ORIGINAL ARTICLE

More reliable determination of daily evaporation from the pan in cold regions by limited meteorological factors

Mehdi Mohammadi[1] · Meysam Salarijazi[1] · Khalil Ghorbani[1] · Amir-Ahmad Dehghani[1]

Abstract

Evaporation from water surfaces is influencing many environmental science processes. Evaporation from pan data is not available as the most well-known method of determining evaporation in many areas, and therefore, the application of experimental mathematical equations in this field is considered. Most of the data for extracting these equations did not belong to cold regions, and as a result, the accuracy of these equations in cold regions has low reliability. In this study, the equations of Trabert (Meteorol Z 13:261–263, 1896), Kohler (Tech Rep Geol Survey Prof Paper 269:127–148, 1954), Kohler et al. (Evaporation from pans and lakes, US Government Printing Office, Washington, 1955), Papadakis (Soil Sci 93:76, 1961), Ântal (Evapotranspiration from com field. Term paper submitted for Dr. R. F. Dale's Agronomy 537 class. Received from personal communication with Dr. Dale (Dept. of Agronomy, Purdue, 1973), Linacre (Agric Meteorol 18:409–424, 1977), Linacre (Water Int 19:5–14, 1994) in Two default and revised modes (14 equations in total) have been used to determine evaporation in cold regions (Emberger climate classifications). Performance index (PI) as an error metric was used to analyze the efficiency of the equations. Findings show that in the absence of proper datasets for revision, Kohler et al. (Evaporation from pans and lakes, US Government Printing Office, Washington, 1955) and Papadakis (Soil Sci 93:76, 1961) equations are more proper options for determining evaporation in cold regions. The revision process increased the efficiency of all equations, with the slightest improvement for Papadakis (Soil Sci 93:76, 1961) and the most improvement for Trabert (Meteorol Z 13:261–263, 1896). According to the behavior of Papadakis (Soil Sci 93:76, 1961) equation in the revision process and its efficiency in both default and revision modes, it can be considered a firm equation in the cold region. The findings reveal that the revised equations have little efficiency difference. It indicates that in cold regions, the influence of the default parameters of the equations on efficiency is more significant than their mathematical formula of the equation. Also, the revision has led to Trabert (Meteorol Z 13:261–263, 1896) equation with relatively good results due to less relative flexibility than other equations. Therefore, it can be concluded that the essential factor to increase the reliability of the application of experimental mathematical equations in determining evaporation from the pan is the use of revised equations with data from cold regions. In addition, among all the equations studied, the revised Kohler et al. (Evaporation from pans and lakes, US Government Printing Office, Washington, 1955) equation was recognized as the most efficient equation for determining evaporation from the pan in the cold regions studied.

Keywords Free surface water evaporation · Optimization of mathematical formula of equation · Emberger · Reliable estimation · Spatial analysis · Cold regions

Introduction

Evaporation is one of the most crucial water balance factors in many natural resources studies considering the spatial and temporal scales (Chen et al. 2019; Hooshmand et al. 2013). A large proportion of the rainfall is lost due to evaporation (Althoff et al. 2019). Evaporation is usually lower in cold regions than other regions (Wu et al. 2016). However, evaporation is a significant factor in analyzing water requirements in cold regions. In cold regions, lakes, wetlands, and water bodies are often abundant (Woo et al. 2008). Due to meteorological changes, the amount of evaporation from water bodies in cold regions has increased significantly, so it is necessary to conduct studies for evaporation determination in cold regions (Woolway et al. 2020). The evaporation pan is the most well-known method for determining evaporation from

---

Extended author information available on the last page of the article

the water surface (Roderick et al. 2004). Evaporation pans are standard at stations that measure meteorological factors (Lu et al. 2018). Due to the remarkable costs of construction, maintenance, and repair of meteorological stations in many areas, access to evaporation data from the pan is impossible (Wu et al. 2020). Experimental mathematical equations to reveal the governing equations of the evaporation phenomenon have been developed to overcome this problem (Qasem et al. 2019). Although the use of new models such as Support Vector Machine (Chen et al. 2019), Neural Networks (Majhi and Naidu 2021), and KNN (Al-Mukhtar 2021) has been considered by researchers in recent years, the mathematical formula of the equation for these models has led to little use in practice in engineering and application projects. Attention to features such as revision in specific meteorological conditions, explicit equations, and available factors make the extracted equations practical. Most studies in the field of evaporation determination have concentrated on different aspects (McMahon et al., 2013), such as actual evaporation from non-saturated surfaces (Anayah and Kaluarachchi 2014), potential evaporation (Kohler and Parmele 1967), lake and storage evaporation (McJannet et al. 2008), reference evapotranspiration (Hargreaves and Allen 2003) and evaporation from shallow lake and pond (Valiantzas 2006).

The equations presented for the study of surface evaporation are varied. However, it should be noted that the data required for these studies are generally unavailable and must be measured for each study. These problems make the application of related equations face severe limitations. Consequently, it is impossible to study the efficiency of the equations in different geographical and meteorological conditions. One of the evaporation pan features is its use in many meteorological stations in different meteorological and geographical conditions. As a result, access to its various data is less limited than other evaporation aspects. A review of the studies shows that studies on the determination of evaporation from the pan compared to similar cases are much less diverse. Therefore, the need for more studies in this field becomes apparent.

On the other hand, the study of the equations developed to determine the evaporation from the pan indicates that most equations require radiation as one of the main input factors. Measured radiation data are more limited than other factors such as temperature, wind velocity, and relative humidity. Therefore, equations that use radiation as one of the main factors also have practical limitations in many regions. Among the equations that use radiation as a significant factor to determine evaporation from the pan can be pointed out to PenPan (Rotstayn et al. 2006), Grifiths (Griffiths 1966), Mehta (Christiansen 1966), Stephen-Stewart (Stephen and Stewart 1963), Christiansen (Christiansen 1960), and Prescott (Prescott, 1940) and Rohwer (Rohwer, 1931). Some

equations have been proposed to determine the amount of evaporation from the pan using limited meteorological factors. However, research in this area has been lower than in similar cases (Wang et al. 2023).

Temperature values measured in cold regions are much lower than in other regions (Salarijazi et al. 2023). Also, some meteorological factors, such as relative humidity and wind velocity, have their characteristics in these regions. Due to the different characteristics, it is essential to study the efficiency of the equations for determining evaporation from the pan in these regions. Also, due to the significant influence of evaporation factors in different fields, the study of selecting equations with more reliability is necessary to determine evaporation in cold regions. Literature reviews in studies applying cold region data indicate the non-simultaneous attention to some necessary conditions to increase the reliability of the equations for determining evaporation from the pan. Suppose conditions such as 1—application of data only from the cold region, 2—development of straightforward equations, and 3—application of a limited number of meteorological factors with a wide range of changes are not conducted simultaneously. In that case, the extracted equations, in addition to low reliability, are not proper in practical use.

This study aims to investigate and revise the evaporation equations of the pan to improve their reliability in cold regions. One of the most critical features of experimental equations is that researchers and engineers use them in various studies. These equations must have reliability in addition to being practical. In this research, the following conditions have been considered for selecting the study region and experimental equations: A—The datasets used belong to cold regions, and the number of them is the maximum amount available concerning quality. B—Meteorological factors in the study areas have a wide range of changes. C—Default equations are presented to determine evaporation from the pan D—Experimental equations studied are diverse E- Mathematical formulas of equations are clear and straightforward and, therefore, can be easily revised by conventional methods. What distinguishes this study from similar cases is that it seems it has not been done in cold regions considering the above conditions.

Materials and methods

Emberger classification

The climate is classified based on evaporation, temperature, and precipitation as critical meteorological factors by Emberger (1930). The precipitation (P in millimeters) is considered on an annual time scale (Derouiche et al. 2022). The mean of maximum temperatures of the hottest month

and average of the minimum temperatures of the coldest month in the year by M and m notation is considered for the temperature factor (Vessella et al. 2022). It has to be noticed that M and m are the strict thermal limits for vegetation growth. However, the temperature factor is considered by $(M/2 \uparrow + m/2)$ in the Emberger classification (Canturk and Kulaç, 2021). Also, the $(M - m)$ as temperature range is the term of the equation for the evaporation factor. The following equation is used for the classification (Caloiero et al. 2016).

$$Q = \frac{1000.P}{\left(\frac{M+m}{2}\right).(M - m)} = \frac{2000.P}{M^2 - m^2} \quad (1)$$

The Emberger climatogram uses Q and m for *y*- and *x*-axes presented in Fig. 1 (Dereure et al. 2009).

Study region

Iran is located in the Middle East, and a range of different meteorological conditions can be identified (Roshan et al. 2017). In this study, the Emberger classification has been used to identify cold region datasets. Initially, 40 datasets were examined using the Emberger classification system, and finally, 23 cases were selected as cold regions datasets. These datasets are located in large areas of Iran's geographical conditions, and their location is shown in Fig. 2. These datasets are in the range of longitude 45° 3′19″ to 60° 54′ 11″ and latitude 40° 33′ 29″ to 38° 18′ 17″ (Modabber-Azizi et al. 2023).

