Al-Baha University Journal of Basic and Applied Sciences 6(2) (2022) 15–24

Article available at Al-Baha University Journal of Basic and Applied Sciences

Journal of Basic and Applied Sciences

Journal homepage: https://portal.bu.edu.sa/web/jbas/

Developing Empirical Models to Estimate Evaporation Rate from the Wadi Alaqiq Reservoir

Khalid A. Alkhuzai *

Civil Engineering Department, Faculty of Engineering, Al-Baha University, Al-Aqiq, Saudi Arabia

ARTICLE INFO

Article history:
Received 28 January 2022;
Received in revised form 12 May, 2022;
Accepted 18 May, 2022

Keywords:
Evaporation
Water Surface
Water Balance
Reservoirs
Dams

ABSTRACT

Evaporation loss is an important component of the hydrological cycle; the precise estimation of evaporation rates from various water sources plays an important role in the planning, design, and operation of natural water resources, particularly in arid regions such as the Kingdom of Saudi Arabia (KSA). Estimating evaporation from the Wadi Alaqiq reservoir is a significant issue for decision-makers; hence, it would be useful to develop an empirical model to calculate evaporation from the dam lake directly using meteorological data. To achieve this, meteorological data, including data on evaporation, relative humidity, temperature, vapor pressure, pressure, and wind speed, were collected and processed for the Wadi Alaqiq dam. Two popular empirical equations in hydrology by Meyer and Harbeck were selected as base points for developing new equations to calculate evaporation from the Wadi Alaqiq reservoir. Calibration was performed for the two equations with the measured records of evaporation; the Meyer equation was robust and provided estimates of measured evaporation with reasonably acceptable accuracy, and its performance was found to be better than that of the Harbeck equation. Using the selected equations and based on the measured climatic data for the Wadi Alaqiq dam and with the help of hydrological and mathematical analyses, new coefficients were developed for the Meyer and Harbeck equations to fit the evaporation calculation from the Wadi Alaqiq reservoir. To develop new coefficients for the developed equations, a methodology based on optimization using three different objective functions was applied. The first objective function was based on minimizing absolute error by applying statistical analysis using Microsoft Excel; the second objective function was a 45-degree line to equality between the measured and calculated evaporation; the third objective function was convergence. These functions helped to produce values of optimized coefficients for the developed equations. Two equations, based on the Meyer and Harbeck equations, were developed to estimate evaporation from the reservoir of the Wadi Alaqiq dam.

1. Introduction

Evaporation rate estimation in irrigated areas and other water bodies is highly complex, due to the nonlinear behavior of various physical processes, which affect vaporization. Several equations exist to calculate evaporation rates of various water bodies and evaporation pans, and each one of them provides different results. Therefore, selecting the most appropriate equation for estimating evaporation rates remains a vital research topic. The availability and accuracy of data is another issue to be addressed. For arid regions, it is of the utmost importance to compare and evaluate methods of estimating evaporation, in order to select the best evaporation equation for the future planning of limiting water resources. Inaccuracies in estimated evaporation will directly affect the design, operation, and maintenance of drainage facilities, irrigation schedules, and runoff estimations. As equations based on physical principles require a lot of data and most of the empirical equations are site-dependent, the empirical parameters of these equations must be determined with an acceptable degree of certainty. Identification of evaporation equation parameters requires the application of a suitable optimization technique. This aspect has not been frequently investigated in past studies.

There are many meteorological factors affecting the rate of evaporation, including (i) the temperature of the water and air, (ii) the difference in vapor pressure between water and air, (iii) wind speed, and (iv) solar radiation. The evaporation rate is also influenced by surrounding air humidity. Humid air (or moist air) has a comparatively smaller thirst for water vapor than drier air, while an absence of wind also decreases the evaporation rate. During non-windy days, water evaporating into adjacent air remains close to the surface of the pond or reservoir and contributes to local humidity. The evaporation rate diminishes

* Corresponding author: Civil Engineering Department, Faculty of Engineering, Al-Baha University, Al-Aqiq, Saudi Arabia.

