensors is representative of conditions over most of the lake, and for many small lakes this is an impossible requirement. Fetch, the distance from the measurement point to the upwind boundary, where surface roughness and fluxes change (the upwind shoreline), needs to be sufficiently long that the sensors are situated within the equilibrium sublayer of the atmosphere, defined as the portion of the atmosphere that is in equilibrium with the evaporating surface. The thickness of the equilibrium sublayer grows with distance downwind of the shoreline, making sensor height an additional factor that determines whether measurements are representative of conditions above the majority of the lake surface. Upwind fetch requirements also depend on surface roughness, atmospheric stability, windspeed, net available energy over the forest canopy and over the lake surface, and the Bowen ratios of the forest canopy and the lake surface. The greater the difference in conditions over the forest canopy relative to those over the lake, the greater the required upwind dimension of the footprint, commonly measured as the fetch-to-height ratio. Fortunately, some of these variables, such as net available energy and the Bowen ratio, tend to offset one another, reducing somewhat the required fetch-to-height ratio for atmospheric equilibrium.

A commonly assumed value for a fetch-to-height ratio sufficient to ensure a reasonable degree of sensor equilibration to an evaporating surface is 100 (e.g., Heilman et al., 1989). However, most evaluations of evaporation sensor footprint and fetch-to-height ratios were developed for sensors that quantify vertical vapor flux at a single sensor height (e.g., Horst and Weil, 1994), whereas a Bowen-ratio measurement requires sensors be located at two heights, in this case at the water surface and at 2 m. Heilman et al. (1989) indicated that a suitable fetch-to-height ratio for a Bowen-ratio measurement could be as little as 20. Stannard (1997) indicated that fetch-to-height ratio for a Bowen-ratio measurement could be substantially smaller than for an eddy-covariance measurement. The fetch-to-height ratio at a much smaller wetland in North Dakota, where the upland typically was hotter and drier than the forest canopy at Mirror Lake, was 48 and the likely error induced by insufficient atmospheric equilibration was determined to be on the order of 0.5% to −2% (Stannard et al., 2004). At Mirror Lake, the fetch relative to the location of the raft where sensors were mounted ranged from 150 to over 350 m, and the upper sensor height, where temperature and vapor pressure of the air were measured, was 2 m. Assuming a suitable fetch-to-height ratio of 100, fetch would be insufficient for some wind directions. If a ratio of 20 were used, fetch would be more than adequate for all wind directions.

However, none of the fetch-to-height considerations take into account the larger scale concerns regarding the height of the tree canopy at the shoreline or the steeply sloping and sharply rising terrain, particularly to the northwest and northeast of Mirror Lake. Flow separations likely occur downwind of the forest canopy. Arya and Shipman (1981) indicated that the separation streamline associated with a modeled low ridge extended downwind a distance of 13 times the ridge height. Substituting a line of trees for the ridge, and assuming a tree height of 10 m at Mirror Lake, the forest-canopy-related separation eddy could extend downwind approximately 130 m, at which point the equilibrium sublayer would begin to form. Similarly, if the terrain upwind of the lake is sufficiently steep to allow flow in the atmosphere to decouple, eddies and rotors can form on the lee side of the steep slope, with the potential of violating evaporation measurement assumptions and confounding measurement attempts.

Many of the variables necessary as input to a sensor-footprint method were not measured at Mirror Lake. Therefore, given the additional concern regarding larger-scale, forest- and terrain-related influences on the evaporation process at Mirror Lake, no attempt was made to estimate a suitable fetch for Mirror Lake. Instead, since insufficient fetch affects the vertical distributions of temperature and vapor pressure, comparisons were made of the ratios of sensible to latent heat (Bowen ratio) at Mirror Lake relative to another lake in a similar climatic setting, but one without concerns about larger-scale terrain or insufficient fetch. Bowen

Table 2 Comparison of Mirror Lake and Williams Lake Bowen ratios for energy-budget periods, sorted by month, measured during the open-water periods of 1982–1986 at Williams Lake and 1982–1987 at Mirror Lake

Month	Lake	*n*	Mean	Std. Dev.	Min.	Max.	Percentile		
							25th	50th	75th
May	Mirror	18	0.216	0.096	0.04	0.44	0.158	0.205	0.278
	Williams	5	0.168	0.155	−0.08	0.32	0.030	0.190	0.295
June	Mirror	18	0.200	0.078	0	0.29	0.145	0.200	0.273
	Williams	9	0.188	0.053	0.1	0.29	0.155	0.200	0.210
July	Mirror	19	0.184	0.045	0.1	0.24	0.160	0.190	0.220
	Williams	12	0.176	0.050	0.07	0.28	0.145	0.180	0.198
August	Mirror	22	0.245	0.055	0.17	0.37	0.200	0.240	0.265
	Williams	9	0.212	0.067	0.08	0.28	0.165	0.240	0.265
September	Mirror	21	0.345	0.072	0.18	0.48	0.300	0.360	0.395
	Williams	9	0.312	0.070	0.24	0.48	0.275	0.290	0.335
October	Mirror	22	0.440	0.137	0	0.65	0.390	0.450	0.503
	Williams	7	0.450	0.144	0.26	0.59	0.260	0.460	0.580

ratios were determined as part of a similar evaporation study at Williams Lake, located in the forested lakes region of north-central Minnesota (Sturrock et al., 1992), and compared with Bowen ratios determined at Mirror Lake. If insufficient fetch or a decoupled atmosphere were corrupting temperature and vapor-pressure profiles, one might expect that Bowen ratios would vary unpredictably and over a greater range in response to intermittent periods when profiles were out of equilibrium. Based on the statistical summary of weekly to approximately biweekly Bowen-ratio averages shown in Table 2, the comparison of Bowen ratios indicates conditions were similar between the two lakes. At both lakes, median Bowen ratios were quite stable until they began to increase during September and October, and standard deviations were consistently small during the summer months for both lakes, indicating that any incidences of insufficient fetch at Mirror Lake either were infrequent or minor.

Results and discussion

Comparisons of monthly average evaporation rates were made for 37 months during 1982–1987. BREB evaporation rates ranged from 0.69 to 3.43 mm d^{-1} and averaged 2.25 ± 0.25 mm d^{-1} during the six-year study period (Fig. 2). Maximum monthly rates were not consistent among years and occurred during June of 1984 and 1986, during July of 1982, 1983 and 1985, and during August of 1987.

Many of the alternate approaches for determining evaporation compared well with the BREB monthly values (Figs. 3 and 4). Six of the 14 alternate methods (Priestley–Taylor, deBruin–Keijman, Penman, Brutsaert–Stricker, mass transfer, Thornthwaite) provided evaporation values that were within 1 mm d^{-1} of the BREB values for all 37 of the monthly comparison periods. Nine of the methods provided mean values that were within the range of error exhibited by the BREB method.