Studied datasets

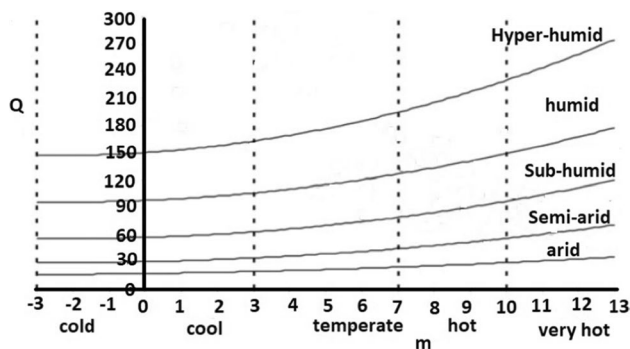The datasets used in this study have been measured in meteorological stations belonging to the Meteorological

Fig. 1 The Emberger climatogram (Dereure et al. 2009)
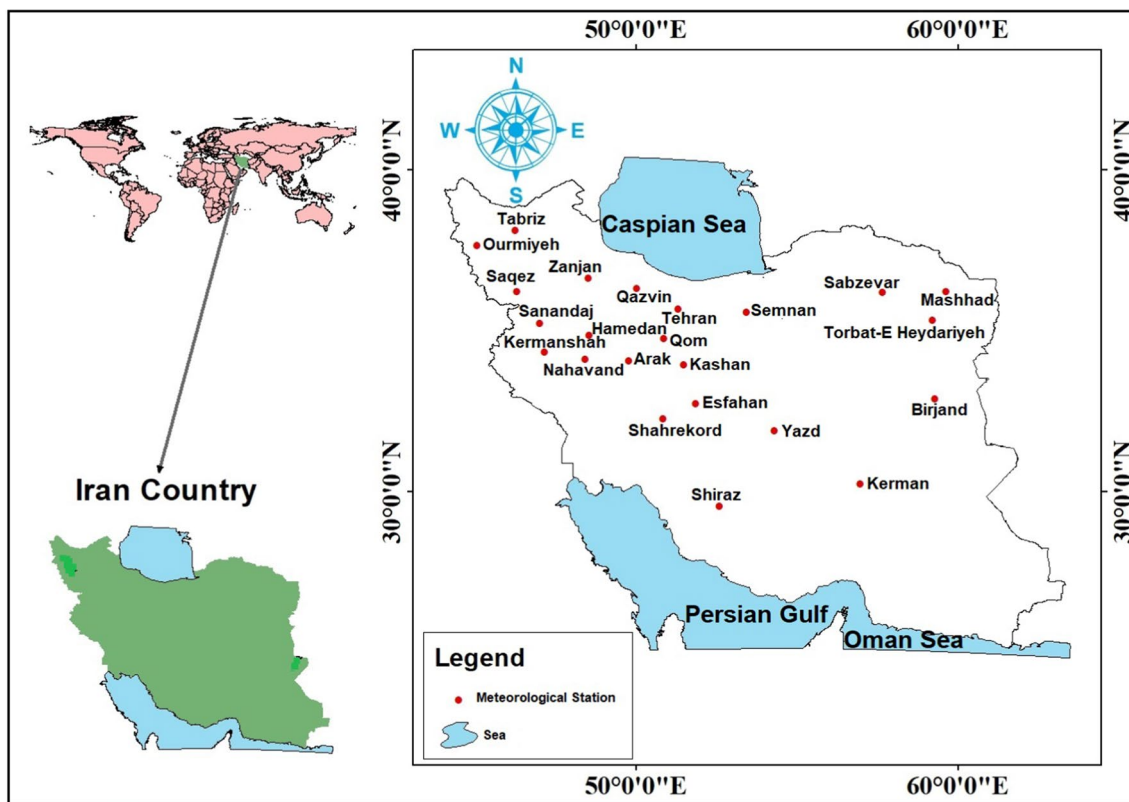

Fig. 2 Location of cold region datasets

Organization of Iran. The information and location of these datasets are presented in Fig. 2 and Table 1. The proper quantity and quality of data have been the most critical criterion in selecting these datasets. The various steps of data pre-processing include the preparation of data and arrangement, the examination of missing data, the identification of marginal data, the study of the Emberger classification, and in the final steps, the selection of proper datasets with details Illustrated in Fig. 3. This study's evaporation data are recorded using class A pans. Class A evaporation pans are used in meteorological stations worldwide, including in Iran. This evaporation pan has a diameter of 121 cm and a depth of 25 cm and is installed slightly above the ground (Shammout et al. 2018).

Box plots of metrological factors in the studied cold regions are presented in Fig. 4. Paying attention to the range of changes of these metrological factors indicates the range and extent of their significant changes. This feature will increase the reliability of the analysis because the related analysis will be valid in a wide range of meteorological factors. Another feature identified in Fig. 4 is that meteorological factors such as temperature, relative humidity, and evaporation show a regular within-the-year pattern. The presented box plot shows the statistical features of the studied datasets.

Experimental equation to determine evaporation from the pan

Evaporation from the pan is measured at well-equipped stations. However, meteorological factors such as temperature, relative humidity, and wind velocity are measured in many regions. In contrast, evaporation data from the pan are not measured or are limited (Gavili et al. 2018). In addition, the measured evaporation data in many datasets do not have a long measurement period and, in many cases, are accompanied by a significant amount of missing data (Abtew et al. 2011). Some research has been done to develop experimental equations for determining evaporation from the pan (Terzi and Keskin 2010). In these experimental equations, an attempt is made to determine the amount of evaporation using a mathematical formula based on some meteorological factors (Irmak and Haman 2003). A set of equations was developed to determine evaporation from the pan using the radiation factor (Xu and Singh 2000). The radiation factor is much less available than wind velocity, temperature, relative humidity, and evaporation (Fulton et al. 2005). This research does not study the experimental mathematical equations that use radiation as an input factor, considering the

Table 1 Information about studied datasets

Dataset Code	Dataset Name	Elevation (m)	Longitude	Latitude	m (°C)	Q
NW1	Tabriz	1361	46°14′ 31″	38° 17′ 18″	−5.81	25.26
NW2	Orumiyeh	1328	45° 3′ 19″	37° 39′ 30″	−6.6	30.75
W1	Saqez	1522.8	46° 18′39″	36° 13′ 18″	−8.5	39.31
W2	Sanandaj	1373.4	47° 0′ 52″	35° 15′ 15″	−5.65	35.08
W3	Kermanshah	1318.5	47° 9′ 11″	31° 21′ 7″	−3.38	35.78
C1	Zanjan	1659.4	48° 31′ 18″	36° 39′ 37″	−7.3	27.32
C2	Qazvin	1279.1	50° 1′ 12″	36° 19′ 9″	−4.7	27.02
C3	Tehran	1191	51° 18′ 33″	35° 41′ 35″	−0.1	21.25
C4	Semnan	1127	53° 25′ 16″	35° 35′ 17″	−0.43	12.29
C5	Hamedan	1740.8	48° 32′ 4″	34° 52′ 9″	−8.34	25.37
C6	Qom	879.1	50° 51′ 19″	34° 46′ 28	−1.22	11.17
C7	Nahavand	1677.8	48° 24′ 43″	34° 8′ 36″	−4.48	31.67
C8	Arak	1702.8	49° 46′ 59″	34° 4′ 18″	−5.6	28.06
C9	Kashan	955	51° 28′ 50″	33° 58′1″	−0.42	10.96
C10	Esfahan	1551.9	51° 51′ 47″	32° 44′ 39″	−5.59	8.3
C11	Shahrekord	2048.9	50° 50′ 21″	32° 14′39″	−8.57	26.2
C12	Yazd	1230.2	54° 17′ 21″	31° 54′ 14″	−0.23	4.86
C12	Kerman	1754	56° 47′ 42″	30° 15′20″	−3.21	12.51
C14	Shiraz	1488	52° 36′ 18″	29° 33′40″	−0.05	29.38
E1	Birjand	1491	59° 16′ 59″	32° 53′ 26″	−2.37	14.67
NE1	Torbat-E Heydariyeh	1451	59° 12′ 20″	35° 19′ 12″	−4.42	23.18
NE2	Sabzevar	962	58° 37′ 57″	36° 12′ 25″	−1.47	15.97
NE3	Mashhad	999.2	59° 37′ 51″	36° 14′ 11″	−3.46	22.68

Fig. 3 Pre-processing steps for cold regions datasets
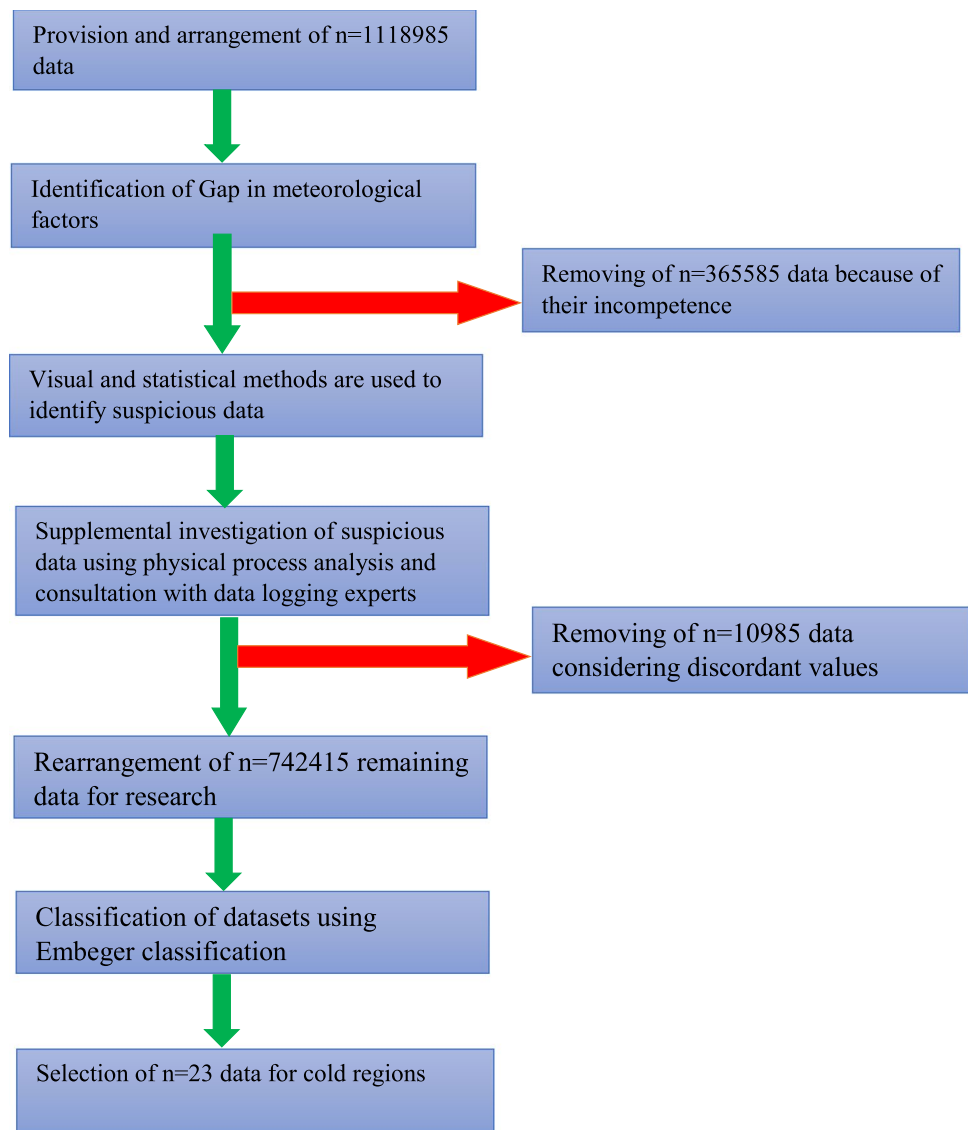
mentioned applied aspect. Considering that factors such as wind velocity, temperature, and relative humidity are more available than other meteorological factors, the experimental equations that ultimately use these three factors have been investigated in this study (Salarijazi et al. 2023).