E-mail address: kalkhuzai@bu.edu.sa.

when the moisture content of the adjacent air reaches the maximum limiting value. The existence of airflow removes the vapor of the air surrounding the water source, which reduces humidity and thus increases the evaporation rate. The evaporation process needs sufficient energy for the latent heat of vaporization. The main source of heat energy is solar radiation.

Numerous methods exist for estimating evaporation from water surfaces. These methods fall into four categories, namely: (i) water budget, (ii) energy budget, (iii) method of mass transfer, and (iv) combined techniques. In energy budget and water budget techniques, the incoming and outgoing amounts are balanced. Equations obtained from this balance are solved by keeping the evaporation rate unknown. Methods which calculate evaporation rates by using meteorological records are the most useful for estimating evaporation.

Despite the variety of existing empirical formulas for evaporation, all of them, with very rare exceptions, can be represented as:

$$E = \alpha(e_0 - e)f(u), \qquad (1)$$

where E = evaporation; e_0 = maximum water vapor pressure corresponding to the water surface temperature; e = actual vapor pressure in the air; u = wind speed; α = coefficient, taking into account the total influence of unaccounted factors in the evaporation process.

In Russia, the most famous are the formulas of V. K. Davydov and B. D. Zaikof.

To estimate evaporation from the surface of small water bodies and reservoirs, the formula of V. K. Davydov is as follows:

$$E = 15d'^{0.80}(1 + 0{,}125u). \qquad (2)$$

2. Study Area

The Wadi Alaqiq dam is located in the south of the Alaqiq governorate (Figures 1 and 2); it is the largest dam in the region and contains large quantities of water storage, which the people of the Al-Baha region use. The dam has a height of 30 m with a lake capacity equal to 19126142 m^3 ; the lake covers an area equal to 1.3 km^2 .

Figure 1. The Wadi Alaqiq dam.

3. Data Collection

The evaporation records and meteorological data, including in relation to relative humidity, temperature, vapor pressure, pressure, and wind speed, were collected from the Ministry of Environment, Water and Agriculture, Saudi Arabia for the period from 1997–2017.

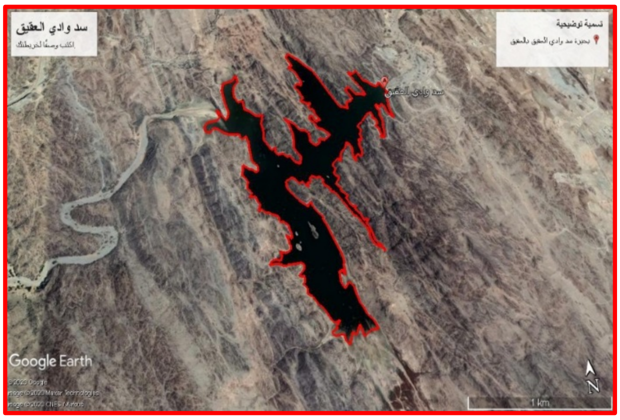

Figure 2. Satellite image showing the boundaries of the lake of the Wadi Alaqiq dam.

The mean values for the meteorological data were calculated and the results are illustrated in Figures 3-8.

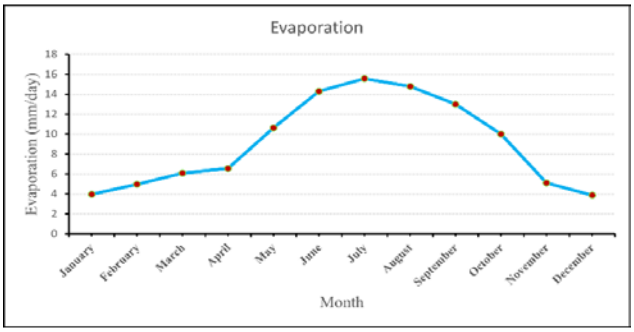

Figure 3. Mean measured evaporation for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

