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Comparison of methods for estimating loss from water storage by evaporation and impacts on reservoir management

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Keywords
efficiency criteria; evaporation; Karkheh dam; reservoir operation; standard operation policy; sensitivity analysis; TOPSIS.

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Abstract

Reservoirs are the key infrastructure of water resources management. A controlling variable of reservoir operation is evaporation, which in semi-arid and arid regions may consume a large fraction of reservoir storage annually. This paper assesses the role of evaporation and the choice of evaporation methods on reservoir operation. The operation of the reservoir is calculated with the standard operation policy (SOP). Several efficiency criteria are employed to rank the evaporation-calculation methods with the technique for the order of preference by similarity to ideal solution (TOPSIS). The method presented in this paper is illustrated by applying its application to Karkheh reservoir, the largest in Iran.

Introduction

Reservoirs constitute the main infrastructure to store freshwater for human use (Gallego-Elvira *et al*., 2013). Iran, for example, has currently 647 reservoirs in operation (Ministry of Energy of the Water Resources Management Company of Iran). In some regions, the annual evaporation losses from reservoirs may equal a great fraction of the storage capacity (Winter *et al*., 2003). Neglecting the effect of evaporation and its method of estimation on reservoir operation may result in the poor estimation of water storage and substandard reservoir operation (Mays, 2010). The estimation of loss by evaporation takes heightened relevance in the context of climate change context, also.

Rosenberry *et al*. (2007) calculated lake evaporation with 14 different methods. Their results showed that the Penman's method had superior performance compared to other methods. Shakir *et al*. (2008) estimated evaporation in a semi-arid region in India using the Bowen ratio, mass transfer and the Priestley-Taylor methods. The results showed that the Priestley-Taylor method (Priestley and Taylor, 1972) was the most accurate in the study region. Sima *et al*. (2013) estimated evaporation from the Urmia Lake in north-western Iran employing satellite images and the Bowen ratio method. Majidi *et al*. (2015) calculated the evaporation from the Doosti Dam level in northeastern Iran with 18 methods. The results showed methods that depend on the air temperature or a combination of air temperature and solar radiation were the most accurate in the study region. Diamond and Jack (2018) evaluated large evaporative losses in the Gariep River, South Africa, by means of stable isotopes. Their results indicated that evaporation in the Gariep River was about 20% of streamflow or 40 m^3/s.

This study compares evaporation in the Karkheh reservoir, Iran, with 12 evaporation methods. Those 12 methods are divided into five groups. The first group is of the combination type that merges energy budget theory and mass transfer principles Solar radiation-temperature methods are based on empirical equations. They are relatively simple and require few input parameters, and their accuracy varies depending on site-specific conditions.

The temperature and day length methods, such as Hamon's, are derived from potential evapotranspiration and mean air temperature (Hamon, 1961). The Papadakis method is a part of the temperature-based group of methods. It calculates evaporation from the difference of the saturation vapour pressures corresponding to the daily minimum and maximum temperatures (Papadakis, 1961; McGuinness and Bordne, 1972).

Several methods have been proposed for calculating lake evaporation as indicated above. Several studies have chosen the Bowen ratio energy budget (BREB) method as the reference method for comparison purposes (Rosenberry *et al*., 2007; Majidi *et al*., 2015; Bozorgi *et al*., 2020) and so does this work. The evaporation methods are ranked with TOPSIS considering efficiency criteria. Novel themes of this paper are assessing the raw water loss by evaporation through various methods and evaluating the calculated evaporation consequences on the management and operation of the reservoir. Moreover, evaporation methods have been ranked based on the performance of the different indexes.

Methodology

Reservoir operation: The standard operation policy (SOP)

Reservoir operation policies are employed to fulfil reservoir functions. River inflow, water demand, precipitation, evaporation, leakage and sediment input govern reservoir operation. Amongst these variables, evaporation constitutes a major water loss from reservoirs in semi-arid and arid regions (Loáiciga, 2002). This paper employs the SOP for guiding reservoir operation of a reservoir in semi-arid Iran. The SOP is relatively simple and useful, even though may not be optimal compared to optimized policies. The SOP is implemented to illustrate how evaporation estimates influence reservoir operation.

The SOP calculates reservoir releases as a sequence of linear functions of reservoir storage (Harboe and Ratnayake, 1993) as depicted in Fig. 1. The first, rising, limb of the SOP makes an increment of water release equal to the increment of reservoir storage. In the second portion of the SOP, the storage increases while the reservoir release is kept constant. The third portion of the SOP occurs when storage exceeds reservoir capacity, in which case the release, by spill, if necessary, equals the water volume in excess of the reservoir capacity.

