Evaporation and Evaluation of Seven Estimation Methods: Results from Brullus Lake, North of Nile Delta, Egypt

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Abstract: Variations in lake evaporation have a significant impact on the energy budget and water budget of lake. Understanding these variations and the role of climate is important for water resource management as well as predicting future changes in Lake Hydrology as a result of climate change. This study presents a comprehensive of 10 years dataset (2003 - 2012) from Lake Brullus (Nile Delta Lake) North-Egypt for monthly and annually variations in lake evaporation. Evaporation during this interval was calculated using six evaporation methods, based on field meteorology, and lake water temperature data. Actual evaporation determined during a month of a year was estimated using a lake energy budget model, and the estimation was used as reference evaporation for evaluation of the six methods. The deviations of method carried out evaporation results from the reference evaporation were compared among the six methods, and an execution rank was suggested based on the root mean squared deviation and coefficient of efficiency. Makkink method was the best method for the whole data interval, followed by DeBruin-Kejiman method and the poor one is Penman method.

Keywords: Lake Brullus, Evaporation, Energy Budget, Temperature

1. Introduction

Accurate estimates of lake evaporation are necessary for water and energy budget studies, lake level forecasts, water quality surveys, water management and planning of hydraulic constructions. Evaporation process depends on the availability of thermal energy and the vapor pressure deficit between the evaporating surface and the overlying air, which in turn depend on meteorological factors such as solar radiation, temperature, relative humidity and wind velocity. Besides climate, lake characteristics as its size, shape, depth, water quality and circulation, even its location can affect the rate of evaporation. Thus, the estimation or measurement of the evaporation over a lake is a very difficult task, for which a multitude of methods exist, which can be classified into several categories including: 1) water budget, 2) measurement, like evaporation pans and eddy correlation technique, 3) energy budget, 4) mass transfer and 5) combination methods. The energy budget and eddy correlation techniques are regarded as the most accurate methods. As eddy correlation method is only suitable for short-term studies, the energy budget is the preferred technique for accurate, long-term monitoring [6, 11, 15, 20, 22, 24, 28 and 34].

Several attempts have been made to estimate evaporation from different zones of the Mediterranean Sea using different techniques [24]. Nielsen, [18] reported evaporation as 175 cm/year. Schott, [26] computed evaporation (187 cm/year) by means of heat balance equations. Sverdrup [29] and Wust [36] calculated evaporation from the surface waters of the Mediterranean Sea as 145 cm/year. The annual evaporation value determined by Carter [9] was 115 cm/year, with minimum value (4 cm) in February and a maximum one (16 cm) in August. On the basis of observations over the sea during the period 1924-1932, Tixeront [30] found that the average evaporation from the Mediterranean Sea amounted to 120 cm/year and Said, [23] computed evaporation (151.5 cm/year). Anonymous [5] represents that during Long-term averages (> 20 years) of the climatic records of two stations within Brullus Wetland the evaporation rate is between 3.3 to 5.6 mm/d. Hussain [14] calculated evaporation from Lake Brullus as 129.42 cm/year in 1988 and 138.6 cm/year in 1989 using aerodynamic method [4]. The evaporation from Lake Brullus has been estimated by Said and Hussein [24] as

157.79 cm/year in 2001 and 147.74 cm/year in 2002.

The present study has two goals: 1) provide an evaporation study using 10 years datasets obtained for Lake Brullus located in the Egyptian coastal zone using six methods; and 2) compare deviations of method-calculated evaporation to the energy budget estimated evaporation, and identify the better methods for estimating lake evaporation for the region.

2. Study Area Description

Brullus Lake is located along the Mediterranean Deltaic coast. It lies at a central position between the two branches of Nile: Damietta to the east and Rosetta to the west. Its coordinates are 31° 36' N and 30° 33' E in north - west, 31° 36' N and 31° 07' E in the north - east, 31° 22' N and 30° 33' E in the south - east, and 31° 22' N and 31° 07' E in the south - east. It has a total area of 460 km^2, which includes the entire area of Lake Brullus with a shoreline of about 65 km Figure 1 [3].