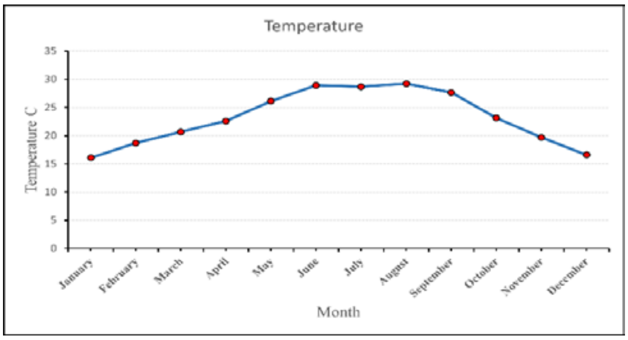

Figure 4. Mean average temperature for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

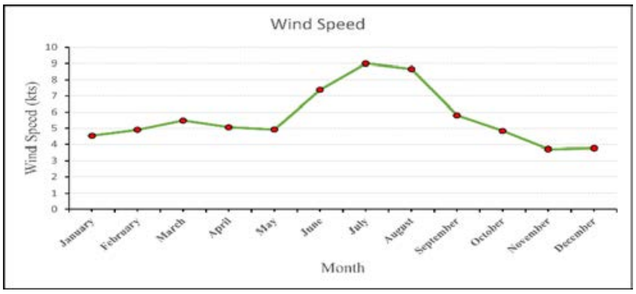

Figure 5. Mean average wind speed for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

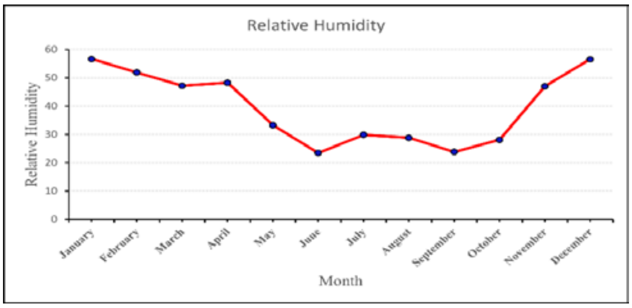

Figure 6. Mean average relative humidity for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

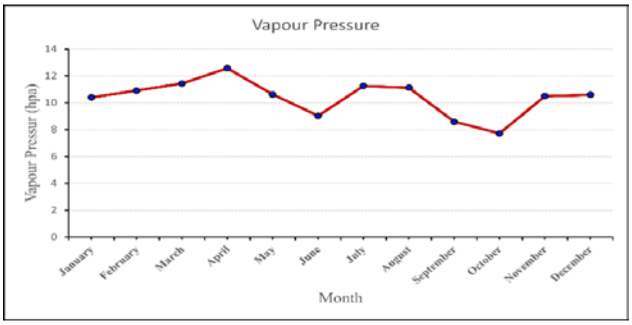

Figure 7. Mean average vapor pressure for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

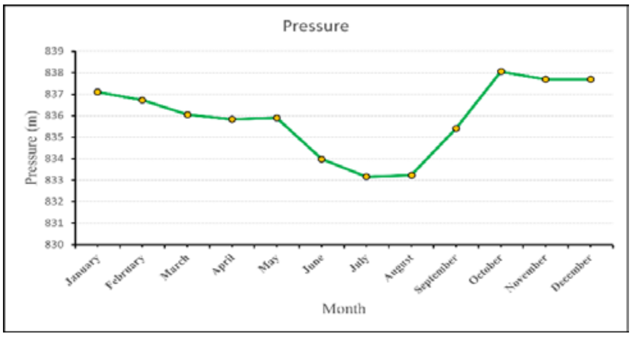

Figure 8. Mean average pressure for the period from 1997–2017. Source: Ministry of Environment, Water and Agriculture, Saudi Arabia.

4. Brief Description of Evaporation Equations

Many equations were derived for the estimation of evaporation. All these equations are based on Dalton's law (Equation 1):

$$E = K(e_w - e_a), \quad (3)$$

where:

E is the daily evaporation, e_w is the saturated vapor pressure at the temperature of water, e_a is the vapor pressure of the air (about 2 m above), and K is a constant.

