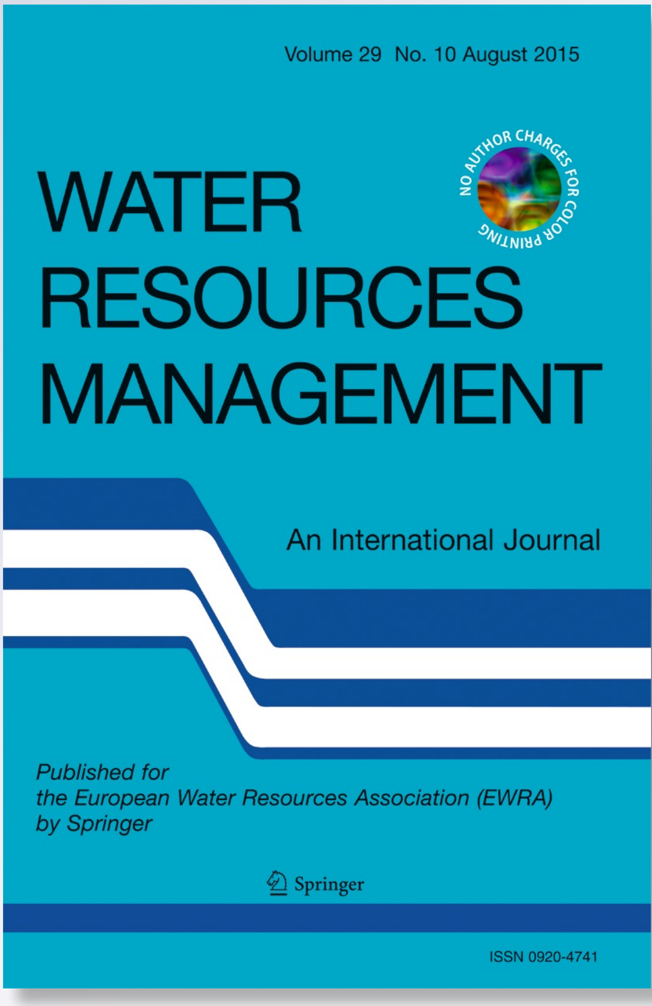
Estimating Evaporation from Lakes and Reservoirs under Limited Data Condition in a Semi-Arid Region

M. Majidi, A. Alizadeh, A. Farid & M. Vazifedoust

Water Resources Management
An International Journal - Published for the European Water Resources Association (EWRA)

ISSN 0920-4741
Volume 29
Number 10

Water Resour Manage (2015)
29:3711-3733
DOI 10.1007/s11269-015-1025-8



Springer

Water Resour Manage (2015) 29:3711–3733
DOI 10.1007/s11269-015-1025-8

Estimating Evaporation from Lakes and Reservoirs under Limited Data Condition in a Semi-Arid Region

M. Majidi [1] **· A. Alizadeh** [1] **· A. Farid** [1] **· M. Vazifedoust** [2]

Received: 22 October 2014 / Accepted: 23 April 2015 /
Published online: 12 May 2015

Abstract The Bowen ration energy balance (BREB) is considered as a standard method for estimating lake evaporation. The BREB method however requires numerous input data which may not be readily available especially in developing countries. This limitation could be solved by using methods with fewer data requirements. Evaporation from lakes and reservoirs in Iran is commonly estimated using pan evaporation because there have not been a consensus on which methods are most applicable under the limited data condition and arid climate. Therefore, the objective of this research was to determine the most appropriate evaporation methods over Doosti dam reservoir in Iran. Eighteen existing methods were tested and ranked based on the BREB method. The Jensen-Haise, Makkink, Penman and deBruin methods were among the most consistent methods with BREB in which the RMSD values were obtained 1.2, 1.34, 1.62 and 1.65 mm d^{-1}, respectively. Finally, we concluded that methods which rely only on air temperature, or air temperature combined with sunshine data (e.g., Jensen-Haise and Makkink), were relatively cost-effective options for estimating evaporation at the study area due to their simplicity, least sensitivity and high accuracy.

Keywords Evaporation · Limited data · Semi-arid · Sensitivity analysis

Nomenclature

E	the evaporation rate (mm d^{-1})
R_n	the net radiation (W m^{-2})
N	the change in the energy storage in the water (W m^{-2})
λ	the latent heat of vaporization
c	the specific heat of water (J kg^{-1})
F_{in} and F_{out}	the heat fluxes from water flows in and out of the water body (W m^{-2})
F_P	the heat inflow from precipitation (W m^{-2})

✉ M. Majidi
maysam.majidi@gmail.com

[1] Water Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran

[2] Water Engineering Department, University of Guilan, Guilan, Iran

G	the heat conducted from the lake to the sediments (W m^{-2})
β	Bowen ratio (dimensionless)
P	the atmospheric pressure (kPa)
c_B	the specific heat of air at constant pressure (0.61 °C^{-1})
T_a	the air temperature (°C) (°F for the Blaney–Criddle Jensen–Haise and Stephens–Stewart equations)
T_w	the water surface temperature (°C)
e_s	the saturation vapor pressure at the water surface temperature (Pa)
e_a	the atmospheric vapor pressure (Pa)
e_a^*	the saturated vapor pressure at temperature of the air (mb)
Δ	the slope of the saturated vapor pressure-temperature curve (Pa °C^{-1})
γ	the psychometric coefficient (Pa °C^{-1})
u	the wind speed (m s^{-1})
α	Priestley–Taylor empirically derived constant (dimensionless)
R_s	the incoming solar radiation (W m^{-2})
C	the mass-transfer coefficient (dimensionless)
A_s	the area of the water body (hec)
D	the hours of daylight
D_{TA}	the total annual hours of daylight
SVD	the saturated vapor density at mean air temperature (g m^{-3})
$e^*_{a,max}$	the saturated vapor pressures at maximum air temperature (Pa)
$e^*_{a,min}$	the saturated vapor pressures at minimum air temperature (Pa)
E_{BREB}	the estimated evaporation values using BREB method (mm d^{-1})
E_{eq}	the estimated evaporation values obtained by any methods (mm d^{-1})

1 Introduction

Water when harvested is commonly stored in dams, but approximately up to half of it may be lost due to evaporation leading to a huge waste of our resources (Maestre-Valero et al. 2013; Martinez-Granados et al. 2011; Gallego-Elvira et al. 2013). Estimating evaporation from lakes and reservoirs is not a simple task as there are a number of factors affecting the evaporation rate, notably the climate and physiography of the water body and its surroundings.

Several methods are currently used to predict evaporation using meteorological data from open water reservoirs. They are generally categorized into: temperature and radiation (Xu and Singh 2000), mass-transfer (aerodynamic) (Singh and Xu 1997), pan coefficient, energy budget and combination methods (Gianniou and Antonopoulos 2007, Rosenberry et al. 2007), for example, by Makkink (1957), Blaney and Criddle (1950), Jensen and Haise (1963), Stephens and Stewart (1963), Hamon (1961), Priestley and Taylor (1972), Stewart and Rouse (1976), de Bruin and Keijman (1979), Brutsaert and Stricker (1979). Based on accuracy and simplicity of their application, each of these methods has advantages and disadvantages. Several of evaporation methods were comprehensively reviewed by de Bruin and Stricker (2000), Lenters et al. (2005), Rosenberry et al. (2007), Stephen et al. (2007), Shakir et al. (2008), Gallego-Elvira et al. (2010), and McJannet et al. (2012).

Winter et al. (1995) compared 11 well-used methods with the energy budget method over Williams Lake, and proposed a ranking based on performance from best to worst. They ranked these methods as Penman, DeBruin-Keijman, Makkink, Priestley-Taylor, Hamon, Jensen-

Haise, mass transfer, deBruin, Papadakis, Stephens-Stewart and Brutsaert-Stricker. Rosenberry et al. (2007) evaluated 15 methods in comparison with the energy budget method. Rasmussen et al. (1995) compared seven methods used in lake temperature modelling. The evaluation of seven methods by Abtew (2001) suggested that simple models such as the modified Turc model which only uses solar radiation and maximum air temperature could perform better than Penman-combination or Priestley-Taylor models which require more input parameters. Four methods of Priestley-Taylor, deBruin-Keijman, Papadakis and Penman were compared with energy budget method by Mosner and Aulenbach (2003) and the Priestley-Taylor method was found to be the best of the four methods. Xu and Singh (2000) tested eight radiation-based evaporation models in order to estimate future lake levels. Singh and Xu (1997) evaluated 13 mass transfer equations in comparison with pan evaporation data. Delclaux et al. (2007) compared five monthly evaporation methods and indicated that the Abtew model and Makkink model led to the best estimates of lake evaporation. Comparisons of estimation methods were also performed by Keskin and Terzi (2006); Majidi et al. (2015) and Sadek et al. (1997). All these comparisons resulted in somehow different conclusions depending on sites and data used. On the other hand, most of these studies have been carried out where the measurements of required data were available.

Several studies were performed in order to compare and assess evapotranspiration methods for land surfaces or estimate of required parameters in limited data conditions around the world (Kisi and Cengiz 2013). On the contrary, a few studies have been conducted to find the most appropriate methods to estimate lake evaporation in the conditions that long term data required are not available. Therefore, there is no clear consensus on which methods are better to employ when lacking important long term measured data such as temperature profile, radiation and heat fluxes as is the case in most lakes and reservoirs in Iran.