Trabert (1896) experimental equation

The experimental equation presented by Trabert (1896) is one of the most widely used equations for determining evaporation from the pan, which is very well-known (Lu et al. 2018). Temperature, relative humidity, and wind velocity are considered meteorological factors of the inputs of the equation (Guan et al. 2020). One of the features of this equation is that it assumes that the wind velocity radical is associated with evaporation, which can be a limiting assumption

(Mohammadi et al. 2021). Trabert (1896) equation, like Papadakis (1961) equation, uses only one parameter to determine evaporation.

$$e_p = \gamma_1 \sqrt{v}(e_s - e_d) \qquad (2)$$

In the Trabert (1896) equation, e_p is determined evaporation from a pan (mm/day), v is wind velocity at the height of 2 m above the ground (m/s), $(e_s - e_d)$ is vapor pressure deficit (kPa) and $\gamma_1 = 0.3075$ is the default parameter.

Kohler (1954) experimental equation

One of the primary research for determining water evaporation is well-known to the Lake Hefner studies. Using the data set measured in this study, Kohler (1954) presented an experimental equation for determining evaporation from the
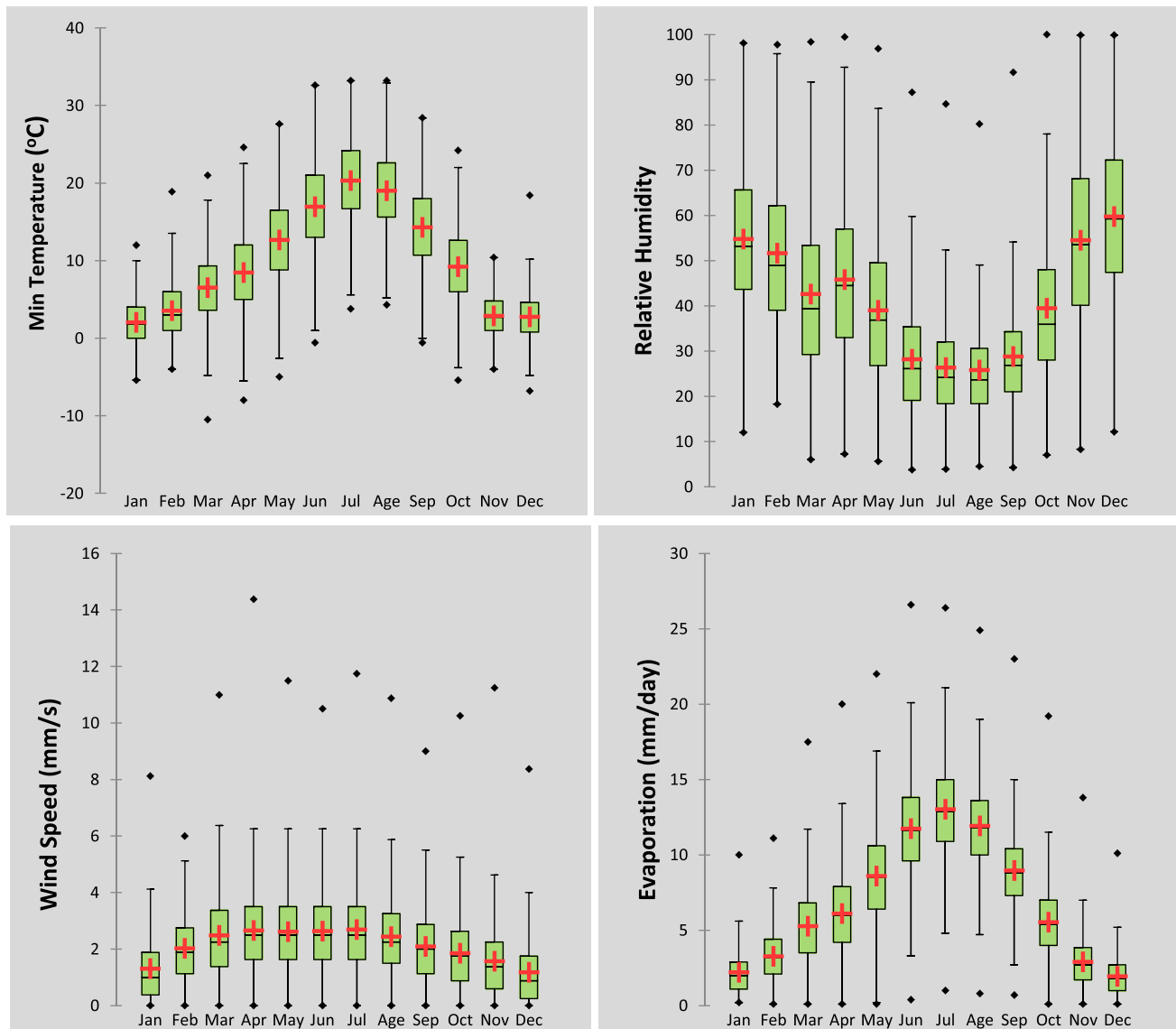
Fig. 4 Box plot of meteorological factors in cold regions

pan. There is a fundamental difference between the Kohler (1954), Antal (1973), and Papadakis (1961) equations, and it is that in Kohler (1954), the wind velocity is also used to determine evaporation (Song et al. 2020).

$$e_P = (e_s - e_d)(\gamma_2 + \gamma_3 v_P) \tag{3}$$

In Kohler (1954) experimental equation, e_P is the amount of determined evaporation from the pan (in/day), $(e_s - e_d)$ is vapor pressure deficit (in Hg), v_P the wind velocity at the standard height of the installation of the evaporation pan from the ground (miles/ day) and $\gamma_2 = 0.42, \gamma_3 = 0.004$ are the default parameters of Kohler (1954) equation.

Kohler–Nordonson–Fox (1955) experimental equation

Further studies by Kohler et al. (1955) revealed that using a power relationship between evaporation from the pan and the vapor pressure deficit is more efficient than the linear relationship (Izady et al. 2020). Based on this, they presented an equation as a revised mathematical formula compared to Kohler (1954) equation. The new equation, Kohler–Nordonson–Fox (1955), has been considered by researchers in various studies (Althoff et al. 2020).

$$e_P = (e_s - e_d)^{\gamma_4}(\gamma_5 + \gamma_6 v_P) \tag{4}$$

In the Kohler–Nordenson–Fox (1955) equation, e_P is the amount of determined evaporation from the pan (in/day), $(e_s - e_d)$ is vapor pressure deficit (in Hg), v_P the wind velocity at the standard height of the installation of the evaporation pan from the ground (miles/ day). In addition, $\gamma_4 = 0.88, \gamma_5 = 0.37, \gamma_6 = 0.0041$ are the default parameters of the equation.

Papadakis (1961) experimental equation

This equation is proposed by Papadakis (1961). Like the Antal (1973) equation, this equation uses temperature and relative humidity factors to determine evaporation. Unlike that equation, it considers the linear relationship between these factors. (Basnyat 1987). The mathematical formula of the Papadakis (1961) equation is much easier to determine evaporation than other similar equations (Bozorgi et al. 2020).

$$e_p = \gamma_7 (e_s - e_d) \tag{5}$$

The e_p is determined amount of evaporation from the pan in (mm/day), $(e_s - e_d)$ is vapor pressure deficit (mbar), and $\gamma_7 = 0.5626$ is the default parameter of the Papadakis (1961) equation.

Antal (1973) experimental equation

The equation proposed by Antal (1973) uses temperature and relative humidity as meteorological factors to determine evaporation from the pan. In this equation, vapor pressure deficit is a secondary factor nonlinearly related to evaporation (Antal 1973; Basnyat., 1987). The relationship between temperature and evaporation is also considered nonlinear. However, this nonlinear relationship is indirectly included in the vapor pressure deficit factor (Agarwal et al. 2020).

$$e_P = \gamma_8 (e_s - e_d)^{\gamma_9} \left(\gamma_{10} + \frac{t}{\gamma_{11}} \right)^{\gamma_{12}} \tag{6}$$

In the above equation, e_p is the amount of determined evaporation from the pan (mm/day), $(e_s - e_d)$ is vapor pressure deficit (mbar Hg), t is the average daily temperature in (°C). Also $\gamma_8 = 1.1, \gamma_9 = 0.7, \gamma_{10} = 1, \gamma_{11} = 273, \gamma_{12} = 2.4$ are default parameters of the Antal (1973) equation.

Linacre- (1977) experimental equation

The equation presented by Linacre (1977) has significant differences from similar equations (Althoff et al. 2020). The first difference is that this equation between meteorological factors uses only temperature. The second difference is that, unlike other equations for determining evaporation from the pan, factors such as elevation and latitude of location are also used in this equation (Linacre 1977).

$$e_P = \frac{\left[\gamma_{13} \left(\frac{(t + \gamma_{14} H)}{(\gamma_{15} - L) + \gamma_{16}(t - t_d)} \right) \right]}{(\gamma_{17} - t)} \tag{7}$$

In Linacre (1977) equation, e_P is the amount of evaporation determined from the pan (mm/day), t is the average daily air temperature (°C), H is the elevation of the area (desired station) from the surface of the seawater (m), L is the latitude of location (degree) and t_d is the dew point temperature (°C). Also $\gamma_{13} = 700, \gamma_{14} = 0.006, \gamma_{15} = 100, \gamma_{16} = 15, \gamma_{17} = 80$ are default values for the Linacre (1977) equation parameters.

Linacre (1994) experimental equation

Another equation was proposed by Linacre (1994) to determine evaporation from the pan. This equation can be considered modified compared to Linacre (1977) equation (Stephens et al. 2018). Unlike Linacre (1977) equation, only meteorological factors are used in this equation. In other words, elevation and latitude of location factors are not required to determine the evaporation from the pan. In addition, this equation uses wind velocity as another meteorological factor in addition to temperature.

$$e_P = \frac{[\gamma_{18} t - \gamma_{19} + \gamma_{20} u (t - t_d]}{\left[\gamma_{21} + \frac{\gamma_{22}}{S} \right]} \tag{8}$$

In the above equation, e_p is the amount of evaporation from the pan (mm/day), u is wind velocity at the height of 2 m above the ground (m/s), t is the average daily temperature (°C), t_d is the dew point temperature (°C) and $\gamma_{18} = 21, \gamma_{19} = 166, \gamma_{20} = 6, \gamma_{21} = 28, \gamma_{22} = 46$ are default values for the Linacre (1994) equation parameters. In Linacre (1994) equation, S is the slope of the psychrometric curve in (mmHg) determined from the following equation (Murry 1967; Basnyat 1987)).

$$S = e_s \left(\frac{4098.03}{(t + 237.3)^2} \right) \tag{9}$$

In the above equation, t is the average daily temperature (°C) and e_s is the saturated vapor pressure at the water surface, which can be obtained from the following equation (Xu et al. 2002):

$$e_s = 6.1078 \exp \left[\frac{17.2694\, t}{(t + 237.3)} \right] \tag{10}$$

Revision process

The parameters of these equations must be revised to increase the efficiency of the experimental equations in determining evaporation from the pan in cold regions. The pan's evaporation values are expected to be determined more efficiently by revising the experimental equations' parameters. In other words, these equations will be adapted for cold regions. It is necessary to use an optimization method to adjust the parameters of the equations. The Nelder and Mead Simplex (NMS) optimization method is well-known in water and environmental engineering studies. This research used the MATLAB environment to apply the optimization method (Ahmadianfar et al. 2016).