According to the map of the world distribution of arid regions (UNESCO, 1977), the northern Mediterranean part of the Nile Delta belongs to the arid region. The climatic conditions are warm summer (20° to 30°C) and mild winter (10° to 20°C) [3].

The lake is roughly rectangular in shape, 60-70km in length and 6-16km with an average width 11km. The depth of the lake varies from 0.42 cm 2.07 cm with an average depth of 1 m. the lake is connected to the Mediterranean Sea through Boughaz El-Brullus; of about 200m width and a maximum depth of 2.8m. It receives a huge amount of brackish water from five main drains per year [24, 25].
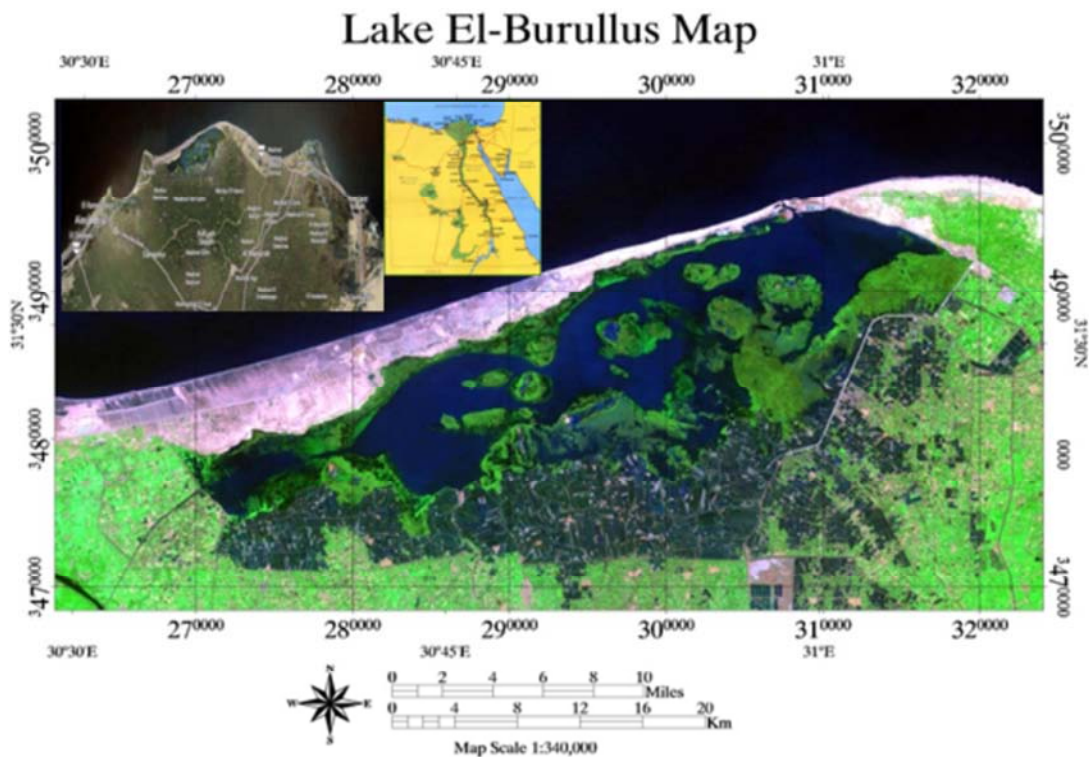

Figure 1. *Lake Brullus study area [1].*

3. Materials and Methods Calculation

The data used for calculations include daily mean air temperature, relative humidity, and wind speed. The processed data are available for the period of 10 years (2003-2012) and obtained from meteorology station located at the eastern part of Lake Brullus. Lake water temperature was measured monthly at multiple stations covering the lake area during the study period. Six methods are selected for calculation of evaporation from Lake Brullus and later compared to each other. They are Hamon (HM), Penman (PM), Priestley-Taylor (PT), DeBruin-Kejiman (DK), Jensen-Haise (JH), and Makkink (MK). Finally, Energy budget was calculated and has been taken as an evaporation reference of the study area.

3.1. Hamon (HM) Method

Yao and Creed [38] estimated the daily evaporation E (mm) from daily air temperature T_a (°C) as follows:

$$E = 0.63D^2 10^{\frac{7.5T_a}{T_a+273}} \qquad (1)$$

Where, D is the ratio of maximum sunshine duration (hour) to 12 hours, and is determined by latitude of the lake and the date:

$$D = \frac{1}{90} \arccos\{-\tan(\phi)\tan[23.45°\sin(\frac{J-80}{365})360°]\}$$

Where φ is the latitude, J is the Julian day of any date of interest.

3.2. Penman (PM) Method

A format of Penman equation, once recommended by Food and Agriculture Organization [2, 13], is used and slightly modified to calculate lake evaporation. The modification is an addition of the lake heat storage change rather than taking only the net radiation. The evaporation is written as:

$$E = \frac{\Delta}{\Delta+\gamma} \frac{R_{net} - S}{\lambda} + \frac{\gamma}{\Delta+\gamma} 0.0026(1+0.54\overline{u})(1-r)e_{sa}n \quad (2)$$

where R_{net} and S are the net radiation (Joule) and lake heat storage change in the interval, λ is the latent heat of vaporization (2.46×10^6 J kg^{-1}), $\overline{u}$ is the mean daily wind speed (m s^{-1}) for the period, r is the mean daily relative humidity (≤ 1.0), e_{sa} is the mean daily saturated vapor pressure (Pa), Δ is the mean slope of the saturated vapor pressure–temperature curve at the air temperature, and n is number of days in the interval. The two terms related to the slope Δ and psychrometric constant γ are expressed as empirical relations of air temperature [39]:

$$\frac{\Delta}{\Delta+\gamma} = 0.439 + 0.01124T_a \quad \frac{\gamma}{\Delta+\gamma} = 0.5495 - 0.01119T_a$$

The saturated vapor pressure is calculated with the Arden Buck Formula [27]:

$$e_{sa} = 611.21\exp[\frac{(18.678 - T_a / 234.5)T_a}{257.14 + T_a}]$$

The net radiation (R_{net}) (MJ m^{-2} day^{-1}) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net long-wave radiation (R_{nl}) [31, 32]:

$$R_{net} = R_{ns} - R_{nl}$$

According to [24] the energy that is taken up by the water body during the warmer months and subsequently released as evaporation during the cooler months by change in water heat storage from one month to the next. The mean monthly water body temperature, T_{wb} defines as the arithmetic mean of epilimnion temperature (taken as water surface temperature, T_w) and the hypolimnion temperature, T_b (Lake Bottom temperature). This assumes that in shallow lakes, the water volumes of the epilimnion and hypolimnion are equal, an as assumption that is not general true. Note, that lake heat gains and losses are primarily surface phenomena. Accordingly, as a first approximation, the change in hypolimnion temperature between one month and the next to be the same as that of the epilimnion when $T_w > T_b$ for shallow lake and negligible for deep lakes (T_b weakly varying), and computed the mean water body temperature change between month j and j-1 from:

$$\Delta T_{wb} = T_{w,j} - T_{w,j-1}$$

Which is valid when $T_w = T_b$. The corresponding change in the heat storage from month j-1 to j per unit area can then be computed by [33]:

$$S = C\rho * \rho * h\Delta T_{wb} / n$$

Where, $C\rho = 4186$ (J kg^{-1} C^{-1}) is specific heat of water, $\rho = 1000$ (kg m^{-3}) is water density, h is the mean depth of lake (1 m) and n is number of days in month.

3.3. Priestley-Taylor (PT) Method

Evaporation is estimated based on radiation and heat storage only, as done by Winter et al. [35]:

$$E = 1.26 \frac{\Delta}{\Delta+\gamma} \frac{R_{net} - S}{\lambda} \quad (3)$$

3.4. De Bruin-Kejiman (DK) Method

The De Bruin-Kejiman equation is written as [35, 12].

$$E = \frac{\Delta}{0.95\Delta + 0.63\gamma} \frac{R_{net} - S}{\lambda} \quad (4)$$

3.5. Jensen-Haise Method

Daily evaporation is calculated by the Equation given by Winter et al., [16, 19, and 35].

$$E = [0.014(1.8T_a + 32) - 0.5]\frac{Rns}{\lambda} \quad (5)$$

3.6. Makkink (MK) Method

Daily evaporation is calculated as Winter et al. [16, 19, and 35]

$$E = 0.61\frac{\Delta}{\Delta+\gamma} \frac{Rns}{\lambda} - 0.012 \quad (6)$$

3.7. Reference Evaporation Derived by Energy Budget

The energy budget is often used for lake evaporation calculations [7, 15, 34, and 37]. For Lake Brullus and for a given time period previously defined, its energy budget is written as:

$$\lambda E = R_{net} + H_{sed} + A_{net} - H - S \quad (7)$$

Where, λE is latent heat energy used by evaporation of lake water during the interval, H_{sed} is heat released by lake sediments and is negligible for most cases, A_{net} is net heat advected into the lake from precipitation, inflows and outflows, and is also negligible [37], H is sensible heat transfer from lake surface to atmosphere and can be expressed as $H = B\lambda E$, where B is the mean Bowen ratio for the period. Removing the two negligible terms, equation (7) is rewritten as:

$$E = \frac{R_{net} - S}{\lambda(1 + B)} \qquad (8)$$

The interval-mean Bowen ratio B is calculated from daily Bowen ratios which are derived from air and lake surface temperatures [7, 10] as:

$$B = \frac{\gamma}{n}\sum_{i=1}^{n}\frac{T_s - T_a}{e_{ss} - e_{sa}}$$

Where, e_{ss} is the saturated vapor pressure (Pa) at Lake Surface and calculated by using the same Arden Buck [8] formula (mentioned before) by replacing water temperature (T_s) instead of air temperature T_a.

4. Comparison and Evaluation of Seven Methods

The root mean square deviation (RMSD) is a frequently-used measure of the differences between values predicted by an estimator and the values observed from the any thing being estimated. Another indication of how well the estimator follows/predicts the variations in the measured values could be given by a coefficient of efficiency (CE) as proposed and applied by Nash and Sutcliffe [17] and Yao [37]. This CE index is expressed as:

$$CE = 1 - \frac{\sum(E_{est} - E_{ref})^2}{\sum(E_{ref} - E_{mean})^2} \qquad (9)$$

Where, E_{est} and E_{ref} are the estimated and reference (or measured) evaporation for an interval respectively, and E_{mean} is the mean of reference evaporations. A larger CE number indicates a more accurate estimator. Both indexes RMSD and CE are used in this study to evaluate and compare the accuracy and performance of the six evaporation methods, and a performance rank was then carried out.

5. Results

Results of reference evaporation calculation for 10 years (2003-2012) are presented first. They are followed by the results of evaporation estimated with the six methods. Then method comparison results are presented.

5.1. Energy Budget

Yearly mean values of meteorological variables are illustrated in Figures 2 & 3. Air temperature and Lake surface water temperature change in an identical way, as is usually expected. Air and water temperature have clear seasonal change, they decrease in winter and increase in summer. To their contrast, relative humidity does not have clear seasonal change, nor does wind speed have clear changes. Very little correspondence is seen between humidity or wind speed and temperature.
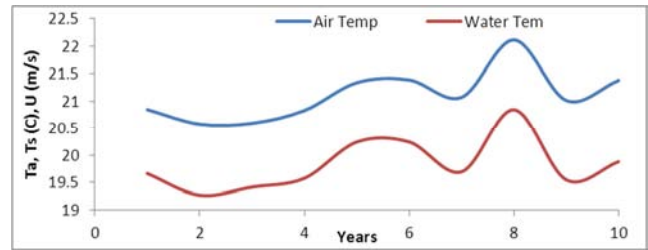

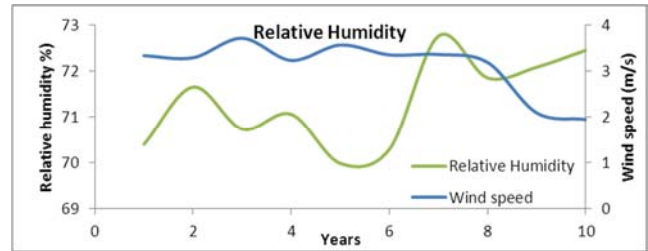*Figure 2. Yearly mean values of Air and water Temperature.*

Figure 3. Yearly mean values of wind speed and humidity.

The total reference evaporation in 10 years, as calculated with the energy budget equations, fluctuates because of its natural changes with meteorological inputs. The evaporation rates for 120 months are representing in Figure 4a. The rate varies between 1.29-5.86 mm/d, with lower rates in January and December, and higher rates in June, July and August as shown in Figure 4b.
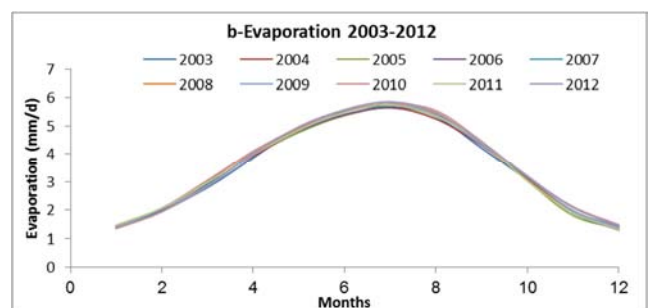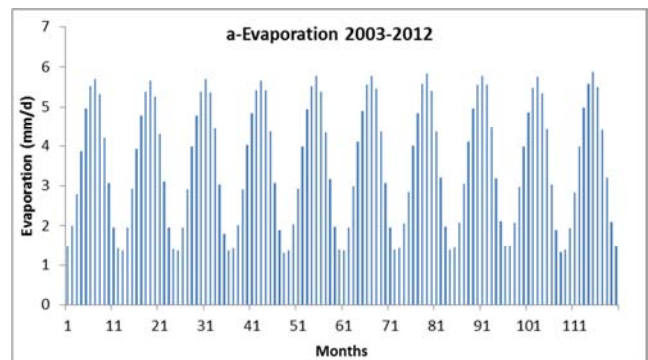

Figure 4. Monthly Mean values of reference evaporation rate (mm/d).

5.2. Evaporation from Six Methods and Method Comparison

Two examples of the results of evaporation obtained from the six methods are shown in Figures 5 & 6. Evaporation from Makkink and De Bruin-Kejimn are mostly close to reference

evaporations, results of Jensin-Harise and Penman are away from the reference. Whereas results of Hamon even farther from the reference. Evaporation of the six methods have almost identical change pattern: low in winter and high in summer.
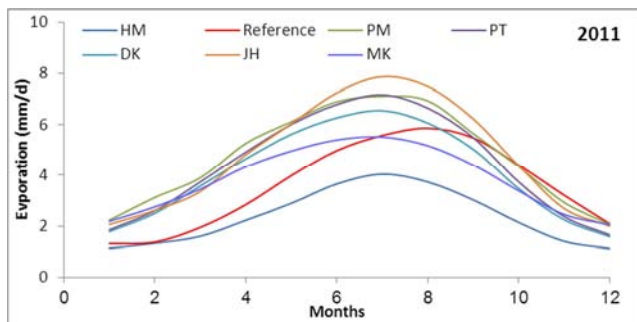

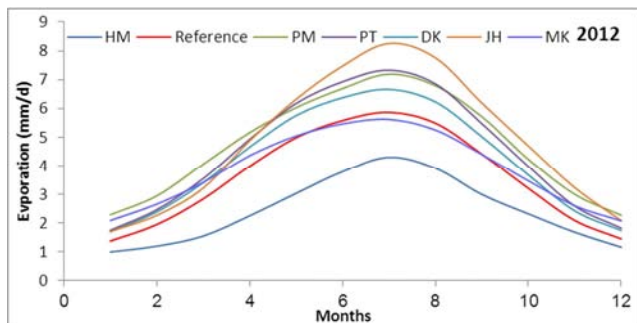***Figure 5.*** *Comparison of six methods-estimated of evaporation with reference evaporation (mm/d) during 2011.*

Figure 6. *Comparison of six methods-estimated of evaporation with reference evaporation (mm/d) during 2012.*

Table 1 represents the evaporation results in cm/year of the study period (2003-2012) carried out using the previous water budget evaporation method in addition to the six methods. Table 2 & 3 represents the evaporation results of years 2011 and 2012 (for example) carried out using the previous six methods in addition to evaporation due to energy budget. The deviations (mm/d) (or error) of methods-estimated evaporation from the reference evaporation are shown in Figure 7. The MK deviations are scattered around the zero level (zero error level), with both positive and negative errors, being the best evenly scattered over the two years (2011 & 2012). The HM deviations are scattered above the zero level (over estimated) for all two years. The DK, PT, PM and JH deviations are scattered below the zero level (under estimated) for all two years.

Table 4 represents the average, maximum and minimum for Lake Brullus evaporation during for the total period (2003-2012) in mm/d. Values of root mean squared deviation (RMSD) between estimated and reference evaporation, and values of coefficient of efficiency (CE) are listed in Table 5. A lower RMSD value or a higher CE value indicates a lower error between the estimated and reference evaporation. Therefore, a performance rank from best to least is determined by the RMSD and CE values, and the out put result rank is: MK, DK, PT, HM, JH and PM.

Table 1. *Evaporation results (2003&2012) carried out by using six different methods and reference evaporation (cm/year).*

Year/Method	HM	PM	PT	DK	JH	MK	Reference
2003	85.43	186.53	159.87	149.01	171.36	139.85	128.79
2004	83.96	184.15	159.29	148.68	169.13	139.44	128.32
2005	84.39	190.29	159.09	148.37	169.63	139.38	128.19
2006	85.63	186.00	160.09	149.15	171.92	140.00	128.94
2007	88.01	194.23	161.83	150.45	176.37	141.21	130.50
2008	88.32	191.21	162.45	150.98	177.16	141.63	130.94
2009	86.77	185.36	162.61	151.35	173.83	140.52	130.79
2010	90.82	189.39	165.69	153.68	182.07	142.76	133.45
2011	86.23	172.38	161.59	150.48	173.28	140.37	129.94
2012	89.10	172.07	164.36	152.67	177.36	141.68	131.94

Table 2. *Evaporation results carried out by using six different methods and reference evaporation yearly mean and total evaporation (cm/year).*

	HM	PM	PT	DK	JH	MK	Reference
Average 2011	7.19	14.37	13.47	12.54	14.44	11.70	10.83
Average 2012	7.42	14.34	13.70	12.72	14.78	11.81	10.99
Total 2011	86.23	172.38	161.59	150.48	173.28	140.37	129.94
Total 2012	89.10	172.07	164.36	152.67	177.36	141.68	131.94

Table 3. *Evaporation results (2011&2012) carried out by using six different methods and reference evaporation (mm/d).*

Month/method	HM	PM	PT	DK	JH	MK	Reference
January-2011	1.13	2.23	1.85	1.78	2.06	2.18	1.47
2	1.32	3.12	2.60	2.50	2.61	2.75	2.07
3	1.60	3.90	3.73	3.58	3.36	3.45	2.98
4	2.22	5.27	4.93	4.66	4.82	4.34	3.98
5	2.89	6.12	6.01	5.63	6.04	4.97	4.87
6	3.65	6.90	6.80	6.27	7.25	5.41	5.48
7	4.04	7.12	7.17	6.55	7.88	5.52	5.76
8	3.73	6.94	6.66	6.07	7.50	5.18	5.35