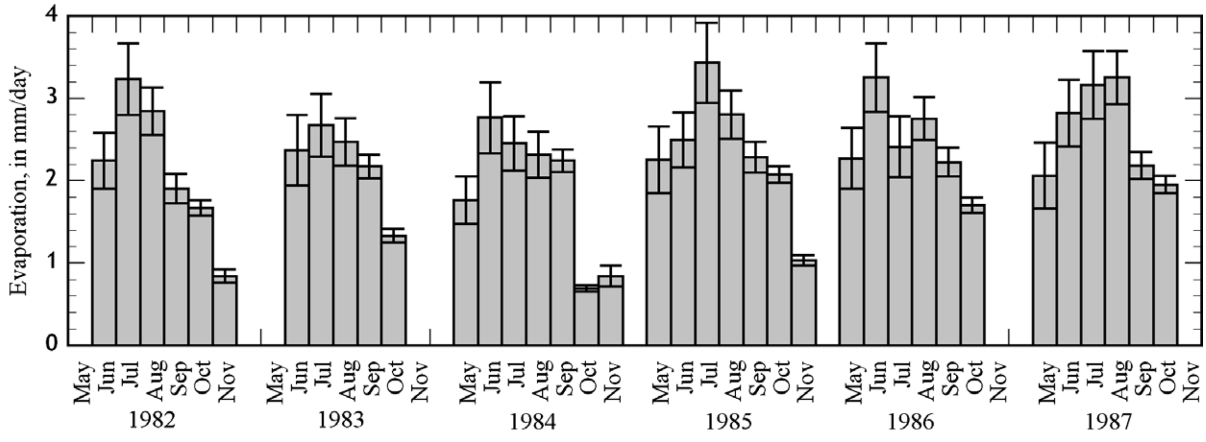

Figure 2 Daily evaporation from Mirror Lake (mm d^{-1}) averaged per month, as determined by the BREB method, 1982–1987 (data from Winter et al., 2003). Error bars from first-order error analysis.

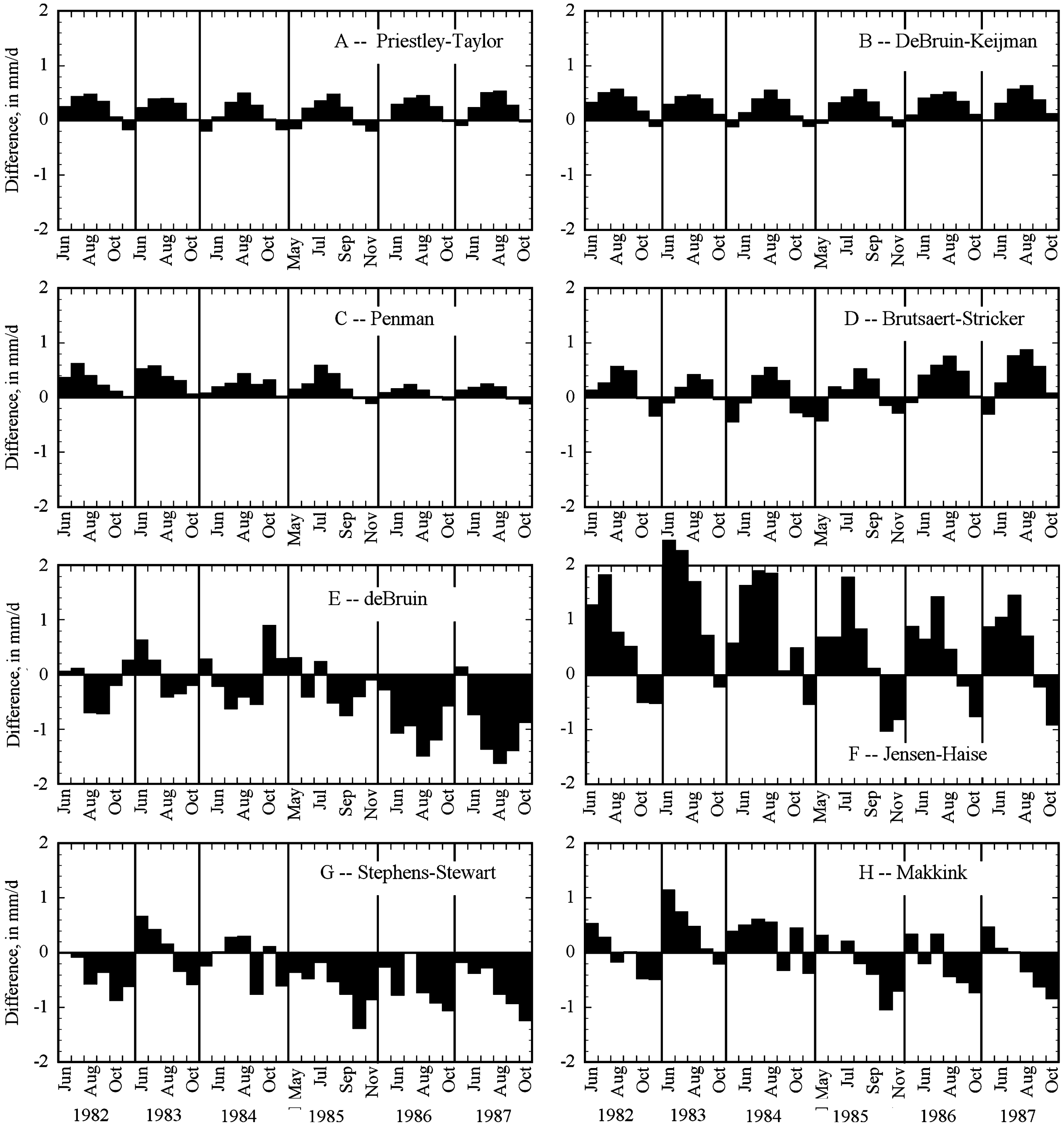

Figure 3 Difference in calculated evaporation between 14 alternate evaporation methods presented in Table 1 and BREB values, in mm d^{-1}.

Three of the five combination methods compared very well with BREB values, having small bias and small standard deviation (Fig. 4). Four of the five combination methods also had a positive bias that was seasonal; overestimates of evaporation occurred during midsummer, and smaller overestimates or underestimates often occurred during spring and fall months (Fig. 3A–D). Priestley–Taylor values were within 0.5 mm d^{-1} of BREB values during 35 of 37 monthly comparison periods and Penman values were within 0.5 mm d^{-1} of BREB values during 33 of 37 periods.