A simplex is made up of $n + 1$ vertices in an n-dimensional space, each of which represents a potential solution to an optimization problem. The worst solution is replaced by a better solution obtained by performing some operations on the vertices in each iteration (Kshirsagar et al. 2020). Figure 5 depicts the NMS method's implementation procedure (Barati 2011). The Nelder-Mead algorithm frequently resulted in remarkable initial iteration improvements and quickly gave satisfactory outputs. On the other hand, the algorithm can lead to many iterations with no significant improvement in the objective function.

Fig. 5 Flowchart for NMS method (Barati 2011)

Analysis of the efficiency of experimental equations

Error metric selection to analyze the efficiency of equations is a critical step in simulation-related research (Ansarifar et al. 2020). Various error metrics have been presented in studies related to meteorological factors. Although the error metrics presented are numerous, multiple simulation aspects should be considered in their application. In this study, two error metrics were used to analyze and compare the efficiency of the experimental equations for determining evaporation from the pan. The first error metric is the mean error (ME), which generally determines the under-determined or over-determined errors (Whang et al. 2020). The second error metric used is the normalized root mean squared deviation (nRMSD). This error metric can consider the efficiency of determining evaporation in equations and is, therefore, a good option for comparing the results of different equations (Siebielec et al. 2004). The equations related to these error metrics are presented below:

$$\text{ME} = 100\% \times \frac{1}{p} \sum_{i=1}^{p} \left(f_i - g_i \right) \tag{11}$$

$$\text{nRMSD} = 100\% \times \frac{\sqrt{\frac{1}{p} \sum_{i=1}^{p} \left(f_i - g_i \right)^2}}{\overline{g}} \tag{12}$$

In the above equations, f_i and g_i represent the measured and determined values, respectively. The best value for the error metrics is 0. The numerous equations studied in this study and the use of two metric errors make it difficult to select and rank the proper equations Performance index (PI) has been used in this study to overcome the difficulty in analyzing the results (Despotovic et al. 2015). The PI simultaneously applies the error metrics, nRMSD and ME, into the calculation. The error metrics must first be scaled to determine the P. This operation causes the high and low values of each error metric do not have a significant influence on the P value. The following equation can scale each error metric (Manju and Sandeep 2019).

$$h_{\text{scaled}} = \left(\frac{h - h_{\min}}{h_{\max} - h_{\min}} \right) \tag{13}$$

The $h_{\max}$, $h_{\min}$, h and h_{scaled} are maximum, minimum, real, and scaled values of error metrics. The maximum and minimum of scaled error metrics transform to 1 and 0.

Using this equation, the values of each of the two error metrics in this study, nRMSD, and ME, will be in the range [0–1]. The following equation can be used to determine P. In this equation, i is the equation under study (Manju and Mavi 2021).
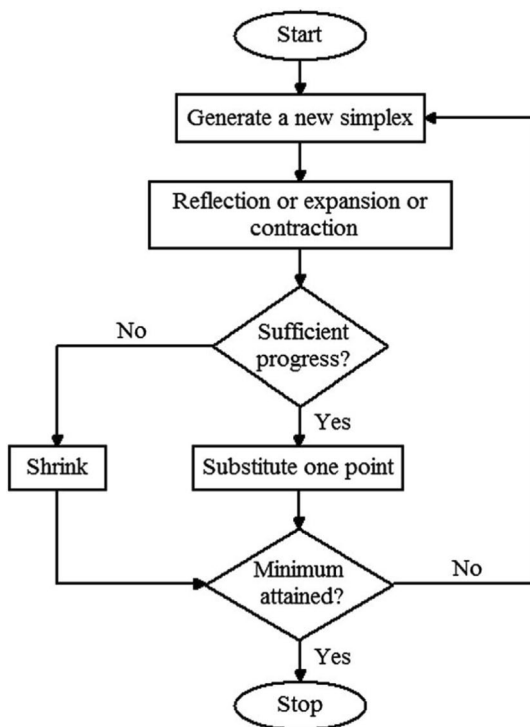
$$P = \sum_{k=1}^{q} c_k \left(s_k - t_{ik} \right) \tag{14}$$

For the presented equation the c_j are constant and consider 1 for ME and nRMSD. The q is the number of applied error metrics and t_{ik} are equal to scaled values of error metrics k for equation i. Moreover, s_k consider as the median of scaled values of error metrics k.

Based on the Mathematical formula of the P equation, it becomes clear that the higher the P value for one equation compared to other equations, the better the rank can be considered. In other words, the method of determining P is such that it creates a final error metric for comparing equations for a particular dataset. Equations with lower P values for a given dataset are in the following ranks (Feng et al. 2018).

Results

Findings of the revision process

The revised values of the experimental equation parameters in the MATLAB environment were determined using the NMS method. The parameters of experimental equations were calibrated considering the minimization of error. Recorded data belonging to all stations simultaneously used for optimization to achieve overall parameters. The minimization pattern of the objective function for these equations is shown in Fig. 6. The horizontal and vertical axes represent the iterations and values of the objective functions, respectively. The parameter values of the equations before and after the revision are shown in Table 2. The parameters' values are expected to change after revision compared to the default mode. The differences among equations' parameters values in the two modes before and after revision lead to exciting findings. The maximum and minimum values of changes in the parameters of the equations belong to two single-parameter equations. The Trabert (1896) equation parameter changed about 900% after revision, while in Papadakis (1961) equation, this change is equivalent to 12%. This difference in the percentage change of the parameters of these two equations is noticeable. For Linacre (1977) and Linacre (1994) equations, the default value of a parameter was changed from 15 and 166 to 0, respectively. Considering the revised value of zero for this parameter, the Linacre (1977) equation is revised more efficiently in a mathematical formula. This revision reveals that the default Mathematical formula of the equation does not work well in determining evaporation from the pan in cold regions. Remarkable changes in the parameters of most equations indicate that the default equations do not have good reliability.

Error metrics maps for efficiency of experimental equations

The ME and nRMSD error metric values, representing efficiency, were determined for all 14 equations, including seven default and seven revised equations. Due to spatial distribution's importance on experimental equations' efficiency for determining evaporation from the pan, the spatial distribution of these error metrics was prepared as a map. Figure 7 shows the spatial distribution of the error metric ME, and Fig. 8 shows the error metric nRMSD as a map. In addition, the visual error metric of the equations in the fit is illustrated in Fig. 9. The default mode was first compared, and then all equations were compared to investigate the efficiency of the experimental equations for determining evaporation.

Comparative analysis of default experimental equations

The spatial distribution of error metrics and the graphical error metric are presented in Figs. 7, 8 and 9. The error metric PI values are illustrated in Fig. 10 to simplify these error metrics. This figure is determined based on considering all the studied datasets. The color spectrum was used to compare the PI for different equations in the analyzed datasets. According to Fig. 10, it is clear that the Kohler–Nordenson–Fox (1955) equation, with a slight difference from the Papadakis (1961) equation, has determined the most proper values among the default equations evaporation from the pan. Interestingly, the mathematical formula of both equations is simple, but for Papadakis (1961) is the simplest of the studied equations, achieving a proper performance by this equation has considerable importance. On the other hand, the two default Trabert (1896) and Linacre (1977) equations had the lowest efficiency in determining evaporation from the pan among the default equations. Trabert (1896) equation has an almost similar formula to Kohler–Nordenson–Fox (1955) equation, and this difference in results is important. Of course, the influence of default values of experimental equation parameters on their proper or improper performance is quite influencing (Yan and Mohammadian 2020). Under-determination or over-determination error is important in determining evaporation from the pan (Lu et al. 2018). The ME error metric analysis for default equations indicates that Antal (1973), Papadakis (1961), and Linacre (1994) equations face over-determination and Kohler (1954), Kohler–Nordenson–Fox (1955) equations, Linacre (1977), and Trabert (1896) to under-determination. The most under-determined and over-determined errors are default Trabert (1896) and Antal (1973) equations. The three equations Kohler–Nordenson–Fox (1955), Linacre (1994), and Papadakis (1961)
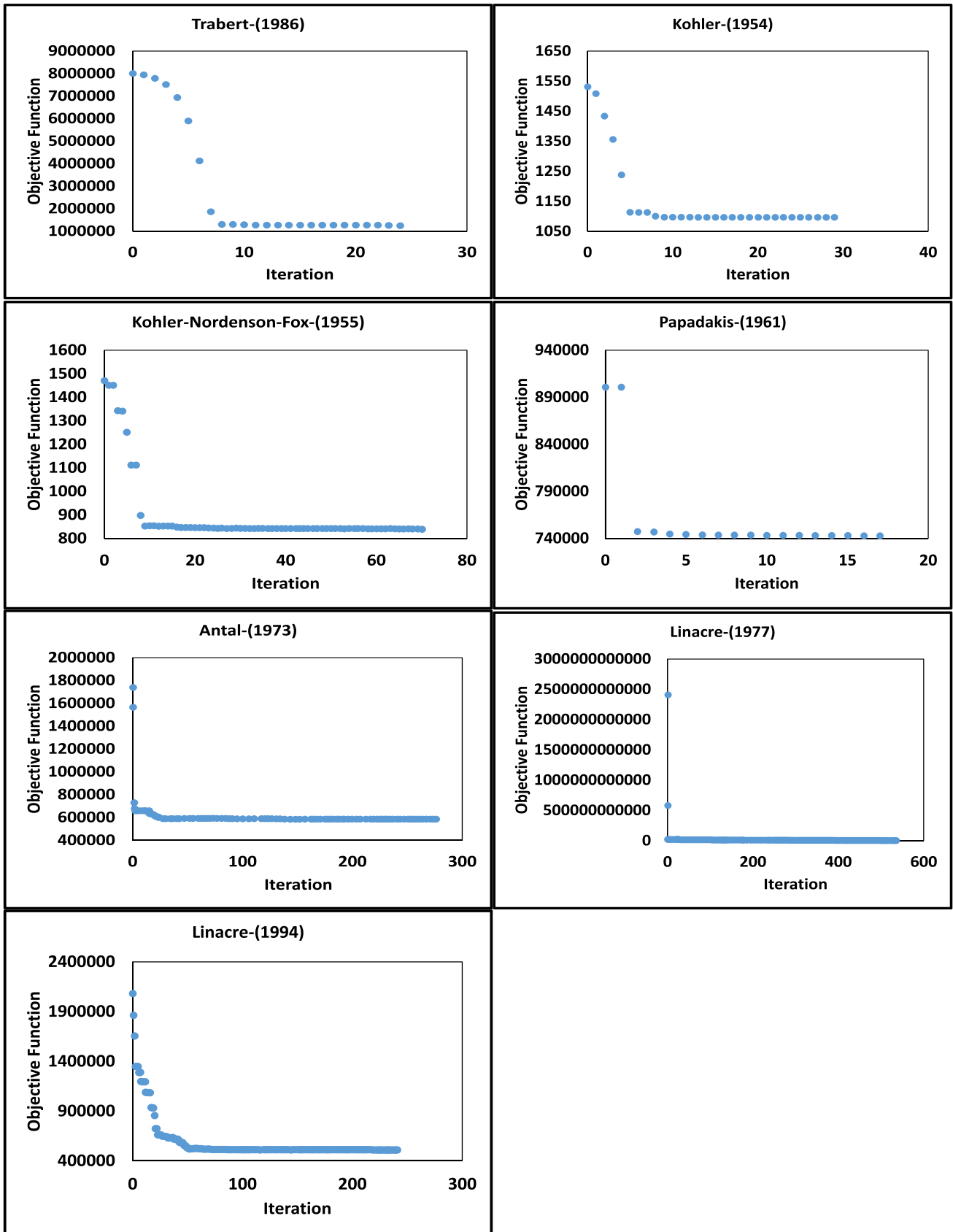
Fig. 6 Minimization of the objective function of the studied equations in cold regions