Although evaporation pan method is well known to have significant uncertainties both in magnitude and timing, it is extensively used in Iran because of its simplicity. Evaporation pan provides a measurement of the combined effect of temperature, humidity, wind speed and solar radiation on the evaporation (Irmak et al. 2002; Sabziparvar et al. 2010; Kim et al. 2013). However, they may not be adequate for the reservoir operations/development and water accounting strategies for managing drinking water in arid and semi-arid conditions which require accurate evaporation estimates (Gokbulak and Ozhan 2006; Mugabe et al. 2003; Shakir et al. 2008; Stets et al. 2009).

Therefore, there is a critical need to evaluate more logical scenarios for estimating evaporation under conditions of lacking some of the measured data. The fundamental question about which equation estimates evaporation most accurately, was considered in this research, followed by a search for the best cost-effective evaporation method with possibly fewer data requirements in our study area, Doosti dam reservoir which is located in a semi-arid region of Iran.

1.1 Theory

1.1.1 Bowen Ratio Energy Balance (BREB) Method

Energy balance is a basic method commonly adopted for determining evaporation in which the latent heat flux (evaporation term) is obtained when all other terms such as net radiation and sensible heat fluxes are known. Since the sensible heat flux cannot be easily determined, Bowen (1926) eliminated this term from the energy balance equation using the so-called

Bowen ratio, β, defined as the ratio between the sensible and latent heat fluxes (Finch and Calver 2008). Bowen's solution to the energy balance equation commonly called as "Bowen Ratio Energy Balance" (BREB) is considered as a standard method (Winter et al. 2003; Lenters et al. 2005; Rosenberry et al. 2007). The evaporation rate in this method is given by (dos Reis and Dias 1998):

$$E = \frac{R_n - N + F_{in} - F_{out} + F_P - G}{\rho(\lambda(1+\beta) + cT_w)} \tag{1}$$

where E is the evaporation rate (mm d^{-1}), R_n is the net radiation (W m^{-2}), N is the change in the energy storage in the water (W m^{-2}), λ is the latent heat of vaporization, c is the specific heat of water (J kg^{-1}), T_w is the temperature of water (°C), F_{in} and F_{out} are the heat fluxes from water flows in and out of the water body (W m^{-2}), F_P is the heat inflow from precipitation (W m^{-2}), and G is the heat conducted from the lake to the sediments (W m^{-2}).

By proper selection of a time period, it is commonly possible to neglect the F_{in}, F_{out}, F_p and G terms. The Bowen ratio (β) is the ratio of sensible to latent heat and is calculated as:

$$\beta = c_B P \frac{T_w - T_a}{e_s - e_a} \tag{2}$$

where P is atmospheric pressure (kPa), c_B is the specific heat of air at constant pressure (0.61 °C^{-1}), T_a is air temperature, e_s is saturation vapor pressure at the water surface temperature (Pa) and e_a is atmospheric vapor pressure (Pa).

The BREB method has been widely evaluated and indicated to be very accurate in most cases and is often considered as a standard method particularly where other methods are validated or calibrated (Assouline and Mahrer 1993; Winter et al. 2003; Lenters et al. 2005; Rosenberry et al. 2007; Finch and Calver 2008). Accuracy of the BREB result depends on the timescale and size of the water body (Anderson 1954; Stewart and Rouse 1976). It needs the longer time interval between measurements of the temperature profile in the larger water bodies to attain reliable result due to the heat storage flux. To improve the accuracy of the BREB method, the surface and profile water temperatures are required at representative points over the water body (Anderson 1954; Sturrock et al. 1992; Assouline and Mahrer 1993; Finch and Calver 2008).

1.1.2 Conventional Methods

Penman (1948, 1963) combined the mass transfer and energy budget approaches, and eliminated the requirement of surface temperature to obtain his expression for evaporation from open waters as follow:

$$E = \frac{\Delta(R_n - N)}{\lambda(\Delta + \gamma)} + \frac{\gamma 0.0026(1 + 0.54u)\left(e_a^* - e_a\right)}{\Delta + \gamma} \tag{3}$$

where Δ is the slope of the saturated vapor pressure-temperature curve (Pa °C^{-1}), γ is the psychometric coefficient (Pa °C^{-1}), e_a^* is the saturated vapor pressure at temperature of the air (Pa) and u is the wind speed at $2m$ elevation (m s^{-1}). The first and second terms in Penman equation are commonly called as "energy term" and "aerodynamic term", respectively. The first term represents the lower limit of evaporation and is also referred to as the "equilibrium rate". Success of Penman's equation when applied in many different locations is attributed to its physical basis (Linacre 1993).

Priestley and Taylor (1972) proposed a simplified version of Penman's "combination equation" for all wet surfaces by neglecting the aerodynamic component, and then considering a correction factor 'α' for the energy component. The Priestley-Taylor equation can be written as:

$$E = \alpha \frac{\Delta}{\Delta + \gamma} \frac{R_n - N}{\lambda} \tag{4}$$

For large water bodies α was found to tend to 1.26 (Stewart and Rouse 1976; Stewart and Ruose 1977; de Bruin and Keijman 1979).

de Bruin and Keijman (1979) derived their model based on Priestley-Taylor equation:

$$E = \frac{\Delta}{0.85\Delta + 0.63\gamma} \frac{R_n - N}{\lambda} \tag{5}$$

They found good agreement between their equation and the energy balance method (Eq. 1).

Brutsaert and Stricker (1979) developed an Advection-Aridity (AA) model by substituting a proposed wind function into the aerodynamic vapor transfer term (drying power of the air) of the Penman equation, and also adopting the partial equilibrium evaporation equation of Priestley-Taylor. Their model is of the form:

$$E = (2\alpha - 1) \frac{\Delta}{\Delta + \gamma} \frac{R_n - N}{\lambda} - \lambda \frac{\gamma}{\Delta + \gamma} f(u) \left(e_a^* - e_a\right) \tag{6}$$

de Bruin (1978) obtained the following formula by combining the Penman and Priestley-Taylor equations, thus eliminating the energy term:

$$E = \frac{\alpha}{\alpha - 1} \frac{\gamma}{\Delta + \gamma} f(u) \left(e_a^* - e_a\right) \tag{7}$$

By this solution, deBruin discarded R_n and N since is not often possible or it is too expensive to make adequate measurements especially for a large water body. He found good agreement with estimations of the energy balance method for intervals of 10 days or more.

Stewart and Rouse (1976) derived a version of Eq. (4) by using a linear function of incoming solar radiation (R_s) to replace the net radiation and heat storage. The empirical coefficients of the function were obtained by regression analysis, therefore are specific to their lake. The resulting equation is identical to the formula of Makkink (1957), who used it to estimate the evaporation from well-watered grass and is as follows:

$$E = 52.6 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} - 0.12 \tag{8}$$

Jensen and Haise (1963) developed an empirical temperature-radiation method for calculating daily evaporation:

$$E = 0.03523 R_s (0.014 T_a - 0.37) \tag{9}$$

Stephens and Stewart (1963) introduced a radiation method adjusted for monthly mean temperature. This method was called as the "Fractional Evaporation-Equivalent of Solar Energy" method, but it had essentially the same form as that of Jensen and Haise (1963):

$$E = 0.03495 (0.0082 T_a - 0.19) R_s \tag{10}$$

The mass-transfer method is one of the oldest methods (Dalton 1802; Penman 1948) and is still an attractive method in estimating open water evaporation because of its simplicity and reasonable accuracy. The mass transfer methods are based on Dalton equation. Harbeck (1962) developed a slightly different equation for estimating evaporation from reservoirs (Finch and Calver 2008):

$$E = Cu(e_s - e_a) \tag{11}$$

where C is the mass-transfer coefficient. The mass transfer method offers the advantage of simplicity in calculation once the empirical constant of C is known. It is not possible to find a value of C applicable to all water bodies. Nevertheless, attempts have been made to produce a generally applicable value (Finch and Calver 2008). Harbeck (1962) also suggested an expression for C that incorporated the area of the water body (A_s). A mass transfer equation by Shuttleworth (1993) was expressed as (Finch and Calver 2008):

$$E = 2.909 A_s^{-0.05} u(e_s - e_a) \tag{12}$$

A similar expression was also given by Shuttleworth based on the work of Brutsaert and Yu (1968) as follows:

$$E = 3.623 A_s^{-0.066} u(e_s - e_a) \tag{13}$$

The weak inverse dependence of the transfer coefficient on the size of the water body reflects the effect of the reduced efficiency of turbulent transfer over the smooth water surface (Shuttleworth 1993; Finch and Calver 2008).

Ryan and Harleman (1973) developed an equation based on Dalton theory to estimate evaporation from heated water bodies (Rasmussen et al. 1995). In that case, both forced (wind driven) convection and free (buoyancy driven) convection effectively control evaporation rates, while the forced convection is the dominant factor for natural water bodies.

$$E = \lambda^{-1}\left[2.7(T_w - T_a)^{1/3} + 3.1u\right](e_s - e_a) \tag{14}$$

Blaney (1959) described his method as a rapid mean of transferring the results of evapotranspiration measurements to other areas with similar climate. Briefly, he correlated monthly measured evaporation data with monthly mean temperature times the percentage of daytime hours during the year in order to develop an monthly empirical evaporation coefficient. The Blaney-Criddle formula is (Schertzer and Taylor 2008):

$$E = 25.4(0.0173 T_a - 0.314) T_a \frac{D}{D_{TA}} \tag{15}$$

where, D is the hours of daylight and D_{TA} is the total annual hours of daylight.

