# Development and application of a new lake evaporation estimation approach based on energy balance

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

## ABSTRACT

An attempt has been made to estimate evaporation from a water body by developing a new approach based on the energy balance model. For this purpose, a new energy balance method for two surfaces was established: water (evaporating surface) and dry bare soil (non-evaporating surface as reference). An identical aerodynamic resistance ratio was assumed for both surfaces due to their similar conditions. With this assumption, a new form of energy balance was obtained which only depends on net radiation and temperature. The derived reference and water surface energy balance (RWEB) method was applied to estimate evaporation from Doosti dam reservoir in Iran. In order to evaluate the performance of the RWEB, comparison was performed with Bowen ratio energy balance (BREB) method as well as some conventional methods. According to the evaluations, the evaporation results of RWEB from 2011 to 2012 were satisfactory with RMSD value of 1.026 mm month$^{-1}$ and $R^2 = 0.937$. Furthermore, the RWEB sensitivity analysis showed the highest sensitivity to air temperature and the lower sensitivity to net radiation. Thus, evaporation from a water body can be estimated accurately by precise measurements of air temperature and relatively reasonable estimations of other parameters (reference, water temperature and net radiation).

**Key words** | energy balance, evaporation, reference surface, water body

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## INTRODUCTION

Estimation of lake evaporation is complicated; therefore, it is common to measure evaporation from a small water pan which is located close to the lake. In this way, the lake evaporation is considered to be the pan evaporation times a so-called 'pan coefficient' (Sabziparvar *et al.* 2010; Kim *et al.* 2013). Nevertheless, due to difference in the environment between the pan and the lake, in many cases, a simple linear relationship cannot be physically justified. Therefore, the pan method may cause significant errors. Due to the complications of formulating the lake evaporation rate, it has been a major challenge for many years (Finch & Calver 2008; McMahon *et al.* 2013).

The pioneering work of Bowen (1926) has undoubtedly been helpful in understanding the physics of evaporation by showing how available energy partitioning between latent heat and sensible heat can be determined from temperature gradients and humidity. Years later, Penman (1948) introduced his broadly used theory for estimating evaporation from open water, bare soil and grass by mixing the energy balance concept with aerodynamic aspects of evaporation.

Thereafter, a wide variety of methods was developed for evaporation estimation. These methods either are empirical findings or are mainly based on energy balance equation and mass transfer model of Dalton (1802) (Rosenberry *et al.* 2007; Finch & Calver 2008; Gallego-Elvira *et al.* 2010).

Depending on accuracy and simplicity of application, each of these methods has pros and cons. Several of these methods are comprehensively reviewed and adopted by Xu & Singh (2000, 2001, 2002), Lenters *et al.*

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(2005), Binyamin *et al.* (2006), Xu *et al.* (2006), Rosenberry *et al.* (2007), McJannet *et al.* (2012), Ngongondo *et al.* (2013), Majidi *et al.* (2015a, 2015b), Koedyk & Kingston (2016), and Almorox & Grieser (2016). In this paper, we developed and applied a new approach for estimating lake evaporation from Doosti dam reservoir, located in an arid region of Iran. Our main goal, adding this method to the long list of existing methods, is to develop a simple and at the same time reasonably accurate method with readily measurable inputs (temperature and net radiation).

## METHODS

### 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.

The sensible heat flux cannot be easily determined, thus, Bowen (1926) eliminated this term from the energy balance equation using the so-called Bowen ratio, $\beta$, defined as the ratio between the sensible and latent heat fluxes (Finch & Calver 2008). Bowen's solution to the energy balance equation commonly known as the 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 & Dias (1998):

$$E = \frac{R_n - N}{\rho(\lambda(1+\beta) + cT_w)} \tag{1}$$

where $E$ is the evaporation rate (mm $\mathrm{d}^{-1}$), $R_n$ is the net radiation (W $\mathrm{m}^{-2}$), $N$ is the change of energy storage in water (W $\mathrm{m}^{-2}$), $\lambda$ is the latent heat of vaporization, $c$ is the specific heat of water (J $\mathrm{kg}^{-1}$), $T_w$ is the water temperature (°C). The Bowen ratio ($\beta$) is the ratio of sensible to latent heat and is calculated as:

$$\beta = c_B P \frac{T_w - T_a}{e_0 - e_a} \tag{2}$$

where $P$ is atmospheric pressure (kPa), $c_B$ is the specific heat of air at constant pressure ($0.61\ {}^\circ\mathrm{C}^{-1}$), $T_a$ is air temperature, $e_0$ is saturation vapor pressure at 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 have been validated or calibrated (Assouline & Mahrer 1993; Winter *et al.* 2003; Lenters *et al.* 2005; Rosenberry *et al.* 2007; Finch & Calver 2008). To improve the accuracy of the BREB method, the surface and profile water temperatures are required over the water body (Anderson 1954; Sturrock *et al.* 1992; Assouline & Mahrer 1993; Finch & Calver 2008).

### New approach

Our new method introduced here is similarly based on the energy balance equation. We call this method 'Reference and Water Energy Balance' (RWEB). The term 'Reference' stands for assuming dry bare soil beside a lake under the same meteorological conditions which provides a non-evaporating reference surface to solve the sensible heat flux term in the energy balance equation. The dry bare soil reference in this research was made with a $34 \times 22.5 \times 15.5\ \mathrm{cm}^3$ box filled with a sandy loam soils. The box's walls were isolated to minimize the lateral heat exchange and its surface was covered by plastic to prevent wetting. It is worth mentioning here that, as discussed later, the soil reference may be replaced with a hypothetical surface with the same characteristics, leading to simplified future application of this method.

The energy balance equation for a water body (lake or reservoir) can be expressed as:

$$R_{nw} = G_w + H_w + \lambda E + N \tag{3}$$

where $R_{nw}$ is the receiving net radiation at water surface, $H_w$ is the sensible heat flux, $G_w$ is the heat conduction occurring between the water and its substrate. Other parameters are as described above.