Table 2 Values of parameters for studied equations

Equation	Parameter	Default	Revised	Changes (%)
Trabert (1896)	γ_1	0.3075	3.0787	901.2
Kohler (1954)	γ_2	0.42	0.71	68.9
	γ_3	0.004	0.001	−73.2
Kohler–Nordenson–Fox (1955)	γ_4	0.88	0.69	−21.4
	γ_5	0.37	0.58	57.1
	γ_6	0.0041	0.0011	−72.9
Papadakis (1961)	γ_7	0.5626	0.4964	−11.8
Antal (1973)	γ_8	1.1	0.37	−66
	γ_9	0.7	0.34	−51.6
	γ_{10}	1	1.28	27.7
	γ_{11}	273	0.98	−99.6
	γ_{12}	4.8	0.71	−85.2
Linacre (1977)	γ_{13}	700	1510	115.7
	γ_{14}	0.006	0.003	−44.4
	γ_{15}	100	121	21.1
	γ_{16}	15	0	−100
	γ_{17}	80	75	−6.5
Linacre (1994)	γ_{18}	21	27	28.9
	γ_{19}	166	0	−100
	γ_{20}	6	2	−64
	γ_{21}	28	61	119.4
	γ_{22}	46	23	−50.2

have the least over-determined and under-determined error compared to other default equations. In other words, they have a balanced behavior in this field. Figure 9 indicates that most of the default equations do not have the proper reliability to determine evaporation from the pan.

Comparing the efficiency of default and revised equations jointly

The error metric PI values are illustrated in Fig. 11 to analyze the performance index of all equations jointly. Comparing these 14 equations shows that the revised Kohler–Nordenson–Fox (1955) was the best equation for determining evaporation from the pan. The Revised Linacre (1994), Revised Linacre (1977), Revised Kohler (1954), Revised Papadakis (1961), and Revised Antal (1973) equations also performed well compared to other equations. Most of the revised equations have performed well in determining evaporation from the pan in cold regions seems to be an important finding. These equations have differences in mathematical formula and input factors, and a relatively small difference in their performance is a finding that was not expected. Among these 14 equations, the two default Trabert (1896) and the Linacre (1977) equations had the lowest efficiency in determining evaporation from the pan,

described in the following section. The lowest value of the under-determined or over-determined error wasfor the revised Papadakis (1961) equation. The revised Kohler (1954) equation has had the slightest error in over-determination or under-determination after the revised Papadakis (1961) equation. The study of the mathematical formula of these two equations shows the more straightforward formula of the revised Papadakis (1961) compared to the revised Kohler (1954). A comparison of the efficiency of the default and revised equations in Figs. 7, 8 and 9 reveals that the revision process has increased the reliability in determining evaporation using experimental equations.

Analysis of improvement due to revision

The difference between equations' efficiency before and after the revision indicates that the highest revision belongs to Trabert (1896) equations. Despite the remarkable revision change on Trabert (1896) equation, the revised Trabert (1896) equation in some cases has led to inefficient results, emphasizing more attention to the mathematical formula of the equation. On the other hand, Papadakis (1961) equation is less affected by revision than other equations. In addition, the efficiency of the Papadakis (1961) equation is proper in both the pre- and post-revision process. This finding reflects the firm behavior of Papadakis (1961) equation. After revising equations parameters, under-determination and over-determination errors have also been adjusted.

Investigation in spatial analysis

The study of the spatial distribution of the studied equations (presented in Figs. 7 and 8) shows that the geographical distribution of the analyzed datasets has not caused a significant difference in the efficiency of the equations. However, it can be said that the efficiency of the equations in the central regions has been somewhat lower than in other regions. On the other hand, the efficiency of the equations in the eastern, northeastern, western, and northwestern regions has been somewhat higher than in other regions.

Discussion

Plots of changes in the objective function in the revision process (Fig. 6) show the efficiency of the applied optimization method. Numerous studies have emphasized the influence of the NMS method in studies related to hydrology (Pinnington et al. 2018), water resources (Lee., 2019), water quality (Ciolofan et al. 2018), climatology (Ntale et al. 2003), and environmental sciences (Yang et al. 2006) and the findings of this study also confirm them. Although in two equations Trabert (1896) and Papadakis (1961) with one parameter,
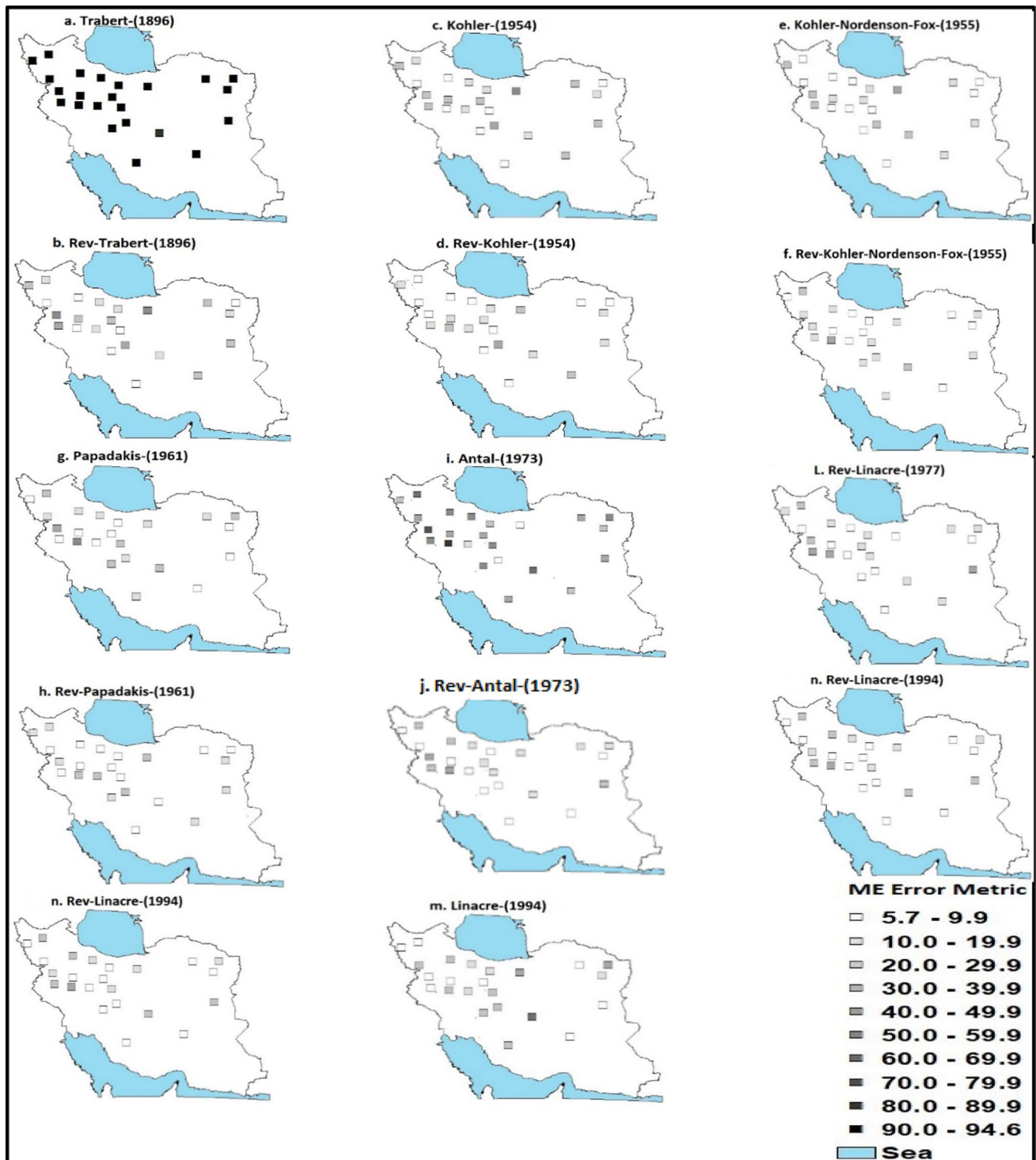
Fig. 7 Spatial distribution of error metric ME for equations in cold regions