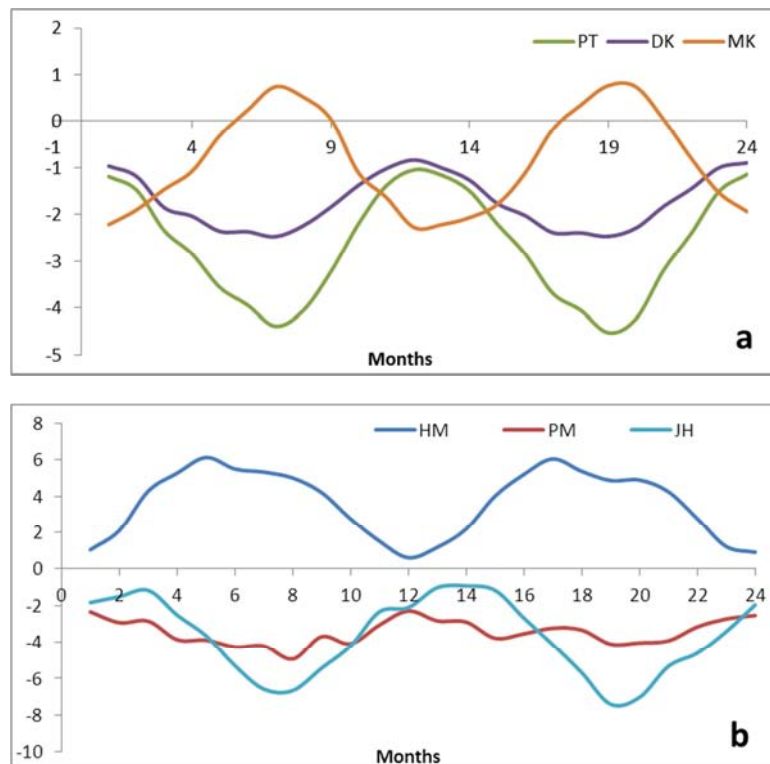| Month/method	HM	PM	PT	DK	JH	MK	Reference
9	3.02	5.66	5.50	5.04	6.24	4.41	4.42
10	2.14	4.34	3.73	3.47	4.39	3.38	3.03
11	1.40	2.93	2.37	2.25	2.69	2.45	1.91
12	1.12	2.06	1.65	1.58	2.00	2.05	1.32
January-2012	0.99	2.28	1.75	1.70	1.70	2.09	1.37
2	1.20	2.94	2.46	2.38	2.26	2.66	1.94
3	1.55	4.06	3.55	3.40	3.21	3.41	2.84
4	2.25	5.16	4.93	4.65	4.88	4.35	3.98
5	3.03	6.03	6.17	5.75	6.32	5.04	4.98
6	3.79	6.69	6.93	6.37	7.47	5.47	5.58
7	4.30	7.19	7.33	6.66	8.26	5.62	5.87
8	3.91	6.79	6.85	6.23	7.76	5.25	5.49
9	2.99	5.72	5.47	5.01	6.19	4.40	4.41
10	2.32	4.23	3.98	3.68	4.70	3.47	3.21
11	1.68	3.00	2.59	2.42	3.23	2.60	2.09
12	1.16	2.27	1.82	1.74	2.08	2.07	1.45

Figure 7. *Deviation of estimated evaporation from reference evaporation (2011-2012) with (a) PT, DK, MK (b) HM, PM, JH and DB.*

Table 4. *Average, maximum, minimum, total and difference from reference evaporation method (mm/d) during the study period 2003 – 2012.*

	HM	PM	PT	DK	JH	MK	Reference
Average	2.37	5.06	4.42	4.11	4.76	3.85	3.56
Maximum	4.30	8.06	7.33	6.66	8.26	5.62	5.87
Minimum	0.99	2.06	1.62	1.55	1.70	2.03	1.30
Total	284.68	607.47	530.09	493.47	570.95	461.55	426.84
Difference	-142.16	180.63	103.25	66.63	144.11	34.72	0.00

Table 5. *RMSD and CE values of estimated vs. reference evaporations, and ranked performance of six evaporation methods when used to study period (2003-2012). The rank of six methods as appeared in Winter et al. [35]; Rosenberry et al. [21] and YAO [37] studies are also listed in this table for comparison.*

Method	RMSD mm	CE	Rank	Rank by YAO [37]	Rank by Winter et al. [35]	Rank by Rosenberry [21]
MK	13.70	0.92	1	2	4	5
DK	17.86	0.86	2	3	3	3
PT	28.66	0.65	3	5	5	2
HM	40.60	0.30	4	6	6	6
JH	41.51	0.27	5	7	7	7
PM	47.20	0.05	6	4	2	4

6. Discussion

The performance rank of the six methods recommended by Winter et al. [35], Rosenberry et al. [21] and YAO [37] are also listed in Table 5. It would be understandable that the all ranks may be different because the lakes are in different locations, and the datasets used are different YAO [37]. Makkink evaporation method being 1st position of the present results rank against 2, 4, and 5 positions in YAO, Winter and Rosenberry ranks respectively. De-Bruin-Kejiman being 2nd position of the present results and the 3rd position among all other three ranks; Jensen-Haise is among those showing poorer results, positioned at 5th of the present results and 7th among all ranks.

In the following discussion try to interpret why the evaporation the ranked methods were fluctuated in their ranks as shown in Table 5. The first-ranked Makkink method has a simple empirical format and uses only air temperature and short-wave radiation as input YAO [37]. These two factors are the most important among many meteorological factors that have a significant effect on the evaporation mechanism in Egypt. Monthly estimates of evaporation using Makkini equation ranged from 2.03 to 5.62 mm/d Table 4. When compared with energy budget, the Makkink equation average underestimated evaporation of total period by as much as 0.15 mm/d and average overestimated evaporation of total period by as much as 0.45 mm/d. During the study period (2003-2012), the total difference in evaporation estimation between the Makkink equation and the energy budget was 34.71 mm Table 4.

The second-ranked DeBruin-Kejiman method it is also an empirical equation, like MK considers more affecting factors (temperature, short and long wave radiations, lake heat storage) than MK does. DeBruin-Kejiman equation determines evaporation rates as a function of the moisture content of the air above the water body, the heat stored in the lake, and the psychrometric constant, which is a function of atmospheric pressure and latent heat of vaporization YAO [37]. Monthly estimates of evaporation using the De-Bruin-Keijman equation ranged from 1.55 to 6.66 mm/d Table 4. When compared with the energy budget, the DeBruin-Keijman equation overestimated evaporation by average of total period as 0.55 mm/d. During the study period, the total difference in evaporation estimation between the DeBruin-Keijman equation and the energy budget was 66.63 mm Table 4.

The third-ranked Priestley-Taylor method is little bit good performance to calculate evaporation from Lake Brullus. Monthly estimates of evaporation by using the Priestly-Taylor equation range from 1.62 to 7.33 mm/d Table 4, Monthly difference range of total period are overestimation by 0.86 mm/d. The total difference in evaporation estimation between the Priestly-Taylor equation and the energy budget of the total period was 103.25 mm Table 4.

The fourth-ranked Hamon method give not bad evaporation estimates, in spite of it is only considers air temperature as the controlling factor.

7. Conclusion

A reference value of the evaporation from Lake Brullus was provided by a lake water energy budget, and was used to evaluate the performance of the six methods. The deviations of method carried out evaporation from reference evaporation were compared among the six methods, and an execution rank was suggested based on the comparison. Monthly evaporation rates were estimated for Lake Brullus in Northern Egypt and for the climatic conditions of the years 2003 – 2012. The estimations of the energy budget consider the standard method, were compared to evaporation rates calculated with six other methods which are the Hamon, Penman, Priestley-Taylor, DeBruin-Kejiman, Jensen-Haise, and Makkink. The Makkink and DeBruin-Kejiman methods are the closest to the energy budget method. The Priestley-Taylor method shows an accepting result with respect to reference method, which though is poor for the Jensen-Haise and Penman methods. The mean rate of evaporation with the energy budget method for the study period (2003 and 2012) under investigation is 3.56 mm/d. The mean evaporation rate has been calculated with the other methods are: for the Hamon method, 2.37 mm/d, for Penman method, 5.06 mm/d, for Priestley-Taylor method, 4.42 mm/d, for DeBruin-Kejiman method, 4.11 mm/d, for Jensen-Haise method, 4.76 mm/d and for Makkink method, 3.85 mm/d, respectively. The availability of climatic data is a main consideration in selecting an evaporation estimation method. The energy budget, Penman, Priestley-Taylor and Makkink methods are data intensive as they require measurement of many meteorological variables. The Hamon method is less data demanding.

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