I.e., Dalton's law states that evaporation is proportional to the difference in vapor pressures ew and ea. A more general form of Eq. (3) is given by:

$$E = K' (e_w - e_a)(a + bV), \quad (4)$$

where K', a, b are constants and V is the wind velocity.

4.1. Meyer's Formula

$$E_L = K_M(e_w - e_a)\left(1 + \frac{U_9}{16}\right), \quad (5)$$

In which E_L, e_w, e_a are as defined in Eq. (1), U_9 = monthly mean velocity in km/h at about 9 m above ground, and K_M = coefficient accounting for various other factors with a value of 0.36 for large deep waters and 0.5 for small, shallow waters.

4.2. Harbeck's Formula

Sene et al. (1991) produced a simple derivation of the bulk transfer equation, which has the following form:

$$E = cu(e_s^* - e), \quad (6)$$

where c is the mass transfer coefficient, u is the wind speed, and e_s^* and e are the saturated vapor pressure of the air at the water surface temperature and the vapor pressure of the air at the reference height.

Based on an extensive measurement program on reservoirs in western USA, Harbeck (1962) suggested an expression for c, which incorporated the area of the water body. In appropriate units, the transfer equation is:

$$E = 2.909 A_s^{-0.05} u_2 (e_s^* - e), \quad (7)$$

where A_s is the area of the water surface in m^2 and u_2 is the wind speed at 2 m above the water surface. This is suitable for lakes in the range of 50 m < $A_s^{-0.05}$< 100 km and are in a relatively arid environment.

These empirical formulae are simple to use and permit the use of standard meteorological data. However, in view of the various limitations of the formulae, they can, at best, expect to produce an approximate magnitude of evaporation.

In using empirical equations, the saturated vapor pressure at a given temperature (e_w) is found from table e_w vs. temperature in C°, or e_w is found through the following formula:

$$e_w = 4.584 \exp\left(\frac{17.27t}{237.3+t}\right), \quad (8)$$

where e_w = saturated vapor pressure in mm of Hg and t = temperature in °C.

Wind velocity data would often be available at an elevation other than that needed in the equation. However, it is known that in the lower part of the atmosphere, up to a height of about 500 m above ground level, wind velocity can be assumed to follow the 1/7 power law as:

$$u_h = Ch^{1/7}, \quad (9)$$

where u_h = wind velocity at height h above the ground and C = constant. This equation can be used to determine the velocity at any desired level if u_h is known.

5. Methodology for Developing an Empirical Evaporation Equation

Evaporation was calculated with the two selected empirical equations (Meyer and Harbeck) without any modification, with the same value for all constants (coefficients) and wind functions in the original equation. To examine equality between measured and calculated evaporation, the 45-degree line is used. The 45-degree works as a guideline, which provides insight into the measured records and as a critical part of the analysis (Figures 9 and 11). Two curves were also plotted for the measured and calculated values of evaporation for a series of data to identify the extent of convergence in the values (Figures 10 and 12).

5.1. Meyer's Formula

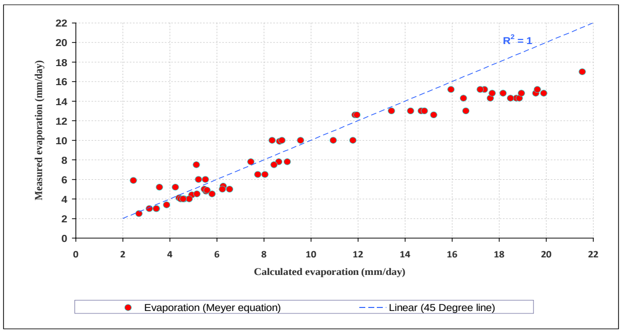

Figure 9. Equality examined between measured and calculated evaporation by the 45-degree line using the Meyer equation.