the revision has caused completely different changes in these parameters. While the revision in the Papadakis (1961) equation slightly changed the parameter's value, the parameter changes were extraordinary in Trabert (1896). This finding indicates an entirely different behavior of the two equations in cold regions. Papadakis (1961) equation can be considered firm in cold regions. Suppose multiple data are unavailable to revise the evaporation equations. In that case, the default Papadakis (1961) equation can be a practical option in this region.
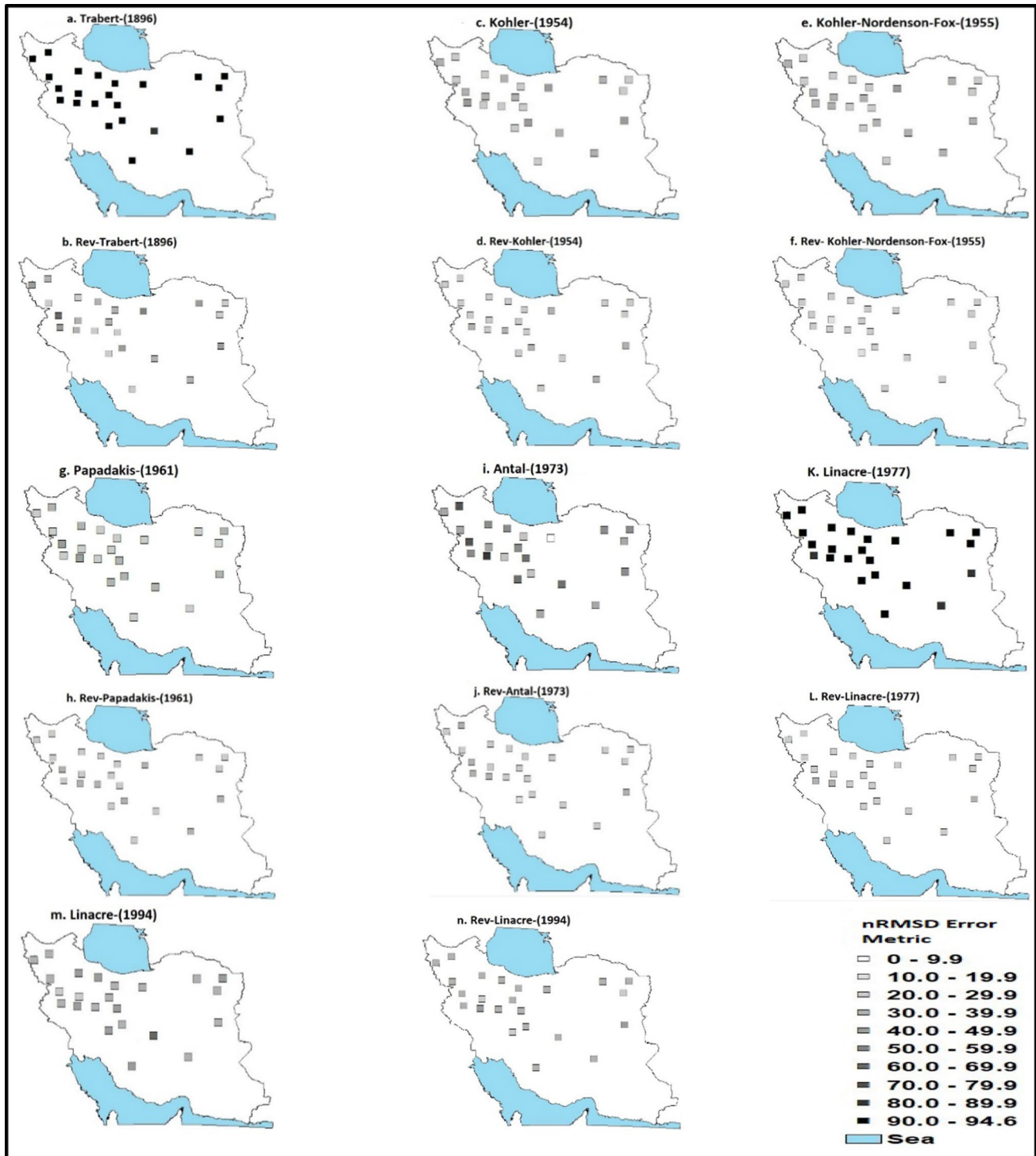
Fig. 8 Spatial distribution of error metric nRMSD for equations in cold regions

Another finding of these two equations is that despite the significant difference in the efficiency of the two equations in the default mode, the efficiency of the two revised equations was relatively similar after the revision process. The two equations Trabert (1896) and Papadakis (1961) had the most and the least influence on revision, respectively. Together, these findings indicate that in cold regions, the influence of default parameters on the inefficiency of the default Trabert (1896) equation was far greater than the mathematical formula of the equation.
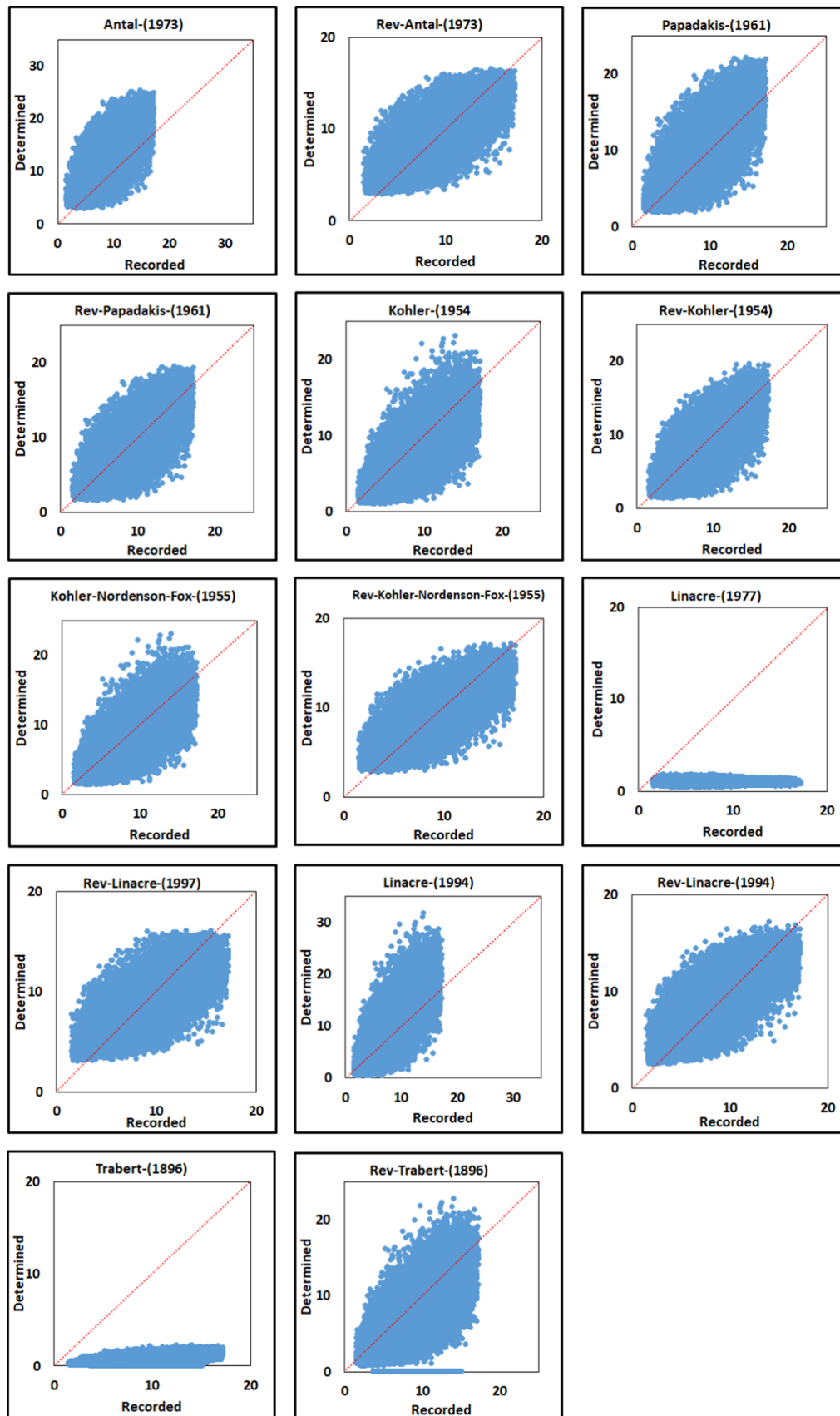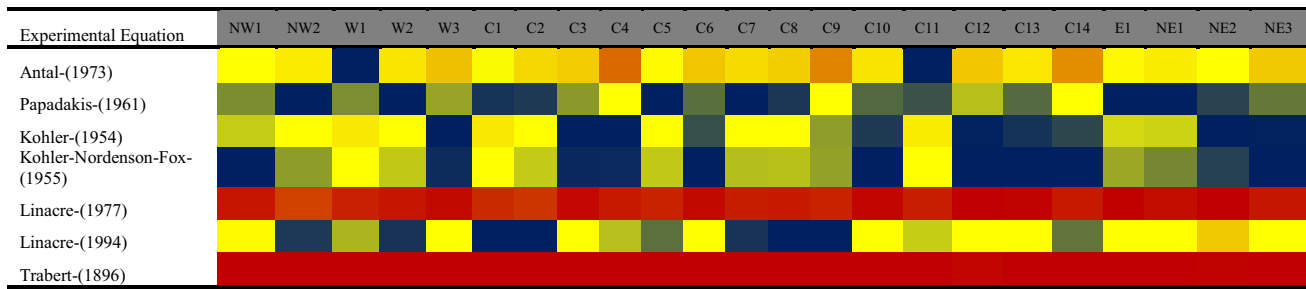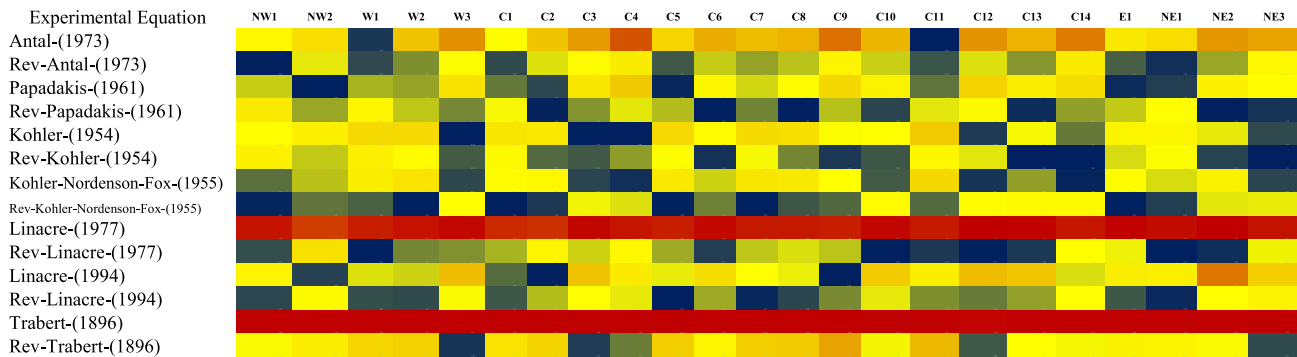
Fig. 9 Investigation of the visual efficiency of experimental equations of evaporation in cold regions

Fig. 10 The performance index for default equations in the cold region (red: lowest performance, blue: highest performance)

Fig. 11 The performance index for default and revised equations in the cold region (red: lowest performance, blue: highest performance)

A comparison between the efficiency of the default equations shows that the two Kohler–Nordenson–Fox (1955) and Papadakis (1961) equations were more efficient than the others. Kohler–Nordenson–Fox's (1955) equation uses wind velocity as a further factor compared to Papadakis (1961) equation, which is the most critical difference between the two equations. The second difference between the two equations is that the relationship between vapor pressure deficit and evaporation is linear in Papadakis- (1961) and nonlinear in Kohler–Nordenson–Fox (1955). In addition, the finding that the simple mathematical formula of Papadakis- (1961) equation has high efficiency compared to other default equations and the low difference between its results and the Kohler–Nordenson–Fox (1955) equation indicates that vapor pressure deficit is the most critical factor affecting evaporation from the pan in cold regions. This finding is confirmed by the study of Matsoukas et al. 2011. In addition, these findings indicate that in the absence of data to revise the default equations, the Kohler–Nordenson–Fox (1955) equation is also a correct option for determining the evaporation of the pan in cold regions. Of course, with a slight difference, Papadakis- (1961) equation is also a valuable option for such conditions.