The equations of water balance (or continuity equations) in a reservoir applying the SOP are given by Equations (1) and (2) (Harboe and Ratnayake, 1993; Jahandideh-Tehrani *et al*., 2015; Sarzaeim *et al*., 2017b):

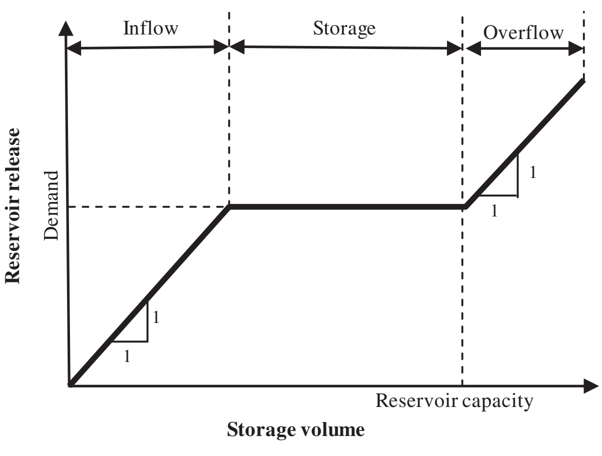

Fig. 1. Standard operation policy (SOP).

$$S_{t+1} = S_t + Q_t - Loss_t - Re_t - GR_t - RSe_t - Sp_t \quad (1)$$

$$Loss_t = \left(\frac{A_t + A_{t+1}}{2}\right)\left(E_t - P_t\right) \quad (2)$$

where S_t and S_{t+1} = the storage at the beginning and end of period t, respectively; Q_t = the inflow volume of the reservoir during period t; $Loss_t$ = water loss (gain) due to evaporation (precipitation) during period t; Re_t = the volume of water released to supply downstream demand during period t; GR_t = the volume of water leakage from the reservoir during period t; RSe_t = the volume of sediment discharge from the reservoir during period t; Sp_t = the volume of overflow (spill) from the reservoir during period t; A_t and A_{t+1} = the reservoir area at the beginning and of period t, respectively; P_t = the precipitation depth on the reservoir during period t; and E_t = evaporation depth from the reservoir during period t.

The storage must be between the minimum (S_{min}) and maximum values (S_{max}):

$$S_{min} \le S_t \le S_{max} \quad (3)$$

The reservoir release and spill are calculated according to the following equations:

$$K_t = S_t + Q_t - Loss_t - GR_t - RSe_t - S_{min} \quad (4)$$

$$Re_t = \begin{cases} De_t & (if \quad K_t \ge De_t) \\ K_t & (if \quad K_t < De_{t)} \end{cases} \quad (5)$$

$$Sp_t = \begin{cases} K_t - S_{max} & (if \quad K_t - Re_t > S_{max}) \\ 0 & (if \quad K_t - Re_t \le S_{max}) \end{cases} \quad (6)$$

where De_t = water demand during period t; K_t = available water in the reservoir in period t.

Efficiency criteria for reservoir operation

The efficiency criteria measure the effectiveness of management policy. This paper implements efficiency criteria in terms of reliability, resiliency and vulnerability introduced by Loucks (1997). The numerical values of the efficiency criteria range between zero and one.

Reliability

Reliability is defined as the probability of success in the operation of a system in a specific period of time: it is an antonym of risk. Reliability is classified as numerical or volumetric. Numerical reliability (Rel_N) is expressed by Equations (7) and (8); it is defined based on the number of deficiencies (N_t) occurring during a period of operation (T):

$$\text{Rel}_N = 1 - \frac{\sum_{t=1}^{T} N_t}{T} \tag{7}$$

$$N_t = \begin{cases} 1 & (if \quad Re_t < De_t) \\ 0 & (if \quad Re_t = De_t) \end{cases} \tag{8}$$

A deficiency occurs when the amount of release is less than the water demand, in which case N_t equals one, otherwise, it equals zero.

The volumetric reliability (Rel_V) is calculated according to the following equation based on the periods in which N_t equals zero:

$$\text{Rel}_V = \frac{\sum_{t=1}^{T} \text{Re}_t}{\sum_{t=1}^{T} De_t} \tag{9}$$

Resiliency

Resiliency represents the probability of a system returning to the desirable state (i.e. successful operation) after a failure (unsuccessful operation):

$$Res = \frac{\sum_{t=1}^{T} N'_t}{\sum_{t=1}^{T} N_t} \tag{10}$$

$$N'_t = \begin{cases} 1 & (if \quad \text{Re}_t < De_t, \text{ and } \text{Re}_{t+1} \geq De_{t+1}) \\ 0 & \text{Otherwise} \end{cases} \tag{11}$$

where N'_t = the number of times a successful operation occurs after an unsuccessful operation.

Vulnerability

Vulnerability measures the largest magnitude of a system failure. It is calculated according to Equation (12):

$$Vul = \frac{max(De_t - \text{Re}_t)}{\sum_{t=1}^{T} (De_t - \text{Re}_t)} \tag{12}$$

Evaporation methods

Methods for calculating evaporation from a free water surface are classified into several groups: energy-budget, combination, solar radiation-temperature, temperature-day length, temperature and pan evaporation method. The equations describing these methods follow next.

Energy methods

The energy-budget method applies the energy conservation equation to a water system. One variant is the Bowen ratio method (BREB), whose effectiveness has been proven in estimating evaporation (Sene *et al.*, 1991; Mahrer and Assouline, 1993). The BREB method is an accurate method for investigating evaporation (Gavilán and Berengena, 2007). The evaporation depth is calculated with the BREB employing Equation (13) (Winter *et al.*, 2003; Rosenberry *et al.*, 2007):

$$E = \frac{Q_{SN} - Q_{LW} - Q_n + Q_{AD-Q_b}}{\rho Le(1+B)} \tag{13}$$

in which E = evaporation rate (ms^{-1}) which is multiplied by 8.64 × 10^7 it is changed to mmd^{-1}; Q_{SN} = net shortwave radiation heat flux (Wm^{-2}); Q_{LW} = net long wave radiation heat flux (Wm^{-2}); Q_n = Net heat flux (Wm^{-2}); Q_{AD} = net heat flux transferred to water surface through precipitation, surface water and groundwater flow (Wm^{-2}); Q_b = heat flux between sediments and water (Wm^{-2}); B = Bowen Ratio (of sensible heat flux to latent heat flux, dimensionless); L_e = latent evaporation heat (J/kg); ρ = freshwater water density (kg m^{-3}).

Typically, Q_{AD} and Q_b are negligible, and Q_n is neglected too because evaporation is calculated in daily time steps (Rosenberry *et al.*, 2007). The Bowen Ratio is calculated from meteorological variables and constants (Bowen, 1926):

$$B = C_b \frac{P}{1000} \frac{T_w - T_a}{e_{sw} - e_a} \tag{14}$$

where P = air pressure (mbar); C_b = Bowen constant equal to 0.61 (1/ºC); T_w and T_a = water surface and air temperature (ºC), respectively; e_{sw} = saturated water vapour pressure at water temperature; and e_a = water vapour pressure (mbar) at the temperature of air measured at a reference height above the water surface (typically 2 m).

The Bowen Ratio energy-budget (BREB) method is commonly used as a reference method for comparing other methods (Winter *et al.*, 2003; Rosenberry *et al.*, 2007; Majidi *et al.*, 2015).

Combination methods

The combination group includes the Priestley-Taylor, DeBruin-Keijman, Penman, Brutsaert-Stricker and DeBruin methods, whose equations are presented in Table 1, where, E = evaporation (mmd^{-1}); S = slope of saturated vapour pressure at air temperature (Pa^oC^{-1}); U_2 = Wind speed at 2 m above ground (ms⁻¹); γ = psychometric constant (Pa^oC^{-1}, actually a variable, see, for example, Monteith and Unsworth, 2008); e_s = saturated vapour pressure at air temperature (mbar); and e_a = water vapour pressure at air temperature measured commonly 2 m above the water surface; β = experimental Priestley-Taylor constant, which is about 1.26 for large water bodies (Stewart and Rouse, 1976; De Bruin and Keijman, 1979; Rosenberry *et al*., 2007).

Solar radiation-temperature methods

The solar radiation-temperature methods are based on empirical formulas involving solar radiation and temperature inputs. Their accuracy depends on site-specific conditions. There are three methods in this group: the Jensen-Haise, Stephens-Stewart and Makkink methods. Their equations are listed in Table 2, where T_a = air temperature (°F) for the Jensen-Haise, Stephens-Stewart methods and Q_s = the incoming solar radiation (Wm^{-2}).

Temperature-day length methods

Amongst the methods based on temperature and daylight hours are the Blaney- Criddle and Hamon methods. Their formulas are listed in Table 3, where, T_a = Air temperature (ºF) for Blaney- Criddle; D_{Ta} = total sunshine hours per year for a given latitude; *SVD* = saturation vapour pressure density at average air temperature (g m^{-3}) and n = the number of daylight hours.

Temperature and pan evaporation methods

The Papadakis method calculates evaporation from the difference of the saturation vapour pressures corresponding to the daily minimum and maximum temperatures according to Equation (25) (Papadakis, 1961):

$$E = 0.5625 \quad [e_{s,max} - e_{s,(min-2)}] \tag{25}$$

where $e_{s,max}$ = saturation vapour pressure at maximum air temperature (mbar) and $e_{s,(min-2)}$ = saturation vapour pressure at a minimum temperature equal to minus 2° and E = estimated evaporation (mm/d).

Evaporation at weather stations is generally measured using the evaporation pan. The evaporation is calculated with Equation (26):

$$E = K \cdot E_{pan} \tag{26}$$

where E_{pan} = pan evaporation and K = lake coefficient, which differs from month to month; an average equal to 0.7 is frequently used (Majidi *et al*., 2015).

Definition of model selection indices

Accuracy index

The accuracy of estimation of the various evaporation methods is evaluated with the root mean square error (RMSE) expressed by Equation (27) (Fallah-Mehdipour *et al*., 2014; Sarzaeim *et al*., 2017a). This paper evaluates the methods' accuracies and compares them with the Bowen Ratio Energy Budget (BREB) method's accuracy.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (E_{\mathrm{BREB}} - E_{\mathrm{method}})^2}{n}} \tag{27}$$

in which n = number of calculation time steps; EBREB = the evaporation calculated with the energy-budget method; E_{method} = the evaporation calculated with a specific method and i = time step.

Simplicity index

Each evaporation method requires inputs to calculate evaporation. A method that is accurate while requiring few and simple input data is preferable to an alternative method with similar accuracy but requiring more elaborate data inputs. The data inputs to the evaporation methods are classified into three categories based on how they are acquired. Cost-effectiveness and data availability are part of the simplicity index. Some monitoring stations, such as synoptic and climatological, gather several input parameters; other stations measure one input parameter. Therefore,

Table 1 Combination evaporation methods

Equation number	Method	Equation	Reference
(15)	Priestley-Taylor	$E=\beta \frac{s}{s+\gamma} \frac{Q_{SN}-Q_{LW}-Q_n}{L_e\rho} \times 86.4$	Stewart and Rouse (1976)
(16)	deBruin-Keijman	$E=\frac{s}{0.85s+0.63\gamma} \frac{(Q_{SN}-Q_{LW}-Q_n)}{L_e\rho} \times 86.4$	deBruin and Keijman (1979)
(17)	Penman	$E=\frac{s}{s+\gamma} \frac{(Q_{SN}-Q_{LW}-Q_n)}{L_e\rho} \times 86.4 + \frac{\gamma}{s+\gamma}(0.26(0.5+0.54U_2)(e_s-e_a))$	Brutsaert (1982)
(18)	Brutsaert-Stricker	$E=(2\beta-1)(\frac{s}{s+\gamma})(\frac{Q_{SN}-Q_{LW}-Q_n}{L_e\rho}) \times 86.4 - \frac{\gamma}{s+\gamma} 0.26(0.5+0.54U_2)(e_s-e_a)$	Brutsaert and Stricker (1979)
(19)	deBruin	$E=1.192(\frac{\beta}{\beta-1})(\frac{\gamma}{s+\gamma})\frac{(2.9+2.1U_2)(e_s-e_a)}{L_e\rho} \times 86.4$	deBruin (1978)

Table 2 Solar radiation-temperature evaporation methods

Equation number	Method	Equation	Reference
(20)	Jensen-Haise	$E = 0.03523 \ \ Q_s \ \ (0.014T_a - 0.37)$	Jensen and Haise (1963)
(21)	Stephens-Stewart	$E = 0.03495\,(0.0082T_a - 0.19)\,(Q_s \times 3.495 \times 10^{-2})$	Stephens and Stewart (1963)
(22)	Makkink	$E = 52.6\frac{s}{s+\gamma}\frac{Q_s}{L_e\rho} - 0.12$	McGuinness and Bordne (1972)

Table 3 Temperature-day length evaporation methods

Equation number	Method	Equation	Reference
(23)	Blaney- Criddle	$E = 25.4\,(0.0173T_a - 0.314)T_a\,\frac{n}{D_{TA}}$	Schertzer and Taylor (2008)
(24)	Hamon	$E = 0.55\left(\frac{n}{12}\right)^2\frac{SVD}{100}\,(25.4)$	Hamon (1961)

simplicity is defined based on the cost-effectiveness and easiness of access to the required data. Methods that require field measurements are ranked as Category 3 (low simplicity); sunshine hours, air pressure and vapour pressure parameters are ranked as Category 2 (average simplicity). Maximum, average and minimum air temperature and wind speed parameters are ranked as Category 1 (simple) because of the simplicity of their measurement and the high density of measurement stations.

Sensitivity index

The parameters of the evaporation estimation methods are meteorological in nature; they are obtained from synoptic stations, hydrometric stations and field studies. These data have errors that affect the estimated evaporation; the less sensitive a method is to the accuracy of the input parameters, the more practical the method becomes. Therefore, sensitivity analysis is herein performed in the form of changes in independent parameters in the range of ±10% (Majidi *et al*., 2015) under five scenarios that reflect different states. The five scenarios are presented in Equations (28) through (32):

$$S_I = X \times 10\% \qquad \text{increase the parameter by 10\%} \tag{28}$$

$$S_{II} = X \times (-10\%) \text{decrease the parameter by 10\%} \tag{29}$$

$$S_{III} = X \times Rand_{(0,10)\%} \quad \text{increase the parameter randomly between 0 and 10\%} \tag{30}$$

$$S_{IV} = X \times Rand_{(-10,0)\%} \quad \text{decrease the parameter randomly between } -10\% \text{ and } 0 \tag{31}$$

$$S_V = X \times Rand_{(-10,10)\%} \text{change the parameter randomly between -10 and 10\%} \tag{32}$$

where $S_I, S_{II}, S_{III}, S_{IV}$ and S_V = the first, second, third, fourth and fifth scenarios, respectively; X = each independent input parameter of the evaporation estimation methods and *Rand* = random number in the cited ranges.

Sensitivity analysis is conducted by changing one parameter, while other parameters remain constant under each scenario. Thereafter, the sensitivities of the method to each parameter are added up to produce the sensitivity of that method according to a specific scenario. This process is repeated for all the scenarios. The calculation of sensitivity relies on Equation (33):

$$a_{ij} = \sum_{k=1}^{9} |y_{ijk}| \qquad i = 1, 2, \ldots, 12; \ j = 1, 2, \ldots, 5 \tag{33}$$

in which a_{ij} = sensitivity of the *i*th method under the *j*th scenario (there are 5 scenarios); y_{ijk} = the sensitivity of the *i*th method under the *j*th scenario with respect to the independent *k*th variable. Not all methods use nine independent input parameters to estimate evaporation. Therefore, the sensitivity of the method equals zero for a parameter that does not enter the calculations. A low value of a_{ij} indicates low sensitivity of a method with respect to the corresponding input parameters.

Multi-criteria decision making

The selection of the best equation amongst evaporation methods most considers the accuracy of estimation, efficiency criteria, simplicity and sensitivity indices. These indices have the same weight for ranking of methods; therefore, each index has the same share of determining the best methods. The decision analysis method of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied in selecting the best method for estimating evaporation. TOPSIS ranks the evaporation

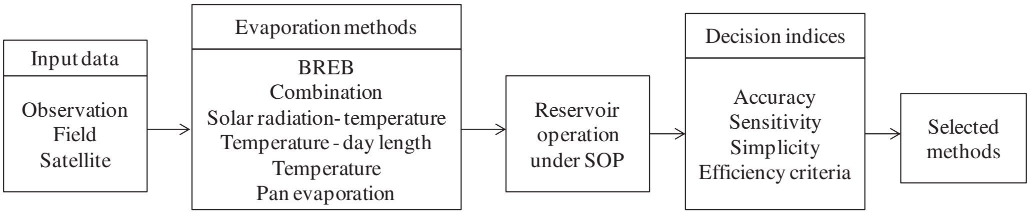

Fig. 2. Flowchart of this paper's methodology.

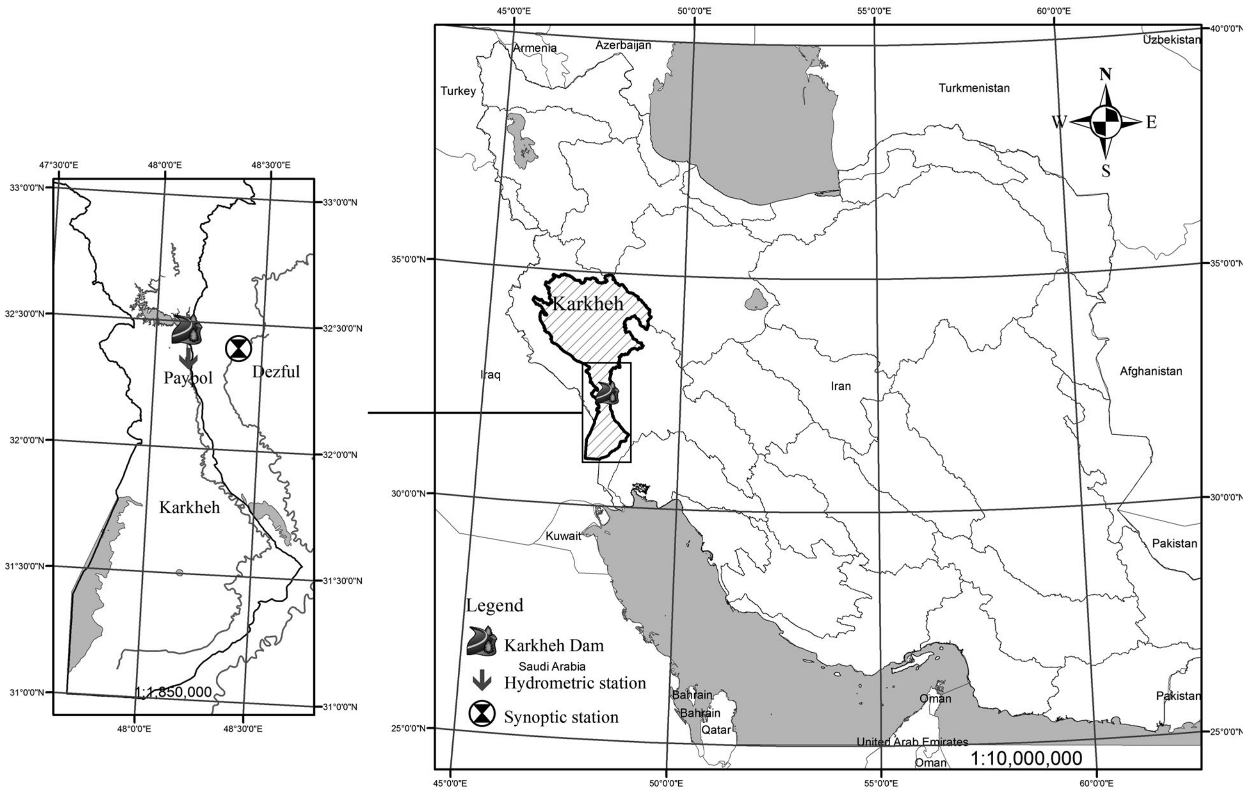

Fig. 3. Karkheh reservoir location and data measurement stations.

methods based on the shortest distance from the positive ideal solution (the best possible condition) (quantified by the *CL* parameter as relative closeness) and the longest distance from the negative ideal solution (the worst possible condition) for more details see Bozorgi *et al*. (2020). The flowchart of this paper's methodology is displayed in Fig. 2.

Case study

Karkheh reservoir which supplies agricultural demand with the raw water is the largest reservoir in Iran and the sixth largest dam in the terms of storage capacity in the world. The Karkheh reservoir area equals 166 km^2, it is 64 km long and stores 5 billion cubic metres storage at a normal level (220 m above seawater), which is equivalent to one-third of the water storage of Iran's dams. A location map of the Karkheh reservoir is shown in Fig. 3.