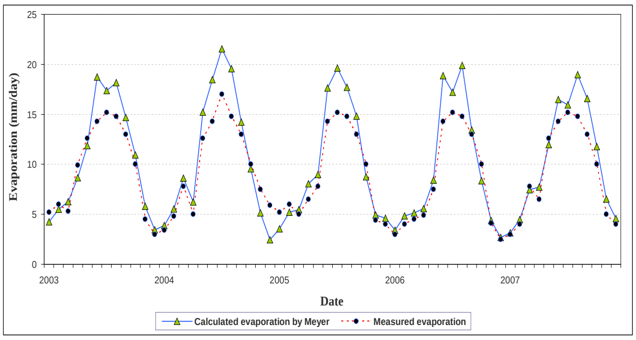

Figure 10. The convergence in values between measured and calculated evaporation using the Meyer equation.

Discussion and Recommendations:

From Figures 9 and 10, there is strong correlation and convergence between minimum records that start from 2 mm to 14 mm, but records of more than 14 mm had a weak correlation. The equation needs a slight adjustment in the constants and wind function to be developed.

5.2. Harbeck's Formula

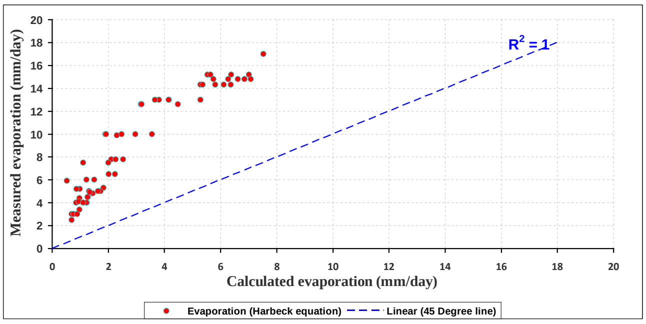

Figure 11. Equality examined between measured and calculated evaporation by the 45-degree line using the Harbeck equation.

Discussion and Recommendations:

Figures 11 and 12 demonstrate that the correlation and convergence between all records is very weak. The weakness of the Harbeck equation is attributed to its dependence on the area of the lake in estimating evaporation. Moreover, the wind function in the Harbeck equation takes the constant form, which is not a mathematical function, as in the Dalton and Meyer equations. The equation needs to develop a drastic and serious adjustment in the constants and wind function.

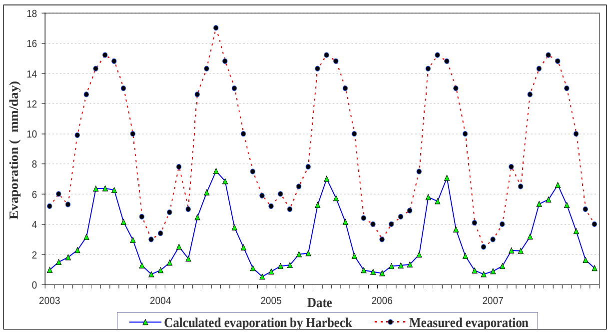

Figure 12. The convergence in values between measured and calculated evaporation using the Harbeck equation.

The performance of the Meyer equation was better than the Harbeck one. Merit wise, these equations can be ranked as Meyer (merit number 1) and Harbeck (2). The results of the simulated evaporation were only close to the 45° line for the Meyer equation. The results from the Harbeck equation were far from the 45° line.

It is worth mentioning here that the merit of equations determined in this research is based on specific measured evaporation and other meteorological data. To confirm the results obtained above, further analysis was conducted by calculating the average absolute error and standard deviation. The maximum, minimum, and average absolute error values for the Meyer and Harbeck equations are shown in Figure 13; the absolute error values indicate that the Meyer equation produces a better absolute error (maximum, minimum, and average) than the Harbeck equation.

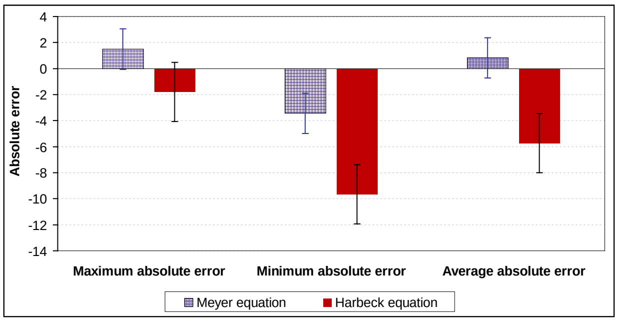

Figure 13. Absolute maximum, minimum, and average error for the Meyer and Harbeck equations.

Discussion and Recommendations:

From the above analysis, we can see that the Meyer equation was robust and provided estimates of measured evaporation with reasonably acceptable accuracy, and its performance was found to be better than the Harbeck equation. The dependence of the Harbeck equation on the area of the lake, in addition to differences in wind function from those in the Dalton equation (which is the basis for all empirical equations), is the main reason for the weakness.

6. Performance Calibration and Validation of the Developed Equations

With the help of Microsoft Excel, statistical functions were used to identify new coefficients (constants and wind functions) for developing (modified) new evaporation equations (Meyer and Harbeck) for the Wadi Alaqiq reservoir. The final developed equations using optimization are given below (Appendices A and B).

6.1. The developed equation based on Meyer's Formula

$$E_L = 0.32(e_w - e_a)\left(1 + \frac{U_9}{19}\right) . \qquad (10)$$

6.2. The developed equation based on Harbeck's Formula

$$E = 6.05A_s^{-0.04}u_2(e_s^* - e). \qquad (11)$$

The results from the two developed equations are presented in Figures 14, 15, 16, and 17. The application of optimization resulted in improved equations. The evaporation estimated by the two newly developed equations was highly accurate, i.e., the results were very close to the 45º line and the convergence in values between measured and calculated evaporation using developed equations was nearly identical. The absolute error values for the newly developed equations are presented in Figures 18, 19, and 20. The developed equations showed better absolute error values than the original equations.

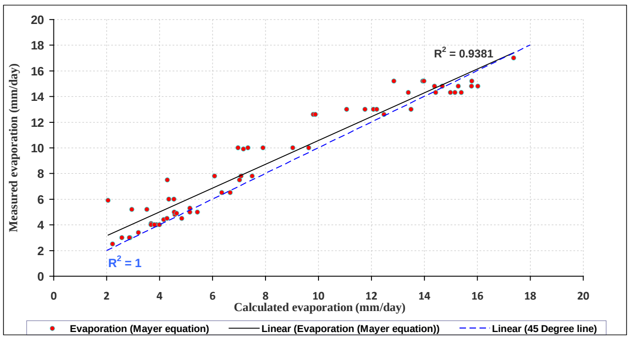

Figure 14. Equality examined between measured and calculated evaporation by the 45-degree line using the developed equation based on the Meyer equation.

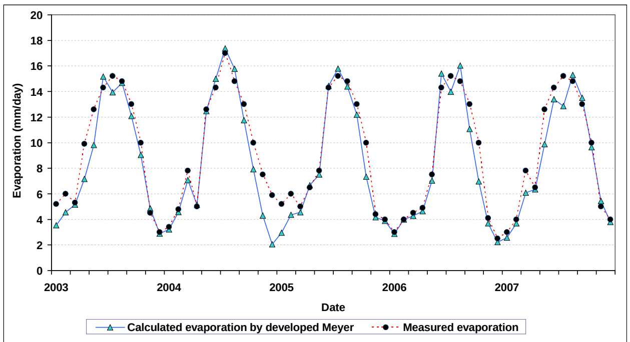

Figure 15. The convergence in values between measured and calculated evaporation using the developed equation based on the Meyer equation.

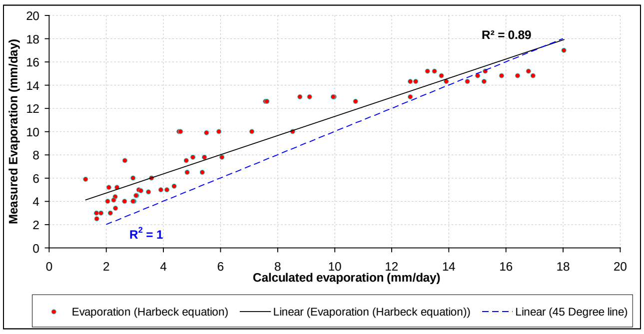

Figure 16. Equality examined between measured and calculated evaporation by the 45-degree line using the developed equation based on the Harbeck equation.