Comparative analysis of all default and revised equations reveals that the highest performance belonged to the revised Kohler–Nordenson–Fox (1955) equation. The revised equations are generally reliable in determining evaporation from the pan. Although the studied equations have been revised to varying magnitudes, ultimately, the revised equations have no extraordinary differences in efficiency. Therefore, it can be concluded that the efficiency of evaporation equations from the pan in the studied cold regions is mainly affected by the default parameters of these equations. The mathematical formula of the studied equations does not cause a tremendous difference in their efficiency. This finding is important because it does not support the assumption that different revised equations perform thoroughly differently in cold regions. This finding was unexpected, considering the equation's mathematical formula and the various inputs of the studied equations. This finding contradicts research findings in coastal areas (Mohammadi et al. 2023) and arid and semi-arid regions (Mohammadi et al. 2023). Another finding in this area is the remarkable efficiency of the revised Trabert (1896) equation. As the equation's mathematical formula shows, the wind velocity's influence on evaporation is radical, meaning it does not change in the revision process. Although other parameters of the equation change in the revision process, it was expected that the mentioned constraint would lead to improper performance of the revised Trabert (1896) equation. The findings of this study showed different results. Studies by Mohammadi et al. in coastal areas (2021) and arid and semi-arid regions (2021)

indicate the low efficiency of the revised Trabert (1896), which contradicts the results of this study. The mathematical form between wind velocity and evaporation from the pan in Trabert (1896) equation includes a multiplier such that when the wind velocity is zero, the evaporation amount equals zero. This problem can lead to a significant problem in determining the amount of evaporation in regions that have days with zero wind velocities for a significant part of the year. It seems that the zero wind velocity data in cold regions has been low, making the efficiency of the revised Trabert (1896) equation acceptable.

Two parameters in the two Linacre (1977) and Linacre (1994) equations have been revised to zero during the revision process. This revision simplifies the Linacre (1977) equation's mathematical formula; therefore, it can be concluded that the default Linacre (1977) equation is not proper for determining evaporation in cold regions. Examining the results of the ME error metric for the equations in both pre- and post-revision modes indicates that the revision process has been able to revise this problem correctly. This finding emphasizes the importance of adjusting the default equations to determine evaporation from the pan in cold regions.

The above combination clarifies that revising the default equations can improve all the studied equations if valid data are available. Revision of the mathematical formula of equations to improve the results has been emphasized in several studies, such as Dubovský et al. (2021) and Metcalfe et al. (2019), and the results of this study also confirmed those findings.

A comparison of the results of the equations in different regions has shown that the geographical distribution has a limited influence on the efficiency of the equations in the cold region. This finding is important because the various study areas had different meteorological characteristics. Therefore, it was expected that the spatial distribution would significantly influence the efficiency of the equations. This finding contradicts the study results by Li et al. (2020).

A joint investigation of the default and revised equations indicates that most of the default equations do not have good reliability and the reliability of the equations in determining evaporation increases with the revision process. For the Linacre (1994) equation, the revision process eliminates one parameter, while for the Linacre (1977) equation, the mathematical formula of the equation is simplified by removing one parameter. In Trabert (1896) equation, the mathematical formula of the relationship between wind velocity and evaporation causes the amount of evaporation to be set to zero on days when the wind velocity is zero, which reduces the reliability of this equation. Therefore, it can be concluded that among the studied equations, Linacre (1977), Linacre (1994), and Trabert (1896) equations are less reliable than other equations.

Conclusion

Evaporation has a significant influence on many environmental science processes. Using an evaporation pan is the standard method of determining the amount of evaporation. However, many regions have no evaporation measuring stations for different reasons. Therefore the use of experimental mathematical equations is necessary. Most of the data presented in various studies to provide experimental mathematical equations are not from cold regions, which creates serious doubts about applying these equations in cold regions. In this study, using the datasets of cold regions of Iran, the efficiency of seven equations Trabert (1896), Kohler (1954), Kohler–Nordenson–Fox (1955), Papadakis (1961), Antal (1973), Linacre (1977), Linacre (1994), examined in both default and revised modes. By examining the results of different equations, it can be concluded that revision has increased the efficiency of the studied equations. Although the magnitude of efficiency improvement has varied in different equations, finally, the revised equations do not differ much for efficiency. However, among these 14 equations, the highest efficiency belongs to the revised Kohler–Nordenson–Fox (1955) equation. This equation is characterized by a nonlinear relationship between vapor pressure deficit and evaporation and wind inclusion as another meteorological factor determining evaporation from the pan. Revision has reduced equations' under-determination/over-determination error, emphasizing the need to revise default experimental equations in cold regions. Although in the central regions, the efficiency of the equations was slightly lower than in other regions, in general, the spatial distribution did not significantly influence the efficiency of the equations in the cold regions. The comparison between the studied equations shows their different reliability in determining the evaporation from the pan in the cold region. The study used recorded data in Iran's cold regions; therefore, it is possible that the results do not cover all relatively similar climates around the world. Improving the research using better datasets from different worldwide cold regions is recommended.

Declarations

Conflict of interest None.

References

Abtew W, Obeysekera J, Iricanin N (2011) Pan evaporation and potential evapotranspiration trends in South Florida. Hydrol Process 25(6):958–969

Agarwal A, Pandey RP, Singh VP (2020) An ANN model for estimation of potential evaporation. Hydrology and water resources. CRC Press, Boca Raton, pp 3–14

Ahmadianfar I, Adib A, Salarijazi M (2016) Optimizing multireservoir operation: hybrid of bat algorithm and differential evolution. J Water Resour Plan Manag 142(2):05015010

Al-Mukhtar M (2021) Modeling of pan evaporation based on the development of machine learning methods. Theor Appl Climatol 146(3–4):961–979

Althoff D, Rodrigues LN, da Silva DD, Bazame HC (2019) Improving methods for estimating small reservoir evaporation in the Brazilian Savanna. Agric Water Manag 216:105–112

Althoff D, Rodrigues LN, da Silva DD (2020) Impacts of climate change on the evaporation and availability of water in small reservoirs in the Brazilian savannah. Clim Change 159(2):215–232

Anayah FM, Kaluarachchi JJ (2014) Improving the complementary methods to estimate evapotranspiration under diverse climatic and physical conditions. Hydrol Earth Syst Sci 18(6):2049–2064

Ansarifar MM, Salarijazi M, Ghorbani K, Kaboli AR (2020) Spatial estimation of aquifer's hydraulic parameters by a combination of borehole data and inverse solution. Bull Eng Geol Env 79(2):729–738

Ântal E (1973) Evapotranspiration from com field. Term paper submitted for Dr. R. F. Dale's Agronomy 537 class. Received from personal communication with Dr. Dale (Dept. of Agronomy, Purdue

Barati R (2011) Parameter estimation of non-linear Muskingum models using Nelder–Mead simplex algorithm. J Hydrol Eng 16(11):946–954

Basnyat MB (1987) Estimation of daily Class A pan evaporation from meteorological data (Doctoral dissertation, Iowa State University)

Bozorgi A, Bozorg-Haddad O, Sima S, Loáiciga HA (2020) Comparison of methods to calculate evaporation from reservoirs. Int J River Basin Manag 18(1):1–12

Caloiero T, Callegari G, Cantasano N, Coletta V, Pellicone G, Veltri A (2016) Bioclimatic analysis in a region of southern Italy (Calabria). Plant Biosyst Int J Deal Aspects Plant Biol 150(6):1282–1295

Canturk U, Kulaç Ş (2021) The effects of climate change scenarios on Tilia ssp.i in Turkey. Environ Monitor Assess 193(12):771

Chen JL, Yang H, Lv MQ, Xiao ZL, Wu SJ (2019) Estimation of monthly pan evaporation using support vector machine in Three Gorges Reservoir Area, China. Theor Appl Climatol 138(1):1095–1107

Christiansen JE (1960) Water requirement for waterfowl areas near the Great Salt Lake. Utah State University, Utah

Christiansen JE (1966) Estimating pan evaporation and evapotranspiration from climatic data. In: Methods for estimating evapotranspiration. ASCE, pp. 193–231

Ciolofan SN, Draghia A, Drobot R, Mocanu M, Cristea V (2018) Decision support tool for accidental pollution management. Environ Sci Pollut Res 25(7):7090–7097

Dereure J, Vanwambeke SO, Malé P, Martinez S, Pratlong F, Balard Y, Dedet JP (2009) The potential effects of global warming on changes in canine leishmaniasis in a focus outside the classical area of the disease in southern France. Vector-Borne Zoonot Dis 9(6):687–694

Derouiche S, Mallet C, Hannachi A, Bargaoui Z (2022) Characterisation of rainfall events in northern Tunisia using self-organising maps. J Hydrol Region Stud 42:101159

Despotovic M, Nedic V, Despotovic D, Cvetanovic S (2015) Review and statistical analysis of different global solar radiation sunshine models. Renew Sustain Energy Rev 52:1869–1880

Dubovský V, Dlouhá D, Pospíšil L (2021) The calibration of evaporation models against the Penman–Monteith equation on lake most. Sustainability 13(1):313

Emberger L (1930) La vegetation de la region méditerranéenne. Essai d'une classification des groupements vegetaux. Rev Botan 503:642–662

Feng Y, Jia Y, Zhang Q, Gong D, Cui N (2018) National-scale assessment of pan evaporation models across different climatic zones of China. J Hydrol 564:314–328

Fulton JW, Koerkle EH, McAuley SD, Hoffman SA, Zarr LF (2005) Hydrogeologic setting and conceptual hydrologic model of the Spring Creek basin, Centre County, Pennsylvania. US Geological Survey, Scientific Investigations Report, 5091.