The three radiation-temperature methods compared less favorably with BREB values than the combination methods. The Stephens–Stewart method produced values with considerable negative bias, the Makkink method provided values with essentially zero bias, and the Jensen–Haise method resulted in values with a substantial positive bias (Fig. 4). Standard deviations of differences between BREB values and Stephens–Stewart and Makkink values were moderate, whereas comparisons with the Jensen–Haise method provided a large standard deviation. All three radi-

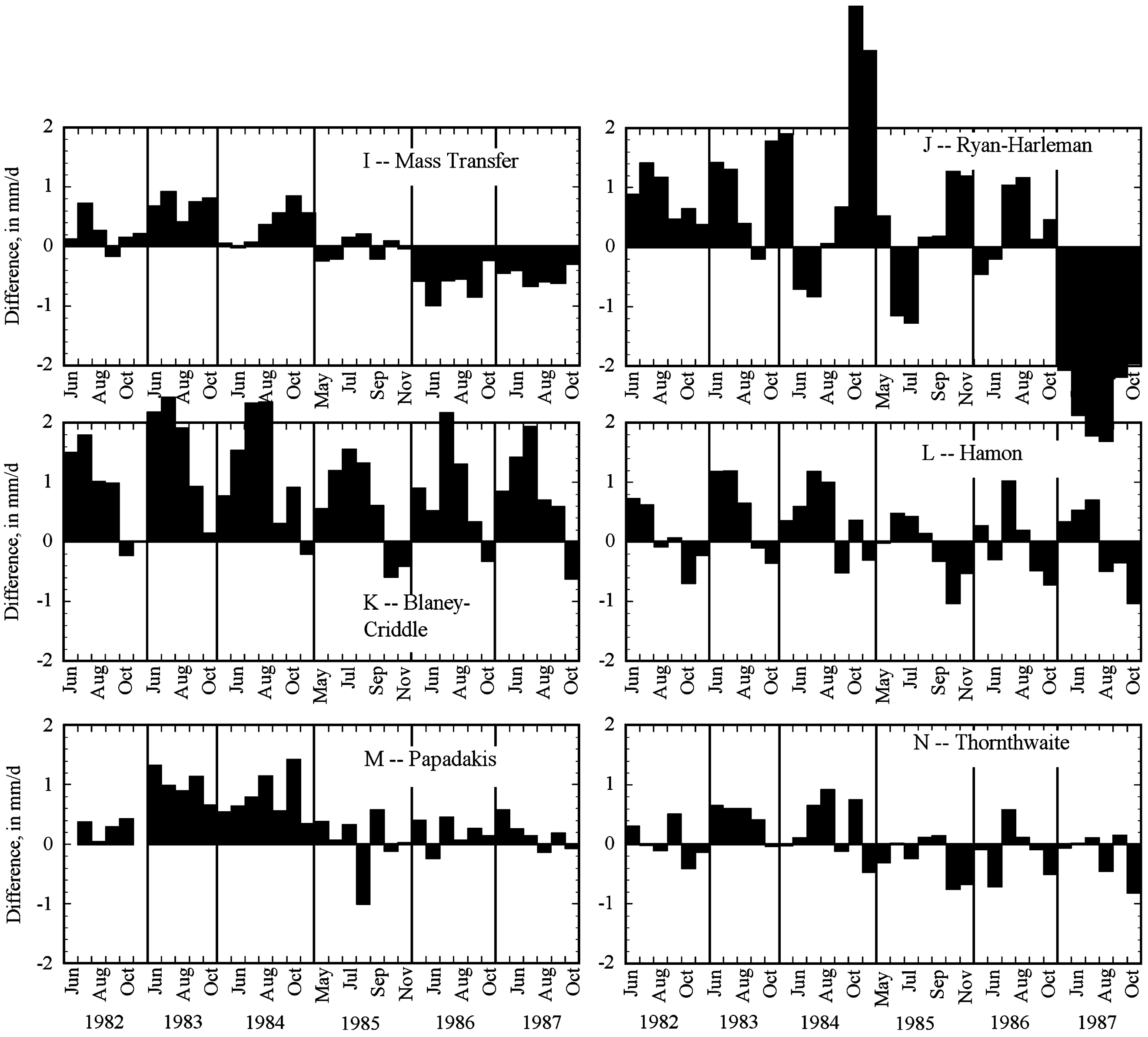

Figure 3 (*continued*)

ation-temperature methods (Fig. 3F–H) showed a seasonal bias during most years, indicating larger amounts of evaporation relative to BREB values during the early part of the open-water season that trended to smaller amounts of evaporation relative to BREB values as the open-water season progressed.

Evaporation values from the two Dalton-type methods varied substantially in comparison with BREB values, although bias was small (Figs. 3I and J and 4). Values generated with the mass-transfer method had zero bias, as would be expected since the mass-transfer coefficient (0.0164) was calibrated to BREB values. However, the Ryan–Harleman method (Fig. 3J) resulted in values that compared with BREB values least favorably of all the alternate evaporation methods. The large standard deviation associated with the Ryan–Harleman method is due primarily to the very large deviations from BREB values during October and November 1984 and during all of 1987.

The two methods that require measurement of T_a and day length also provided mixed results (Figs. 3K and L and 4). Values from the Blaney–Criddle method (Fig. 3K) indicated a considerable positive and seasonal bias, while values from the Hamon method (Fig. 3L) compared better with BREB values. Both methods tended to underestimate evaporation during fall months.

Considering their simplicity, values from the two methods that require measurement of T_a only compared surprisingly well with the BREB standard. Values from the Papadakis method indicated a positive bias, values from the Thornthwaite method indicated zero bias, and both methods provided values with an intermediate variance relative to BREB values (Fig. 4). Values from the Papadakis method (Fig. 3M) showed a large positive bias during 1983

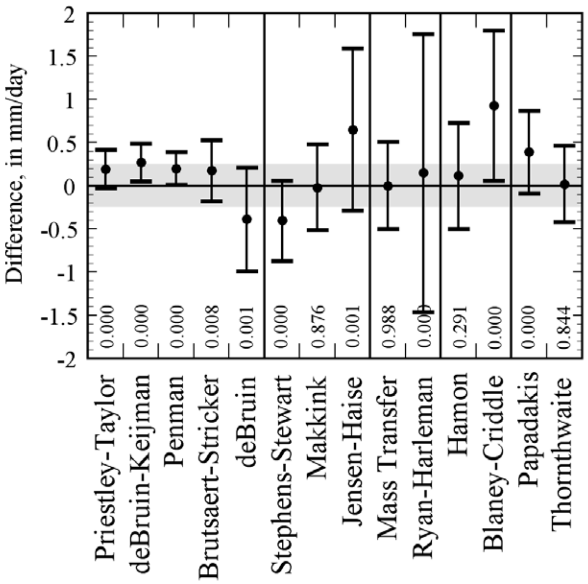

Figure 4 Differences (mean ± 1 standard deviation) between alternate and BREB-determined evaporation using monthly data from Mirror Lake. Shaded area displays uncertainty associated with BREB estimates. Values at bottom of plot are probabilities that the means are equal. Since the Shapiro–Wilk test indicated three distributions were not normal (Makkink, Hamon, Blaney–Criddle), the Wilcoxon test for mean difference was used to generate probabilities.

and 1984, but otherwise provided good comparisons with BREB values, particularly during 1986 and 1987. Values from the Thornthwaite method (Fig. 3N) provided more consistent inter-annual and seasonal comparisons with BREB values than those from the Papadakis method.

Comparisons of 1986–1987 results relative to BREB values were substantially different from other years for four of the 14 methods. Values from the Brutsaert–Stricker method (Fig. 3D) indicated a positive bias, whereas values from the deBruin (Fig. 3E) and mass-transfer (Fig. 3I) methods indicated considerable negative biases during 1986 and 1987. The Ryan–Harleman method (Fig. 3J) provided values that indicated a very large negative bias during 1987 only. Additional inter-annual anomalies occurred during 1983 and 1984, when values from the Jensen–Haise, Makkink, mass-transfer, and Papadakis methods (Fig. 3F, H, I, and M) indicated positive biases during one or both years.