Hamon (1963) formulated a simplified expression based on the relation between potential evapotranspiration, maximum possible incoming radiant energy and the moisture-holding capacity of the air at the prevailing air temperature. It is often used to estimate lake evaporation or watershed potential evaporation because of its simplicity (Yao and Creed 2005). The expression is represented by the equation:

$$E = 0.63 D^2 \times 10^{\frac{7.5 \times T_a}{T_a + 273}} \tag{16}$$

Also based on Lu et al. (2005), the following equation can be used:

$$E = 35.755 D\left(\frac{e_a^*}{T_a + 273.3}\right) \tag{17}$$

And another equation for Hamon method by Schertzer and Taylor (2008) is read as:

$$E = 13.97\frac{SVD}{100}\left(\frac{D}{12}\right)^2 \tag{18}$$

where, SVD is the saturated vapor density at mean air temperature.

Papadakis (1961) equation does not account the heat flux that occurs in the lake body to determine evaporation (Winter et al. 1995; Finch and Calver 2008). Instead, the equation depends on the differences in the saturated vapor pressure above the water body at maximum and minimum air temperatures, and evaporation is defined by the equation:

$$E = 0.5625\left[e^*_{a,\max} \times 10^{-2} - \left(e^*_{a,\min} \times 10^{-2} - 2\right)\right] \tag{19}$$

where, $e^*{}_{a,max}$ and $e^*{}_{a,min}$ are the saturated vapor pressures at daily maximum and minimum air temperatures.

2 Materials and Methods

2.1 Study Area and Data Collection

Our study site was the Doosti dam reservoir located between Iran and Turkmenistan borders, which was constructed by the Ministry of Water and Land Reclamation of the Republic of Turkmenistan and the Khorasan Razavi Regional Water Board of Islamic Republic of Iran (Fig. 1). Doosti Dam is one of the most important freshwater storage facilities in Iran. Since the selected dam is located in a semi-arid region of Iran, evaporation causes a huge waste of water in this reservoir. The Doosti dam has a height of 78 m above the foundation, reservoir capacity of 1250 mcm, average reservoir area of about 35 km^2, and normal water level of 473.8 m above mean sea level. The reservoir of the Doosti dam is a clear and relatively deep lake, with a maximum and mean depth of 35 and 15 m, respectively. This dam supplies irrigation and municipal water demands of both Iran and Turkmenistan. Climate of this region is semi-arid with annual mean temperature of 17.9 °C, annual mean precipitation of 187.37 mm and annual mean relative humidity of 47.7 %.

To accomplish this research, meteorological data including maximum and minimum air temperature and evaporation from class A pan were acquired from the Doosti Dam weather station. Relative humidity, wind speed, atmospheric pressure and precipitation were acquired from the Pol-Khatoon weather station. Dew point temperature and sunshine data were collected from the Sarakhs weather station. Lake area was estimated from the hypsometric curve in relation to lake level data.

Temperature measurements were often performed in 16-day periods or biweekly from September 2011 to September 2012. Temperature profile of the lake (required for lake evaporation estimation) was measured at different points of the reservoir using a portable multi-meter.

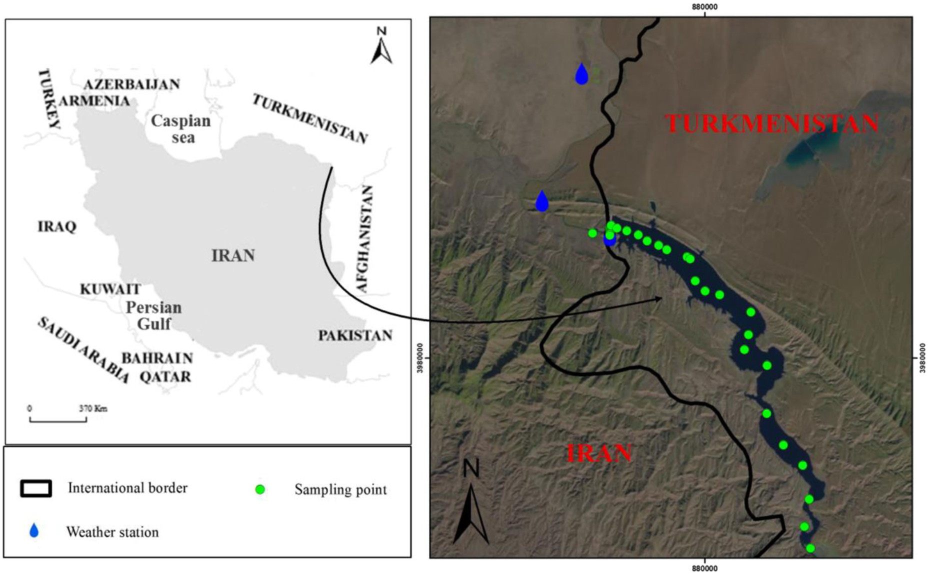


Fig. 1 Map of Doosti dam reservoir showing approximate locations of the meteorological station and biweekly temperature profiles

2.2 Evaluations

We evaluated the methods introduced above for estimating evaporation from the Doosti dam reservoir (described below) in comparison with the BREB method. We adopted the root mean square difference (*RMSD*) for evaluating these methods, calculated as follows:

$$RMSD = \left[1/M \sum_{i=1}^{M} \left(E_{BREB,i} - E_{eq,i} \right)^2 \right]^{0.5} \tag{20}$$

where M denote the number of data, E_{BREB} and E_{eq} are the estimated evaporation values using BREB method and any of the studied methods, respectively.

3 Results and Discussion

3.1 Temperature and Radiation of the Lake

Average of the measured temperature profile for February, June, August and October (2011–2012) is presented in Fig. 2 indicating a nearly uniform profile in February and October and a decreasing one in June and August.

All of the temperature data for air and lake water are shown in Fig. 3. The water temperatures are lower than air temperatures during summer and vice versa during winter. Evaporation rate from the lake may be more than expected in winter and is slightly reduced in summer since as the water depth increases, the maximum evaporation is shifted from about a month after the summer solstice to 4 months (Mironov et al. 2003). As this figure indicates, all

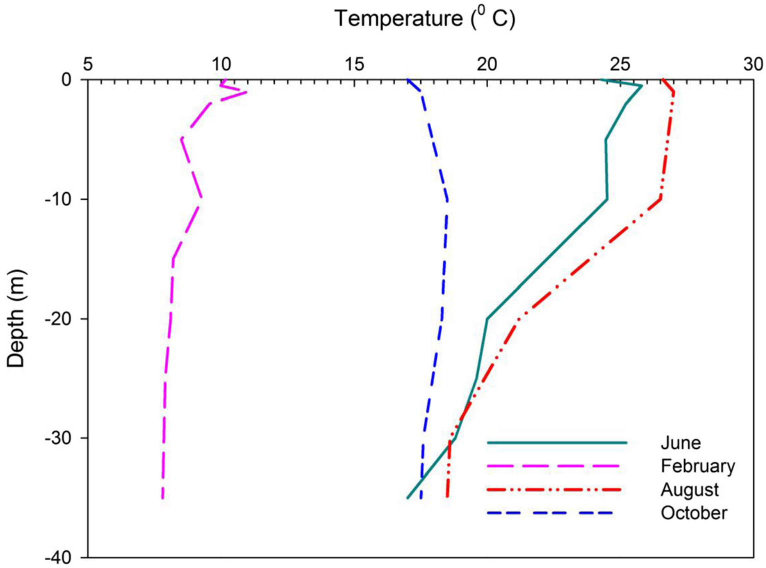


Fig. 2 Average measured thermal profile data on February, June, August and October, 2011–2012

measured temperatures have relatively similar variations; thus, their correlation can be considered for estimating them especially for daily basis applications.

As shown in the "Theory" part, daily data are needed in some of the methods. In order to reconstruct the daily water temperatures, possibly from air temperature data which were available daily, we tried to find relationships between water surface temperature and air temperatures (max, mean and min) (Fig. 4). To do so, several regression models were tested

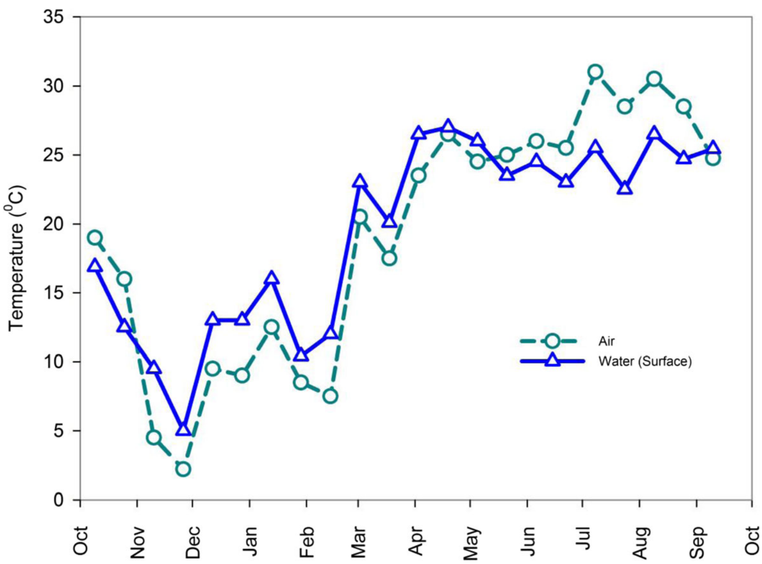


Fig. 3 Measured water surface and air temperatures, during 2011–2012

and the best model based on the determination coefficient ($R^2 = 0.809$) was chosen, which was a linear model relating the surface water temperature to the mean air temperature. This procedure was also used for regenerating daily thermal profile based on the mean air temperature (Fig. 5). Energy storage was then calculated using the time steps and resulting temperature profiles.