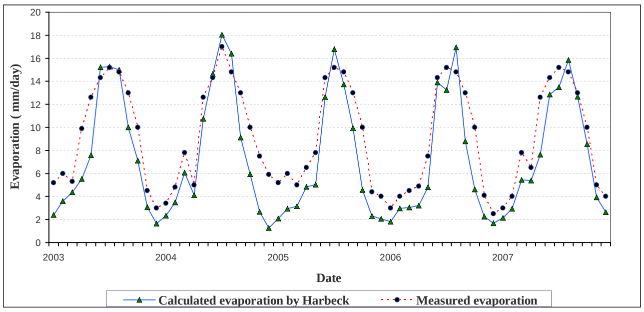

Figure 17. The convergence in values between measured and calculated evaporation using the developed equation based on the Harbeck equation.

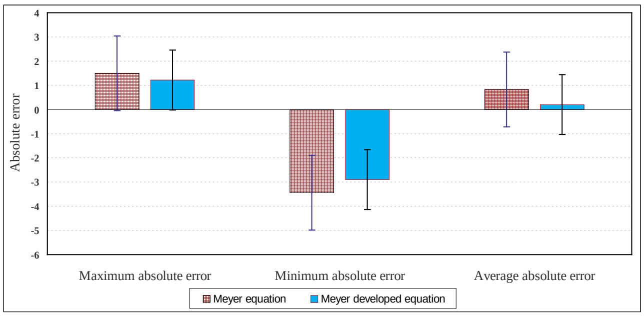

Figure 18. Absolute error calculated by the Meyer equation and the Meyer developed equation.

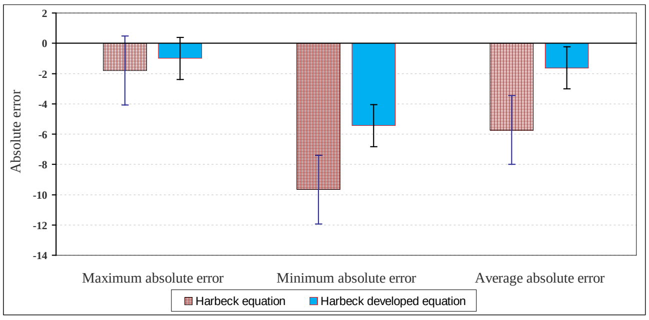

Figure 19. Absolute error calculated by the Harbeck equation and the Harbeck developed equation.

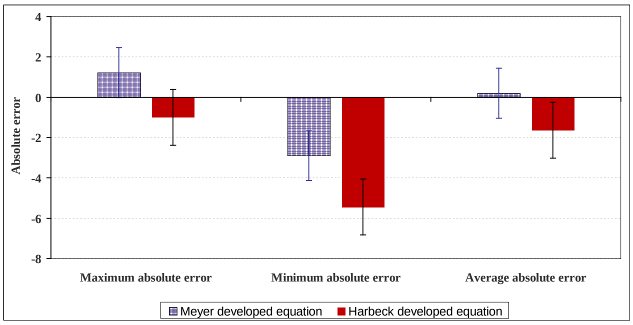

Figure 20. Absolute error calculated by the developed equations (Meyer and Harbeck).

7. Conclusion

This paper presented performance evaluation and analysis of full Extensive records of measured evaporation, temperature, relative humidity, vapor pressure, pressure, and wind speed were used in this study for the analysis and development of evaporation equations. Evaporation was estimated using two different empirical equations, the Meyer and Harbeck equations. The results of these two equations were compared based on extensive measured data relating to measured evaporation, temperature, relative humidity, vapor pressure, pressure, and wind speed. It was concluded that the Meyer equation was robust and provided estimates of measured evaporation with a reasonably acceptable accuracy. Its performance was found to be better than that of the Harbeck equation. The dependence of the Harbeck equation on the area of the lake, in addition to the difference in wind function from that in the Dalton equation (which is the basis for all empirical equations), is the main reason for this weakness.In order to develop new coefficients for the developed equations, a methodology based on optimization using three different objective functions was applied. The first objective function was based on minimizing absolute error, by applying a statistical analysis using Microsoft Excel; the second objective function was a 45-degree line to equality between measured and calculated evaporation; the third objective function was convergence. These functions helped produce values of optimized parameters for the developed equations. Two equations based on the Meyer and Harbeck equations were developed to estimate evaporation from the reservoir of the Wadi Alaqiq dam.

Acknowledgement

This paper is based on the results obtained from the research project entitled "Development of empirical models for evaporation rate in Al-Baha region using reservoirs dam meteorological data" funded by the Deanship of Scientific Research, Al-Baha University, KSA (Grant No. 28/1439). The assistance of the deanship is gratefully acknowledged.

References

1. Andersen, M. E. and Jobson, H. E. 1982 Comparison of techniques for estimating annual lake evaporation using climatological data. Water Resources Research, 18, pp.630-636.
2. Babkin V.I. Evaporation from the water surface. L.: Gidrometeoizdat, 1984. p.80.
3. Dalton I. Experiments and observations to determine whether the quantity of rain and dew is equal to the quantity of water carried off by the river and raised by evaporation, with an enquiry into the origin of springs. Mem. Manchester Lit. and Phil. Sec. S. 1802.
4. Chow, V.T., 1988. Handbook of Applied Hydrology. McGraw-Hill Book.
5. Finch, J. W. 2003 Empirical factors for estimating open-water evaporation from potential evaporation. Journal of the Chartered Institution of Water and Environmental Management, 17, pp.51-53.
7. Fraedrich, K., Erath, B. G. and Weber, G. 1977 A simple model for estimating the evaporation from a shallow water reservoir. Tellus, 29, pp.428-434.
8. Harbeck, G. E. 1962 A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. USGS Professional Paper 272-E, pp.101-105. US Geological Survey.
9. Harbeck, G. E., Kohler, M. A. and Koberg, G. E. 1954 Water-loss investigations: Lake Hefner Studies. USGS Professional Paper 269, pp.1-158. US Geological Survey.
10. Harbeck, G. E., Kohler, M. A. and Koberg, G. E. 1958 Water-loss investigations: Lake Mead studies. US Geological Survey Professional Paper 298, p.9, US Geological Survey.
11. Hounam, C. E. 1973 Comparison between pan and lake evaporation. Technical Note 126, World Meteorological Organization.
12. Khalid A. H. Alkhuzai and Sami H. E. Taglawi 2021 Development of empirical models for evaporation rate in Albaha region using reservoirs dam meteorological data, Scientific Research, Al-Baha University, KSA (Grant No. 28/1439).
13. K Subramanya, Handbook of Engineering Hydrology, India, April 2008.
14. Sene, K. J., Gash, J. H. and McNeil, D. D. 1991 Evaporation from a tropical lake: comparison of theory with direct measurements. Journal of Hydrology, 127, 193-217.
15. Shuttleworth, W. J. 1993 Evaporation. In: Maidment, D.R., (ed.) Handbook of Hydrology, New York: McGraw-Hill, p.53.
16. Vardavas, I. M. and Fountoulakis, A. 1996 Estimation of lake evaporation from standard meteorlogical measurements: application to four Australian lakes in different climatic regions. Ecological Modelling, p.84, pp.139-150.
17. V. Chow, D. Maidment, and L. Mays, 1988. Applied Hydrology, McGraw- Hill Book Company, New York.
18. Vikulina Z.A. Water balance of lakes and reservoirs of the Soviet Union. L.: Gidrometeoizdat, 1974. p.175 .
19. Zaikov B.D. Essays on lake studies. - L .: Gidrometeoizdat, 1960. p.239.