In Equation (3), the net radiation term can be estimated by the incoming and outgoing solar radiations, $G_w$ is assumed to be negligible (Sturrock *et al.* 1992; dos Reis & Dias 1998; Winter *et al.* 2003; Rosenberry *et al.* 2007) and

$H_w$ is given by (Brutsaert 1982):

$$H_w = \frac{\rho c_p}{r_a}(T_w - T_a) \tag{4}$$

where $\rho$ is density of air, $c_p$ is the air specific heat at constant pressure, $r_a$ is aerodynamic resistance (s m$^{-1}$), $T_w$ and $T_a$ are temperatures of water surface and air at a reference height, respectively (°C). The change in the energy storage can be calculated as:

$$N = \frac{\rho_w . c_{pw}}{A_w} \sum_z A_z \Delta z \left(\frac{\Delta T_w}{\Delta t}\right) \tag{5}$$

where $A_w$ and $A_z$ are lake area at depth 0 and $z$, respectively, $\Delta T_w$ is the change in spatially averaged temperature of the water body in time step $\Delta t$ at depth $z$, and $\Delta z$ is layer thickness. The coefficient $\lambda$ depends on water temperature and can be calculated by:

$$\lambda = 2.5 - 0.0024 T_w \tag{6}$$

The energy balance for a dry non-evaporating bare soil can be written as:

$$R_{ns} = G_s + H_s \tag{7}$$

where $R_{ns}$ is the net radiation of the dry bare soil, $G_s$ is the heat flux to the soil, $H_s$ is the sensible heat flux from dry bare soil to air. The heat flux to the soil ($G_s$) is negligible (Allen *et al.* 1998). The sensible heat flux is calculated as:

$$R_{ns} - G_s = H_s = \frac{\rho c_p}{r_a}(T_s - T_a) \tag{8}$$

Considering that the aerodynamic resistance is mainly affected by wind speed rather than surface properties (e.g. Liu *et al.* 2006), and that the wind speed is almost the same over the lake and the adjacent bare soil, it can be assumed that the aerodynamic resistance is nearly the same for the two surfaces. Note that a similar assumption is commonly made for modeling evaporation from a drying soil surface based on the reference dry soil properties (for example, Ben-Asher *et al.* 1983 and Qiu *et al.* 1998). Based on this assumption and by combination of Equations (3), (7), (6) and (8), evaporation can be obtained as follows:

$$E = \lambda^{-1}[R_{nw} - \tau(R_{ns} - G_s) - N] \tag{9}$$

where $\tau$ represents $(T_w - T_a)/(T_s - T_a)$.

Equation (9) formulates the lake evaporation as a function of readily obtainable variables of net radiation and temperature. The net radiation (for lake and soil surface) can be measured directly or calculated from short wave and long wave radiation components. The temperatures of air, water body and soil surface can be measured readily. Note that for the daily calculations; $G_s$ is neglected as discussed earlier, thus, removed from Equation (9).

In fact, this method can be considered as a solution to the energy balance equation in a different manner from the Bowen method since it adopts a dimensionless temperature of $\tau$ instead of the dimensionless Bowen ratio, $\beta$, to solve the sensible heat term.

## Conventional methods

In order to evaluate the accuracy of the proposed method, we compared its results with those of BREB (as the reference method). Some conventional methods for estimating the open water evaporation, briefly described in this part, were also analyzed.

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

$$E = \frac{\Delta R_n}{\lambda(\Delta + \gamma)} + \frac{\gamma f(u)(e_a^* - e)}{\Delta + \gamma} \tag{10}$$

where $\Delta$ is the slope of the saturated vapor pressure–temperature curve, $\gamma$ is the psychometric coefficient, $e_a^*$ is the saturated vapor pressure at air temperature, $e$ is the vapor pressure and relative humidity of the air and $f(u)$ is the wind speed function as the following empirical linear approximation (Penman 1948):

$$f(u) = 0.0026(1 + 0.54u) \tag{11}$$

in which, $u$ is the wind speed at 2 m elevation. The success of Penman's equation when applied in many different locations is attributed to its physical basis (Linacre 1993).

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

$$E = 0.03523 R_s \left(0.014 T_a - 0.37\right) \tag{12}$$

where $R_s$ is the incoming solar radiation (W m$^{-2}$).

The equation of Papadakis (1961) does not count the heat flux that occurs in the lake body to determine evaporation (Winter *et al.* 1995). Instead, the equation depends on the difference in the saturated vapor pressure above the water body at maximum and minimum air temperatures, and evaporation is defined by the following equation:

$$E = 0.5625\left[e^{*}_{a,\max} \times 10^{-2} - \left(e^{*}_{a,\min} \times 10^{-2} - 2\right)\right] \tag{13}$$

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

### Evaluations

We evaluated the methods introduced above for estimating evaporation from the Doosti dam reservoir in comparison with the BREB method. The methods can be specifically listed as the new proposed method and the methods of pan, Penman, Jensen-Haise, and Papadakis.

We adopted the root mean square difference (RMSD) and Nash Sutcliffe Efficiency (NS) for evaluating these methods. The RMSD is calculated as follows:

$$RMSD = \left[\frac{1}{M}\sum_{i=1}^{M}\left(E_{BREB,i} - E_{eq,i}\right)^2\right]^{0.5} \tag{14}$$

where $E_{BREB}$ and $E_{eq}$ are the estimated evaporation value using BREB method and any of the studied methods, respectively, and $M$ is the total number of observations.

The NS is defined as:

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(X_{oi} - X_{si}\right)^2}{\sum_{i=1}^{n}\left(X_{oi} - \bar{X}\right)^2}$$

where $\bar{X}$ is the average measured value during the simulation period; $X_{oi}$ is the observed average daily output over month $i$; $X_{si}$ is the simulated average daily output over month $i$, and $n$ is total number of months in the simulation (Nash & Sutcliffe 1970).

## STUDY AREA AND DATA

Our study site was the Doosti dam reservoir located between Iran and Turkmenistan borders (35°56′55″ N 61°09′48″ E) 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. Doosti dam is one of the most important freshwater storage facilities. Since the selected dam is located in an arid region of Iran, the evaporation losses are a major challenge of this dam. The Doosti dam has a height of 78 m above the foundation, reservoir capacity of 1,250 million cubic meters, 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 m and 15 m, respectively. This dam supplies both countries' irrigation and municipal water demands. Climate of this region is arid with average annual mean temperature of 17.9 °C, annual mean precipitation of 187.37 mm, and annual mean relative humidity of 47.7%.

Daily meteorological data including maximum and minimum air temperature, relative humidity, wind speed, dew temperature, sunshine data, atmospheric pressure, precipitation, and evaporation from class A pan were acquired from Sarakhs (with pan coefficient about 0.7), Pol-Khatoon and Doosti dam weather stations (Figure 1). Lake area was estimated from hypsometric curve in relation with lake level data.

Temperature measurements in the lake were performed at various depths in 16-day periods from September 2011 to September 2012. Temperature profile of the lake required for lake evaporation estimation (through term N) was measured at different points of the reservoir using a portable multimeter. As mentioned earlier, a dry bare soil in a box was considered as a reference surface. Hence, the bare soil box was kept always dry during the measurement period and its temperature was measured regularly by an infrared thermometer.

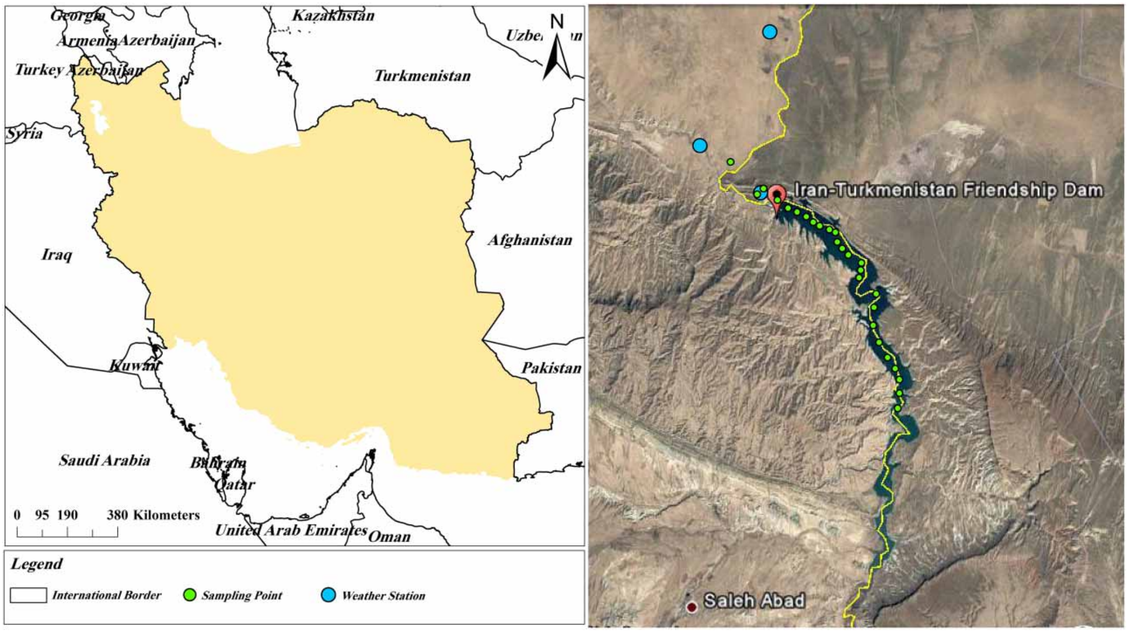

**Figure 1** | Map of Doosti dam reservoir showing approximate locations of the meteorological station and biweekly temperature profiles.

## RESULTS AND DISCUSSION

### Temperature of the water body and dry bare soil

Average of the measured temperature profiles for February, June, August and October (2011–2012) is presented in Figure 2 indicating a nearly uniform profile in February and October and a decreasing profile in June and August. During the early spring, the lake exhibits a nearly uniform temperature distribution with depth. As the year progresses and the weather warms up, the water body receives heat at an increasingly rapid rate. As the rate of heating continues to increase, it begins to exceed the rate of heat transfer to deeper layers with the result that the temperature of the surface layers increases faster than those of the deeper layers.

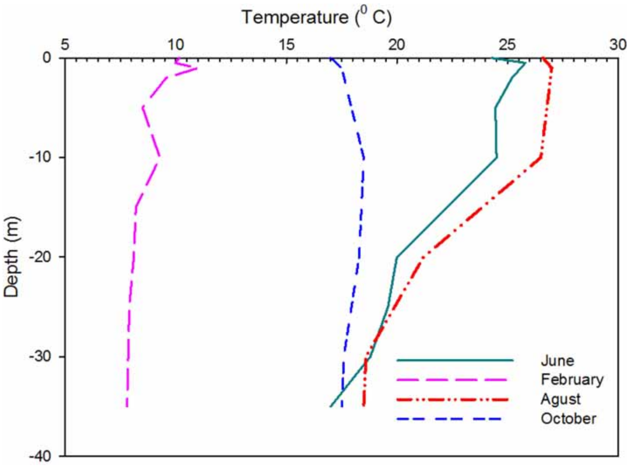

**Figure 2** | Average measured thermal profile data on February, June, August and October, 2011–2012.

All of our temperature data for air, soil, and lake water surface are shown in Figure 3. The water temperatures are lower than air temperatures during the summer and vice versa during the winter. Thus, the evaporation rate of a lake depends not only on meteorological conditions but also on the size, depth and thermal regime of the lake. So we cannot expect a standard pattern rate of evaporation (Mironov *et al.* 2003). In addition as this figure indicates, all measured temperatures have relatively similar variations, thus it seemed that they can be correlated for estimating missing temperature data.

The data, presented in Figure 4, show that dry bare soil surface and mean air temperatures were highly correlated ($R^2 = 0.97$). It means estimating dry bare soil surface temperature (as reference surface) data from mean air temperature,

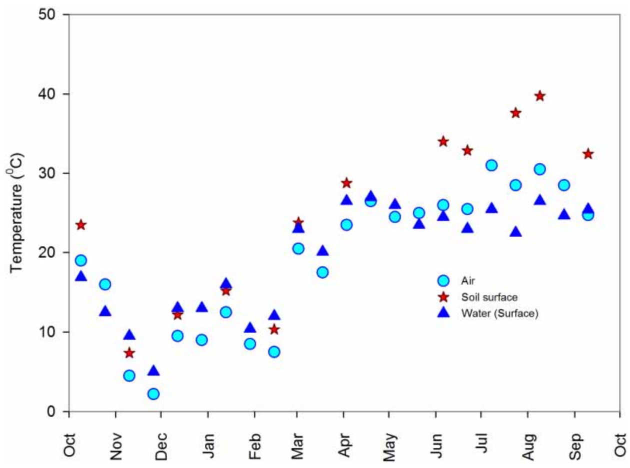

**Figure 3** | Measured water, air and dry bare soil temperatures, during 2011–2012.

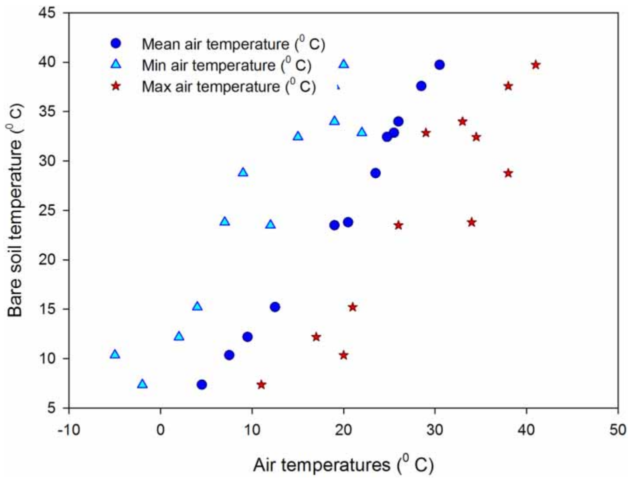

**Figure 4** | Relationship between dry bare soil surface temperature and air temperature data.

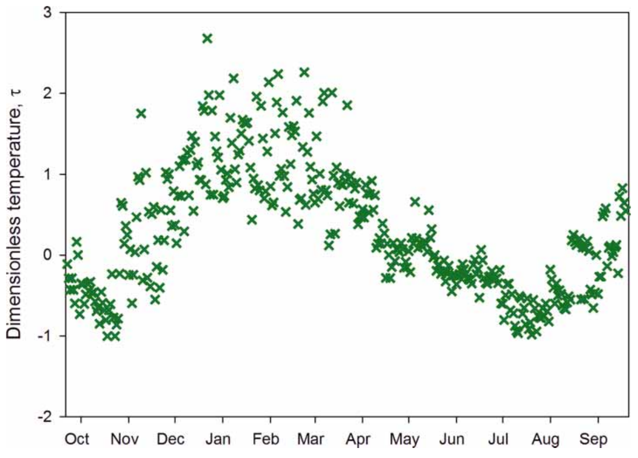

**Figure 5** | Variation of dimensionless temperature parameter $\tau = (T_W - T_a)/(T_S - T_a)$ during 2011–2012.

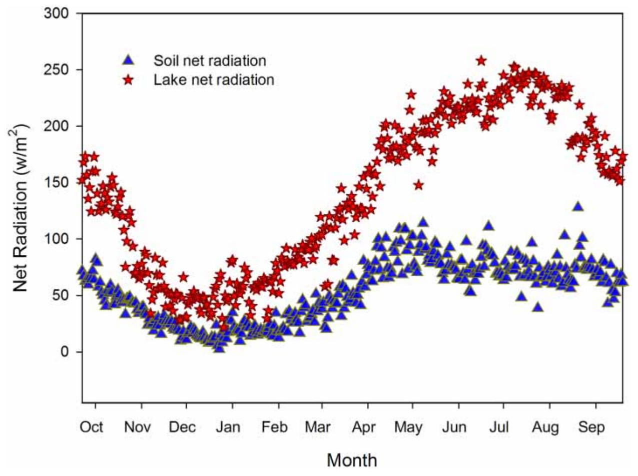

**Figure 6** | Variation of net radiation for dry bare soil and water surface, during 2011–2012.

produce relatively acceptable results. These results indicate that in the absence of a real reference surface, this procedure can be used for applying the proposed method. The possibility of considering a hypothetical reference surface instead of a real one is an advantage of the method, because it could ensure wide applicability of this method. Since the reference surface (dry bare soil) does not evaporate its temperature must be higher than evaporating surfaces.

Using the air, water and soil surface temperatures, the dimensionless parameter of $\tau$ was obtained. This parameter, as shown in Figure 5, has values ranging from $-1$ to 2.7 and as discussed later, plays a major role in estimating evaporation by Equation (9). It can be worthwhile finding a relationship between $\tau$ and easily measurable parameters such the air temperature. This achievement can be an advantage of the proposed method.

## Evaporation estimations

The net radiations of lake and bare soil required for estimating evaporation by the proposed approach, Equation (9), were calculated by conventional algorithms based on short-wave and long-wave radiation data and with the assumption of albedo about 35% and 7% for dry bare soil and water surface, respectively (Cogley 1979). The obtained net radiations are presented in Figure 6. In the proposed method, Equation (9), rate of the net radiation of lake to the soil ($\rho = R_{nw}/R_{nsoil}$) also can be considered as a parameter by slight variation. Figure 7 shows that $\rho$ can range from 1.4 to 7.3 (dimensionless). Apparently, it is possible to obtain simpler forms of the new method, Equation (9), using these two dimensionless parameters, $\tau$ and $\rho$.

The behavior of the new proposed method in relation to its dimensionless parameters is shown in Figure 8. As this figure indicates, the new proposed method is more dependent on dimensionless temperature ($\tau$) than ratio of net radiation ($\rho$). It illustrates the importance of availability of temperature data and suggests that $\rho$ could be replaced by a constant value, perhaps for the entire year.

Obviously, based on Equation (9), an inverse relationship between evaporation rate and dimensionless temperature ($\tau$) was expected, but in fact it can be concluded that the evaporation rate depends on negative or positive values of $\tau$. In this case, the maximum of evaporation rate occurred when $\tau$ reached its minimum value in summer and minimum of evaporation rate occurred at maximum value of $\tau$ in winter. Based on these results, considering conditions of this study, where the reference temperature ($T_s$) is almost always higher than the air temperature ($T_a$) (see Figure 3), the water surface temperature ($T_w$) can be considered as a key factor determining $\tau$ and thus the evaporation rate in Equation (9). Of course, the important role of heat storage is not negligible, and is also affected by temperature of water surface and depth.

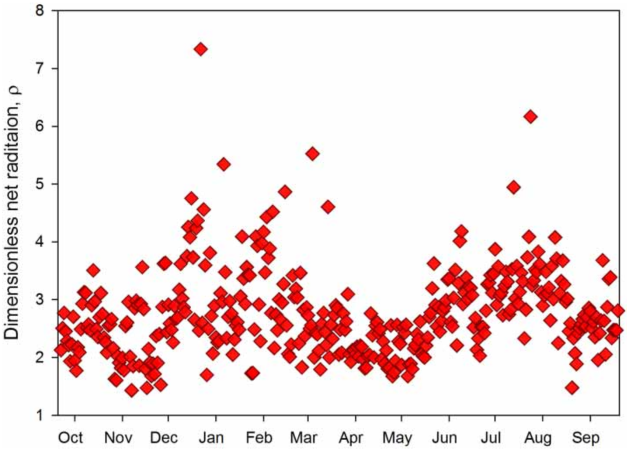

**Figure 7** | Variation of dimensionless net radiation parameter $\rho = R_{nw}/R_{nsoil}$ during 2011–2012.

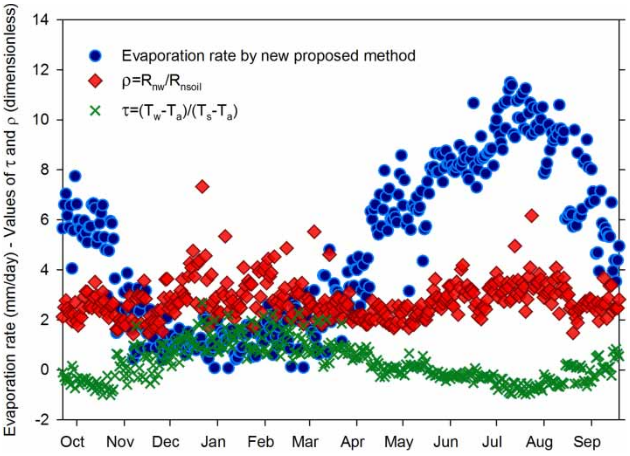

**Figure 8** | Variation of evaporation rate, $\tau$ and $\rho$ during 2011–2012.

The result of monthly evaporation values based on measured parameters by proposed new method (RWEB) in comparison with BREB method are shown in Figure 9. As shown in this figure, the new method is almost consistent with BREB method. However, overestimated and underestimated evaporation values resulting from the new method compared with the BREB method are noticeable slightly in cold and warm seasons, respectively. Nevertheless, it can be concluded that the new method provides reliable results especially compared with the pan method.

An additional review of new proposed method (RWEB) compared with other methods based on BREB is discussed

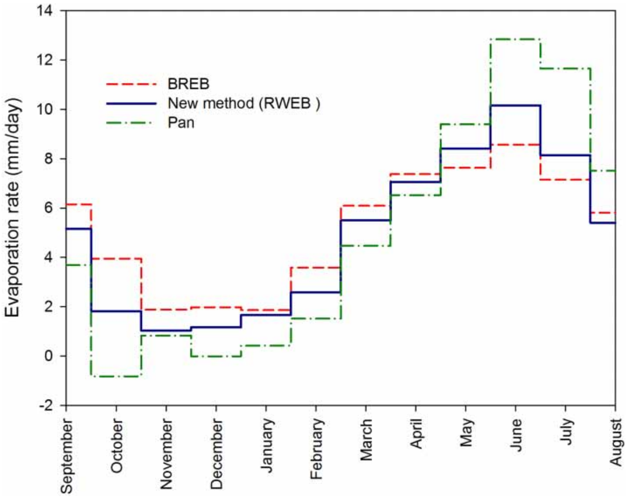

**Figure 9** | Monthly evaporation rate (mm day$^{-1}$) from Doosti dam reservoir determined by new approach, pan and BREB methods, during 2011–2012.

here. As a result, Papadakis and pan methods had the highest overestimation and underestimation, respectively (Figure 10). It seems that Penman method has achieved good results, however, some underestimations were evident during the cold months and overestimations during the warm months. Underestimations in evaporation rate obtained by Jensen-Haise method can be seen in most months. The major difference in evaporation results for this method is considered regarding to the coefficients used in this method that emphasizes to various extents the impact of air temperature and solar radiation (Rosenberry *et al.* 2007). Simplicity and reasonable accuracy of Jensen-Haise method are the most important advantage of applying it in this region. The results of the Papadakis method showed somehow a different behavior. Probably, these changes can be interpreted by changing the maximum and minimum temperatures. However, despite these fluctuations, this method afforded relatively good results.

The estimated annual evaporation from Doosti dam reservoir is given in Table 1. As shown, annual estimated evaporation by all of applied methods in this study, ranged from 62 to 77 mcm year$^{-1}$. Most of the alternate methods for determining evaporation compared well, and as good as the new method with the BREB.

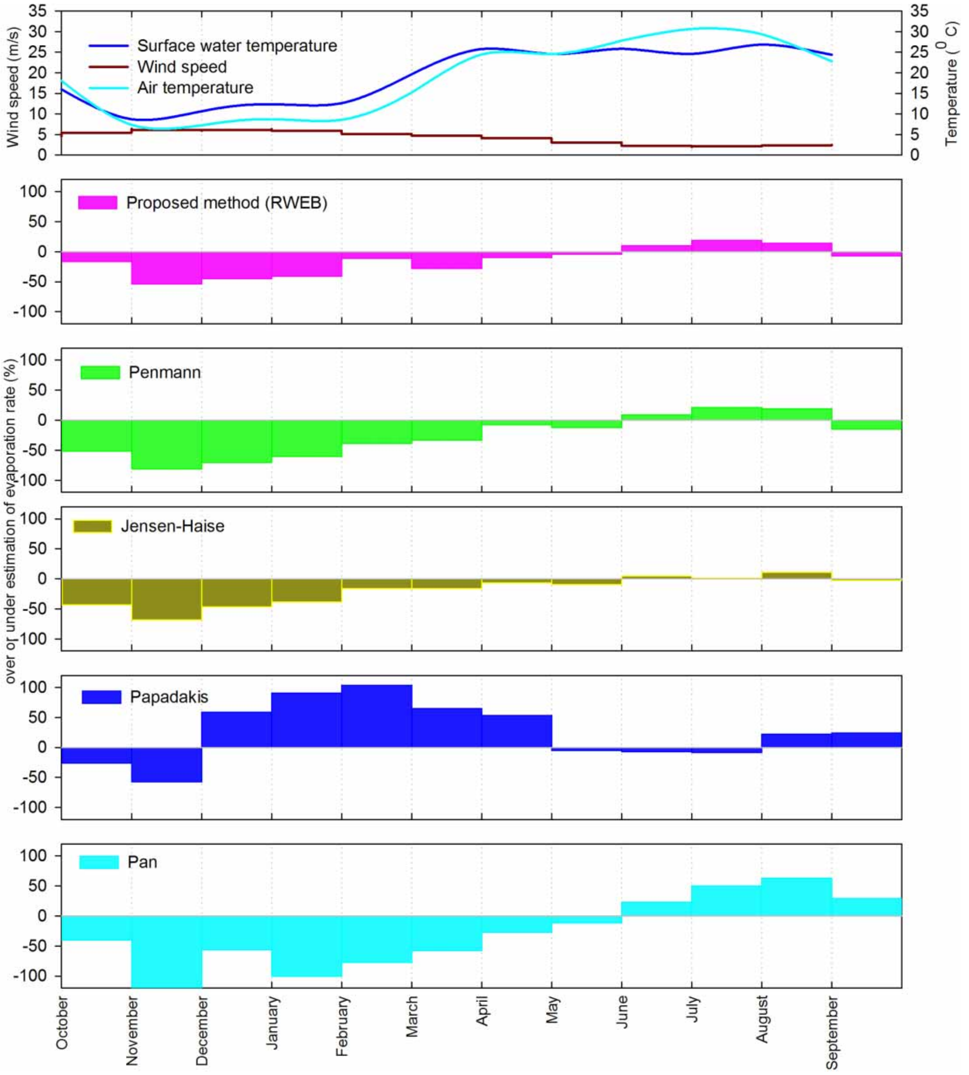

**Figure 10** | Comparison of evaporation rate obtained by different methods with BREB-determined evaporation rate, during 2011–2012.

**Table 1** | Annual evaporation (mcm year$^{-1}$) estimated from Doosti dam reservoir, during 2011–2012

| Evaporation methods | Annual evaporation (mcm year$^{-1}$) |
|---|---|
| Pan | 71.46 |
| BREB | 69.87 |
| New proposed method (RWEB) | 67.57 |
| Penman | 62.76 |
| Jensen-Haise | 62.92 |
| Papadakis | 77.13 |

## Sensitivity analysis

The consistency of the evaporation estimation methods can be discussed through sensitivity analysis to their input variables. Here, we analyze the impact of individual input variables on evaporation estimates of the RWEB method, by varying their value by ±10%.

The results of the RWEB analysis showed that the method has the highest sensitivity to air temperatures and the least sensitivity to soil surface temperature and soil net radiation values (Table 2). According to the sensitivity analysis results, errors of ±10% in the water surface temperatures will result in changes of ±19% in the evaporation rate. Meanwhile, errors of ±10% in the air temperature will result in changes from −16% to +37% in evaporation rate and errors of ±10% in the reference surface temperature will result in changes from −1.39% to +5% in evaporation rate.

As shown in Figure 11, the proposed method shows a strong error resistance to simultaneous changes in the air, water and soil surface temperatures. Based on the results, when all of the temperature variables used in the RWEB method are adjusted by ±10% at the same time, then errors in evaporation are quite small (errors of ±10% will result changes ±0.35% in the evaporation rate).

**Table 2** | Result of sensitivity analysis of RWEB method to input data

| | Change in variables (%) | | | | | |
|---|---|---|---|---|---|---|
| | Radiation | | Temperature | | | Cumulated error |
| | Water | Soil | $T_a$ | $T_w$ | $T_s$ | |
| Changes in evaporation rate (%) in proposed method (RWEB) | 9.83 | 1.24 | 31.06 | 20.51 | 4.63 | 67.27 |

$T_a$ = air temperature; $T_w$ = water surface temperature; $T_s$ = dry bare soil surface temperature.

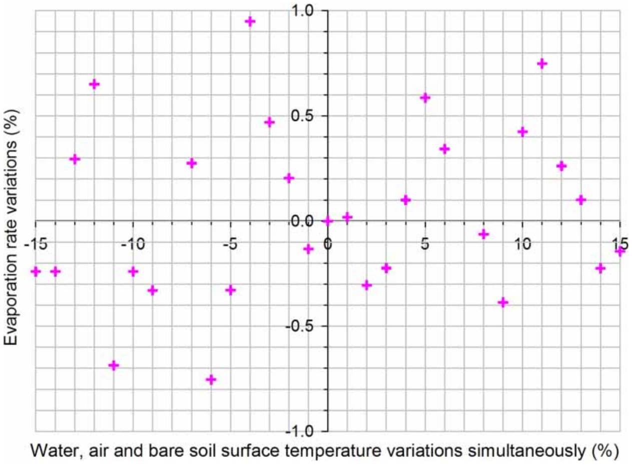

**Figure 11** | Sensitivity of proposed method to simultaneous air, water and reference surface temperature changes, during 2011–2012.

Errors of ±10% in the lake net radiation will result in changes of ±9.8% in evaporation. Finally the lowest sensitivity of the model is subjected to the data of soil net radiation, where errors of ±10% will result in changes of about ±1.2% in evaporation rate estimation.

A promising result about the proposed method is that the soil and lake parameters (soil and water temperatures and net radiations) errors had the lowest effect compared to the air temperature, on accuracy of evaporation estimation. This result promises wide applicability of this method because it encourages the possibility of considering a hypothetical reference surface instead of a real one.

## Ranking of different methods

In this study, as mentioned before, some conventional evaporation estimation methods were compared with the proposed method and their performance was evaluated based on BREB evaporation estimates. Then the evaporation estimation methods were ranked based on RMSD criteria (Table 3).

According to the results, the new method (RWEB) for estimating evaporation looks promising. It is noteworthy

**Table 3** | Ranking evaporation estimation methods based on BREB evaporation values using RMSD criteria, during 2011–2012

| Evaporation methods | RMSD (mm month$^{-1}$) | *Rsqr* | NS | Rank |
|---|---|---|---|---|
| New method (RWEB) | 1.0267 | 0.937 | 0.78 | 1 |
| Jensen-Haise | 1.2104 | 0.882 | 0.75 | 2 |
| Penman | 1.6523 | 0.855 | 0.74 | 3 |
| Papadakis | 1.7584 | 0.569 | 0.43 | 4 |
| Pan | 2.7094 | 0.783 | 0.65 | 5 |

that principle similarity between the BREB and new proposed energy balance methods and using BREB as the base method for ranking may be one of the reasons for the superiority of the new proposed method compared to other methods, though the new method resulted in reasonable evaporation estimations even with limited measured data. However, further studies are needed regarding reduction of the input parameters, the possibility of eliminating the heat storage term by introducing another surface and application of this new method for remote sensing study and applications.

Jensen-Haise and Penman methods also had a relatively reasonable performance. Jensen-Haise method used incoming solar radiation to replace the net radiation and heat storage. In this way the uncertainty of these parameters was reduced and therefore this method could provide reliable results. Considering its simplicity, values from Jensen-Haise method that require measurement only of air temperature and solar radiation compared surprisingly well with the BREB method.

## SUMMARY AND CONCLUSIONS

The aims of this study were to: (a) estimate evaporation from Doosti dam reservoir; (b) develop a new method based on energy balance concept; and (c) compare and evaluate the proposed method. Introducing the concept of reference surface (here dry bare soil), an attempt has been made to provide a simple solution to the energy balance equation called Reference and Water Surface Energy Balance (RWEB) method. This led to an equation to estimate evaporation from water bodies of which the input data are only temperature (air, water and reference surface) and net radiation.

The results showed that the proposed method is reasonably accurate. The physical basis of the RWEB method and its good agreement with the BREB method promises that the proposed method may be considered as a reference method for lake or reservoir evaporation estimation.

The sensitivity analyses showed that RWEB has the highest sensitivity to the air temperature values and less sensitivity to the bare soil (reference surface) net radiation. This result ensures wide applicability of this method due to the possibility of considering a hypothetical reference surface instead of a real one.

The greatest advantages of RWEB method when compared with BREB method could be recognized as: (i) less complicated and fewer input data requirements; (ii) less sensitivity to input data; and (iii) ease of estimation of input data specifically by remote sensing data.

However, future studies are needed regarding reduction of input data, reduction of sensitivity of RWEB method to the input data, and the possibility of eliminating the heat storage term. Since all of the inputs in RWEB method are estimable by satellites or other remote sensors, future studies on this method are recommended for remote sensing applications.

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## CONFLICT OF INTEREST

We declare that we have no conflicts of interest in the authorship or publication of this manuscript.

## REFERENCES

Allen, R. G., Pereira, L. S., Raes, R. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements.* Irrigation and Drainage Paper 56, UN Food and Agriculture Organization, Rome, 300 pp.

Almorox, J. & Grieser, J. 2016 Calibration of the Hargreaves-Samani method for the calculation of reference evapotranspiration in different köppen climate classes. *Hydrology Research* **47**, 521–531. DOI: 10.2166/nh.2015.091.

Anderson, E. R. 1954 Energy-budget studies. In: *Water Loss Investigations: Lake Hefner Studies.* US Geological Survey Professional Paper 269, pp. 71–119.

Assouline, S. & Mahrer, Y. 1993 Evaporation from Lake Kinneret: 1 Eddy correlation system measurements and energy budget estimates. *Water Resources Research* **29**, 901–910.

Ben-Asher, J., Matthias, A. D. & Warrick, A. W. 1983 Assessment of evaporation from bare soil by infrared thermometry. *Soil Science Society of America Journal* **47**, 185–191.

Binyamin, J., Rouse, W. R., Davies, J. A., Oswald, C. J. & Schertzer, W. M. 2006 Surface energy balance calculations for small northern lakes. *International Journal of Climatology* **26**, 2261–2273.

Bowen, I. S. 1926 The ratio of heat losses by conduction and by evaporation from any water surface. *Physical Review* **27**, 779–787.

Brutsaert, W. 1982 *Evaporation into the Atmosphere: Theory, History and Applications.* D. Reidel Publishing Company, Dordrecht, The Netherlands.

Cogley, J. G. 1979 The albedo of water as a function of latitude. *Monthly Weather Review* **107**, 775–781.

Dalton, J. 1802 Experimental essays on the constitution of mixed gases; on the force of steam or vapour from water and other liquids in different temperatures, both in a Torricellian vacuum and in air; on evaporation and on the expansion of gases by heat. *Memoirs of the Manchester Literary and Philosophical Society* **5–11**, 535–602.

dos Reis, R. J. & Dias, N. L. 1998 Multi-season lake evaporation: energy-budget estimates and CRLE model assessment with limited meteorological observations. *Journal of Hydrology* **208**, 135–147.

Finch, J. & Calver, A. 2008 Methods for the quantification of evaporation from lakes. The World Meteorological Organization's Commission for Hydrology. CEH Wallingford, Wallingford, UK.

Gallego-Elvira, B., Baille, A., Martín-Górriz, B. & Martínez-Álvarez, V. 2010 Energy balance and evaporation loss of an agricultural reservoir in a semi-arid climate (southeastern Spain). *Hydrological Processes* **24**, 758–766.

Jensen, M. E. & Haise, H. R. 1963 Estimating evapotranspiration from solar radiation. *Journal of Irrigation and Drainage Engineering* **89**, 15–41.

Kim, S., Shiri, J., Kisi, O. & Singh, V. P. 2013 Estimating daily pan evaporation using different data-driven methods and lag-time patterns. *Water Resources Management* **27**, 2267–2286.

Koedyk, L. P. & Kingston, D. G. 2016 Potential evapotranspiration method influence on climate change impacts on river flow: a mid-latitude case study. *Hydrology Research* **47** (5), 951–963. DOI: 10.2166/nh.2016.152.

Lenters, J. D., Kratz, T. K. & Bowser, C. J. 2005 Effects of climate variability on lake evaporation: results from a long-term energy budget study of Sparkling Lake, northern Wisconsin (USA). *Journal of Hydrology* **308**, 168–195.

Linacre, E. T. 1993 Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agricultural and Forest Meteorology* **64**, 237–256.

Liu, S., Mao, D. & Lu, L. 2006 Measurement and estimation of the aerodynamic resistance. *Hydrology and Earth System Sciences* **3**, 681–705.

Majidi, M., Alizadeh, A., Farid, A. & Vazifedoust, M. 2015a Analysis of the effect of missing weather data in estimating daily reference evapotranspiration under different climatic conditions. *Water Resources Management* **29**, 2107–2124.

Majidi, M., Alizadeh, A., Farid, A. & Vazifedoust, M. 2015b Estimating evaporation from Lakes and reservoirs under limited data condition in a semi-arid region. *Water Resources Management* **29**, 3711–3733. DOI: 10.1007/s11269-015-1025-8.

McJannet, D. L., Webster, I. T. & Cook, F. J. 2012 An area-dependent wind function for estimating open water evaporation using land-based meteorological data. *Environmental Modelling and Software* **31**, 76–83.

McMahon, T. A., Peel, M. C., Lowe, L., Srikanthan, R. & McVicar, T. R. 2013 Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. *Hydrology and Earth System Sciences* **17**, 1331–1363.

Mironov, D., Kirillin, G., Heise, E., Golosov, S., Terzhevik, A. & Zverev, I. 2003 Parameterization of lakes in numerical models for environmental applications. In: *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, pp. 135–143.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual models, part I – a discussion of principles. *Journal of Hydrology* **10**, 282–290.

Ngongondo, C., Xu, C.-Y., Tallaksen, L. M. & Alemaw, B. 2013 Evaluation of the FAO Penman-Monteith, Priestly-Taylor and Hargreaves models for estimating reference evapotranspiration in southern Malawi. *Hydrology Research* **44**, 706–722.

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

Penman, H. L. 1948 Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society* **A193**, 120–145.

Penman, H. L. 1963 *Vegetation and Hydrology.* Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England, 125 pp.

Qiu, G. Y., Yano, T. & Momii, K. 1998 An improved methodology to measure evaporation from bare soil based on comparison of surface temperature with a dry soil surface. *Journal of Hydrology* **210**, 93–105.

Rosenberry, D. O., Winter, T. C., Buso, D. C. & Likens, G. E. 2007 Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA. *Journal of Hydrology* **340**, 149–166.

Sabziparvar, A. A., 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 Resources Management* **24**, 909–920.

Sturrock, A. M., Winter, T. C. & Rosenberry, D. O. 1992 Energy budget evaporation from Williams Lake – a closed lake in north central Minnesota. *Water Resources Research* **28**, 1605–1617.

Winter, T. C., Rosenberry, D. O. & Sturrock, A. M. 1995 Evaluation of 11 equations for determining evaporation for a small lake in the north central United States. *Water Resources Research* **31**, 983–993.

Winter, T. C., Buso, D. C., Rosenberry, D. O., Likens, G. E., Sturrock, A. M. J. & Mau, D. P. 2003 Evaporation determined by the energy budget method for Mirror Lake, new Hampshire. *Limnology and Oceanography* **48**, 995–1009.

Xu, C.-Y. & Singh, V. P. 2000 Evaluation and generalisation of radiation-based equations for calculating evaporation. *Hydrological Processes* **14**, 339–349.

Xu, C.-Y. & Singh, V. P. 2001 Evaluation and generalisation of temperature-based equations for calculating evaporation. *Hydrological Processes* **15**, 305–319.

Xu, C.-Y. & Singh, V. P. 2002 Cross-comparison of mass-transfer, radiation and temperature based evaporation models. *Water Resources Management* **16**, 197–219.

Xu, C.-Y., Gong, L., Jiang, T., Chen, D. & Singh, V. P. 2006 Analysis of spatial distribution and temporal trend of reference evapotranspiration in Changjiang (Yangtze River) catchment. *Journal of Hydrology* **327**, 81–93.

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