Net radiation was calculated by conventional algorithm based on short-wave and long-wave radiation data and with the assumption of albedo equal to 0.07 for water surface (Cogley 1979). The calculated net radiations are presented in Fig. 6. A similar behavior to net radiation is expected for evaporation rate as well. It can be seen that maximum net radiation occurs approximately when air and water temperatures reach their maximum value.

3.2 Evaporation Estimations

The estimated annual evaporation values from Doosti dam reservoir is given in Table 1. As shown in Table 1, the BREB annual evaporation value obtained equal to 69.86 mcm and evaporation rate averaged 5.47 mm d^{-1} during the study period. According to the results, there is a relatively large difference among the obtained evaporation values from the adopted methods. However, many established methods do not guarantee their universal application without a proper adjustment in their parameters. Therefore, calibration or adjustment of some methods remains as a need in the future studies.

3.3 Sensitivity Analysis

The difference between the highest and the lowest evaporation estimates is 7 mm d^{-1}. This variation would be unrealistic because all the methods include empirical equations or coefficients which associated errors are difficult to estimate. On the other hand, the

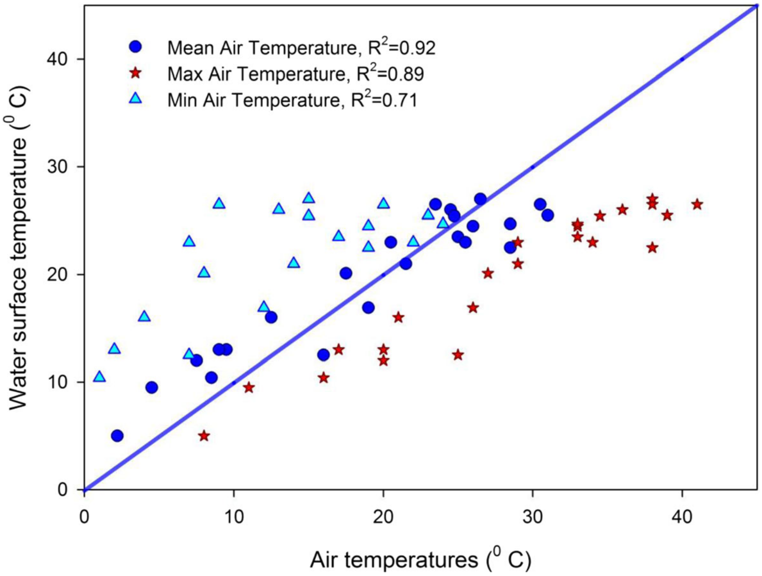


Fig. 4 Relationship between water surface temperature and air temperature, during 2011–2012

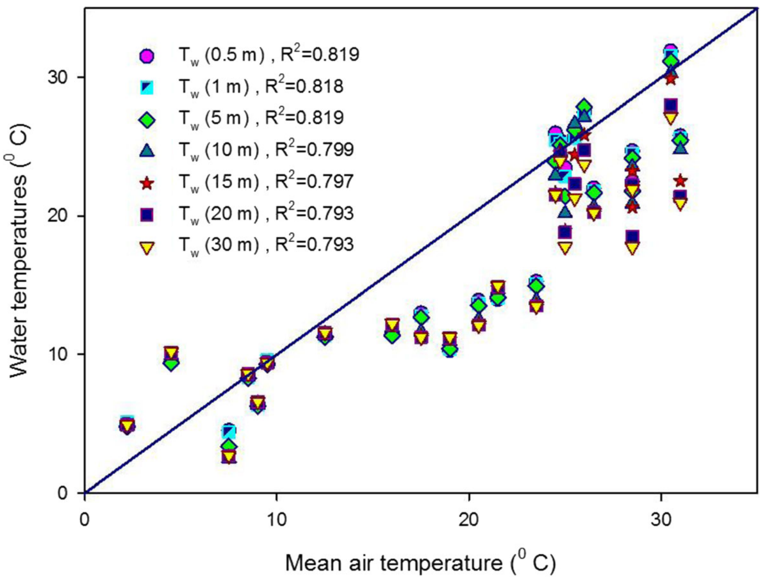


Fig. 5 Regression analyses between water temperature profile and the mean air temperature, during 2011–2012

uncertainties of measured parameters are unknown in most cases (Vallet-Coulomb et al. 2001). Hence, the consistency of the results can be discussed through sensitivity analysis of all methods to their input variables (Vallet-Coulomb et al. 2001). In the following, we analyze the impact of each input variable on evaporation estimates for each method, by varying their value by 10 %.

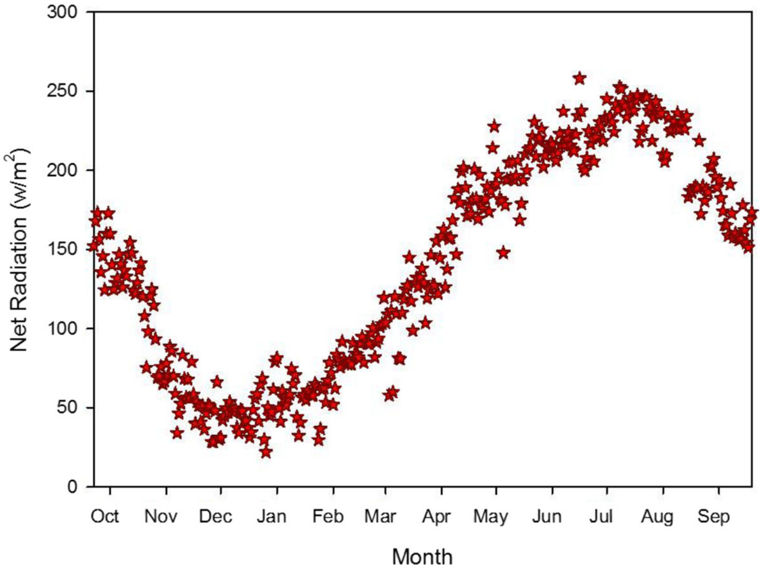


Fig. 6 Variation of net radiation for water surface, during 2011 to 2012

Table 1 Annual evaporation (mcm) from Doosti dam reservoir, during 2011–2012

Methods		Using measured data (16 days)	Using reconstructed data (daily)
Energy balance	BREB, Eq (1)	69.87	72.93
Combination group	Penman, Eq. (3)	62.76	62.76
	Priestley-Taylor, Eq. (4)	85.80	85.80
	deBruin-Keijman, Eq. (5)	99.25	99.25
	Brutsaert-Stricker, Eq. (6)	79.71	79.71
	deBruin, Eq. (7)	52.19	52.19
Solar radiation-temperature group	Makkink, Eq. (8)	58.33	58.33
	Jensen-Haise, Eq. (9)	62.92	62.92
	Stephens-Stewart, Eq. (10)	39.11	39.11
Dalton group	Mass transfer 1, Eq. (11)	113.03	113.03
	Mass transfer 2, Eq. (12)	83.67	83.67
	Mass transfer 3, Eq. (13)	78.85	78.85
	Ryan-Harleman, Eq. (14)	74.58	74.58
Temperature-day length group	Blaney-Criddle, Eq. (15)	43.33	43.33
	Hamon 1, Eq. (16)	21.40	21.40
	Hamon 2, Eq. (17)	57.70	57.70
	Hamon 3, Eq. (18)	35.16	35.16
Temperature group	Papadakis, Eq. (19)	77.13	77.13
Pan	pan	71.46	71.46

3.3.1 Radiation (Sunshine Data)

The sunlight data, which leads to the energy source of evaporation (solar radiation), is the most effective parameter in estimating evaporation (Vallet-Coulomb et al. 2001). As the result indicated, Hamon methods (Eqs. 16 and 17) had the highest sensitivity to solar radiation (sunshine data), so that 10 % change in this parameter resulted in 21 % change in evaporation rate (Table 2). Error of 10 % in sunlight data led to 11.54 % error in evaporation rate determined by Brutsaert-Stricker. Also, Priestley-Taylor, deBruin-Keijman, BREB and Penman methods showed the sensitivity of about 8 %, and solar radiation-temperature methods (Makkink, Jensen-Haise and Stephens-Stewart) had the sensitivity of about 6 %. Note that the uncertainty in solar radiation comes from the measurements of daily sunshine duration.

3.3.2 Air Temperature

Most of the methods were relatively sensitive to air temperature (Table 2). The Papadakis method was the most sensitive one to this parameter, followed by deBruin and Ryan-Harleman methods. Changes in evaporation rates induced by a 10 % change in air temperature were about 21, 19 and 17 % for these methods, respectively. Papadakis method relies heavily on air temperature. This method depends on vapor pressure using minimum and maximum air temperatures. Since 10 % variation was applied to both minimum and maximum air temperatures, it showed relatively large sensitivity to air temperature. In addition, air temperature appears directly in equations (Ryan-

Harleman), or it is used for calculating the slope of the saturated vapor pressure or applied for estimating the saturation deficit (deBruin); thus, the sensitivity of these methods to temperature was also relatively large. Hamon (Eqs. 17 and 18) showed the least sensitivity to air temperature since 10 % change in air temperature resulted in 0.7 % change of evaporation estimation.

3.3.3 Wind Speed

Uncertainties on wind speed data effect evaporation rate, which was determined by Dalton group (mass transfer and Ryan-Harleman) and also combination methods (deBruin, Brutsaert-Stricker). As shown in Table 2, errors of 10 % in wind speed resulted in changes of about 10 % in evaporation rate by Dalton methods and it changed evaporation rate estimated by deBruin method by 7 %. Penman method showed the least sensitivity to wind speed when 10 % error resulted in 0.03 % change of evaporation estimation.

3.3.4 Water Surface Temperature

Another input parameter in some methods is water surface temperature. This parameter appears in BREB for calculating Bowen ratio, saturation vapor pressure at the water surface temperature (such as Dalton methods) and long-wave radiation (such as combination methods). The BREB and all three forms of mass transfer methods were the most sensitive to water surface temperature by resulting in variation of 19.75 % and 18.05 % of evaporation rate, respectively. The Ryan-Harleman method had the least sensitivity to water surface temperature.

Table 2 Range of variation (%) in evaporation estimates resulting from 10 % error in the input parameters

Methods		Solar radiation	Air temperature	Water surface temperature	Wind speed	Cumulated error
Energy balance	BREB, Eq (1)	8.86	1.88	19.75	–	30.49
Combination group	Penman, Eq. (3)	8.82	12.07	7.76	0.03	28.68
	Priestley-Taylor, Eq. (4)	8.86	12.04	7.79	–	28.69
	deBruin-Keijman, Eq. (5)	8.86	12.03	7.79	–	28.68
	Brutsaert-Stricker, Eq. (6)	11.54	9.67	10.15	2.43	33.79
	deBruin, Eq. (7)	–	19.87	–	7.34	27.21
Solar radiation-temperature group	Makkink, Eq. (8)	6.30	–	–	–	6.30
	Jensen-Haise, Eq. (9)	6.28	8.74	–	–	15.02
	Stephens-Stewart, Eq. (10)	6.28	8.14	–	–	14.42
Dalton group	Mass transfer 1, Eq. (11)	–	–	18.05	10	28.05
	Mass transfer 2, Eq. (12)	–	–	18.05	10	28.05
	Mass transfer 3, Eq. (13)	–	–	18.05	10	28.05
	Ryan-Harleman, Eq. (14)	–	17.43	2.04	10.05	29.52
Temperature-day length group	Blaney-Criddle, Eq. (15)	10.00	13.24	–	–	23.24
	Hamon 1, Eq. (16)	21.00	14.26	–	–	35.26
	Hamon 2, Eq. (17)	21.00	0.72	–	–	21.72
	Hamon 3, Eq. (18)	10.00	0.72	13.64	–	24.36
Temperature group	Papadakis, Eq. (19)	–	21.91	–	–	21.91

3.4 Performance of the Methods

The sensitivity analysis of the studied evaporation methods for some input parameters, presented in Table 2, indicated that Hamon method (Eq. 16) was the most sensitive method to the input parameters followed by Brutsaert-Stricker and BREB, and radiation-temperature methods (Makkink, Jensen-Haise and Stephen-Stewart) had the least sensitivity to input data. Additionally, air temperature, solar radiation (sunshine data), water surface temperature and wind speed data had the most pronounced effect on lake evaporation estimations, respectively. As mentioned earlier, finding a reasonably accurate estimation method which also requires fewer input parameters would be ideal, especially where measured data are not readily available. A discussion on the accuracy of the conventional evaporation methods follows.

3.4.1 Pan Method

Evaporation rate determined by the evaporation pan and BREB is shown in Fig. 7. In this case, the commonly-accepted pan coefficient of 0.7 was used for estimating evaporation rate from the lake. The result indicated that pan evaporation rate in times of cold weather was lower than BREB and it was more than that in warm weather. The evaporation rate from pan has been enhanced when the mean air temperature exceeds from about $25°C$: It should be considered that the pan coefficient may vary with time since it takes account for the lag due to heat storage, whereas the pan is too small for any lag effect (Winter 1981). Hence, it seems that evaporation rate obtained by pan method could be improved by adjusting the pan coefficient or using long time monthly coefficients.

3.4.2 Combination Group

The difference between evaporation rate by BREB and the five combination methods of Penman, Priestly-Taylor, deBruin-Keijman, Brutsaert and Stricker and deBruin at monthly scale is exhibited in Fig. 8. Some underestimations during the cold months and overestimations during the warm months were evident. However, the deBruin method underestimated evaporation in all months. Rosenberry et al. (2007) indicated that combination

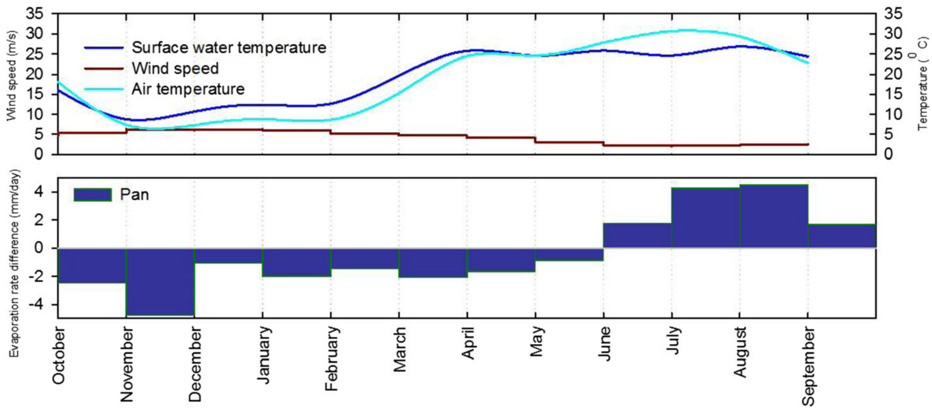


Fig. 7 Differences between pan and BREB-determined evaporation rate, during 2011–2012

methods are susceptible to increase or decrease of wind speed. They also emphasized that the reduced wind speed is partially responsible for the relatively large reduction in the deBruin estimates of evaporation. However, in this group, the deBruin and Penman methods yielded good estimates and the deBruin-Kejman estimations were poor.

3.4.3 Solar Radiation-Temperature Group

Underestimations in evaporation rate also can be seen in most months in the solar radiation-temperature methods group (see Fig. 9). The highest difference in evaporation estimates in this group is considered to be due to the coefficients used in these methods. It emphasizes the impact of air temperature and solar radiation to some extents (Rosenberry et al. 2007). In this

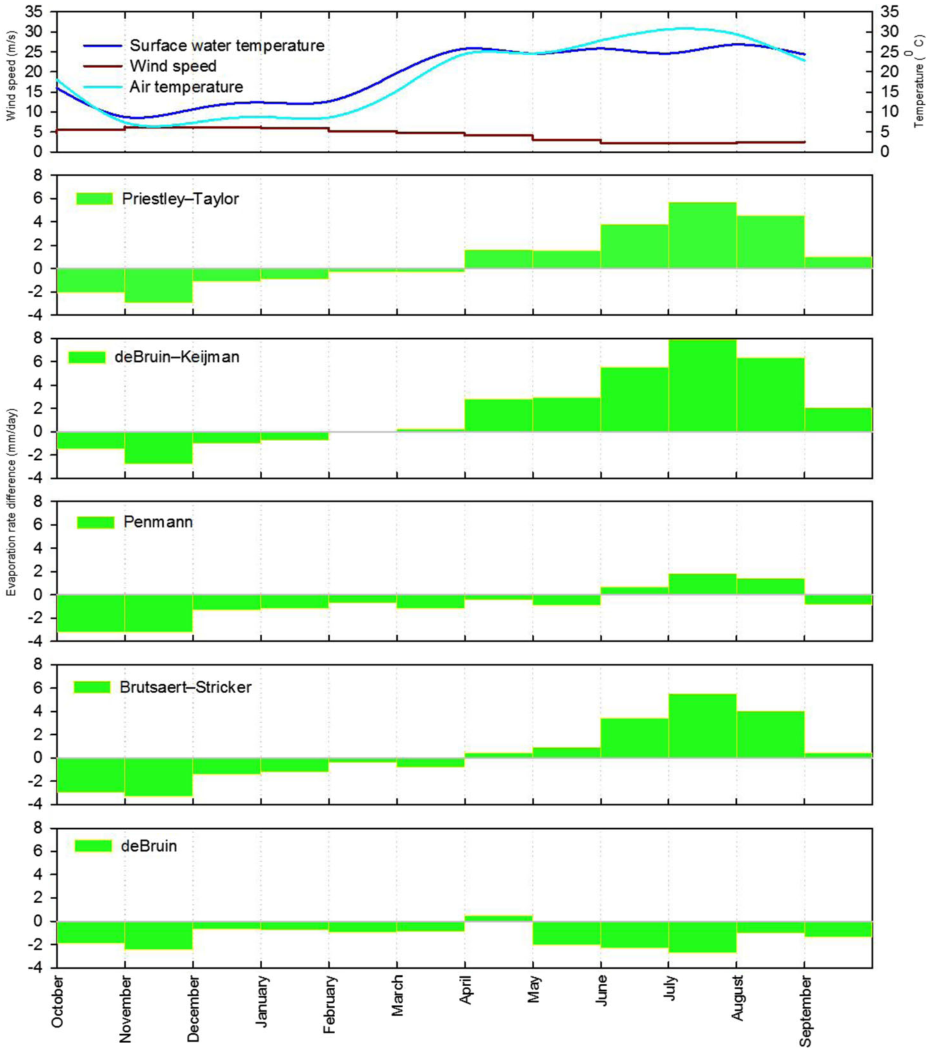


Fig. 8 Differences between combination methods and BREB-determined evaporation rate, during 2011–2012

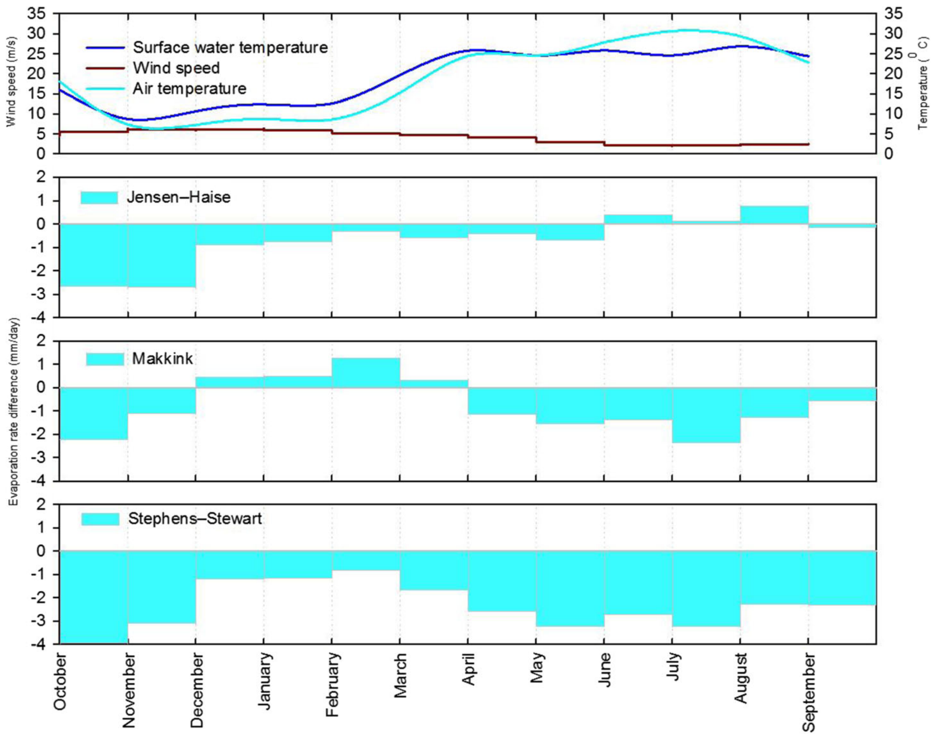


Fig. 9 Differences between Solar radiation-temperature methods and BREB-determined evaporation rate, during 2011–2012

case, despite the lack of heat storage terms in these methods, they interestingly showed a higher accuracy. It seems that the coefficients of the Stephens-Stewart methods need to be improved for this condition. Simplicity and reasonable accuracy of these methods (Jensen-Haise and Makkink) were the most important advantages of applying them in this region.

3.4.4 Dalton Group

Two of the Dalton methods (mass transfer and Ryan-Harleman) were compared here. Since the mass-transfer method requires an empirical coefficient that is site-dependent (Rosenberry et al. 2007), an attempt has been made to adopt some applied coefficients for this method. Different behavior of mass transfer methods is related to these various coefficients. In addition, similar to Rosenberry et al. (2007), another Dalton-type method (Ryan-Harleman) that does not require a site-specific calibration is also compared with BREB estimates. It can be inferred that the highest overestimation of these methods often occurred when temperatures of air and water were close to each other. This occurrence coupled with wind speed reduction led to high overestimations, whereas the evaporation rate declined with decreasing difference between vapor pressure of water surface and air. It seems that in this circumstance, the mass transfer coefficient became more prominent than other parameters.

Based on Fig. 10, we can observe a disparity in estimations of various mass transfer methods due to various coefficients when compared with BREB. However, the coefficient

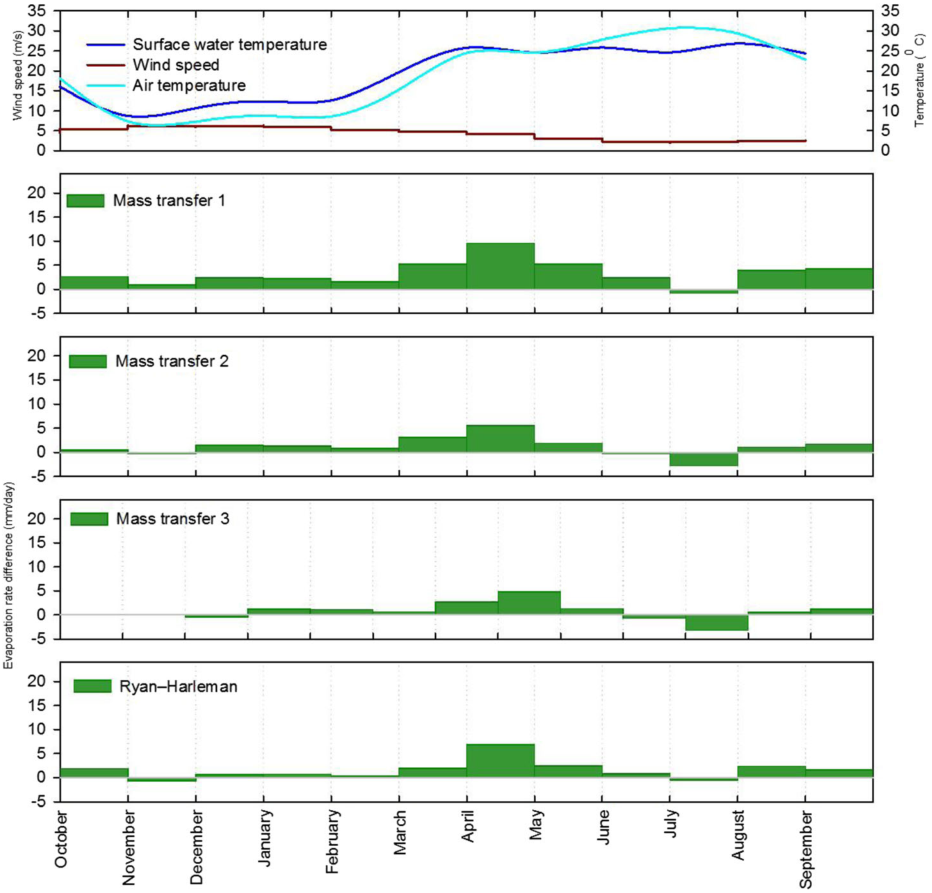


Fig. 10 Differences between Dalton methods and BREB-determined evaporation rate, during 2011–2012

of Eq. (13), named here mass transfer 3, seems to result more favorable. As the results indicated, Dalton methods often overestimated the evaporation rate especially along the spring season, when water level in the lake was higher than other times, and air and water temperatures started to increase. This overestimating cannot be attributed only to coefficient calibration because Ryan-Harleman method gave similar results as well. Thus, calibration of mass transfer coefficient for Doosti dam reservoir seems to be helpful.

3.4.5 Temperature and day Length Group

Both methods that require air temperature and day length (Blaney-Criddle and Hamon), provided underestimated results for most of the months (Fig. 11). The values of evaporation rate increased when air temperature and day length increased. In this group, the form of Hamon method by Eq. (18) (Lu et al. 2005) matched better with BREB values. The results of Papadakis method (temperature group) showed somehow a different behavior. These changes may be interpreted by the changes of the maximum and minimum temperatures. However, despite these fluctuations, this method performed as nearly well as the Hamon method.

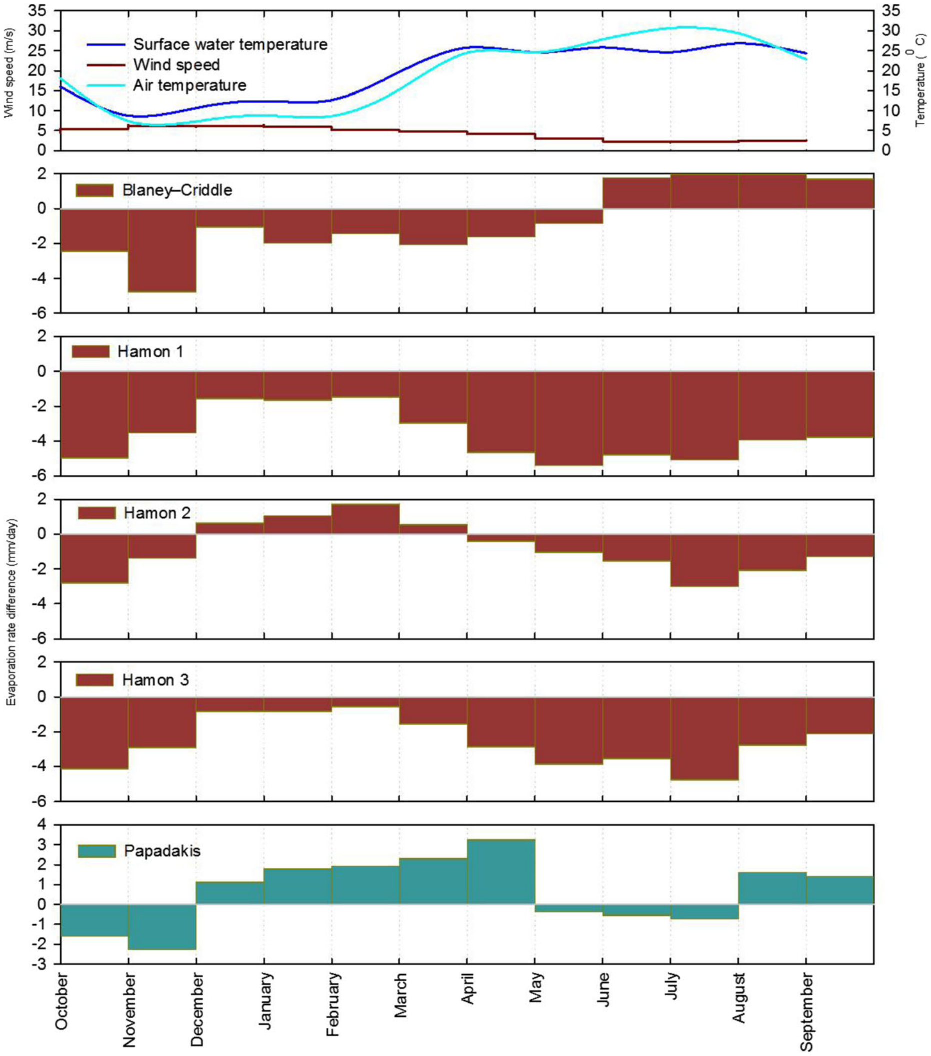


Fig. 11 Differences between temperature and temperature-day length group methods with BREB-determined evaporation rate, during 2011–2012

3.5 Ranking of the Methods

In this study, as mentioned earlier, 18 conventional evaporation estimation methods were selected to compare with the BREB method in order to evaluate their performances. For this reason, we investigated the sensitivity analysis of these methods to input data and also evaluated their accuracy in comparison with BREB. Additionally, an attempt has been made to rank these methods based on their estimation *RMSD* for daily and monthly evaporation values.

All evaporation estimation methods in this study have been ranked as shown in Table 3. Based on the results, some methods for estimating evaporation look promising. On a daily

Table 3 RMSD (mm d^{-1}) and ranking of evaporation equation methods at daily and monthly scales based on BREB method

Methods		Monthly		Daily	
		RMSD	Rank	RMSD	Rank
Combination group	Penman, Eq. (3)	1.65	4	2.00	3
	Priestley-Taylor, Eq. (4)	2.70	13	2.99	10
	deBruin-Keijman, Eq. (5)	3.71	16	3.97	16
	Brutsaert-Stricker, Eq. (6)	2.63	12	2.95	9
	deBruin, Eq. (7)	1.62	3	2.13	5
Solar radiation-temperature group	Makkink, Eq. (8)	1.34	2	1.70	2
	Jensen-Haise, Eq. (9)	1.21	1	1.59	1
	Stephens-Stewart, Eq. (10)	2.53	11	2.74	8
Dalton group	Mass transfer 1, Eq. (11)	4.16	18	5.47	18
	Mass transfer 2, Eq. (12)	2.21	8	3.51	14
	Mass transfer 3, Eq. (13)	1.98	7	3.27	12
	Ryan-Harleman, Eq. (14)	2.42	10	3.54	15
Temperature-day length group	Blaney-Criddle, Eq. (15)	2.21	9	2.46	6
	Hamon 1, Eq. (16)	3.89	17	4.05	17
	Hamon 2, Eq. (17)	1.66	5	2.06	4
	Hamon 3, Eq. (18)	2.89	15	3.14	11
Temperature group	Papadakis, Eq. (19)	1.76	6	2.52	7
Pan	pan	2.71	14	3.43	13

basis, Jensen-Haise and Makkink (solar radiation, temperature group), Penman (Combination group) and Hamon (temperature, day length group) methods had relatively reasonable performance. Jensen-Haise and Makkink used incoming solar radiation as a replacement for the net radiation and heat storage. It probably reduced the uncertainty of these parameters, and therefore, their methods could provide reliable results especially at a daily time scale. There is also such a case in Hamon method since the dependence on the net radiation has been eliminated. Considering their simplicity, the values from the two methods, that require only measurements of air temperature and solar radiation, performed surprisingly well in comparison with the BREB method.

The findings also suggested that several of the other methods have relatively acceptable performance. The deBruin, Blaney-Criddle and Papadakis methods could be considered as appropriate methods. Meanwhile, Stephens-Stewart, Priestley-Taylor, Brutsaert-Stricker, mass transfer, pan and Ryan-Harleman methods showed almost similar accuracy, and they have been ranked as the moderate methods. In this case, the deBruin-Keijman and two forms of Hamon and mass transfer methods had less accuracy.

Nearly similar results were obtained on a monthly basis. The comparison of *RMSD* values for daily and monthly evaporation estimates indicated that all of the adopted methods gave slightly better results in the monthly scale. The better performance of these methods could be attributed to longer time periods since the uncertainty associated with parameters of evaporation equations usually reduces. Additionally, the monthly evaporation estimates were more

Table 4 Review of the conventional methods for estimating evaporation from Doosti dam reservoir in a semi-arid region of Iran

Methods		Required data	Sensitivity	Simplicity	Accuracy
Combination group	Penman, Eq. (3)	$\Delta, R_n, N, \gamma, e_a^*, e, u$	High	Most complex	High
	Priestley-Taylor, Eq. (4)	Δ, R_n, γ, N	High	Complex	Low
	deBruin-Keijman, Eq. (5)	Δ, R_n, γ, N	High	Complex	Low
	Brutsaert-Stricker, Eq. (6)	$\Delta, R_n, N, \gamma, e_a^*, e, u$	High	Most complex	Moderate
	deBruin, Eq. (7)	$\Delta, \gamma, e_a^*, e, u$	High	Complex	High
Solar radiation-temperature group	Makkink, Eq. (8)	Δ, γ, R_s	Low	Simple	High
	Jensen-Haise, Eq. (9)	R_s, T_a	Moderate	Very simple	Highest
	Stephens-Stewart, Eq. (10)	R_s, T_a	Low	Very simple	Moderate
Dalton group	Mass transfer 1, Eq. (11)	$e_s,\ e_a, T_w, T_a, u$	High	Complex	Lowest
	Mass transfer 2, Eq. (12)	$e_s,\ e_a, T_w, T_a, u, A_s$	High	Complex	Moderate
	Mass transfer 3, Eq. (13)	$e_s,\ e_a, T_w, T_a, u, A_s$	High	Complex	Moderate
	Ryan-Harleman, Eq. (14)	$e_s,\ e_a, T_w, T_a, u, A_s$	High	Complex	Moderate
Temperature-day length group	Blaney-Criddle, Eq. (15)	T_a, D	Moderate	Simple	Moderate
	Hamon 1, Eq. (16)	T_a, D	High	Simple	Low
	Hamon 2, Eq. (17)	T_a, D, e_a^*	Moderate	Simple	High
	Hamon 3, Eq. (18)	$D,\ SVD$	Moderate	Simple	Low
Temperature group	Papadakis, Eq. (19)	$T_{a,max},\ T_{a,min}$	Moderate	Very simple	High
Pan	pan	_	_	Very simple	Low

reliable than daily evaporation values because the adopted methods were validated by biweekly measurements in Doosti dam reservoir. In spite of the similarity, ranking of some methods was changed for the monthly-basis analysis. The most obvious changes were for the Dalton methods which showed better performance compared to the daily values.

Based on the results for the monthly scale, Jensen-Haise and Makkink produced the most accurate evaporation estimates even by the limited measurements of the input data. It is worthwhile to note that these two methods, in spite of their simplicity, provided more reliable evaporation estimates than several more complex methods; thus, providing very cost-effective methods.

Moreover, combination group (deBruin and Penman) and temperature based methods (Hamon and Papadakis) produced accurate results in monthly basis. The deBruin-Keijman and two forms of Hamon and mass transfer methods had less accuracy.

4 Summary and Conclusions

This study was carried out aimed at estimating evaporation from Doosti dam reservoir, and comparison and evaluation of various conventional methods to find the most accurate method(s) for limited data condition. Complete review of 19 evaporation methods were performed in several categories. At first, the influence of input variables on evaporation estimates for each method has been analyzed. The results indicated that Hamoon (Eq. 16), Brutsaert-Stricker and BREB methods were the most sensitive methods to input data and radiation-temperature methods showed the least sensitivity to their input data. In addition, air temperature and solar radiation data had the greatest influence on evaporation estimates. In the next step, the adopted methods were evaluated in comparison with Bowen ration energy balance as the standard method in monthly basis. These examinations recognized Jensen-Haise, Makkink, Hamon (Eq. 17), Penman and deBruin methods as the most consistent methods with the monthly rate of BREB evaporation estimates. After all, 18 conventional evaporation estimation methods were ranked in terms of their accuracy compared to the BREB method (Table 4). The results showed that radiation-temperature methods (Jensen-Haise and Makkink) have appropriate accuracy especially in the monthly basis. Also deBruin, Penman (combination group), Hamon and Papadakis (temperature group) methods produced relatively accurate results. The results revealed that it is necessary to calibrate and adjust some evaporation estimation methods for Doosti dam reservoir.

According to the required input data, sensitivity and accuracy of these methods, it can be concluded that Jensen-Haise and Makkink were the most appropriate methods for estimating the lake evaporation in this region especially when measured data were not available.

Acknowledgments The authors gratefully acknowledge the support from the Khorasan Razavi Regional Water Authority. Also the authors would like to thank the anonymous reviewers for their precious and insightful comments and suggestions that greatly improved the quality of this manuscript.

References

Abtew W (2001) Evaporation estimation for Lake Okeechobee in South Florida. J Irrig Drain Eng 127:140–147

Anderson ER (1954) Energy-budget studies. In: water loss investigations: Lake Hefner studies. U.S. Geological Survey Professional Paper 269, 71–119

Assouline S, Mahrer Y (1993) Evaporation from Lake Kinneret: 1 Eddy correlation system measurements and energy budget estimates. Water Resour Res 29:901–910

Blaney HF (1959) Monthly consumptive use requirements for irrigated crops. J Irrig Drain Div Amer Soc Civil Eng 85(IR1):1–12

Blaney HF, Criddle WD (1950) Determining water requirements in irrigated areas from climatological irrigation data. Technical Paper No. 96, US Department of Agriculture, Soil Conservation Service, Washington, D.C., 48 pp

Bowen IS (1926) The ratio of heat losses by conduction and by evaporation from any water surface. Phys Rev 27:779–787

Brutsaert W, Stricker H (1979) An advection-aridity approach to estimate actual regional evapotranspiration. Water Resour Res 15(2):443–450

Brutsaert W, Yu SL (1968) Mass transfer aspects of pan evaporation. J Appl Meteorol 7:563–566

Cogley JG (1979) The albedo of water as a function of latitude. Mon Weather Rev 107:775–781

Dalton J (1802) Experimental essays on the constitution of mixed gases; on the force of steam or vapor from water and other liquids in different temperatures, both in a Torricellian vacuum and in air; on evaporation and on the expansion ofgases by heat. Mem Manchester Lit Philos Soc 5–11:535–602

de Bruin HAR (1978) A simple model for shallow lake evaporation. J Appl Meteorol 17:1132–1134

de Bruin HAR, Keijman JQ (1979) The Priestley-Taylor evaporation model applied to a large shallow lake in the Netherlands. J Appl Meteorol 18:898–903

de Bruin HAR, Stricker JNM (2000) Evaporation of grass under non-restricted soil moisture conditions. Hydrol Sci J 45:391–406

Delclaux F, Coudrain A, Condom T (2007) Evaporation estimation on Lake Titicaca: a synthesis review and modelling. Hydrol Process 21:1664–1677

dos Reis RJ, Dias NL (1998) Multi-season lake evaporation: energy-budget estimates and CRLE model assessment with limited meteorological observations. J Hydrol 208:135–147

Finch J, Calver A (2008) Methods for the quantification of evaporation from lakes. Prepared for the World Meteorological Organization's Commission for Hydrology. CEH Wallingford, Oxfordshire

Gallego-Elvira B, Martínez-Alvarez V, Pittaway P, Brink G, Martín-Gorriz B (2013) Impact of micrometeorological conditions on the efficiency of artificial monolayers in reducing evaporation. Water Resour Manag 27:2251–2266

Gianniou SK, Antonopoulos VZ (2007) Evaporation and energy budget in lake Vegoritis, Greece. J Hydrol 345: 3–4, 212–223

Gokbulak F, Ozhan S (2006) Water loss through evaporation from water surfaces of lakes and reservoirs in Turkey. E-Water 1–6

Hamon WR (1961) Estimating potential evapotranspiration. Hyraul Div Am Soc Civ Eng 87:107–120

Hamon WR (1963) Computation of direct runoff amounts from storm rainfall. Int Assoc Sci Hydrol Publ 63:52–62

Harbeck GE (1962) A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. USGS Professional Paper 272-E, 101-105. US Geological Survey

Irmak S, Haman D, Jones W (2002) Evaluation of class A pan coefficients for estimating reference evapotranspiration in humid location. J Irrig Drain Eng 128(3):153–159

Jensen ME, Haise HR (1963) Estimating evapotranspiration from solar radiation. J Irrig Drain Div ASCE 89:15–41

Kim S, Shiri J, Kisi O, Singh VP (2013) Estimating daily pan evaporation using different data-driven methods and lag-time patterns. Water Resour Manag 27(7):2267–2286

Lenters JD, Kratz TK, Bowser CJ (2005) Effects of climate variability on lake evaporation: results from a long-term energy budget study of Sparkling Lake, northern Wisconsin (USA). J Hydrol 308:168–195

Linacre ET (1993) Data-sparse estimation of lake evaporation, using a simplified Penman equation. Agric Forest Meteorol 64:237–256

Lu J, Sun G, McNulty S, Devendra MA (2005) A comparison of six potential evaportranspiration methods for regional use in the southeastern United States. J Am Water Resour Assoc 41:621–633

Keskin ME, Terzi O (2006) Evaporation estimation models for Lake Egirdir, Turkey. Hydrol Process 20:2381–2391

Kisi O, Cengiz TM (2013) Fuzzy genetic approach for estimating reference evapotranspiration of Turkey: Mediterranean Region. Water Resour Manag 27:3541–3553

Makkink GF (1957) Ekzameno de la formulo de Penman. Netherlands. J Agric Sci 5:290–305

McJannet DL, Webster IT, Cook FJ (2012) An area-dependent wind function for estimating open water evaporation using landbased meteorological data. Environ Model Softw 31:76–83

Maestre-Valero JF, Martínez-Granados D, Martínez-Alvarez V, Calatrava J (2013) Socio-economic impact of evaporation losses from reservoirs under past, current and future water availability scenarios in the semi-arid Segura Basin. Water Resour Manag 27:1411–1426

Majidi M, Alizadeh A, Farid A, Vazifedoust M. (2015) Analysis of the effect of missing weather data in estimating daily reference evapotranspiration under different climatic conditions. Water Resour Manage, 29: 2107–2124

Martinez-Granados D, Francisco Maestre-Valero J, Calatrava J, Martinez-Alvarez V (2011) The economic impact of water evaporation losses from water reservoirs in the Segura Basin, SE Spain. Water Resour Manag 25(13):3153–3175

Mironov D, Kirillin G, Heise E, Golosov S, Terzhevik A, Zverev I. 2003. Parameterization of lakes in numerical models for environmental applications. Proc. of the 7th Workshop on Physical Processes in Natural Waters, A. Yu. Terzhevik, Ed., Northern Water Problems Institute, Russian Academy of Sciences, Petrozavodsk, Karelia, Russia, 135−143

Mosner MS, Aulenbach BT (2003) Comparison of methods used to estimate lake evaporation for a water budget of Lake Semnole, southwestern Georgia and northwestern Florida. Proceedings of the 2003 Georgia Water Resources Conference, Athens, Georgia, USA

Mugabe FT, Hodnett MG, Senzanje A (2003) Opportunities for increasing productive water use from dam water: a case study from semi-arid zimbabwe. Agr Water Manage 62:149–163

Papadakis J (1961) Climatic tables for the world. Buenos Aires, (Original not seen, cited in Grassi, 1964)

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc 193:120–145

Penman HL (1963) Vegetation and hydrology. Tech. Comm. No. 53. Commonwealth Bureau of Soils, Harpenden,
125 pp

Priestley CHB, Taylor RJ (1972) On the assessment of the surface heat flux and evaporation using large-scale parameters. Mon Weather Rev 100:81–92

Rasmussen AH, Hondzo M, Stefan HG (1995) A test of several evaporation equations for water temperature simulations in lakes. Water Resour Bull 31:1023–1028

Rosenberry DO, Winter TC, Buso DC, Likens GE (2007) Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA. J Hydrol 340:149–166

Ryan PJ, Harleman DRF (1973) An analytical and experimental study of transient cooling pond behavior, R. M. Parsons Laboratory, Technical Report No. 161, MIT

Sabziparvar AA, Tabari H, Aeini A, Ghafouri M (2010) Evaluation of class A pan coefficient models for estimation of reference crop evapotranspiration in cold semi-arid and warm arid climates. Water Resour Manag 24(5):909–920

Sadek MF, Shahin MM, Stigter CL (1997) Evaporation from the reservoir of the High Aswan Dam, Egypt: a new comparison of relevant methods with limited data. Theor Appl Climatol 56:57–66

Schertzer WM, Taylor B (2008) Report to the Okanagan water supply and demand study on Lake evaporation: assessment of the capability to compute Lake evaporation from Lake Okanagan and its Mainstem Lakes using the existing database (Draft Report). Prepared for the Okanagan basin Water Board

Shakir A, Narayan CG, Ranvir S (2008) Evaluating best evaporation estimate model for water surface evaporation in semi-arid region, India. Hydrol Process 22:1093–1106

Shuttleworth WJ (1993) Evaporation. In: Maidment DR (ed) Handbook of hydrology. McGraw-Hill, New York, pp 4.1–4.53

Singh VP, Xu CY (1997) Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation. Hydrol Process 11:311–323

Stephen BKT, Eng BS, Lloyd HCC (2007) Modelling hourly and daily open-water evaporation rates in areas with an equatorial climate. Hydrol Process 21:486–499

Stephens JC, Stewart EH (1963) A comparison of procedures for computing evaporation and evapotranspiration. Publication 62, International association of scientific hydrology. International Union of Geodynamics and Geophysics, Berkeley, pp 123–133

Stets EG, Striegl RG, Aiken GR, Rosenberry DO, Winter TC (2009) Hydrologic support of carbon dioxide flux revealed by wholelake carbon budgets. J Geophys Res 114, G01008

Stewart RB, Rouse WR (1976) A simple method for determining the evaporation from shallow lakes and ponds. Water Resour Res 12:623–628

Stewart RB, Ruose WR (1977) Substantiation of the priestley-taylor parameter alpha=1.26 for potential evaporation in high latitudes. J Appl Meteorol 16:649–650

Sturrock AM, Winter TC, Rosenberry DO (1992) Energy budget evaporation from Williams Lake—a closed lake in North Central Minnesota. Water Resour Res 28:1605–1617

Vallet-Coulomb C, Legesse D, Gasse F, Travi Y, Chernet T (2001) Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). J Hydrol 245:1−18

Winter TC (1981) Uncertainties in estimating the water balance of lakes. Water Resour Bulletin 17:82–115

Winter TC, Buso DC, Rosenberry DO, Likens GE, Sturrock AMJ, Mau DP (2003) Evaporation determined by the energy budget method for Mirror Lake, New Hampshire. Limnol Oceanogr 48(3):995–1009

Winter TC, Rosenberry DO, Sturrock AM (1995) Evaluation of 11 equations for determining evaporation for a small lake in the north central United States. Water Resour Res 31:983–993

Xu C-Y, Singh VP (2000) Evaluation and generalization of radiation-based methods for calculating evaporation. Hydrol Process 14:339–349

Yao H, Creed IF (2005) Determining spatially-distributed annual water balances for ungauged locations on Shikoku Island, Japan: a comparison of two interpolators. Hydrol Sci J 50:245–263