Gavili S, Sanikhani H, Kisi O, Mahmoudi MH (2018) Evaluation of several soft computing methods in monthly evapotranspiration modelling. Meteorol Appl 25(1):128–138

Griffiths JF (1966) Another evaporation formula. Agric Meteorol 3(3–4):257–261

Guan Y, Mohammadi B, Pham QB, Adarsh S, Balkhair KS, Rahman KU, Linh NTT, Tri DQ (2020) A novel approach for predicting daily pan evaporation in the coastal regions of Iran using support vector regression coupled with krill herd algorithm model. Theor Appl Climatol 142:349–367

Hargreaves GH, Allen RG (2003) History and evaluation of Hargreaves evapotranspiration equation. J Irrig Drain Eng 129(1):53–63

Hooshmand A, Salarijazi M, Bahrami M, Zahiri J, Soleimani S (2013) Assessment of pan evaporation changes in South Western Iran. Afr J Agric Res 8(16):1449–1456

Irmak S, Haman DZ (2003) Evaluation of five methods for estimating class A pan evaporation in a humid climate. HortTechnology 13(3):500–508

Izady A, Nikoo MR, Bakhtiari PH, Baawain MS, Al-Mamari H, Msagati TA, Nkambule TT, Al-Maktoumi A, Chen M, Prigent S (2020) Risk-based stochastic optimization of evaporation ponds as a cost-effective and environmentally-friendly solution for the disposal of oil-produced water. J Water Process Eng 38:101607

Kohler MA (1952) Lake and pan evaporation. Water-Lossa Investigations: Lake Hefner Studies. Tech Rep Geol Survey Profession Paper 269:127–148

Kohler MA, Parmele LH (1967) Generalized estimates of free-water evaporation. Water Resour Res 3(4):997–1005

Kohler MA, Nordenson TJ, Fox WE (1955) Evaporation from pans and lakes, vol 30. US Government Printing Office, Washington

Kshirsagar R, Jones S, Lawrence J, Tabor J (2020) Optimization of TIG welding parameters using a hybrid Nelder Mead-evolutionary algorithms method. J Manuf Mater Process 4(1):10

Lee KH (2019) Simulation of dam-breach outflow hydrographs using water level variations. Water Resour Manage 33(11):3781–3797

Li Z, Wang S, Li J (2020) Spatial variations and long-term trends of potential evaporation in Canada. Sci Rep 10(1):1–14

Linacre ET (1977) A simple formula for estimating evaporation rates in various climates, using temperature data alone. Agric Meteorol 18(6):409–424

Linacre ET (1994) Estimating US Class A pan evaporation from few climate data. Water Int 19(1):5–14

Lu X, Ju Y, Wu L, Fan J, Zhang F, Li Z (2018) Daily pan evaporation modeling from local and cross-station data using three tree-based machine learning models. J Hydrol 566:668–684

Majhi B, Naidu D (2021) Pan evaporation modeling in different agro-climatic zones using functional link artificial neural network. Inf Process Agric 8(1):134–147

Manju S, Mavi S (2021) Harmonic analysis of annual global irradiation in the cities of India. J Clean Prod 295:126461

Manju S, Sandeep M (2019) Prediction and performance assessment of global solar radiation in Indian cities: a comparison of satellite and surface measured data. J Clean Prod 230:116–128

Matsoukas C, Benas N, Hatzianastassiou N, Pavlakis KG, Kanakidou M, Vardavas I (2011) Potential evaporation trends over land between 1983–2008: driven by radiative fluxes or vapour-pressure deficit? Atmos Chem Phys 11(15):7601–7616

McJannet DL, Webster IT, Stenson MP, Sherman BS (2008) Estimating open water evaporation for the Murray-Darling basin: a report to the Australian government from the CSIRO Murray-Darling basin sustainable yields project, vol 50. CSIRO, Melbourne

Metcalfe RA, Petzold H, Luce JJ, Buttle JM (2019) Evaluating seasonal and regional calibration of temperature-based methods for estimating potential evaporation in Ontario, Canada. Water Resour J 44(1):2–21

Modabber-Azizi S, Salarijazi M, Ghorbani K (2023) A novel approach to recognize the long-term spatial-temporal pattern of dry and wet years over Iran. Phys Chem Earth Parts a/b/c. https://doi.org/10.2166/wcc.2023.459

Mohammadi M, Salarijazi M, Ghorbani K, Dehghani AA (2023) Coastal cities-wide estimation of daily class A pan evaporation from few hydrometeorological variables. Urban Water J. https://doi.org/10.1080/1573062X.2023.2209561

Mohammadi M, Salarijazi M, Ghorbani K, Dehghani AA (2023) Improvement of daily pan-evaporation calculation in arid and semi-arid regions by limited climatic data. J Water Clim Change. https://doi.org/10.2166/wcc.2023.459/99671

Murray FW (1967) On the computation of saturated vapor pressure. J of Appl Meteorol 6:203–204

Ntale HK, Gan TY, Mwale D (2003) Prediction of East African seasonal rainfall using simplex canonical correlation analysis. J Clim 16(12):2105–2112

Papadakis J (1962) Climatic tables for the world. Soil Sci 93(1):76

Pinnington E, Quaife T, Black E (2018) Impact of remotely sensed soil moisture and precipitation on soil moisture prediction in a data assimilation system with the JULES land surface model. Hydrol Earth Syst Sci 22(4):2575–2588

Qasem SN, Samadianfard S, Kheshtgar S, Jarhan S, Kisi O, Shamshirband S, Chau KW (2019) Modeling monthly pan evaporation using wavelet support vector regression and wavelet artificial neural networks in arid and humid climates. Eng Appl Comput Fluid Mech 13(1):177–187

Roderick ML, Farquhar GD (2004) Changes in Australian pan evaporation from 1970 to 2002. Int J Climatol J R Meteorol Soc 24(9):1077–1090

Roshan GR, Ghanghermeh AA, Attia S (2017) Determining new threshold temperatures for cooling and heating degree day index of different climatic zones of Iran. Renew Energy 101:156–167

Salarijazi M, Ghorbani K, Mohammadi M, Ahmadianfar I, Mohammadrezapour O, Naser MH, Yaseen ZM (2023) Spatial-temporal estimation of maximum temperature high returns

periods for annual time series considering stationary/nonstationary approaches for Iran urban area. Urban Climate 49:101504

Shammout MAW, Qtaishat T, Rawabdeh H, Shatanawi M (2018) Improving water use efficiency under deficit irrigation in the Jordan Valley. Sustainability 10(11):4317

Siebielec G, McCarty GW, Stuczynski TI, Reeves JB III (2004) Near- and mid-infrared diffuse reflectance spectroscopy for measuring soil metal content. J Environ Qual 33(6):2056–2069

Song C, Sheng Y, Zhan S, Wang J, Ke L, Liu K (2020) Impact of amplified evaporation due to lake expansion on the water budget across the inner Tibetan Plateau. Int J Climatol 40(4):2091–2105

Stephens JC, Stewart EH (1963) A comparison of procedures for computing evaporation and evapotranspiration. Publication 62:123–133

Stephens CM, McVicar TR, Johnson FM, Marshall LA (2018) Revisiting pan evaporation trends in Australia a decade on. Geophys Res Lett 45(20):11–164

Terzi Ö, Keskin ME (2010) Comparison of artificial neural networks and empirical equations to estimate daily pan evaporation. Irrig Drain 59(2):215–225

Trabert W (1896) Neue beobachtungen über verdampfungsgeschwindigkeiten. Meteorol Z 13:261–263

Valiantzas JD (2006) Simplified versions for the Penman evaporation equation using routine weather data. J Hydrol 331(3–4):690–702

Vessella F, Schirone B (2022) Forest conservation and restoration using the emberger index: cork Oak as study case. Forests 13(2):252

Wang H, Sun F, Liu F, Wang T, Liu W, Feng Y (2023) Reconstruction of the pan evaporation based on meteorological factors with machine learning method over China. Agric Water Manag 287:108416

Whang WJ, Yoo YS, Kim HS, Yoon G (2020) Influence of corneal spherical aberration on prediction error of the Haigis-L formula. Sci Rep 10(1):1–8

Woo MK, Rouse WR, Stewart RE, Stone JM (2008) The Mackenzie GEWEX Study: a contribution to cold region atmospheric and hydrologic sciences. Cold region atmospheric and hydrologic studies. The Mackenzie GEWEX Experience. Springer, Berlin, Heidelberg, pp 1–22

Woolway RI, Kraemer BM, Lenters JD, Merchant CJ, O'Reilly CM, Sharma S (2020) Global lake responses to climate change. Nature Rev Earth Environ 1(8):388–403

Wu M, Huang J, Wu J, Tan X, Jansson PE (2016) Experimental study on evaporation from seasonally frozen soils under various water, solute and groundwater conditions in Inner Mongolia, China. J Hydrol 535:46–53

Wu L, Huang G, Fan J, Ma X, Zhou H, Zeng W (2020) Hybrid extreme learning machine with meta-heuristic algorithms for monthly pan evaporation prediction. Comput Electron Agric 168:105115

Xu CY, Singh VP (2000) Evaluation and generalization of radiation-based methods for calculating evaporation. Hydrol Process 14(2):339–349

Yan X, Mohammadian A (2020) Estimating future daily pan evaporation for Qatar using the Hargreaves model and statistically downscaled global climate model projections under RCP climate change scenarios. Arab J Geosci 13(18):1–15

Yang X, Yang Z, Shen Z, Li J (2006) A grey-encoded hybrid accelerating genetic algorithm for parameter optimisation of environmental models. Int J Environ Pollut 28(3–4):239–252

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Mehdi Mohammadi[1] · Meysam Salarijazi[1] · Khalil Ghorbani[1] · Amir-Ahmad Dehghani[1]

✉ Meysam Salarijazi
meysam.salarijazi@gmail.com; meysam.salarijazi@gau.ac.ir

Mehdi Mohammadi
mehdi.mohammadi2644@gmail.com

Khalil Ghorbani
ghorbani.khalil@yahoo.com

Amir-Ahmad Dehghani
a.dehghani@gau.ac.ir

[1] Department of Water Engineering, Faculty of Water and Soil Engineering, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran