Title

Comparison of methods to calculate evaporation from reservoirs

Journal
International Journal of River Basin Management, 18(1)

ISSN
1571-5124

Authors
Bozorgi, Atiyeh
Bozorg-Haddad, Omid
Sima, Somayeh
et al.

Publication Date
2020-01-02

DOI
10.1080/15715124.2018.1546729

Peer reviewed

International Journal of River Basin Management

ISSN: 1571-5124 (Print) 1814-2060 (Online) Journal homepage: www.tandfonline.com/journals/trbm20

Comparison of methods to calculate evaporation from reservoirs

Atiyeh Bozorgi, Omid Bozorg-Haddad, Somayeh Sima & Hugo A. Loáiciga

To cite this article: Atiyeh Bozorgi, Omid Bozorg-Haddad, Somayeh Sima & Hugo A. Loáiciga (2020) Comparison of methods to calculate evaporation from reservoirs, International Journal of River Basin Management, 18:1, 1-12, DOI: 10.1080/15715124.2018.1546729

To link to this article: https://doi.org/10.1080/15715124.2018.1546729

Published online: 03 Dec 2018.

INTL. J. RIVER BASIN MANAGEMENT
2020, VOL. 18, NO. 1, 1–12
https://doi.org/10.1080/15715124.2018.1546729

Taylor & Francis
Taylor & Francis Group

RESEARCH PAPER

Check for updates

Comparison of methods to calculate evaporation from reservoirs

Atiyeh Bozorgi[a], Omid Bozorg-Haddad[a], Somayeh Sima[b] and Hugo A. Loáiciga[c]

[a]Department of Irrigation & Reclamation Engineering, Faculty of Agriculture Engineering & Technology, College of Agriculture & Natural Resources, University of Tehran, Karaj, Iran; [b]Department of Civil & Environmental Engineering, Tarbiat Modares University, Tehran, Iran; [c]Department of Geography, University of California, Santa Barbara, USA

ABSTRACT
Large volumes of water evaporate from reservoirs in arid and semi-arid regions. Such water losses are substantial in the regional water balance, and must be considered in the management of water resources. This paper evaluates 12 reservoir evaporation methods that are applied to calculate daily evaporation from Karkheh reservoir (Iran) created by the world's sixth largest dam. The Bowen ratio energy budget (BREB) formula is chosen as the reference method for the purpose of evaluating 12 alternative evaporation methods. The evaporation methods are ranked based on their accuracy, sensitivity to input variables, and simplicity of application by means of the technique for order of preference by similarity to ideal solution (TOPSIS) multi-criteria decision analysis method. Our results from a multi-year data set for Karkheh reservoir indicate that the best-ranked methods by TOPSIS considering the performance indices are the solar radiation-temperature based methods and the Blaney and Criddle method that is based on temperature and daylight duration variables.

ARTICLE HISTORY
Received 21 March 2018
Accepted 7 November 2018

KEYWORDS
Evaporation; Karkhe dam; sensitive analysis; simplicity; Bowen ratio energy-Budget (BREB); TOPSIS

1. Introduction

Iran's water resources management (IWRM) company estimates that 420 billion cubic metres of water is received on average annually as precipitation in Iran, of which 120 billion cubic metres can be managed for human use. Iran's managed water consumption is currently about 90 billion cubic metres annually. It is estimated that about 30 billion cubic metres of water evaporate on average annually from 647 reservoirs built in Iran. Evidently, evaporation from reservoirs plays a major role on the national water availability for human use in Iran due to its semi-arid climate.

The Energy-Budget method is often adopted as the reference method to calculate evaporation from water bodies (Winter *et al.* 2003, Rosenberry *et al.* 2007, Majidi *et al.* 2015). The Bowen ratio energy budget (BREB), preeminent among the energy-budget methods, is frequently applied for estimating evaporation for water surfaces (Ikebuchi *et al.* 1988, Sene *et al.* 1991, Mahrer 1993, Budyko 1997, Dingman 2015).

Sima *et al.* (2013) estimated the evaporation from Urmia Lake in north-western Iran using the BREB method and satellite images. The spatial and temporal variations of water surface temperature (WST) were studied between 2007 and 2010 with Moderate Resolution Imaging Spectroradiometer (MODIS) products such as Land Surface Temperature (LST). Deleclaux *et al.* (2007) applied several evaporation models to Lake Titicaca, which is located in the semi-arid North Andean Altiplano of South America. The annual evaporation varied between 1350 and 1900 mm. Finch (2001) developed an evaporation model based on the equilibrium temperature method to estimate the average annual evaporation from the Kempton Park reservoir in England. The input data for the equilibrium temperature method include daily weather variables such as solar radiation, wind speed, relative humidity, and average daily temperature. The average annual evaporation was estimated to be 619 mm, which was 6% less than the measured amount of evaporation from a reservoir at Kempton Park. Finch's (2001) model was less successful in estimating the monthly evaporation. Dogan *et al.* (2010) modelled the evaporation of the Yuvacik reservoir in Turkey using Adaptive Neuro-Fuzzy Inference System (ANFIS). The ANFIS model relies on evaporation pan data modified by weather variables (average temperature, relative humidity, direct solar radiation, wind speed) in estimating reservoir evaporation. Majidi *et al.* (2015) applied the Energy-Budget method and 18 other methods to estimate evaporation from the Doosti reservoir in north-eastern Iran. Their results indicated that methods that depend on air temperature or the combination of air temperature and solar radiation (such as the Jensen-Haise and Makkink methods) were superior to others due to their simplicity, low sensitivity, and high accuracy. Rosenberry *et al.* (2007) applied 14 methods to estimate the evaporation from Lake Mirror, located in New Hampshire (United States) and compared the results with those from the BREB method. The 14 methods were classified into several groups. The combined group of methods rely on energy input and aerodynamic factors, and yielded the results closest to those from the BREB method. Winter *et al.* (1995) compared 11 methods for estimating evaporation in Lake William (Australia). The DeBruin-Keijman, Priestley-Taylor, and Penman methods produced the evaporation estimates closest to those from the BREB method.

This paper evaluates 12 reservoir evaporation methods that are applied to calculate daily evaporation from the Karkheh reservoir, Iran. The evaporation methods are ranked based on their accuracy, sensitivity, and simplicity applying the technique for order of preference by similarity to ideal solution (TOPSIS), multi-criteria decision analysis method. Accuracy is measured by closeness to the evaporation

CONTACT Omid Bozorg-Haddad obhaddad@ut.ac.ir Department of Irrigation & Reclamation Engineering, Faculty of Agriculture Engineering & Technology, College of Agriculture & Natural Resources, University of Tehran, Karaj, Alborz 31587-77871, Iran.

estimates from the BREB method. The ranking of evaporation methods based on multiple pertinent quantitative criteria with TOPSIS is the novelty introduced in this paper.

2. Methodology

Methods for calculating evaporation from a water surface are herein classified into several groups: Energy-Budget, combination (i.e. combine energy balance and mass transfer factors), solar radiation-temperature, day length- temperature, and pan evaporation. Each of these groups features unique evaporation formulas of varying accuracy and complexity. The following sections describe the evaporation methods herein considered and their data requirements.

2.1. The Bowen ratio energy budget

The BREB method (Harbeck 1962, Fritschen *et al.* 1989, Winter 2003) for estimating evaporation from a water surface is based on the following expression of the energy balance equation:

$$E = \frac{Q_{SN} - Q_{LW} - Q_n + Q_{AD} - Q_b}{\rho L_e (1 + B)} \tag{1}$$

where E = evaporation rate (m/s); Q_{SN}= net short-wave radiation onto the water surface (w/m^2); Q_{LW}= net long wave radiation emitted by the lake (W/m^2); Q_n= the change in heat stored in the lake-water body (W/m^2); Q_{AD}= net heat flux into the water body from precipitation (W/m^2); net flux carried by surface water and ground water (Wm^2); Q_b= net energy conducted from the lake to the lake sediments (W/m^2); ρ= density of the lake water (kg/m^3); L_e= latent heat of vaporization (J/kg) at the temperature of the evaporating water; and B= Bowen ratio (dimensionless). The evaporation given by Equation (1) is multiplied by the factor 8.64×10^7 to convert it to evaporation in mm/day that can be compared to the estimates of the evaporation expressed in mm/day obtained with other methods applied in this paper.

The terms of Q_b, Q_{AD} and Q_n are relatively small and are commonly neglected (Rosenberry *et al.* 2007). The net shortwave radiation is herein calculated as follows:

$$Q_{SN} = (1 - \alpha) Q_{Sin} \tag{2}$$

$$Q_{Sin} = \left(a + b\frac{n}{N}\right) Q_o \tag{3}$$

in which α= water surface albedo; Q_{Sin}= incoming solar radiation estimable with the Savinov Angstrom formula (Budyko 1974); a and b = local regression parameters; n and N = the actual and maximum possible number of hours of sunshine (i.e. the time of sunset mins the time of sunrise expressed in hours) in the day when the evaporation is calculated, respectively; and Q_o= solar radiation at the top of the atmosphere (W/m^2).

Net long wave radiation is calculating with Equation (4) (Clark *et al.* 1974):

$$\begin{aligned} Q_{LW} &= k_b \varepsilon T_w^4 (0.39 - 0.05\sqrt{e_a})(1 - 0.69C^2) \\ &\quad + 4k_b \varepsilon T_w^3 (T_w - T_a) \end{aligned} \tag{4}$$

where Tw and Ta = reservoir surface and air temperature 2 m above the lake's surface, respectively, in °K; k_b= Boltzmann coefficient; ε= emissivity of the water body; C = cloud cover fraction; and e_a= atmospheric vapour pressure 2 m above the lake's surface (mbar).

The Bowen ratio equals the sensible heat divided by the latent heat (Bowen 1926) and is calculated with the following formula:

$$B = c_b \frac{p}{1000} \frac{T_w - T_a}{e_{sw} - e_a} \tag{5}$$

where p = atmospheric pressure (mbar); c_b = Bowen's constant equal to 0.61 (1/°c) (Bowen 1926); and e_{sw} = saturated vapour pressure at the water surface temperature (mbar).

Although the BREB method is chosen as the reference method to compare estimates with other methods (Winter *et al.* 2003, Rosenberry *et al.* 2007, Majidi *et al.* 2015) it has some limitations that have been identified in previous research (Blad and Rosenberg 1974, Lang *et al.* 1983, Dugas *et al.* 1991, Todd *et al.* 2000, Xing *et al.* 2008).

Other methods for estimating evaporation are classified into five groups and their equations are listed in Table 1. The following notation applies to symbols appearing in Table 1 that have not been defined above. E = evaporation rate (mm/day); S = slope of the saturated vapour pressure vs. temperature curve at the mean air temperature (Pa/°c); U_2 = wind speed 2 m above the lake's surface (m/s); γ = psychrometric constant (Pa/°c); e_s = saturated vapour pressure at air temperature 2 m above the lake surface (mbar); SVD = saturated water-vapour density at mean air temperature (g/m^3); β = Priestly-Taylor constant (dimensionless) that is equal to 1.26; T_a = mean air temperature (°F) for Blaney-Criddle, Jensen-Haise, and Stephens-Stewart methods; $e_{s,\max}$ = saturated vapour pressure at maximum air temperature; $e_{s,(\text{min-}2)}$ = saturated vapour pressure at minimum air temperature minus 2 degrees; E_{pan} = the pan evaporation; k = the pan coefficient set equal to 0.7 in this work; and D_{TA} = the total annual hours of daylight.

The research steps followed in this work are diagramed in Figure 1. Evaporation is calculated with the various methods listed in Table 1. Input data are field observations and satellite measurements. The accuracy, sensitivity, and simplicity of the evaporation methods are discussed and this is followed by the ranking of the methods with the TOPSIS approach.

2.2. Basics of indices affecting ranking methods decision making

2.2.1. The accuracy index

The accuracy of the evaporation calculations is measured with the root mean square error (RMSE). The RMSE for evaporation calculated with a specific method is given by Equation (18):

$$\text{RMSE} = \sqrt{\frac{\sum_{z=1}^{m} (E_{\text{BREB}} - E_{\text{method}})^2}{m}} \tag{18}$$

where m = number of times when evaporation calculations are made; E_{BREB}= evaporation calculated with the BREB method; E_{method} = evaporation from a specific evaporation method; and z = time step index. Recall the BREB method is the reference method against which other methods are compared. The smaller the RMSE, the more accurate the method.

Table 1. Methods for calculating evaporation.

Method	Reference	Equation number	Equation
Combination group			
Priestley-Taylor	Stewart and Rouse (1976)	(6)	$E = \beta \frac{s}{s+\gamma} \frac{Q_{SN} - Q_{LW} - Q_n}{L_e \rho} \times 86.4$
deBruin-Keijman	deBruin and Keijman (1979)	(7)	$E = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_{SN} - Q_{LW} - Q_n)}{L_e \rho} \times 86.4$
Penman	Brutsaert (1982)	(8)	$E = \frac{s}{s+\gamma}\left(\frac{Q_{SN} - Q_{LW} - Q_n}{L_e \rho}\right) \times 86.4 + \frac{\gamma}{s+\gamma}(0.26(0.5 + 0.54U_2)(e_s - e_a))$
Brutsaert-Stricker	Brutsaert and Stricker (1979)	(9)	$E = (2\beta - 1)\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_{SN} - Q_{LW} - Q_n}{L_e \rho}\right) \times 86.4 - \frac{\gamma}{s+\gamma} 0.26(0.5 + 0.54U_2)(e_s - e_a)$
deBruin	deBruin (1978)	(10)	$E = 1.192\left(\frac{\beta}{\beta - 1}\right)\left(\frac{\gamma}{s+\gamma}\right)\frac{(2.9 + 2.1U_2)(e_s - e_a)}{L_e \rho} \times 86.4$
Solar radiation-temperature group			
Jensen-Haise	Jensen and Haise (1963)	(11)	$E = 0.03523Q_s(0.014T_a - 0.37)$
Makkink	McGuinness and Bordne (1972)	(12)	$E = 52.6 \frac{s}{s+\gamma} \frac{Q_s}{L_e \rho} - 0.12$
Stephens-Stewart	Stephens and Stewart (1963)	(13)	$E = 0.03495(0.0082T_a - 0.19).(Q_s \times 3.495 \times 10^{-2})$
Temperature-day length group			
Blaney- Criddle	Schertzer and Taylor (2008)	(14)	$E = 25.4(0.0173T_a - 0.314)T_a \frac{n}{D_{TA}}$
Hamon	Hamon (1961)	(15)	$E = 0.55\left(\frac{n}{12}\right)^2 \frac{SVD}{100}(25.4)$
Temperature group			
Papadakis	Papadakis (1961)	(16)	$E = 0.5625[e_{s.\max} - e_{s.(\min - 2)}]$
Pan evaporation		(17)	$E = K(E_{pan})$

2.2.2. The simplicity index

The simplicity index is applied in the selection of the best formula to estimate evaporation. This index focuses on the data required to implement each evaporation method, emphasizing availability and cost-effectiveness. The simplicity index has not been considered in previous studies except in a few cases when was qualitatively assessed without having significant impact on method selection (Majidi *et al.* 2015). This work quantifies the role of the simplicity index.

Some of the variables required in various evaporation methods include the maximum, mean, and minimum temperatures, wind speed, solar radiation, air pressure, water-vapour pressure, and water surface temperature. Each of these variables is ranked from 1 to 3 according to its level of availability and ease of measurement, with 1 denoting the most simple method and 3 the least simple method. The maximum, mean, and minimum temperatures, and wind-speed parameters are ranked as number 1 based on their availability and ease of measurement at climatology and synoptic stations. Solar radiation, air pressure, and water-vapour pressure are measurable at synoptic stations. Due to the lower density of these stations than that of climatology stations the latter variables are ranked as number 2. The data related to water-surface temperature which is commonly frequently measured by field study is ranked 3.

2.2.3. The sensitivity index

Data and input variables' uncertainty is frequently unknown in many cases (Vallet-Coulomb *et al.* 2001). Each evaporation formula contains a set of variables. There are errors imbedded in the measurements of these variables stemming from improperly calibrated instruments, inappropriateness of the place of measurement, the influence of external factors on measurement devices, and errors in reading measured variables. Each evaporation formula exhibits sensitivity with respect to the variables involved. This paper evaluates the sensitivity of the evaporation formulas with respect to the input variables by allowing those variables to range either deterministically or randomly ± 10% about their reported or measured values (Majidi *et al.* 2015). These changes are captured with five scenarios according to the origin and type of error.

The first and second scenarios describe conditions in which the errors in their variables are due to improperly calibrated measurement devices. Scenarios I and II apply changes equal to + 10% or −10% about the reported or measured values of their variables, respectively. These changes are imposed on each variable at a time while the others are kept constant for the purpose of evaluating the change or sensitivity of the calculated evaporation expressed as a percentage with respect to the variable being subjected to change.

The third and fourth scenarios apply changes to their variables in the ranges (0, +10%) and (−10%, 0), respectively. The change made to each input variable individually is obtained by multiplying the measured variable by a random number in the range (0, +10%) or (−10%, 0) when implementing scenarios III and IV, respectively, and then adding that

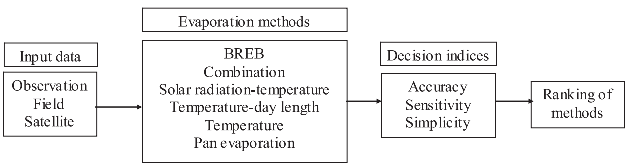

Figure 1. Flowchart of the research approach.

Table 2. Ranking of evaporation methods based on accuracy and RMSE.

Group	Method	RMSE (mm/day)	Ranking
Combination	Priestley-Taylor	1.08	1
	DeBruin-Keijman	2.70	4
	Penman	1.53	2
	Brutsaert-Stricker	2.43	3
	DeBruin	3.68	7
Solar radiation-temperature	Jensen-Haise	4.45	9
	Makkink	4.18	8
	Stephens-Stewart	3.19	5
Temperature-day length	Blaney- Criddle	3.64	6
	Hamon	6.97	10
Temperature	Papadakis	8.64	11
Pan evaporation	evaporation pan	8.85	12

change to the measured value of the variable being evaluated for sensitivity prior to calculating the evaporation while the other variables are held constant.

Scenario V applies a change in the range (−10,+10)% to each evaporation variable individually while the other variables are held constant. Specifically, the variable being evaluated for sensitivity is multiplied by a random number in the range (−10,+10)% and the result of the multiplication is added to the reported or measured value of the variable in question. The scenarios are listed in Table 3.

The sensitivity of each evaporation method i ($i = 1, 2, \ldots, m = 12$) is calculated with respect to each of its variables. There are $M = 9$ possible variables in this work, which from 1 to 9 are respectively: solar radiation, water-surface temperature, mean daily air temperature, wind speed, air pressure, water-vapour pressure, minimum and maximum daily air temperatures, and pan evaporation. The total sensitivity of method i is then calculated by summing the sensitivities with respect to each variable. Let the sensitivity indices be denoted by the counters $j = 2, 3, 4, 5$, and 6. The counters $j = 1$ and $j = 7$ represent the accuracy and simplicity indices, respectively. With this convention one writes the total sensitivity of evaporation method i ($i = 1, 2, \ldots, m = 12$) with respect to sensitivity scenario j as follows:

$$a_{ij} = \sum_{k=1}^{M} |y_{ijk}| \qquad i = 1, 2, \ldots, m = 12; j = 1, 2, 3, 4, 5, 6, 7 \tag{19}$$

in which a_{ij} = the total sensitivity of the i-th method with respect to sensitivity scenario j; y_{ijk} = the sensitivity of the i-th method with respect to its k-th variable and corresponding to sensitivity scenario j. Notice that not all variables are present in each method, which means that the sensitivity with respect to a variable i absent in a method equals zero in Equation (19). Table 4 lists the sensitivity analysis results.

Table 3. Sensitivity analysis scenarios: list of changes applied to each input parameter.

Scenario	
I	Each independent input parameter × 10%
II	Each independent input parameter × −10%
III	Each independent input parameter × Random number in the range of (0,+10)%
IV	Each independent input parameter × Random number in the range of (−10, 0)%
V	Each independent input parameter × Random number in the range of (−10, +10)%

2.3. The TOPSIS decision making model

This model is one of the leading multiple attribute decision making (MADM) methods (Mysiak *et al.* 2005, Hajkowicz *et al.* 2007, Dai *et al.* 2010, Behzadian *et al.* 2012). TOPSIS is based on the concept that a chosen alternative method should have a minimum distance from the best solution (the ideal solution) and the longest distance from the worst solution. This study evaluates 12 alternative evaporation methods and ranks them with TOPSIS.

The steps for implementing TOPSIS start by creating a decision matrix whose elements are given by Equation (20):

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}^2} \tag{20}$$

where a_{ij}= the value of alternative evaporation method i (there are $m = 12$ alternative evaporation methods listed in Table 1) with respect to decision index j (recall that there are decision indices $j = 1$: accuracy, $j = 2, 3, 4, 5, 6$ for sensitivity under five scenarios, and $j = 7$ for simplicity); and n_{ij}= scaled value of the i-th alternative evaporation method with respect to the j-th decision index. The elements n_{ij} are in the range (0,1) for positive a_{ij} values. The values a_{i1} for the accuracy index are listed in the third column of Table 2, those for the simplicity index (elements a_{i7}) are listed in column 8 of Table 5, and those corresponding to the sensitivity scenarios (elements a_{ij}, $j = 2, 3, 4, 5, 6$) are listed in columns 3–7 of Table 4.

For each evaporation method i ($i = 1, 2, \ldots, 12$ in this study) the elements n_{ij} ($j = 1, 2, \ldots$, n, $n = 7$ in this study) are multiplied respectively by the best value (v_j^+) achieved among all the alternative evaporation methods with respect to the decision index j. For example, the best value for the index simplicity equals $v_7^+ = 1$. Therefore, the elements n_{i7} are multiplied by the value v_7^+, $i = 1, 2, \ldots, 12$. Similarly the elements n_{i1}, n_{i2}, n_{i3}, n_{i4}, n_{i5}, n_{i6} are multiplied by v_1^+, v_2^+, v_3^+, v_4^+, v_5^+, and v_6^+, respectively, $i = 1, 2, \ldots, 12$. These multiplications produce a scaled matrix with elements v_{ij}^+. A second matrix is obtained by multiplying the elements n_{i1}, n_{i2}, n_{i3}, n_{i4}, n_{i5}, n_{i6}, n_{i7} by v_1^-, v_2^- v_3^-, v_4^-, v_5^-, v_6^-, v_7^-, respectively, $i = 1, 2, \ldots, 12$, in which v_j^-, $j = 1, 2, \ldots, 7$, represents the worst values of the accuracy, sensitivity, and simplicity indices achieved among all the alternative evaporation methods. For example, the worst value for the simplicity index equals $v_7^- = 3$, which multiplies the elements n_{i7}, $i = 1, 2, \ldots, 12$. These multiplications by v_j^- produce a scaled matrix whose elements are denoted by v_{ij}^-.

The best and worst solutions with respect to criteria j are denoted by $v_j^{b+}$and v_j^{w-}, respectively. To exemplify, the best

Table 4. The results of the sensitivity analysis.

Group	Method	Scenario I	Scenario II	Scenario III	Scenario IV	Scenario V	Ranking
Combination	Priestley-Taylor	64.91	65.73	32.80	30.73	8.39	11
	DeBruin-Keijman	63.69	64.63	32.20	30.28	8.34	10
	Penman	38.77	38.31	19.51	19.48	1.25	8
	Brutsaert-Stricker	130.12	133.25	54.22	62.85	26.17	12
	DeBruin	40.23	41.69	20.47	20.83	0.43	9
Solar radiation-temperature	Jensen-Haise	11.06	11.06	5.47	5.53	0.20	4
	Makkink	8.53	8.96	4.32	4.45	0.10	3
	Stephens-Stewart	10.47	10.47	5.27	5.24	0.19	1
Temperature-day length	Blaney- Criddle	23.45	22.60	11.74	11.37	0.62	5
	Hamon	35.69	31.90	17.68	16.26	1.31	7
Temperature	Papadakis	35.15	30.10	17.34	15.43	1.23	6
Pan evaporation	evaporation pan	10.00	10.00	5.03	5.01	0.19	2

Table 5. Decision matrix.

	Criteria						
Method	Criterion 1 Accuracy	Criterion 2-scenario I Sensitivity	Criteria 2- scenario II Sensitivity	Criteria 2- scenario III Sensitivity	Criterion 2- scenario IV Sensitivity	Criteria 2- scenario V Sensitivity	Criterion 3 Simplicity
Priestley-Taylor	1.08	64.91	65.73	32.80	30.73	8.39	3
deBruin-Keijman	2.70	63.69	64.63	32.20	30.28	8.34	3
Penman	1.53	38.77	38.31	19.51	19.48	1.25	3
Brutsaert-Stricker	2.43	130.12	133.25	54.22	62.85	26.17	3
deBruin	3.68	40.23	41.69	20.47	20.83	0.43	2
Jensen-Haise	4.45	11.06	11.06	5.47	5.53	0.20	2
Makkink	4.18	8.53	8.96	4.32	4.45	0.10	2
Stephens-Stewart	3.19	10.47	10.47	5.27	5.24	0.19	2
Blaney- Criddle	3.64	23.45	22.60	11.74	11.37	0.62	2
Hamon	6.87	35.69	31.90	17.68	16.26	1.31	2
Papadakis	8.64	35.15	30.10	17.34	15.43	1.23	1
Evaporation pan	8.85	10.00	10.00	5.03	5.01	0.19	1

and worst solutions for the simplicity index are $v_7^{b+} = 1$ and $v_7^{w-} = 3$. The Euclidean distance between the vector of values of the criteria achieved with each alternative evaporation method i and the vector of best solutions for each criteria is denoted by d_i^+. The Euclidean distance between the vector of values of the criteria achieved with each alternative evaporation method i and the vector of worst solutions for each criteria is denoted by d_i^-. The distances d_j^+ and d_j^- are calculated with Equations (21) and (22):

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij}^+ - v_j^{b+})^2} \quad i = 1, 2, \ldots, m = 12 \qquad (21)$$

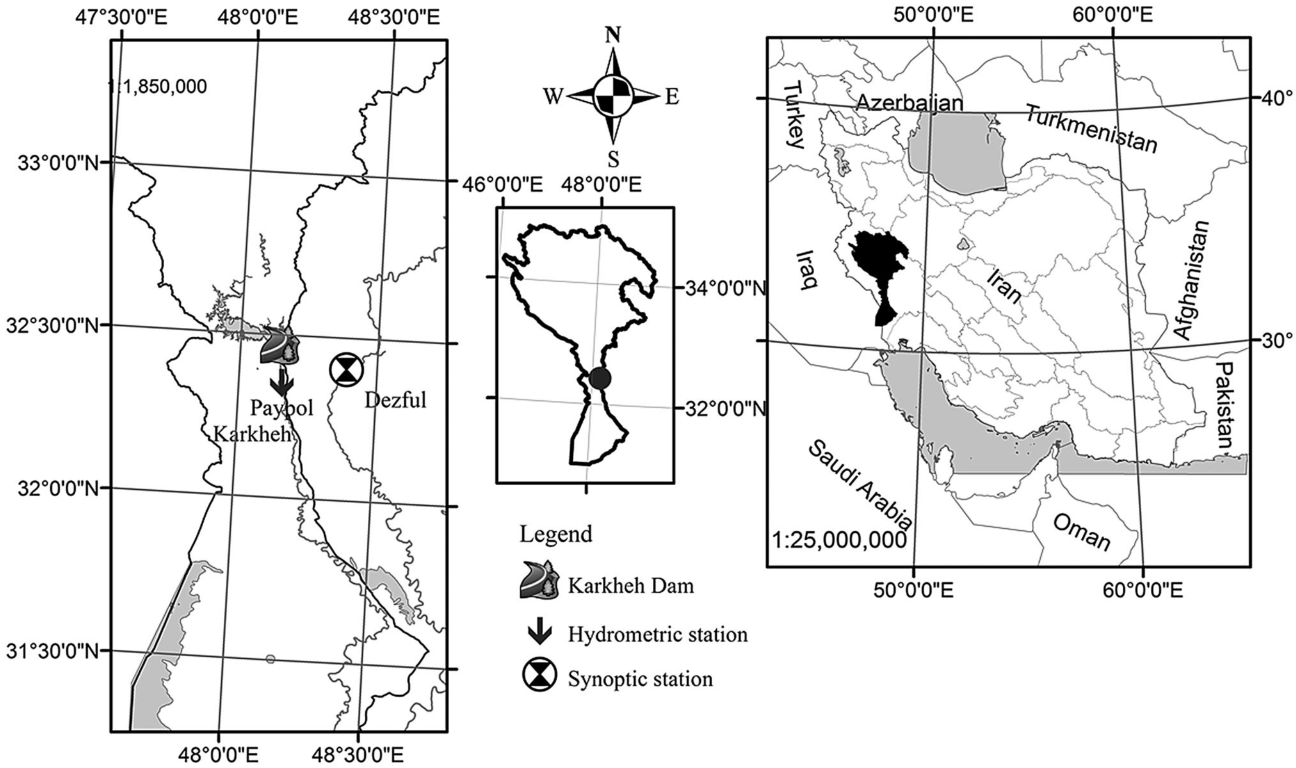

Figure 2. The location of the Karkheh dam and data measurement stations.

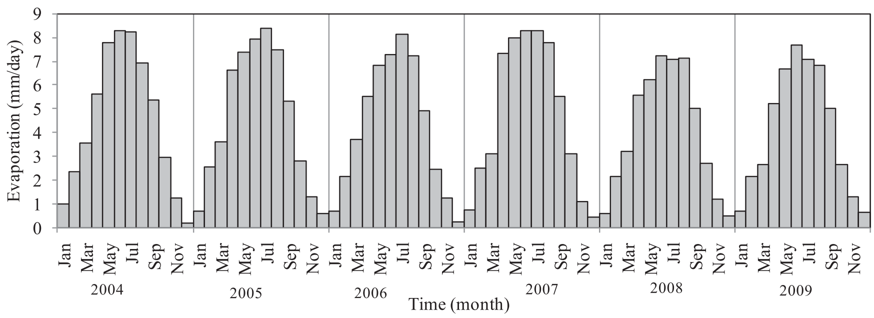

Figure 3. Evaporation calculated with the BREB method.

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij}^- - v_j^{w-})^2} \quad i = 1, 2, \ldots, m = 12 \tag{22}$$

The relative closeness of an alternative evaporation method i to the best solution is denoted by CL_i, and is calculated as follows:

$$CL_i = \frac{d_i^+}{d_i^+ + d_i^-} \quad i = 1, 2, \ldots, m = 12 \tag{23}$$

The best alternative evaporation method is that with the smallest CL_i.

3. Case study

3.1. The Karkhe basin and reservoir

The Karkheh basin features a wide range of climates from humid to dry and warm to cold. Among the 32 climates identified in the modified De Martonne classification method 16 of its climatic zones are available in this basin. The annual rainfall of the region varies from 205 mm in the southern and low-altitude areas to about 1000 mm in mountainous and highlands. The average annual rainfall in the entire Karkhe basin area is about 477 mm. Also, the maximum rainfall in the region is also observed in winter, and there is rarely significant rainfall in summer. The average annual temperature in the study area is about 15.3 ° C, varying from about 25 ° C in the southern region to about −1 ° C in the highlands of the basin. This paper estimates evaporation from Karkhe reservoir located in the Karkheh basin with several alternative methods.

Karkheh dam is the sixth long earthen dam in the world and the largest dam in Iran. Its lake extends over 166 km^2 and a capacity of five billion cubic metres. Karkheh dam is located at 48 degrees 16 min east longitude and 32 degrees 40 min north latitude. Karkhe dam's location is illustrated in Figure 2.

3.2. Meteorology data

Required meteorology data include the minimum, maximum, and mean daily temperatures, wind speed, air pressure, water-vapour pressure, and solar radiation, which were gathered daily from Dezful synoptic stations located 27 km from Karkheh reservoir. Pan evaporation data were gathered with Paypol hydrometric stations daily over the period 2004–2009.

3.3. Field data

The water surface temperature is needed in the BREB calculations and some other evaporation methods. This variable was measured during the years 2006–2007. These measurements were made at 3 points inside the Karkheh reservoir at kilometres of 43, 52 and 64 upstream from the dam in addition to the reservoir upstream boundary. Due to the incompletes of the collected data in space and time they were supplemented with satellite images.

3.4. Remote Sensing data

Water-surface temperature data were inferred with the MODIS products. The MODIS sensor features 36 spectral bands, 12 bit radiometric resolution, daily temporal resolution, and 1 km spatial resolution. MODIS sensor is installed on the Terra and Aqua satellites. The product MOD11A1 from the Aqua satellite was applied to estimate water surface temperature. Regression equation between field data and satellite images were fitted with an $R^2 = 0.86$. The values from the images were validated with field data and the water surface temperature data were calculated for the entire time period.

4. Results

4.1. The BREB method results

Evaporation values were calculated daily from 2004 to 2009 with the BREB method. The evaporation values were aggregated to monthly duration to make them compatible with the time step of reservoir operations. Figure 3 depicts the monthly evaporation values at Karkhe reservoir calculated with the BREB method. The largest evaporation equalled 8.37 mm/day in July 2005 and the minimum equalled 0.23 mm/day in December 2004.

4.2. Comparison of methods

The evaporation was calculated with the 12 evaporation methods estimating from 2004 to 2009 and the results were compared with the BREB method's. Figures 4–7 depict the maximum, mean, and minimum differences between the BREB evaporation values and those of the 12 alternative methods.

It is evident from Figure 4 that the Priestley-Taylor, DeBruin-Keijman, and Brutsaert-Stricker methods generally yield evaporation estimates that are less than the BREB method's; whereas the Penman and DeBruin methods calculate evaporation larger than the BREB method's. These patterns are accentuated during the warm months. The Makkink and the Stephens-Stewart radiation-temperature methods shown in Figure 5 produced evaporation that is less than the BREB method's; while the Jensen-Haise method estimates exceed the BREB method's estimates. The two temperature-daylight length methods illustrated in Figure 6 produce evaporation estimates smaller than the BREB method's, although the Blaney-Criddle method is more accurate than the Hamon method. Figure 7 shows the Papadakis method is merely a temperature method which estimates the evaporation from maximum and minimum of temperature. It is of simple implementation and exhibited low accuracy relative to the BREB method and other methods. The pan method, which is frequently applied in operation and management studies, overestimates the evaporation in most months compared with the BREB method. The pan method exhibited the largest RMSE, as seen in Table 2. The Priestly-Taylor method had the smallest RMSE. Notice in Table 2 that the evaporation methods received ranks that increased with increasing RMSE. Therefore, the ranks of 1 (best with respect to accuracy) and 12 (worst with respect to accuracy) went to the Priestly-Taylor and pan evaporation methods, respectively.

4.3. The analysis sensitivity results

The sensitivity analysis results are shown in Figures 8–11 and Table 4. Figures 8–11 shows the total sensitivities as a percentage for each input variable and corresponding to the five

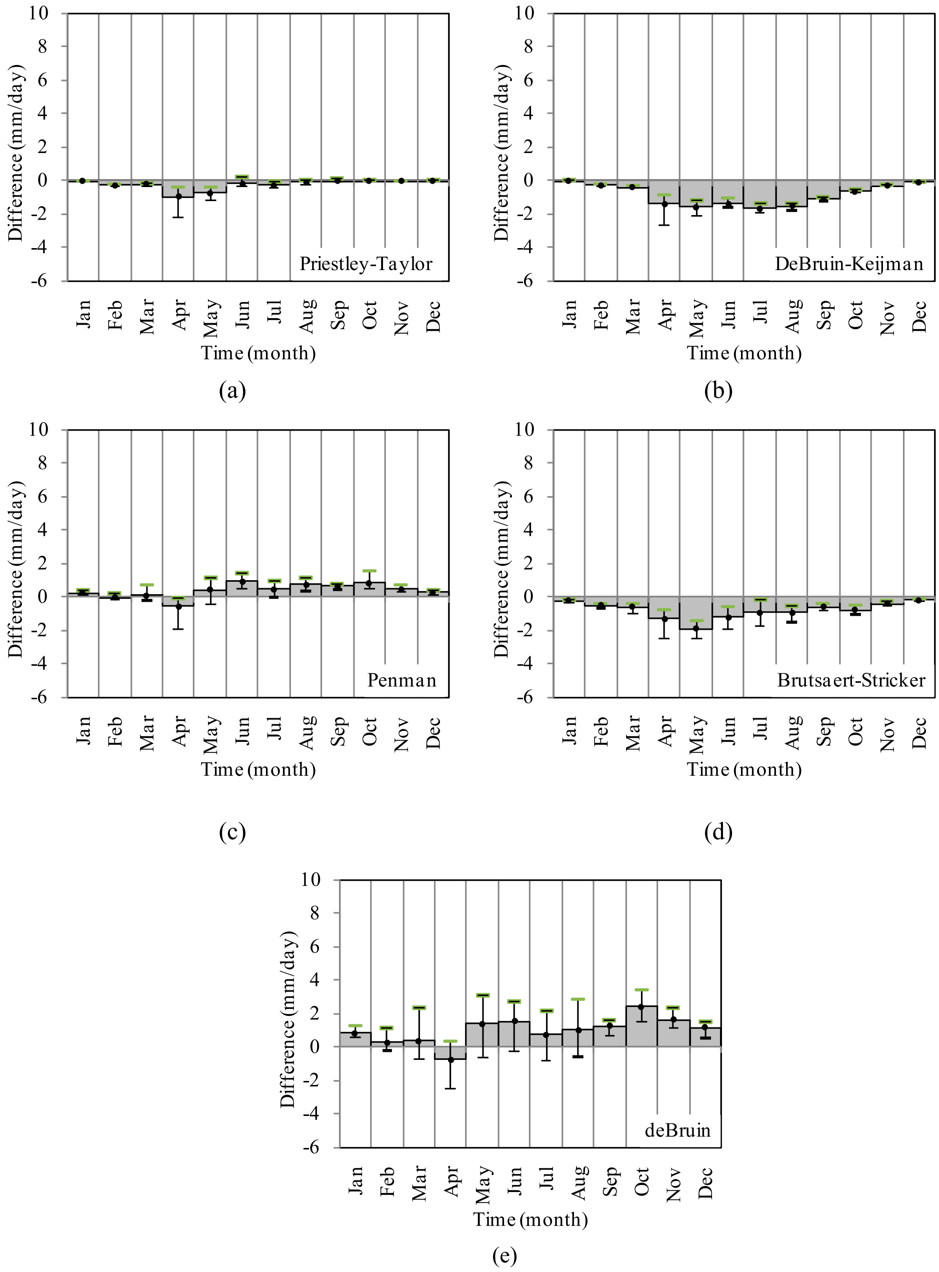

Figure 4. Difference between the average monthly evaporation calculated with combination methods and with the BREB method from 2004 through 2009.

scenarios defined in Table 3. Table 4 lists the elements a_{ij} calculated with Equation (19) that quantifies the total sensitivities associated with the five sensitivity scenarios.

It is seen in Figure 8 that the combination methods exhibit high sensitivity with respect to air and water temperature changes. Rosenberry (2007) reported that combination methods are sensitive to wind speed. Also, solar radiation-temperature methods are highly sensitive to the solar radiation variable rather than temperature. Table 4 illustrates that solar radiation-temperature methods exhibited superior ranking according to the sensitivity index. Moreover, the methods of temperature-day length methods had moderate ranking because of the type and number of input parameters.

4.4. Ranking using TOPSIS method

The technique for order of preference by similarity to ideal solution (TOPSIS) was applied to rank the evaporation methods considering accuracy, sensitivity, and simplicity. Table 5 lists the valuation of the evaporation methods according to the seven performance indices. Table 6 provides an overall ranking of the evaporation methods based. Figure 12 depicts an overall ranking based on the index of closeness to the best solution [Equation (20)]. The overall rankings shown in Table 6 and Figure 12

Table 6. Overall ranking of evaporation methods.

Group	Method	Rank
Combination	Priestley-Taylor	10
	deBruin-Keijman	11
	Penman	6
	Brutsaert-Stricker	12
	deBruin	7
Solar radiation-temperature	Jensen-Haise	3
	Makkink	2
	Stephens-Stewart	1
Temperature-daylight length	Blaney- Criddle	4
	Hamon	8
Temperature	Papadakis	9
Pan evaporation	evaporation pan	5