The data required for calculating of reservoir operation were obtained from the Ministry of Energy of the Water Resources Management Company of Iran. Also, the data required to calculate evaporation were collected from Dezful Synoptic Station located 27 km from the dam site. The data were taken from Iran's meteorological organisation (IMO) from 2004 to 2009. For this case study, the monthly average precipitation, reservoir inflow and annual average temperature equal 22.5 mm, 277.5 × 10^6 m^3 and 15.3ºC, respectively. The pan evaporation data were collected daily

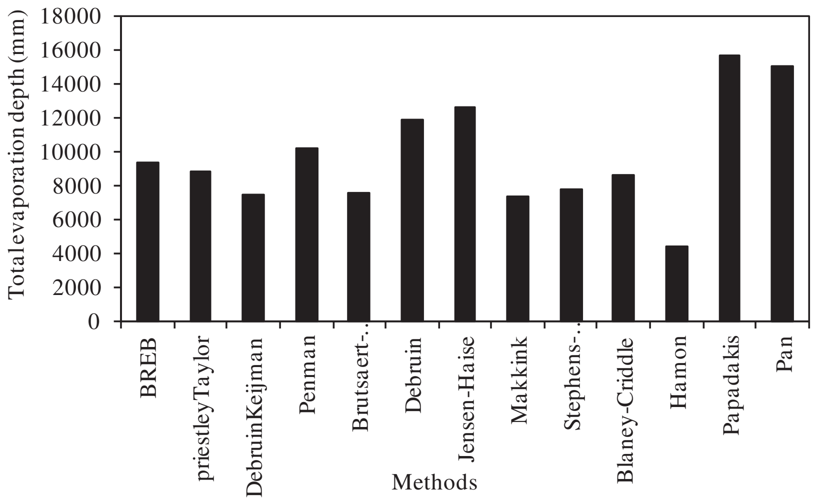

Fig. 4. Total evaporation (mm) from the Karkheh reservoir during 2004–2009.

at the Paypal hydrometric station from 2004 to 2009 which is the nearest station to the case study. The location of the station is illustrated in Fig. 3. Water surface temperature parameter was measured in the field at distances of 0, 43, 52 and 64 kilometres from the Karkheh dam in 2006–2007. Satellite images were used to fill data gaps due to the inconsistency between the time coverage of water temperature measurements and time interval employed in the reservoir operation in this research. This work applied the MOD11A1 of the MODIS sensor on the Terra satellite with 36-band, 12-bit radiometric resolution, daily temporal resolution, with a spatial resolution of 1 km. The correlation between field data and satellite imagery was calculated with R^2 = 0.86 with and slope coefficient equal to 0.7. This correlation is employed to calibrate satellite data; the daily calibrated water temperature data are used to estimate daily evaporation. Daily evaporation is summed to calculate monthly evaporation for reservoir operation.

Results and discussion

The operation of the Karkheh reservoir under SOP was carried out using evaporation values obtained from the various evaporation methods with a monthly time step (71 months total in the reservoir operational period). The evaporation values calculated with the various methods differ amongst themselves; thus, the simulated reservoir storage also differs amongst the various methods during the operational period. The effect of evaporation methods, which are site sensitive, on reservoir operation was assessed by evaluating the differences between storage, performance indices and efficiency criteria calculated with the various methods.

The calculated evaporation depth obtained from different methods is shown in Fig. 4. The evaporation depth which was calculated by the BREB method cumulatively over the study period (2004–2009) equals 9,343 mm. The Priestley-Taylor and Papadakis methods were, respectively, the best and worst methods in terms of the accuracy of the estimation of evaporation depth. The evaporation calculated with each method was converted to evaporated water volume and was given as input to the SOP for Karkheh reservoir operation. The calculated evaporation volume during the operational period is displayed in Fig. 5. Water storage and reservoir area were calculated based on geometric characteristics relate to water elevation, reservoir area and reservoir storage. The cumulative or total water storage during the operating period corresponding to the various evaporation methods is depicted in Fig. 6. The total storage calculated with the BREB method equals 157 million cubic metres. The Priestley-Taylor and pan evaporation methods are, respectively, the best and the worst

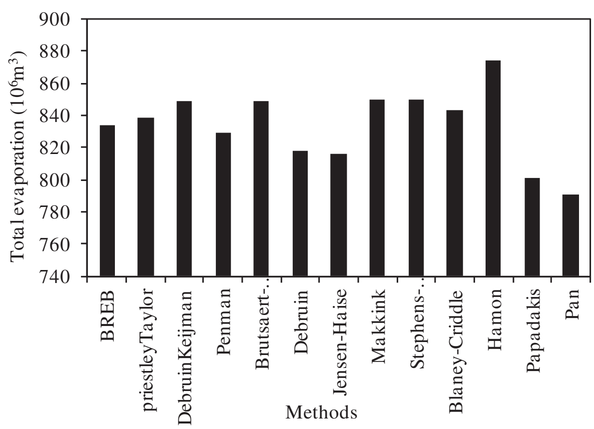

Fig. 5. Total evaporation (10^6 m^3) from the Karkheh reservoir during 2004–2009.

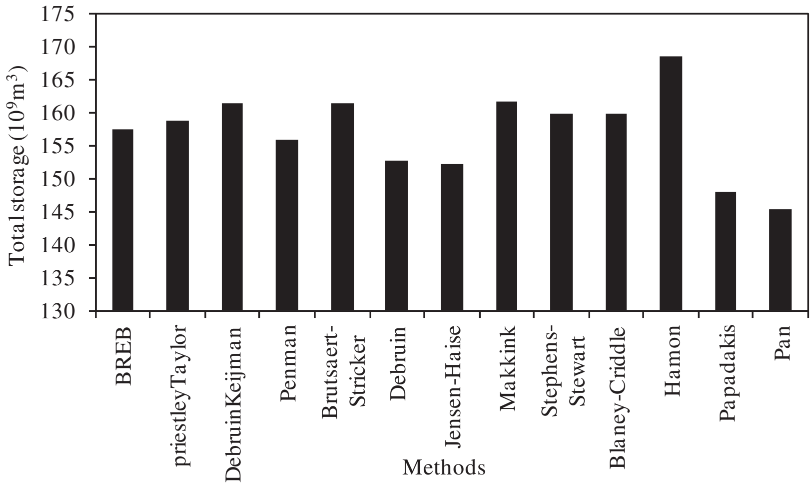

Fig. 6. Total storage in the Karkheh reservoir during 2004–2009.

Table 4 The difference between reservoir storage calculated with each evaporation method and with the reference (BREB) method

Group	Method	Difference (109m3)	Percentage of water demand
Combination	Priestley-Taylor	1.37	5.67
	DeBruin-Keijman	4.12	17.04
	Penman	–1.44	–5.96
	Brutsaert-Stricker	4.18	17.29
	DeBruin	–4.64	–19.17
Solar radiation-temperature	Jensen-Haise	–5.06	–20.92
	Makkink	4.31	17.81
	Stephens-Stewart	2.51	10.37
Temperature-day length	Blaney- Criddle	2.51	10.37
	Hamon	11.17	46.19
Temperature	Papadakis	–9.42	–38.92
Pan evaporation	Pan evaporation	–12.00	–49.60

methods in terms of accuracy of the estimation of storage. The evaporation volume is calculated by multiplying evaporation depth by reservoir area. The geometry of the reservoir is obtained from surface-volume-height formulas showing a small decrease in water elevation causes a major reduction in reservoir area and volume. Therefore, the evaporation depth causes a remarkable change in loss volume and consequently it affects reservoir operation.

The Priestley-Taylor method, being the most accurate for calculating evaporation, overestimates reservoir storage by 1.37 billion cubic metres compared to the reference BREB method. This overestimation error equals 5.67% of the total water demand (24×10^6 m^3). The pan evaporation method, being the least accurate, underestimated reservoir storage by 12 billion cubic metres over the study period, which amounts to an error equal to 49.46% of the total water demand.

Table 4 lists the performance of the various evaporation methods related to the BREB method. The application of evaporation methods that overestimate the storage would cause deficits in water supply; conversely, applying methods that underestimate the storage would cause errors in flood control. Table 4 illustrates that a few millimetres of error in calculating the evaporation depth can lead to an error of up to several billion cubic metres of water in reservoir storage.

Figure 7 depicts the differences between the values of storage calculated with the evaporation methods and with the reference method (BREB). Pan evaporation exhibits the largest difference in the calculated storage (2 billion cubic metres in a year), while the Priestley-Taylor method produced the smallest difference (0.24 billion cubic metres in a year).

The accuracy of storage estimation was assessed with the RMSE (the reference method was BREB). The decision matrix (a_{ij}) corresponding to volumetric and numeric reliability, resiliency, and vulnerability, simplicity and sensitivity with respect to each evaporation method is listed in Table 5. The values listed in Table 5 served as input to TOPSIS for ranking the methods. The ranking of evaporation methods is listed in Table 6.

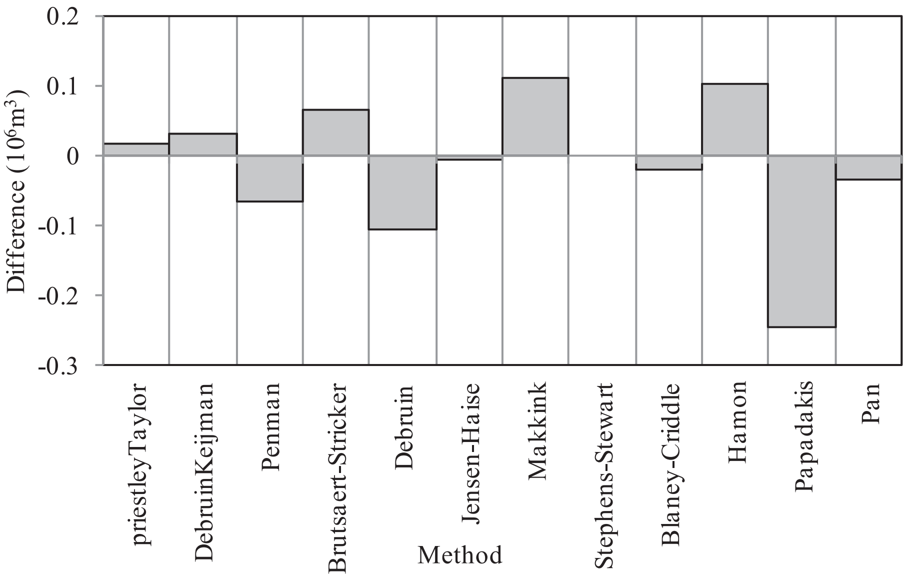

Fig. 7. The annual difference between storage calculated with evaporation methods and with the reference (BREB) method.

Table 5 Decision matrix (a_{ij})

Criteria methods	$RMSE_{storage}$ (MCM)	Efficiency criteria				Sensitivity					Simplicity
		***Rel**$_N$* (%)	***Rel**$_V$* (%)	***Res*** (%)	***Vul*** (%)	S_I (%)	S_{II} (%)	S_{III} (%)	S_{IV} (%)	S_V (%)	
Priestley-Taylor	25.07	76.05	74.41	18.11	11.76	64.91	8.39	30.73	32.80	65.73	3
DeBruin-Keijman	75.94	77.46	77.52	17.80	12.50	63.69	8.34	30.28	32.20	64.63	3
Penman	27.87	76.05	74.41	18.35	11.76	38.77	1.25	19.48	19.51	38.31	3
Brutsaert-Stricker	76.64	77.46	77.52	17.83	12.50	130.12	26.17	62.85	54.22	133.25	3
DeBruin	88.13	74.64	73.49	18.64	5.55	40.23	0.43	20.83	20.47	41.69	2
Jensen-Haise	96.68	74.64	73.49	18.78	5.55	11.06	0.20	5.53	5.47	11.06	2
Makkink	78.07	77.46	77.52	17.75	12.50	8.53	0.10	4.45	4.32	8.96	2
Stephens-Stewart	44.68	77.46	77.52	17.85	12.50	10.47	0.19	5.24	5.27	10.47	2
Blaney- Criddle	44.69	77.46	77.52	18.06	12.50	23.45	0.62	11.37	11.74	22.60	2
Hamon	205.21	77.46	77.52	17.07	12.50	35.69	1.31	16.26	17.68	31.90	2
Papadakis	179.21	77.46	73.49	19.31	5.55	35.15	1.23	15.43	17.34	30.10	1
Evaporation pan	219.56	76.05	74.41	19.20	11.76	10.00	0.19	5.01	5.03	10.00	1

Table 6 Ranking of different methods based on TOPSIS

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

The relative closeness of each method to the ideal state is determined by the *CL* index and shown in Fig. 8. The evaporation methods can be divided into three categories based on the TOPSIS ranking. The first group includes the Jensen-Haise, Stephens-Stewart and Makkink methods from the solar radiation-temperature group and the Blaney-Criddle method from the temperature-day length group. The solar radiation-temperature group exhibits desirable accuracy in the estimation of reservoir storage. Based on the indicators of simplicity and sensitivity, the radiation-temperature group achieved a favourable ranking amongst all the methods. Therefore, this is the best-ranked group of methods. The next group includes the deBruin and Penman methods from the combination group, the Hamon,

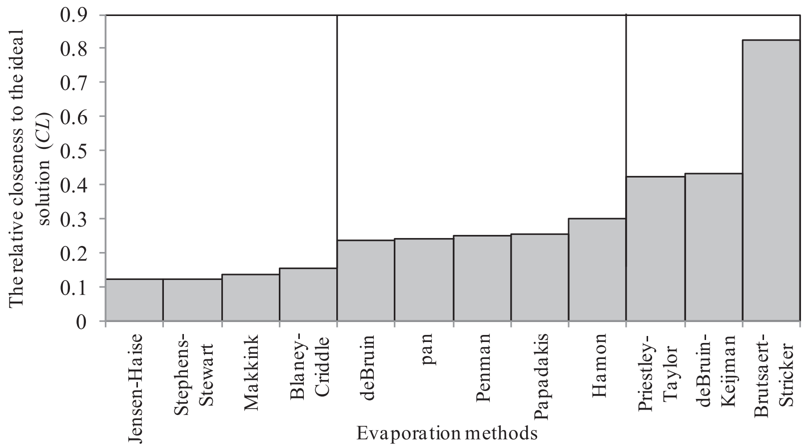

Fig. 8. The ranking of methods for estimating evaporation with TOPSIS.

Papadakis and the pan evaporation methods. Though the accuracy of the pan evaporation method is low, this method has a favourable ranking considering other indices. Therefore, it achieved a suitable overall rating. The last category comprises the Priestley-Taylor, deBruin-Keijman and Brutsaert-Stricker methods from the combination group. The combination group had the best performance according to accuracy (RMSE); yet, it had low ranking according to other indices such as sensitivity and simplicity, thus being the lowest ranked group of methods by TOPSIS.

Concluding remarks

The operation of the Karkheh dam under SOP was simulated considering evaporation calculated with several methods. Accuracy and efficiency criteria for each evaporation method were calculated. The Priestley-Taylor and Penman methods among the combination group of methods, and the Stephens-Stewart, and Blaney-Criddle methods were the most accurate methods, with their RMSE values for calculated reservoir storage ranging from 25.07 to 44.69 million cubic metres, respectively. The Papadakis, Hamon and pan evaporation methods were the least accurate methods for estimating reservoir storage during Karkheh reservoir operation with RMSE ranging 21 to 192.56 million cubic metres in order. The pan evaporation method underestimated reservoir storage by 12.00 billion cubic metres, which is equivalent to 49.5% of the total water demand during the operation period. An evaporation error of a few millimetres amount to billions of cubic metres of error of reservoir storage. This paper's results show various methods to calculate evaporation produce differences in reservoir storage ranging between 1.37 and 12 billion cubic metres, which has large implications for reservoir operation. The TOPSIS ranking of methods to calculate evaporation considering accuracy, efficiency criteria, simplicity and sensitivity identify the solar radiation-temperature methods and Blaney-Criddle method as the best methods for calculating evaporation.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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