Alternate evaporation methods were related to BREB values using least-squares linear regression with BREB as the independent variable (Table 3). The Priestley–Taylor, deBruin–Keijman, Penman, and Brutsaert–Stricker methods ranked best based on the strength of the regression relation, and the Ryan–Harleman, Thornthwaite, Stephens–Stewart, Penman, and Makkink methods ranked best, respectively, using proximity to a regression slope of 1 as the ranking criterion. In several cases, the degree of correlation with BREB values did not coincide with the regression slope being near unity. For example, the slope coefficient for the Ryan–Harleman BREB relation was very close to unity, but the regression relation explained only 60% of the variance.

The alternate evaporation methods also were ranked based on the percentage of monthly periods during which values from alternate methods were within 5%, 10%, and 20% of BREB values (Table 3). The methods are ordered in Table 3 based on the 20% criterion. Although the Priestley–Taylor method ranks best using the 20% criterion, the Penman method would rank best if the 10% criterion was used, and the Thornthwaite method would rank best if the 5% criterion was used. The four best methods, based on the 20% criterion, are combination methods, which require the greatest number of measured variables. However, the Papadakis and Thornthwaite methods ranked 5th and 6th and require measurement of T_a only; they provided values that were within 10% of BREB values for nearly half of the periods.

Table 3 Regression R^2, slope, and offset coefficients for method output versus BREB values

Alternate method	R^2 regressed against BREB	Regression slope coeff. versus BREB	Regression offset versus BREB	Results within 5% of BREB (%)	Results within 10% of BREB (%)	Results within 20% of BREB (%)
Priestley–Taylor	0.97	1.24	−0.35	24	38	97
deBruin–Keijman	0.97	1.24	−0.27	14	30	95
Penman	0.96	1.15	−0.13	30	62	92
Brutsaert–Stricker	0.92	1.33	−0.57	22	38	65
Papadakis	0.57	0.79	0.87	11	43	60
Thornthwaite	0.73	1.04	−0.07	38	46	59
Mass transfer	0.55	0.77	0.53	14	35	57
Stephens–Stewart	0.74	1.13	−0.69	14	22	57
Makkink	0.74	1.18	−0.42	14	27	54
deBruin	0.38	0.60	0.50	5	19	49
Hamon	0.71	1.31	−0.57	14	19	46
Ryan–Harleman	0.60	1.02	0.64	3	16	22
Jensen–Haise	0.74	1.83	−1.21	3	11	19
Blaney–Criddle	0.73	1.71	−0.66	3	3	19

Percent of monthly periods that alternate evaporation values are within 5%, 10%, and 20% of BREB values. $n = 37$ except for Papadakis method where $n = 35$.

Monthly departures relative to measured variables

Explanations for some of the trends and patterns in the results from alternate evaporation methods relative to BREB estimates can be found by plotting monthly departures from normal for several evaporation variables (Fig. 5). Departures from normal for each variable were obtained by determining an average value for each month during the study and then subtracting each monthly value from the averaged monthly value.

Four of the five combination methods have a seasonal bias when compared to BREB values. This is the result of including Q_v and Q_b in the BREB method but not in the alternate methods. The deBruin method does not indicate a seasonal bias because it does not explicitly measure the available-energy term. The positive bias for the Brutsaert–Stricker method (Fig. 3D) and the negative bias for the deBruin method (Fig. 3E) during 1986–1987 are particularly noteworthy. This is due in part to the consistently smaller-than-normal windspeed during those two years (Fig. 5). The Brutsaert–Stricker method multiplies the Penman available-energy term by a factor of 1.52 and then subtracts the windspeed term to compensate. The deBruin method is notably more susceptible to variations in windspeed because it does not include an available-energy term and compensates by enhancing the much smaller windspeed function (Table 1). For example, a 10% decrease in windspeed during the entire six-year study period results in a 5% decrease in evaporation according to the deBruin method but a 1% increase in evaporation according to the Brutsaert–Stricker method. Therefore, the reduced windspeed during 1986–1987 is partially responsible for the small increase in Brutsaert–Stricker-derived evaporation and the relatively large reduction in deBruin-derived evaporation relative to the BREB values (Fig. 3D and E). The Penman method also is influenced slightly by reduced windspeed during 1986–1987 (Fig. 3C); the positive bias is reduced during those two years.

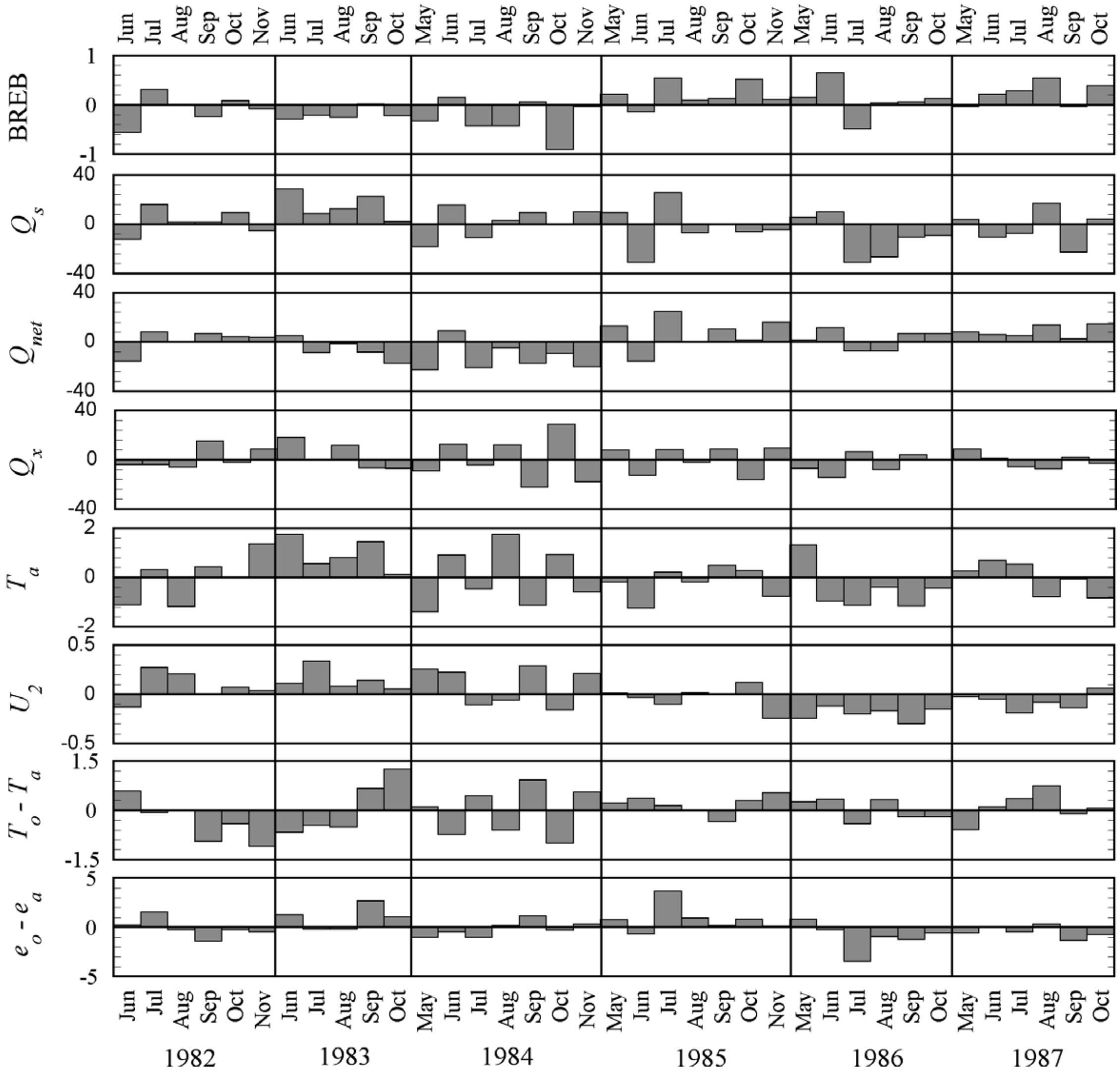

Figure 5 Departure from normal monthly values for BREB evaporation and seven other variables related to one or more evaporation methods.

The relative responses of the Penman and Brutsaert–Stricker methods during 1986–1987 appear to indicate that the influence of windspeed is overemphasized by evaporation methods that require measurement of windspeed when applied to Mirror Lake. Horizontal windspeed may affect evaporation to a lesser extent at Mirror Lake than at other locations, because the tall trees and steeply rising terrain along much of the north, west, and east sides of the lake may occasionally enhance the vertical component of windspeed, which was unmeasured. In such a setting, the significance of the measured horizontal component of windspeed on evaporation would be decreased, and methods that include a windspeed term would be unduly influenced by windspeed.

The negative, neutral, and positive biases shown by the three temperature-radiation evaporation methods (Fig. 3F–H) are the result of the coefficients used in the methods that emphasize to various extents the influences of T_a and Q_s. All three methods also generate larger evaporation estimates trending to smaller estimates from the beginning to the end of each open-water season, relative to BREB values. The lack of a lake heat-storage term is responsible for this seasonal bias. The mean monthly values for Q_x transition in a near linear manner from +48 W m^{-2} during May to −62 W m^{-2} during November. Strong linear relations between mean monthly Q_x and mean monthly departures for each of the three temperature-radiation methods (Jensen–Haise and Stephens Stewart $R^2 = 0.62$; Makkink $R^2 = 0.98$) indicate that Q_x is responsible for nearly all of the seasonal bias of the three temperature-radiation methods.

The two Dalton-type methods (Fig. 3I and J) are sensitive to windspeed and vapor-pressure gradient. This explains the smaller rates of evaporation relative to BREB values during most or all of 1986–1987, when windspeed was smaller than normal during 11 of 12 months and vapor-pressure difference was smaller than normal during 9 of 12 months (Fig. 5). However, the Ryan–Harleman method produced some very large departures from BREB values that cannot be explained by windspeed and vapor-pressure difference alone. The Ryan–Harleman method relies on $T_0 - T_a$, in addition to $e_0 - e_a$, and U_2. All three variables were smaller than normal during October 1984 (Fig. 5), and the method indicated a smaller-than-normal evaporation rate. However, the BREB-derived evaporation rate for that month was the smallest relative to normal of the entire study (Fig. 5); therefore, even reduced, the Ryan–Harleman-derived evaporation rate exceeded BREB evaporation and overestimated evaporation for October 1984. The cause of the exceptionally small BREB evaporation rate was related to much smaller-than-normal atmospheric radiation during September, which caused the lake to cool more rapidly than normal. With a cooler-than-normal lake temperature and warmer-than-normal air temperature during October, the temperature gradient was smaller than normal, the vapor-pressure gradient was about normal, making the Bowen ratio much smaller than normal. Additionally, since Q_n was only slightly greater than zero, evaporation was slightly greater than zero. During the following month, all three Ryan–Harleman variables were larger than normal whereas BREB evaporation was slightly smaller than normal (Fig. 5), resulting in the large positive departure shown in Fig. 3J for that month. The large negative bias of the Ryan–Harleman-derived evaporation during all of 1987, but not during 1986, is particularly interesting because values for U_2, while smaller than normal during both 1986 and 1987, were smallest during 1986, which would indicate that 1986 should be the more aberrant year (Fig. 5). The large 1987 departure can be explained primarily by the larger-than-normal BREB-determined evaporation during nearly all of 1987 while the variables included in the Ryan–Harleman method were a mix of larger- and smaller-than-normal values (Fig. 5). During 4 of 6 months, BREB values were larger than normal; during 5 of 6 months, Ryan–Harleman values were smaller than normal, leading to a consistently negative Ryan–Harleman bias during the entire open-water season (Fig. 3J).

Prior to the past two decades, numerous Dalton-type equations were used to estimate evaporation from lakes, perhaps because they did not require measurement of solar or atmospheric radiation, which were more expensive and difficult to measure than with sensors currently available. The Ryan–Harleman method was chosen for comparison because it represented a Dalton-type method that does not require a site-specific calibration coefficient. In addition, it was the best of seven Dalton-type methods compared by Rasmussen et al. (1995) using data collected from a variety of lakes and ponds in Minnesota. Although the method performed well over a range of lake sizes and lake settings in Minnesota, it provided poor evaporation estimates when applied to the relatively narrow range of environmental conditions at Mirror Lake.

Of the remaining four methods, the large Blaney–Criddle departures from BREB values (Fig. 3K) indicate that this version of the method is not well suited for use at Mirror Lake. This conclusion also is reached based on the slope coefficient of 1.71 from linear regression with BREB values (Table 3). All four of the remaining methods also show larger rates of evaporation relative to BREB values for the early part of the open-water seasons of 1983 and 1984 (Fig. 3K–N). For 1983, this can be attributed to warmer-than-normal air temperature during June through September (Fig. 5). During 1984, air temperature oscillated from month to month between warmer and colder than normal. During the colder-than-normal months, the reduction in evaporation indicated by these temperature methods was less than the reduction in evaporation based on the BREB method, so the departures from the BREB standards remained positive.

Method adjustments

Results from several of the alternate evaporation methods would compare much more favorably with BREB values if a simple offset was provided. In other instances, the significance of various method parameters could be reapportioned to achieve better comparison with BREB values. Several of the methods were adjusted for better fit with BREB values so that greater accuracy might be achieved if these methods are used at other lakes in a physical and climatic setting similar to Mirror Lake.

The four true combination methods all provided evaporation rates that were positively biased relative to BREB values. These methods typically do not include Q_v or Q_b energy terms because, as mentioned previously, they usually are insignificantly small or are not measured. However, Mirror Lake, situated in a humid climate in a steeply sloping basin with much exposed bedrock, occasionally receives a large amount of stream discharge relative to the volume of water in the lake, which then is warmed in the lake and lost to surface outflow and to ground water, giving Q_v a greater significance. Occasional significance of Q_v is likely in many small mountain reservoirs. When the four combination evaporation methods are modified to include Q_v and Q_b (Table 4), both of which were measured at Mirror Lake, the small positive bias becomes even smaller (Figs. 6 and 7). The modified Priestley–Taylor, deBruin–Keijman, and Penman methods indicate biases relative to BREB values of 0.04, 0.12, and 0.09 mm d^{-1}, respectively, and standard deviations also are reduced relative to the unmodified methods (Fig. 7). Although the standard deviation from the modified Brutsaert–Stricker method is about double that of the other modified combination methods, the bias is reduced to zero. A small seasonal bias remains for three of these combination methods, but is not apparent for the Penmen method (Fig. 6). Attempts to modify the deBruin method were not fruitful, perhaps because the method emphasizes vapor pressure and windspeed, two variables that may be temporally unstable in a mountain setting where intermittent atmospheric decoupling is likely.

Two of the three methods that make use of Q_s and T_a, Jensen–Haise and Stephens–Stewart, were developed for greatly different climatic conditions. The Stephens–Stewart method was developed for use in the warm, humid conditions of Florida, and the Jensen–Haise method was developed for use in the arid western United States. Neither is particularly well suited for use at Mirror Lake based on comparisons with BREB values. Both methods were modified to eliminate bias relative to the BREB standard. New coefficients for air-temperature functions were determined through multiple regression forced through the origin. The two methods become virtually identical when the temperature functions are modified to create best comparisons with BREB values because the Q_s multipliers of the two methods are virtually identical (3.459×10^{-2} for Stephens–Stewart; 3.523×10^{-2} for Jensen–Haise). However, the multiplier for temperature in the modified method is essentially zero (−0.0008) and statistically insignificant, indicating that temperature is not a significant parameter relative to solar radiation in these modified methods. Because of substantial multicollinearity between Q_s and T_a, regression methods that make use of Q_s, T_a, or both, provide nearly identical results. Therefore, only a regression equation based on T_a is included in Table 4.

The modified Ryan–Harleman method also was adjusted by forced multiple regression against BREB values to obtain new temperature and wind-speed functions and provides data that compare with BREB values slightly better than mass-transfer values. The adjusted method achieves a better match with BREB values through a small decrease in the emphasis on temperature difference and a larger decrease in emphasis on windspeed (Tables 1 and 4).

Both methods that rely on T_a and day length were modified to eliminate bias relative to BREB values, although the Hamon method might not have warranted modification because it already had relatively small bias (Fig. 4). The Blaney–Criddle method presented in Table 1 commonly is referred to as the SCS version (McGuinness and Bordne, 1972) and was developed for estimating evapotranspiration when only air-temperature data are available. The method has undergone several modifications since it was first presented during the late 1940s, but two widely accepted versions have evolved. The SCS version contains an empirical temperature function, a crop coefficient (set to 1 for open water), and a day length function. The day length function

Table 4 Methods for calculation of E, modified for best fit with BREB measurements at Mirror Lake, in mm d^{-1}

Method	Reference	Modified equation
Priestley–Taylor	Stewart and Rouse (1976)	$E = \alpha \frac{s}{s+\gamma} \frac{Q_n - Q_x + Q_v - Q_b}{L\rho} \times 86.4$
deBruin–Keijman	deBruin and Keijman (1979)	$E = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_n - Q_x + Q_v - Q_b)}{L\rho} \times 86.4$
Penman	Brutsaert (1982)	$E = \frac{s}{s+\gamma} \left(\frac{Q_n - Q_x + Q_v - Q_b}{L\rho} \right) \times 86.4 + \frac{\gamma}{s+\gamma} (0.26(0.5 + 0.54U_2)(e_s - e_a))$
Brutsaert–Stricker	Brutsaert and Stricker (1979)	$E = (2\alpha - 1) \left(\frac{s}{s+\gamma} \right) \left(\frac{Q_n - Q_x + Q_v - Q_b}{L\rho} \right) \times 86.4 - \frac{\gamma}{s+\gamma} (0.26(0.5 + 0.54U_2)(e_s - e_a))$
Regressed T_a		$E = (0.115T_a + 0.633)$
Ryan–Harleman	Rasmussen et al. (1995)	$E = \frac{(2.22(T_0 - T_a)^{0.333} + 2.13U_2)(e_0 - e_a)}{L\rho} \times 86.4$
Blaney–Criddle	McGuinness and Bordne (1972)	$E = p(0.46T_a + 0.75)$
Hamon	Hamon (1961)	$E = 0.523 \left(\frac{D}{12} \right)^2 \frac{\mathrm{SVD}}{100} (25.4)$
Papadakis	McGuinness and Bordne (1972)	$E = 0.481(e_s \max - (e_s \min - 2)) \left(\frac{10}{d} \right)$

All coefficients not listed are described in Table 1.
p = monthly mean daily percentage of annual daytime hours for 44° N latitude.

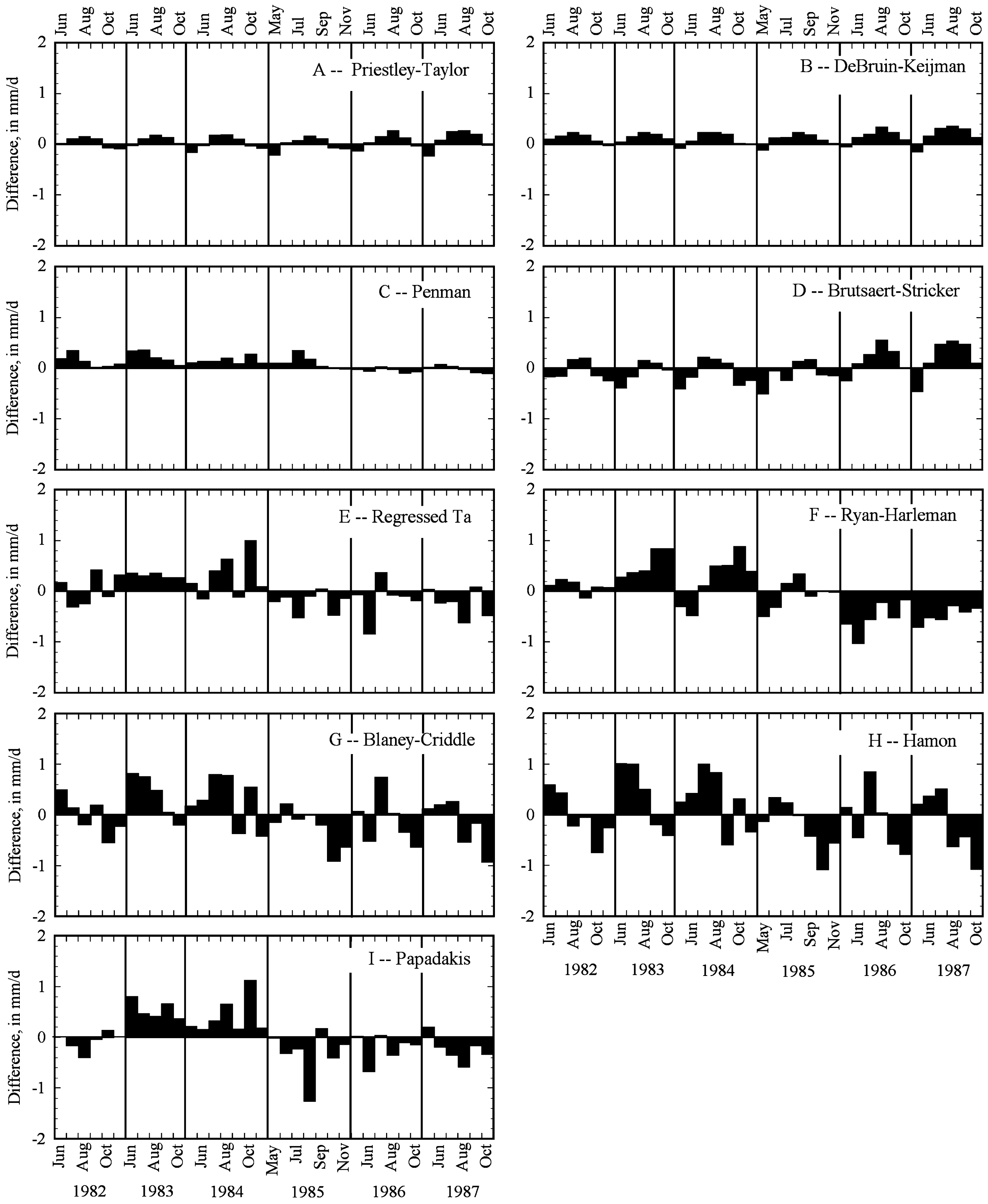

Figure 6 Difference in calculated evaporation between nine modified alternate evaporation methods shown in Table 4 and BREB values, in mm d^{-1}.

was determined for the latitude of Mirror Lake (43° 56′) from sunrise–sunset tables from a US Navy website (http://aa.usno.navy.mil/data/docs/RS_OneYear.html). The newer FAO-24 version (Doorenbos and Pruitt, 1977; Brouwer and Heibloem, 1986) also was used to calculate evaporation from Mirror Lake:

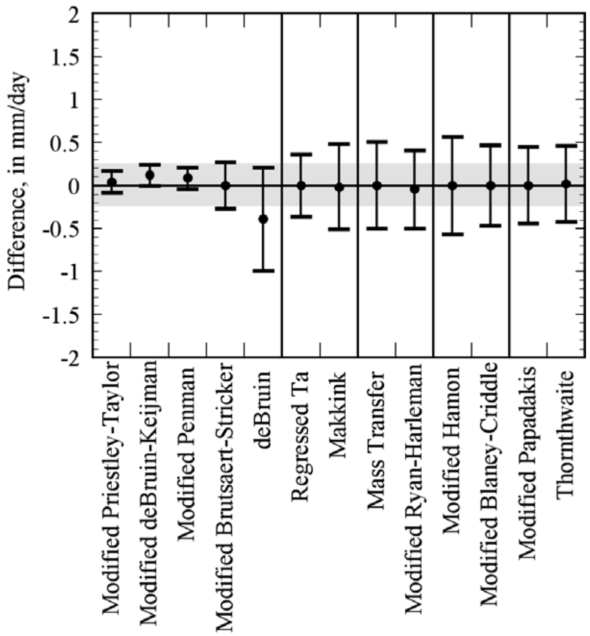

Figure 7 Differences (mean ± 1 standard deviation) between alternate and BREB-determined evaporation following modification of nine of the 14 alternate evaporation methods using Mirror Lake monthly data collected during 1982–1987.

$$E = p(0.46T_a + 8), \tag{4}$$

where p is the monthly mean of the daily percentage of annual total sunlight hours for a particular latitude. Results were strongly positively biased. Mean monthly evaporation rates calculated with the FAO-24 version were 2.2 mm d^{-1} larger than mean BREB values, and the standard deviation of the differences between FAO-24 and BREB monthly values was 0.7 mm d^{-1}. However, when the offset of 8 in the FAO-24 method is replaced with 0.75 (Table 4), bias is eliminated, the standard deviation is reduced to 0.47 mm d^{-1}, and this method results in values that compare quite well with BREB values (Figs. 6 and 7).

Both the Papadakis and Thornthwaite methods require measurement of only T_a, making these the simplest methods compared here. The Papadakis method required a 14% reduction in the 0.5625 multiplier (Table 4) to eliminate the original bias when compared with BREB values, and the modified values have a relatively small standard deviation of 0.45 mm d^{-1} (Fig. 7). The mean and standard deviation of differences between modified Papadakis and BREB values are nearly identical to the mean and standard deviation of values from the unmodified Thornthwaite method (Fig. 7).

Following modifications, all except the deBruin and Hamon methods provide evaporation results that are within 0.5 mm d^{-1} of BREB values for 67% (one standard deviation) of the comparison periods (Fig. 7). Values from the Priestley–Taylor, deBruin–Keijman, and Penman methods are within 0.25 mm d^{-1} of BREB values during 67% of the comparison periods. A re-ranking of the evaporation methods following modifications results in no change in the ordering of the four best combination methods (Table 5). However, results from the modified version of the relatively simple Papadakis method and the regressed-T_a method compare nearly as well with BREB values as results from the more complex Brutsaert–Stricker method.

The surprisingly good performance of evaporation methods that make use only of air temperature is an indication that air temperature is better correlated with the evaporation process at Mirror Lake than at many other lakes. This enhanced correlation may come at the expense of a reduced correlation between evaporation and measured horizontal windspeed, especially during relatively calm periods when windspeed is insufficient to flush out saturated air above the water surface. For example, during 1986–1987, when average windspeeds decreased at Mirror Lake, values from the deBruin and mass-transfer methods decreased sharply relative to BREB values. The Ryan–Harleman method produced values during 1987 that were greatly reduced relative to BREB values. As suggested earlier, the steep local relief, combined with the tall, mature forest that extends to the shoreline, may lead to intermittent

Table 5 Percent of monthly periods that alternate evaporation values (methods modified for use at Mirror Lake are underlined) are within 5%, 10%, and 20% of BREB values

Alternate model	Results within 5% of BREB (%)	Results within 10% of BREB (%)	Results within 20% of BREB (%)
Priestley–Taylor[a]	46	97	100
deBruin–Keijman[a]	46	92	100
Penman[a]	59	84	97
Brutsaert–Stricker[a]	27	59	81
Regressed T_a[a]	11	51	81
Papadakis[a]	16	46	81
Ryan–Harleman[a]	14	38	68
Blaney–Criddle[a]	11	43	62
Thornthwaite	38	46	59
Mass transfer	14	35	57
Makkink	14	27	54
Hamon[a]	8	24	54
deBruin	5	19	49

n = 37 except for Papadakis method where n = 35.

[a] Methods modified for use at Mirror Lake.

formation of separation eddies over the lake, which would decouple the near-surface air column from the regional atmospheric flow, resulting in reductions of wind-speed, temperature, and vapor-pressure gradients near the lake surface. Evaporation would be influenced to a greater extent by intermittent gusts and bursts, sudden whole-lake-scale advections of air and water vapor in the vertical dimension, which would be poorly represented in the time-averaged measurements of horizontal windspeed and near-surface vapor-pressure gradient. Blanken et al. (2003) used high frequency eddy-covariance measurements to observe that the majority of evaporation occurred during such events, even though they were infrequent and in a setting where local topography was inconsequential. If atmospheric stagnation was enhanced by the significant local relief at Mirror Lake, and the frequency of these atmospheric-flushing events was retarded, then evaporation would be correlated to a lesser extent than normal with aerodynamic measurements. Atmospheric flow separation occurs in the lee of mountains at slopes greater than about 20° (Taylor et al., 1987). Slopes steeper than 20° exist along several upwind axes at Mirror Lake. This, along with concerns regarding atmospheric separations associated with the upwind forest edge, could invalidate and corrupt evaporation measurements made with many of the models compared here, including the BREB standard. The fact that the gradient-based Bowen ratios were relatively stable (Table 2), and that results from the various models ranked similarly relative to one another, as at other study sites where forest and terrain were not a concern (Winter et al., 1995; Rosenberry et al., 2004), lends support to the conclusion that insufficient fetch, forest edge, and terrain were not significant factors in measurement of the evaporation process, at least when averaged over monthly periods.

The Priestley–Taylor α is an indication of the relative significance of the aerodynamic process associated with evaporation. For a well-mixed atmosphere, α is assumed to be 1.26, indicating that the aerodynamic influence on the evaporation process is 26% of the available-energy influence. If the aerodynamic influence was decreased at Mirror Lake, then the Priestley–Taylor α would be unduly large and the method would overestimate evaporation. Most values from the Priestley–Taylor method were slightly larger than BREB values. Even following inclusion of Q_v and Q_b in the Priestley–Taylor method, an α of 1.235 would be required to eliminate the bias between the two methods. Other studies also have noted that the aerodynamic term may be overemphasized in some evaporation estimates. Souch et al. (1996) indicated that evaporation from a wetland was more strongly related to available energy and was suppressed by humid air flowing across the wetland from nearby Lake Michigan. They determined that α was 1.035 based on comparison with evaporation rates obtained with eddy-covariance.

Cost versus accuracy

Several of the ''simplified'' methods that were compared with the BREB method are not substantially different and require as many, or nearly as many, measured variables, reducing their value for studies that are searching for a less expensive means for estimating evaporation. The Priestley–Taylor, deBruin–Keijman, and Penman methods provided evaporation estimates that most closely compared with BREB values. Of these three, the Penman method (as well as the Brutsaert–Stricker method) requires the greatest number of variables. The Penman and Brutsaert–Stricker methods both require the same number of variables as the BREB method; they eliminate the need to measure water-surface temperature (and calculated vapor pressure at the water surface) with the tradeoff that they require that windspeed be measured. Therefore, the Priestley–Taylor and deBruin–Keijman methods are the most cost effective of these combination methods, requiring measurement of only T_a, Q_n, and Q_x. However, unless a case can be made that Q_x can be adequately represented with temperature-profile measurements at one location within the lake, as has been done for other sites (Rosenberry et al., 1993; Parkhurst et al., 1998), Q_x remains a prohibitively expensive variable for many budgets, due to high labor costs. One potential solution, however, is to deploy strings of relatively inexpensive temperature recorders in several locations in the lake-water column. The remaining combination method (deBruin) did not compare well with BREB values and requires measurement of T_a, e_a, and U, making it a poor choice for use at Mirror Lake.

The Dalton-type methods are the next most complex, requiring measurement of T_0, T_a, e_a, and U. The mass-transfer method also requires a locally determined mass-transfer coefficient. Both methods provided evaporation values that ranked in the middle to near the bottom of the list of methods ordered based on their comparison with BREB values (Table 3), making them a poor choice for measuring evaporation at a lake in a setting similar to Mirror Lake.

The three models that make use of T_a and Q_s (Jensen–Haise, Makkink, Stephens–Stewart) all ranked in the lower half of the list presented in Table 3. This was somewhat surprising because these methods provided results that compared relatively well with BREB values at other sites in Minnesota and North Dakota (Winter et al., 1995; Rosenberry et al., 2004). The regression coefficients associated with these methods were developed for climatic and physical settings different from Mirror Lake and, apparently, they do not transfer well to Mirror Lake.

The two methods that require measurement of only T_a compared surprisingly well with BREB values. The Papadakis and Thornthwaite methods ranked 5th and 6th and were the highest ranked evaporation methods next to the much more data intensive combination methods. These methods provided evaporation values that were within 5% of BREB values during 11% and 38% of the monthly comparison periods, respectively, and values from both methods were within 10% of BREB values during nearly half of the monthly periods (Table 3). If that level of accuracy is sufficient, these may be the most cost effective of the methods compared for this study. The Hamon and Blaney–Criddle methods both provided relatively poor evaporation estimates compared to BREB values and, given that day length also needs to be determined for these methods, there would be little reason to choose one of these methods over the simpler Papadakis or Thornthwaite methods.

Summary and Conclusions

Evaporation methods that include available-energy and aerodynamic terms (combination methods) provide the best comparisons with BREB evaporation measured at Mirror Lake. Three of the four combination methods (Priestley—Taylor, deBruin—Keijman, Penman) provided values that were within 20% of BREB values during more than 90% of the energy-budget periods. Although small relative to other energy terms, inclusion of advected energy associated with rainfall, ground-water and surface-water fluxes, and energy conducted to or from the lake sediments, in the net radiation term improved evaporation estimates when compared with BREB values. With the inclusion of these two terms, values from the Penman method were within 20% of BREB values during 36 of the 37 monthly comparison periods and values from the Priestley—Taylor and deBruin—Keijman methods were within 20% of BREB values during all of the comparison periods.

Methods may be unduly sensitive to windspeed when applied to Mirror Lake. During periods when windspeed was substantially larger or smaller than normal, methods that contain a windspeed term provided evaporation values that were substantially different from BREB values. This may be the result of the sharply rising terrain on three sides of Mirror Lake, which may decouple the near-surface air column from the regional atmospheric flow. In such a setting, vertical transfer of vapor from the lake to the atmosphere would occur to a greater extent during intermittent gusts and bursts, making time-averaged measurements of horizontal windspeed less relevant to the evaporation process at Mirror Lake.

Methods that require measurement of both solar radiation and air temperature are not substantially better than methods that require measurement only of air temperature when applied to Mirror Lake data. For example, simple linear regression of results from the Jensen—Haise method, which requires measurement of solar radiation and air temperature, and BREB results explains 74% of the variance between the two methods. Linear regression of air temperature and BREB evaporation explains 73% of the variance.

Other temperature-only methods also compared remarkably well with BREB values. Given their simplicity, temperature-only methods, such as Thornthwaite or Papadakis, are cost effective and provide evaporation estimates that are more accurate than several more complex methods. Thornthwaite results were within 10% of BREB values during nearly half of the evaporation periods.

Modification of evaporation methods to eliminate bias and reduce standard deviation resulted in nearly all evaporation estimates for all methods being within 0.5 mm d^{-1} of BREB values. These modified methods also may serve well for estimating evaporation at many other lakes with a physical and climatic setting similar to that of Mirror Lake.

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