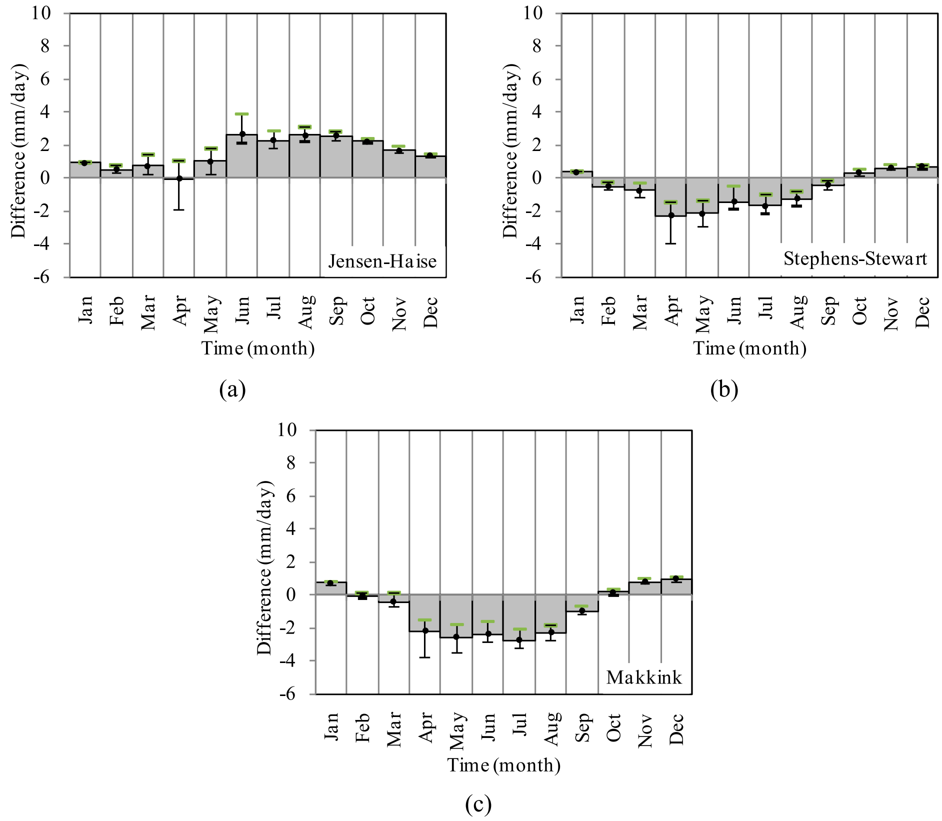

Figure 5. Difference between the average monthly evaporation calculated with solar radiation-temperature methods and with the BREB method from 2004 through 2009.

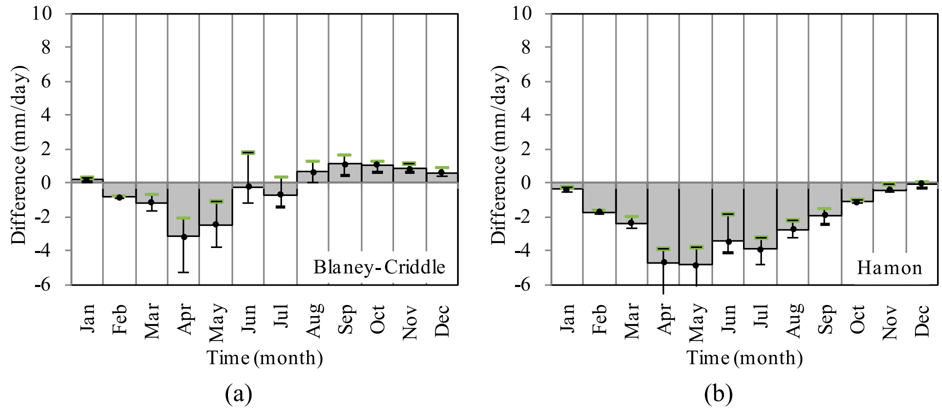

Figure 6. Difference between the average monthly evaporation calculated with temperature-day length methods and with the BREB method from 2004 through 2009.

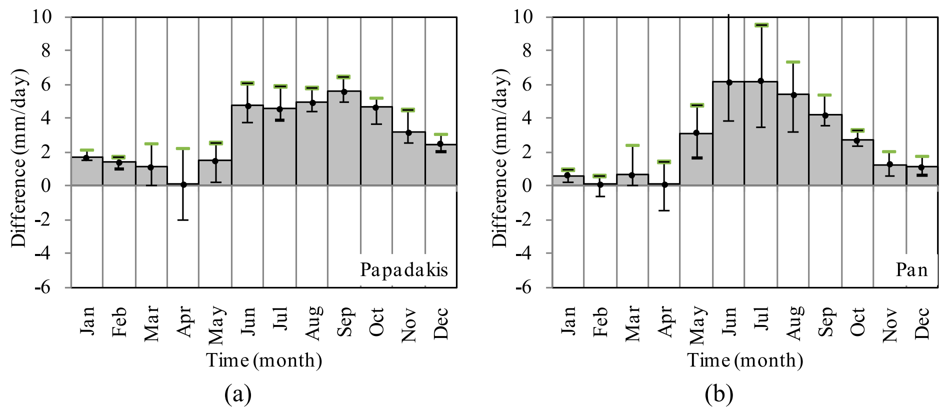

Figure 7. Difference between the average monthly evaporation calculated with temperature and pan evaporation methods and with the BREB method from 2004 through 2009.

establish the Stephens-Stewart solar radiation-temperature method and the Brutsaert-Stricker combination method were the best ranked (rank 1) and worst ranked (rank 12) in this evaporation study in the Karkheh reservoir. The best four ranks in decreasing order of quality belong to the Stephens-Stewart, Makkink, and Jensen-Haise solar radiation-temperature methods, and to the Blaney-Criddle temperature-daylight length method, respectively. The worst three methods in decreasing order of quality are the Priestley-Taylor, DeBruin-Keijman, and Brutsaert-Stricker combination methods. The combination methods are theoretically the most sound by virtue of being grounded on energy balance and mass-transfer principles. Yet, the diversity and number of parameters involved in the combination methods introduce high sensitivity and complexity in the estimation of evaporation; thus, the low ranking of the combination methods in spite of their relative good accuracy (see Table 2 and the second column of Table 5 for accuracy valuation). The closeness-index ranking achieved with TOPSIS indicates that the among the twelve evaporation methods herein considered the best-performing ones were the solar radiation-temperature

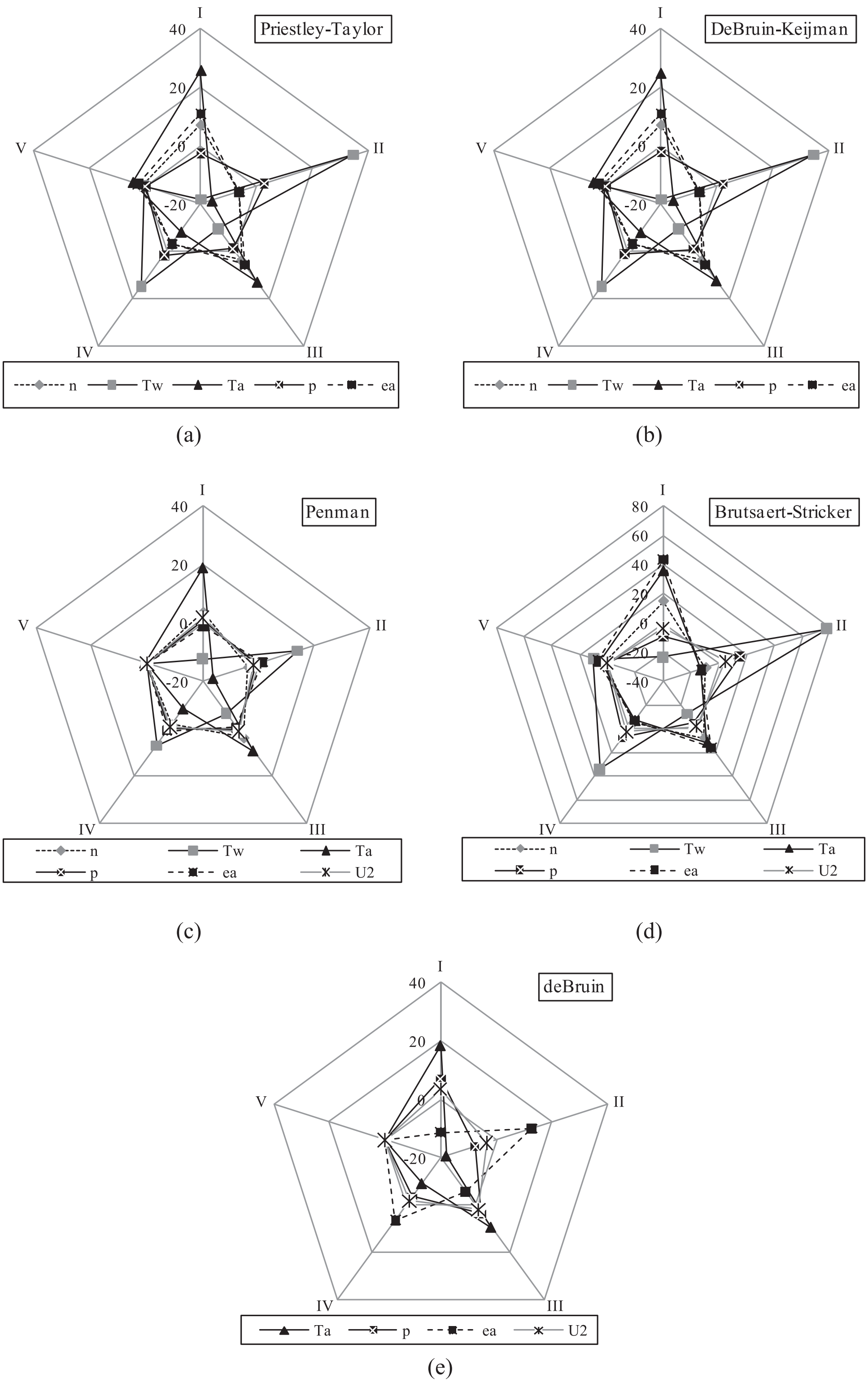

Figure 8. Sensitivity analysis of the combination methods with respect to input variables according to 5 scenarios.

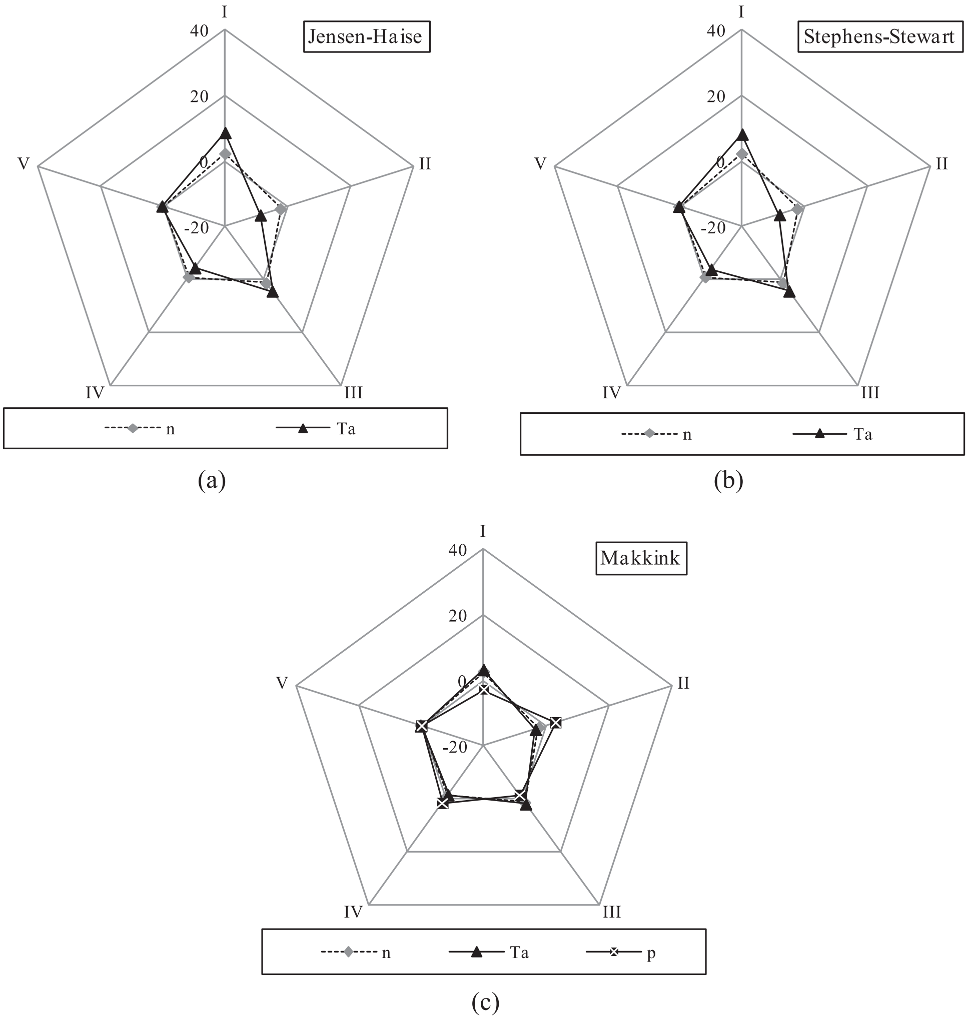

Figure 9. Sensitivity analysis of the solar radiation-temperature methods with respect to input variables according to 5 scenarios.

methods and the Blaney-Criddle method (temperature and daylight duration based).

Results by previous authors concerning the comparative performance of evaporation methods are worthy of notice. Rosenberry *et al.* 2007 showed that methods which require both solar radiation and air temperature are not substantially better than methods based on air temperature when applied to Mirror Lake in New Hampshire data. Methods based on temperature, such as Papadakis, performed well in comparison with the BREB method, they are cost effective, and provide evaporation estimates that are more accurate than those produced by several more complex methods. Majidi *et al.* (2015), reported that radiation-temperature methods such as Jensen-Haise and Makkink have reasonable accuracy especially with monthly time step. The deBruin, Penman, Hamon, and Papadakis methods produced relatively accurate

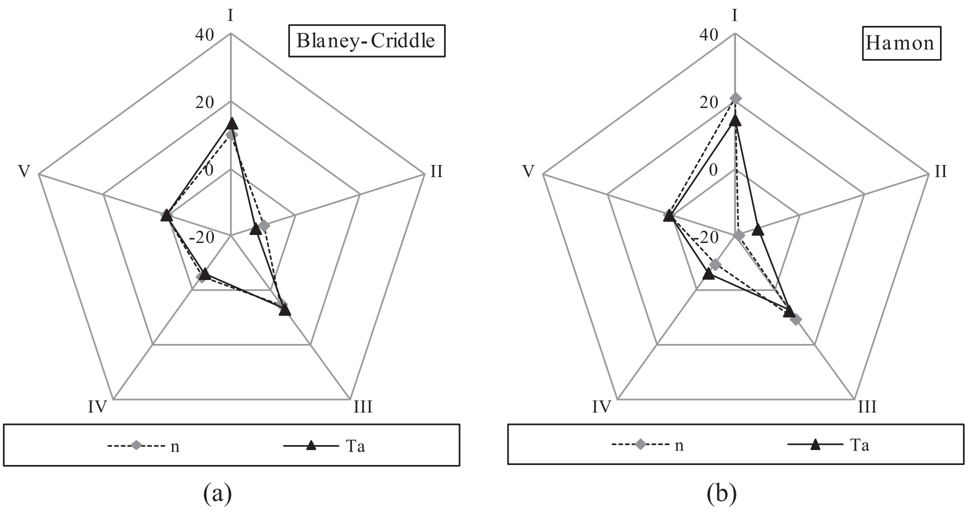

Figure 10. Sensitivity analysis of the temperature-day length methods with respect to input variables according to 5 scenarios.

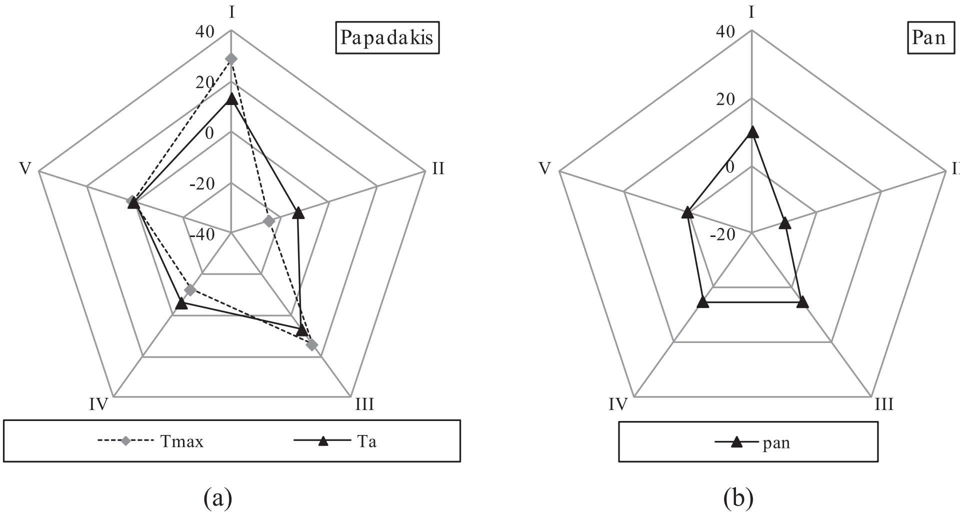

Figure 11. Sensitivity analysis of the temperature and pan evaporation methods with respect to input variables according to 5 scenarios.

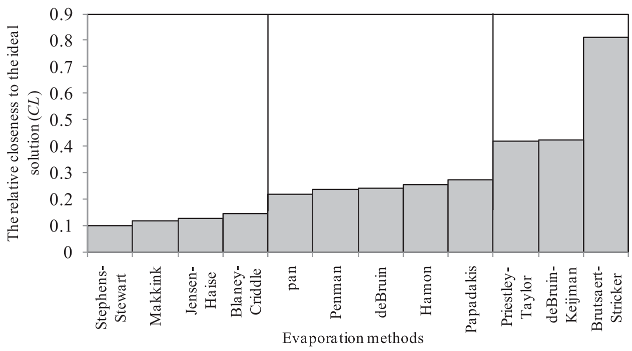

Figure 12. The ranking of methods according to the closeness to the ideal solution (*CL*).

results. The Jensen-Haise and Makkink methods were the most accurate methods for estimating the evaporation in Doosti reservoir, which is located in IRAN.

Other authors have concluded that the location of a case study and also the choice for ranking methods influence the relative performance of alternative evaporation methods. This paper considered quantitively the key criteria for comparing the performance of alternative evaporation methods.

5. Concluding remarks

Estimates of evaporation from large open water bodies, among them reservoirs, are required for a variety of purposes in water resource management. Choosing a suitable method for estimating evaporation is imperative to develop accurate regional water balance. This paper ranks evaporation calculation methods considering their accuracy, simplicity, and sensitivity based on a leading multi-attributed decision making approach. The ranking of evaporation methods applies an accuracy index calculated assuming the BREB method as the reference for comparing 12 other methods. Moreover, a simplicity index is defined quantitatively. A sensitivity index is also employed in the comparison and ranking of evaporation calculation methods. The evaporation methods were ranked with the multiple attribute decision making method TOPSIS, a novelty in the comparative evaluation of evaporation methods. This work's results demonstrate the pan method, which is frequently applied to estimate the evaporation from reservoirs, exhibited poor accuracy relative to the Bowen method at Karkheh reservoir. The Stephens-Stewart, Makkink, Jensen-Haise, and Blaney- Criddle methods were the best, second-best, and third-best ranked for calculating evaporation from Karkheh reservoir taking into account the accuracy, simplicity, and sensitivity criteria. The combination methods exhibited poor performance in this paper's ranking.

Acknowledgement

The authors thank Iran's National Science Foundation (INSF) for its financial support of this research.

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

Behzadian, M., *et al.*, 2012. A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications*, 39 (17), 13051–13069.

Blad, B.L. and Rosenberg, N.J., 1974. Lysimetric calibration of the Bowen ratio-energy balance method for evapotranspiration estimation in the central Great Plains. *Journal of Applied Meteorology*, 13 (2), 227–236.

Bowen, I.S, 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physical Review*, 27 (6), 779–787.

Brutsaert, W., 1982. *Evaporation into the atmosphere. theory, history, and applications*. Dordrecht: Reidel Publishing Company.

Brutsaert, W. and Stricker, H, 1979. An advection aridity approach to estimate actual regional evapotranspiration. *Water Resources Research*, 15 (2), 443–450.

Budyko, M.I., 1974. *Climate and life*. New York: Academic Press. 508.

Budyko, M.I., 1977. *Climatic changes*. Washington, DC: American Geophysical Union.

Clark, N.E., *et al.*, 1974. Heat exchange between ocean and atmosphere in the eastern North Pacific for 1961–1971. NOAA Technical Report NMFS (SSRF-682), US Department of Commerce.

Dai, J., *et al.*, 2010. Integrated water resource security evaluation of Beijing based on GRA and TOPSIS. *Frontiers of Earth Science in China*, 4 (3), 357–362.

De Bruin, H.A.R, 1978. A simple model for shallow lake evaporation. *Journal of Applied Meteorology*, 17 (8), 1132–1134.

De Bruin, H.A.R. and Keijman, J.Q, 1979. The Priestley-Taylor evaporation model applied to a large, shallow lake in the Netherlands. *Journal of Applied Meteorology*, 18 (7), 898–903.

Delclaux, F., Coudrain, A., and Condom, T, 2007. Evaporation estimation on lake Titicaca: A synthesis review and modeling. *Hydrological Processes*, 21 (13), 1664–1677.

Dingman, L., 2015. *Physical Hydrology*. Long Grove, IL: Waveland Press Inc.

Dogan, E., *et al*., 2010. Modelling of evaporation from the reservoir of Yuvacik dam using adaptive neuro-fuzzy inference systems. *Engineering Applications of Artificial Intelligence*, 23 (6), 961–967.

Dugas, W.A., *et al*., 1991. Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat. *Agricultural and Forest Meteorology*, 56 (1–2), 1–20.

Finich, J.W., 2001. A comparison between measured and modeled open water evaporation from a reservoir in south-east England. *Hydrological Processes*, 15 (14), 2771–2778.

Fritschen, L.J. and Simpson, J.R, 1989. Surface energy and radiation balance systems: General description and improvements. *Journal of Applied Meteorology*, 28 (7), 680–689.

Hajkowicz, S. and Collins, K, 2007. A review of multiple criteria analysis for water resource planning and management. *Water Resources Management*, 21 (9), 1553–1566.

Hamon, W.R., 1961. Estimating potential evapotranspiration. *Journal of Hydrologic Engineering*, 87, 107–120.

Harbeck, G.E., 1962. *A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory*. Washington: US Government Printing Office.

Ikebuchi, S., Seki, M., and Ohtoh, A, 1988. Evaporation from lake Biwa. *Journal of Hydrology*, 102 (1–4), 427–449.

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

Lang, A.R.G., *et al*., 1983. Inequality of eddy transfer coefficients for vertical transport of sensible and latent heats during advective inversions. *Boundary-Layer Meteorology*, 25 (1), 25–41.

Mahrer, Y. and Assouline, S, 1993. Evaporation from lake Kinneret, estimation of the horizontal variability using a two dimensional numerical mesoscale model. *Water Resources Research*, 29 (4), 911–916.

Majidi, M., *et al*., 2015. Estimation of evaporation from lakes and reservoirs under limited data conditions in a semi-arid region. *Water Resources Management*, 29 (10), 3711–3733.

McGuinness, J.L. and Bordne, E.F., 1972. "A comparson of lysimeterderived potential evapotranspiration with computed values." Technical Bulletin 1452, US Department of Agriculture Agricultural Research Service, Washington, DC.

Mysiak, J., Giupponi, C., and Rosato, P, 2005. Towards the development of a decision support system for water resource management. *Environmental Modelling & Software*, 20 (2), 203–214.

Papadakis, J., 1961. *Climatic tables for the world*. Buenos Aires: Buenos Aires publication.

Rosenberry, D.O., *et al*., 2007. Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA. *Journal of Hydrology*, 340 (3), 149–166.

Schertzer, W.M. and 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.

Sene, K.J., Gash, J.H.C., and McNeil, D.D., 1991. Evaporation from a tropical lake: comparison of theory with direct measurements. *Journal of Hydrology*, 127 (1–4), 193–217.

Sima, S., Ahmadalipour, A., and Tajrishy, M., 2013. Mapping surface temperature in a hyper-saline lake and investigating the effect of temperature distribution on the lake evaporation. *Remote Semsing of Environment*, 136, 374–385.

Stephens, J.C. and Stewart, E.H, 1963. A comparison of procedures for computing evaporation and evapotranspiration. *Publication*, 62, 123–133.

Stewart, R.B. and Rouse, W.R, 1976. A simple method for determining the evaporation from shallow lakes and ponds. *Water Resources Research*, 12 (4), 623–628.

Todd, R.W., Evett, S.R., and Howell, T.A., 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. *Agricultural and Forest Meteorology*, 103 (4), 335–348.

Vallet-Coulomb, C., *et al*., 2001. Lake evaporation estimates in tropical Africa (lake Ziway, Ethiopia). *Journal of Hydrology*, 245 (1), 1–18.

Winter, T.C., Rosenberry, D.O., and 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 (4), 983–993.

Winter, T.C., *et al*., 2003. Evaporation determined by the energy-budget method for Mirror lake, New Hampshire. *Limnology and Oceanography*, 48 (3), 995–1009.

Xing, Z., *et al*., 2008. Validating evapotranspiraiton equations using Bowen ratio in New Brunswick, Maritime, Canada. *Sensors*, 8 (1), 412–428.