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Developing equations for estimating reference evapotranspiration in Australia

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Abstract

Quantifying reference evapotranspiration (ET_0) is essential in water resources management. Although, many methods have been developed with different level of accuracy, in this study, two new equations were developed and optimized for estimating ET_0 using Honey-Bee Mating Optimization (HBMO) algorithm. The first equation estimates ET_0 from extraterrestrial radiation (R_a), relative humidity (RH) and mean daily temperature (T_{mean}), while the second uses the same parameters except that mean daily temperatures is replaced with maximum daily air temperature (T_{max}). Both equations were developed using climatic data from eight weather stations in Western Australia and subsequently verified using data from ten sites across Australia. The estimated ET_0 values from both equations versus the FAO56-Penman-Monteith have a coefficient of determination, R^2, of larger than 0.96. Moreover, the performance of six commonly used methods of estimating ET_0 including Hargreaves-Samani, Thornthwaith, Hamon, Mc Guinness-Bordne, Irmak and Jensen-Haise were assessed and the Hargreaves-Samani method performed better than others. An attempt was made to calibrate the

Hargreaves-Samani equation; however, its overall performance did not improved and the two newly proposed equations are suggested to be used in Australia.

Key Words

Reference evapotranspiration, FAO56-Penman-Monteith, Temperature-based equations, Honey-Bee Mating Optimization

1 Introduction

Water resources scarcity due to droughts in Australia and other countries is a particularly serious challenge for decision makers. In this regard, accurate estimation of ET_0 is necessary for purposes such as water management, water balance and scheduling irrigation (Martí et al. 2011; Oudin et al. 2010). ET_0 is also a key component of hydrologic cycles and different methods have been developed for estimating it. Direct measurement of ET_0, using costly and time consuming methods such as a lysimeter, is not recommended in engineering applications (Valiantzas 2006). In hydrology, ET_0 is commonly estimated from climate variables, using techniques varying from simple empirical formulas to complex physically-based methods (Efthimiou et al. 2013). Allen et al. (1998) recommended worldwide use of the FAO56 Penman-Montieth (FAO56-PM) method, which requires various input data, which are not readily available at many meteorological stations, including air temperature, relative humidity, wind speed and solar radiation. As an alternative to FAO56-PM, several other methods have been proposed and examined (Landeras et al. 2008; Sabziparvar et al. 2010; Trajkovic 2007; Valiantzas 2012; Valiantzas 2012). Abtew (1996) proposed and calibrated simple models of estimating ET_0 that were comparable with FAO56-PM for South Florida's climate. Hargreaves and Samani (1985) developed an alternative approach which only requires mean maximum and minimum air temperature and extraterrestrial radiation. This method has been tested across different climate ranges; however, it usually underestimates ET_0 values in very dry zones, semiarid and arid locations (Azhar and Perera 2010; Jensen et al. 1990) and overestimates in humid climates (Heydari and Heydari 2014; Itenfisu et al. 2003). Several temperature and radiation-based equations have also been developed. Jensen and Haise (1963) proposed an equation which was later modified by Jensen (1967) and Jensen et al. (1970), based on 3,000 measured ET_0 values for different geographical locations in the USA.

Alexandris et al. (2006) proposed the “Copais” empirical method using bilinear surface regression analysis using solar radiation, temperature and relative humidity. The estimated ET_0 from this equation were comparable with ASCE Penman–Monteith, CIMIS–Penman, FAO56-PM, and daily Hargreaves–Samani methods (Alexandris et al. 2006). Trajkovic and Kolakovic (2009) developed a wind-adjusted equation based on the Turc method for estimating daily ET_0 in humid European climatic conditions. The Valiantzas equation (Valiantzas 2012) is one of the newest methods which estimates the spatial distribution of ET_0, for different hydrological applications (Kisi 2013; Valipour 2014). Irmak et al. (2003) examined 21 methods for estimating ET_0 in Florida, and the results differed significantly from the FAO56-PM. They proposed two new equations and recommended the calibration of existing methods. Their first proposed equation uses solar radiation, while the second benefits from the use of net radiation and air temperature. Both equations are practical for estimating ET_0 in developing countries, where available and reliable climate data are limited. Kisi and Cengiz (2013) investigated the applicability of fuzzy genetic approach in order to model reference ET_0 using daily solar radiation, air temperature, relative humidity and wind speed data of two stations in Mediterranean region of Turkey. The estimated ET_0 were compared with those of the artificial neural networks (ANN). They indicated that the fuzzy genetic models generally performed better than the ANN models in ET_0 modelling. In India, Chauhan and Shrivastava (2009) attempted to develop an alternative method to estimate ET_0 against FAO56-PM for the Mahanadi reservoir project (MRP) area located at Raipur. Their study identified the ability of ANNs for estimation of ET_0 in comparison to climatic based methods. Their results indicated that ANN models were performed better than the climatic based methods in all performance indices, and also suggested that the ET_0 can be estimated from maximum and minimum temperature using ANN approach in MPR area.

Xu et al. (2016) applied the symbolic regression method to establish equations with the same inputs to simple Hargreaves-Samani equation in arid China. They derived new equations for five stations, which their performance increased with an increase in the equation complex index (CI). They concluded that the site-specific trade-off equation performs better than the simplest one and the locally calibrated HS equation. In another study, Alavi and Rahimikhoob (2016) derived a simple linear equation with three components from the FAO56-PM equation using 297 NOAA satellite images over 10 years in Khuzestan province, Iran.

For each component, a linear regression equation was fitted to NOAA satellite data. Results indicated that the simplified model estimates ET_0 with a determination coefficient of 0.92.

Considering the operational costs and time for direct measurements of ET_0, it would be beneficial to use simplified existing formulas or develop new equations that require fewer data sets than FAO56-PM (Allen et al. 1994a). Therefore, the objectives of this study are: (1) to assess the performance of some of commonly used evapotranspiration methods; (2) to develop and validate new equations, with fewer climate inputs for estimating reference evapotranspiration in Australia; and (3) to compare the estimation of ET_0 from the proposed equations with the commonly used methods.

2 Material and Methods

2.1 The Study Area

The climatic data for the Pilbara region of Western Australia were used to develop the new equations for estimating evapotranspiration and they were verified using data from other parts of Australia. Fig. 1 shows the Pilbara region that is a sparsely populated region, extending from the Indian Ocean to the west and the Northern Territory border to the east (Longitude 129°E), covering more than 500,000 km^2, which is almost 20 percent of the land area of Western Australia.

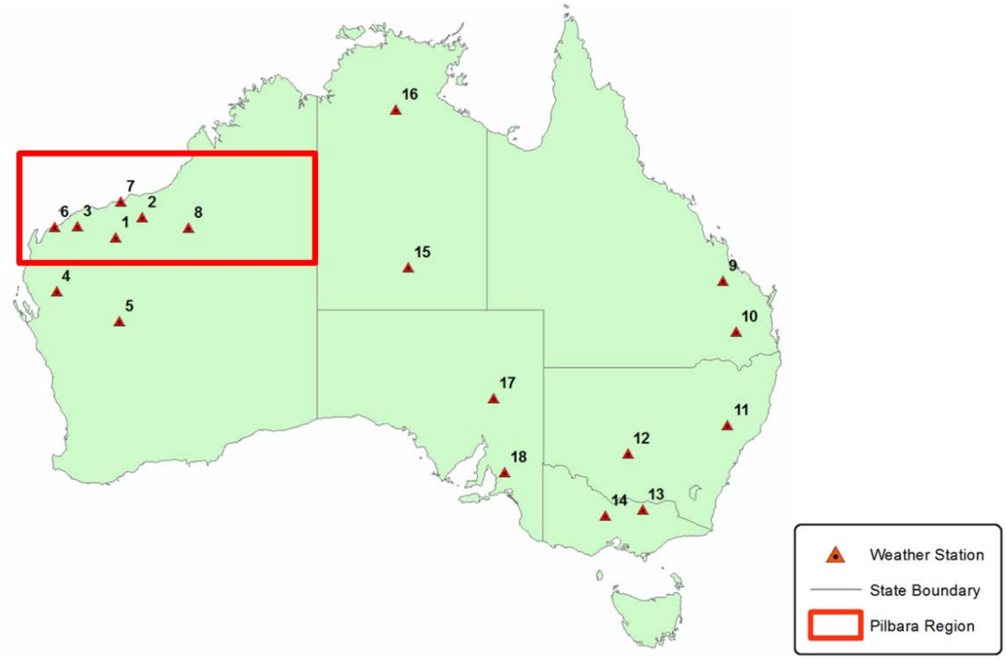


Fig. 1 Location of weather stations in Australia

The Pilbara climate is classified as arid-tropical in nature with two distinct seasons of hot summer (October to April) and mild winter (May to September). The maximum daily temperature in the summer months often exceeds 40^{0}C, with a minimum of approximately 25^{0}C (Van Vreeswyk 2004). The annual rainfall of 330 mm is highly variable (Johnson and Wright 2003), and influenced by two primary climatic systems; a northern rainfall system associated with tropical lows and, a winter rainfall event associated with low pressure frontal systems (Eberhard et al. 2005; Van Vreeswyk 2004). Daily climatic data including air temperature and relative humidity for 18 stations across Australia were collected from the Australian Government Bureau of Meteorology (BOM) for a period of 10 years from January 2001 to December 2011. The weather station information including names, latitude and longitude coordinates and elevation are presented in Table 1. The data from the first eight stations, located in Western Australia, were used to develop and calibrate the proposed equations; while the data from other stations were used to verify the equations. The numbers next to each station in Fig. 1 corresponds to station numbers in Table 1.

Table 1 Weather station sites details

Station Number	**Station Name**	**State**	**Latitude (Decimal)**	**Longitude (Decimal)**	**Station Height (AHD) (m)**
1	Wittenoom	Western Australia	-22.2425	118.3358	463.00
2	Marble Bar	Western Australia	-21.1756	119.7497	182.30
3	Pannawonica	Western Australia	-21.6392	116.3308	200.00
4	Gascoyne Junction	Western Australia	-25.0544	115.2100	144.00
5	Meekatharra Airport	Western Australia	-26.6136	118.5372	517.00
6	Onslow Airport	Western Australia	-21.6689	115.1092	10.50
7	Port Headland Airport	Western Australia	-20.3725	118.6317	6.40
8	Telfer Aero	Western Australia	-21.7125	122.2281	291.90
9	Thangool Airport	Queensland	-24.4935	150.5709	193.10
10	Dalby Airport	Queensland	-27.1605	151.2634	343.90
11	Scone Airport AWS	New South Wales	-32.0335	150.8264	221.40
12	Hillston Airport	New South Wales	-33.4915	145.5249	122.00
13	Wangaratta Aero	Victoria	-36.4206	146.3056	152.60
14	Bendigo Airport	Victoria	-36.7395	144.3266	208.00
15	Alice Sprig Airport	Northern Territory	-23.7951	133.8890	546.00
16	Larrimah	Northern Territory	-15.5748	133.2137	180.00
17	Leigh Creek Airport	South Australia	-30.5963	138.4219	258.80
18	Nuriootpa Viticultural	South Australia	-34.4761	139.0056	275.00

2.2 Basic Reference Evapotranspiration Equation

Alike many other places around the world, in Australia the FAO56-PM method is used for estimating ET_0. This method was given by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al. 1998), and its suitability under various climate conditions has been confirmed by different studies (Gundekar et al. 2008; Irmak et al. 2003; Jabloun and Sahli 2008; Temesgen et al. 2005). The general form of the FAO56 Penman-Montieth is described as (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 = reference evapotranspiration [mm day^{-1}]; G = soil heat flux density [MJ m^{-2} day^{-1}]; R_n = net radiation [MJ m^{-2} day^{-1}]; γ = psychometric constant [kPa (^{0}C)$^{-1}$]; T_{mean} = mean air temperature [^{0}C]; u_2 = average 24 h wind speed at 2 m height [m s^{-1}]; Δ = slope of the saturation vapour pressure function [kPa (^{0}C)$^{-1}$]; and e_s-e_a = vapour pressure deficit [kPa].

ET_0 values from the FAO56-PM are available from the Scientific Information for Land Owners (SILO) for different regions in Australia.

Table 2 Reference evapotranspiration estimation methods

Method	Reference	Representative equation
Hargreaves-Samani	(Hargreaves & Samani, 1985)	$^*ET_o = 0.0023R_a(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}$
Thornthwaith	(Thornthwaite, 1948)	$ET_O = 16\left(\frac{10T_i}{I}\right)^a \left(\frac{N}{12}\right)\left(\frac{1}{30}\right)$ $I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$ $a = (492390 + 17920I - 771I^2 + 0.675I^3) \times 10^{-6}$
Hamon	(Hamon, 1961)	$ET_o = 0.55\left(\frac{N}{12}\right)^2 \frac{SVD}{100}(25.4)$
Mc Guinness-Bordne	(McGuinness & Bordne, 1972)	$^*ET_o = R_a(\frac{T+5}{68})$
Irmak	(Irmak, Irmak, et al., 2003)	$^{**}ET_o = 0.149R_s + 0.079T_m - 0.611$
Jensen-Haise	(Marvin E Jensen & Haise, 1963)	$^*ET_o = (0.0252T_{mean} + 0.078)R_s$

* R_a and R_s in mm/d ** R_a and R_s in MJm^{-2}/d

R_s is the global solar radiation, R_a is the extraterrestrial radiation, RH is the relative humidity (%), T_i = the mean monthly temperature (^oC), T_{mean} is the average temperature (^oC), T_{max} is the maximum temperature (^oC), T_{min} is the minimum temperature (^oC), N is the mean monthly sunshine hour and SVD is the saturated vapour density at mean air temperature (gr/m^3)

Presented in Table 2 are the six commonly equations (Hargreaves-Samani, Thornthwaite, Hamon, Mc Guinness-Bordne, Irmak and Jensen-Haise methods) were used for estimating ET_0 in the Pilbara. The performance of these methods and the two proposed equations were assessed using the statistical parameters MBE, RMSE, RE and R^2 which will be defined later.

2.3 Developing New Equations

Two new equations were derived using the surface polynomial regression technique, with the aim of reducing the number of input parameters. Considering the Penman equation (1963), evaporation is a combination of three components: (1) incoming short wave net radiation, (2) outgoing long wave net radiation, and (3) the aerodynamic term (Valiantzas 2006). The aerodynamic term is directly estimated from the mean vapour pressure deficit (D_{av}), and it is suggested that D_{av} can be estimated from $(1-\frac{RH}{100})$ (Shuttleworth 1993). Moreover, ET_0 is directly related to extraterrestrial radiation (R_a) (Hargreaves and Allen 2003). Therefore, $(1-\frac{RH}{100})$ and R_a were combined with the air temperature to develop the new equations. It was assumed that the variables influencing the estimation of ET_0 are independent. The first equation was formed by combining the climate parameters T_{mean}, R_a and RH, while T_{max}, R_a and RH formed the second equation.

The general form of surface polynomial equation is defined as:

$$ET_0 = k_0 + k_1x_1 + k_2x_2x_3 \qquad (2)$$

where ET_0 is estimated from the FAO56-PM, k_0 is intercept, k_1 and k_2 represent the slope of the regression line, x_1, x_2 and x_3 are the independent variables represented by T_{max}, T_{mean}, R_a and RH. From the surface polynomial regression, the two proposed equations are:

$$ET_0 = 0.252R_a + 0.221T_{mean}\left(1-\frac{RH}{100}\right) \qquad (3)$$

$$ET_0 = 0.29R_a + 0.15T_{max}\left(1-\frac{RH}{100}\right) \qquad (4)$$

where R_a is extraterrestrial radiation (mm day^{-1}), T_{mean} is the mean daily air temperature calculated as the average of daily maximum and minimum air temperatures (°C), RH is relative humidity (%), and T_{max} is maximum daily air temperature.

As mentioned earlier, the performance of the proposed equations and other commonly used equations versus the FAO56-PM were assessed using the statistical parameters MBE, RMSE, RE and R^2 (Jacovides and Kontoyiannis 1995) defined as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(y-x) \qquad (mm\ day^{-1}) \qquad (5)$$

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}(y-x)^2\right)^{0.5} \qquad (mm\ day^{-1}) \qquad (6)$$

$$RE = \frac{RMSE}{\bar{x}} \times 100 \tag{7}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(y-\bar{y})(x-\bar{x})\right]^2}{\sum_{i=1}^{n}(y-\bar{y})^2 \sum_{i=1}^{n}(x-\bar{x})^2} \tag{8}$$

where y is the estimated ET_0 (mm day^{-1}) from the proposed or commonly used equations, x is the ET_0 from the FAO56-PM (mm day^{-1}), and n is the number of data.

Equations 3 and 4 were further optimized using Modified Honey-Bee Mating Optimization (MHBMO) algorithm which is a heuristic method. This algorithm is inspired by the biological behaviour of a bee colony (Esmi Jahromi and Afzali 2014) comprising of a single egg laying long-lived queen, zero to several thousand drones, workers, and broods (Moritz and Southwick 1992). The algorithm starts with a population of honey bees which is randomly generated based on state variables constraints. An appropriate fitness function is selected to calculate for each individual of the initial population. Accordingly, the initial population is sorted to differentiate each cast of the colony. The individual with the best fitness value is considered as the queen. The individuals with the higher fitness function values, from the sorted initial population form the drone population. Eventually, sperms of the drones whose mating probability meets the probabilistic conditions, store in the queen's spermatheca and a spetmatheca matrix is generated. Then, the brood population is generated according to an improved mating process. In the improvement process, three sperms are randomly selected from the queen’s spermatheca and two improved new drones will be generated. The best individual (corresponding to the best fitness value) among these drones and the brood generated by the original HBMO is considered as a new brood. This modification strategy improves the mating process and avoids the local convergence which is undesirable. Figure 2 shows detailed flow diagram of the MHBMO process.

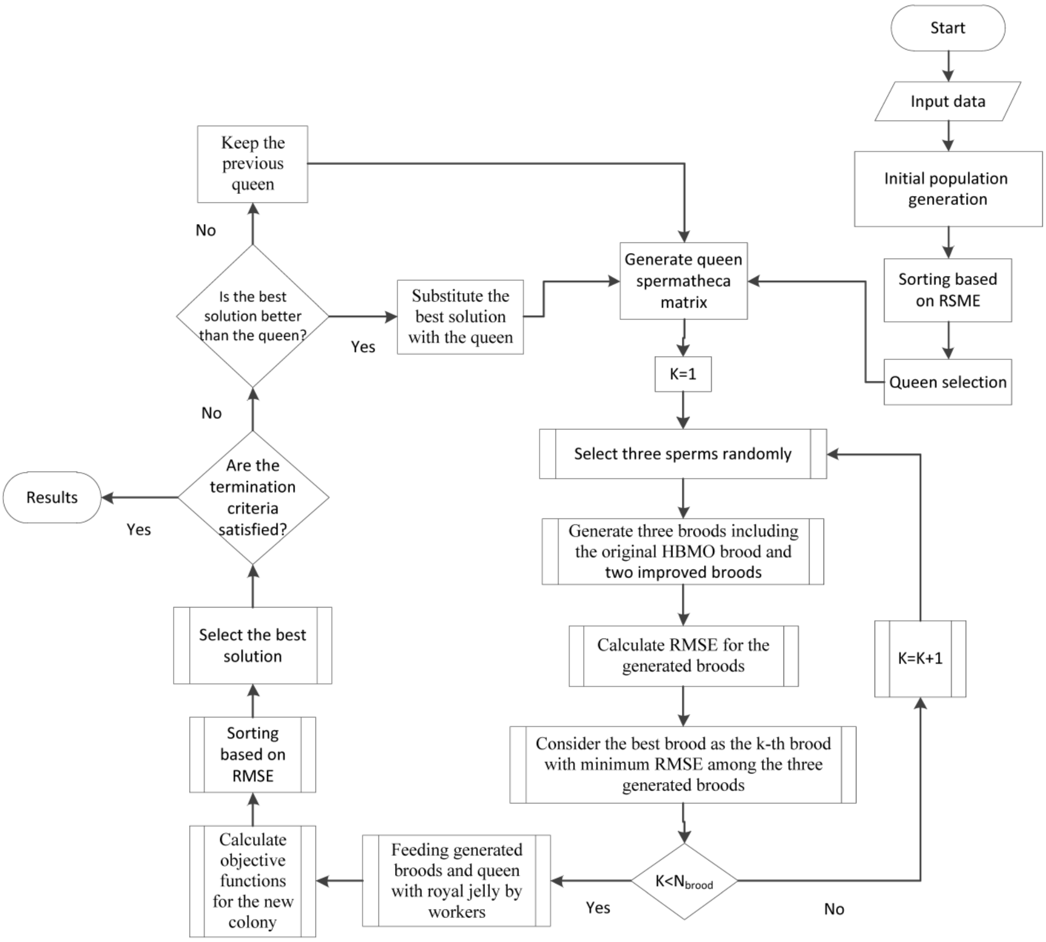


Fig. 2 Flowchart of the MHBMO algorithm

2.4 Application of MHBMO Algorithm

Procedures for using the MHBMO algorithm are explained below. Consider the objective function defined as:

$$Objective\ Function = Minimize\ [ET_{0_{estimated}} - ET_{0_{MHBMO}}] \tag{9}$$

in which:

$$ET_{0_{MHBMO}} = (a)0.252R_a + (b)0.221T_{mean}\left(1 - \frac{RH}{100}\right) + c \tag{10}$$

and $ET_{0\ estimated}$ is ET_0 from the FAO56 Penman-Montieth.

The unknown parameters in this function are ‘a’, ‘b’ and ‘c’, which are determined from the HBMO explained in a number of steps summarized in Table 3. This table also demonstrates the correspondence between the main components of bees’ natural mating system and elements of the optimization algorithm along with the mathematical descriptions. In the MHBMO algorithm, the breeding process is improved following the generation of brood population. The details of the modification process can be found in Ahooghalandari et al. (2016). The validity of the method is controlled by estimating statistical parameters MBE, RMSE, RE and R^2.

Table 3 Five steps of determination of unknown parameters in objective function from the MHBMO

Seq.	Natural process	Optimization algorithm	Mathematical description	Mathematical equation
1	Formation of bee population (hive)	Input data definition, parameter specification, and initial population generation	A set of random possible solution	$Initial\ Population = \begin{bmatrix} X_1 \\ X_2 \\ \dots \\ X_{N_{ipop}} \end{bmatrix}$ $X_i = [x_j]_{1\times n} = [a \quad b \quad c] \qquad i = 1,2,\dots,N_{ipop}$ $x_j = rand \times \left(x_j^{max} - x_j^{min}\right) + x_j^{min} \qquad j = 1,2,\dots,n$
2	Queen selection	Selecting the best individual based on the best fitness function	The fittest solution	$Sorted\ Initial\ Population = \begin{bmatrix} SX_1 \\ SX_2 \\ \dots \\ SX_{N_{ipop}} \end{bmatrix} \qquad Queen = SX_1 = [sx_{Best}^1 \quad sx_{Best}^2 \quad \dots \quad sx_{Best}^n]$
3	Drone population selection	Selecting drone population from the sorted initial population	Trial solutions	$Drone\ Population = \begin{bmatrix} SX_2 \\ SX_3 \\ \dots \\ SX_{N_{Drone+1}} \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ \dots \\ D_{N_{Drone}} \end{bmatrix} \quad D_i = [d_j]_{1\times n} =$ $[a \quad b \quad c] \quad \begin{cases} i = 1,2,\dots,N_{Drone} \\ j = 1,2,\dots,n \end{cases}$
4	Mating flight between the queen and each drone	Queen's spermatheca matrix generation (crossover pool)	A probabilistic function determines the trial solutions.	$Probe_i = e^{-\frac{\lvert RMSE_{Queen} - RMSE_{Drone} \rvert}{Speed_{Queen}^{i}}} \qquad \mathrm{i} = 1,2,\dots,\mathrm{N_{Drone}}$

				$Spermatheca\ Matrix = \begin{bmatrix} SP_1 \\ SP_2 \\ \dots \\ SP_{N_{Sperm}} \end{bmatrix}$ $SP_i = \left[sp_j\right]_{1\times n} = [a \quad b \quad c]$ $\begin{cases} i = 1,2,\dots,N_{Sperm} \\ j = 1,2,\dots,n \end{cases}$
5	Breeding process	Broods population generation using crossover function	Solution improvement	$Queen = [sx_{Best}^{1} \quad sx_{Best}^{2} \quad \dots \quad sx_{Best}^{n}]$ $SP_i = [sp_i^1 \quad sp_i^2 \quad \dots \quad sp_i^n]$ $X_{Brood_j} = Queen + rand \times (Queen - SP_i)$ $\mathrm{j} = 1,2,\dots,\mathrm{N}_{\mathrm{Brood}}$

3 Results and Discussion

3.1 Calibration of New Equations

As discussed before, the proposed Eqs. (3) and (4) were initially derived from the climatic data from the Pilbara region of Western Australia. The statistical parameters of MBE, RMSE, RE and R^2 for these equations versus the FAO56-PM method are presented in Table 4. It can be noticed that the coefficient of determination for Eqs. (3) and (4) are 0.942 and 0.959, respectively.

Table 4 Summary statistics of daily ET_0 estimated by Equations 3 and 4

Method	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)	R^2
Equation 3	0.850	0.933	16.01	0.942
Equation 4	0.941	0.998	17.13	0.959

These equations were further improved using the MHBMO algorithm described previously. The MHBMO method has some advantages over other optimization techniques including the feasibility of finding a global optimum for several problems, implementation with several optimization problems and availability for real and binary problems (Yuce et al. 2013). These advantages encouraged the authors to use the MHBMO for calibrating the proposed new equations. The modified form of Eqs. (3) and (4) are defined as:

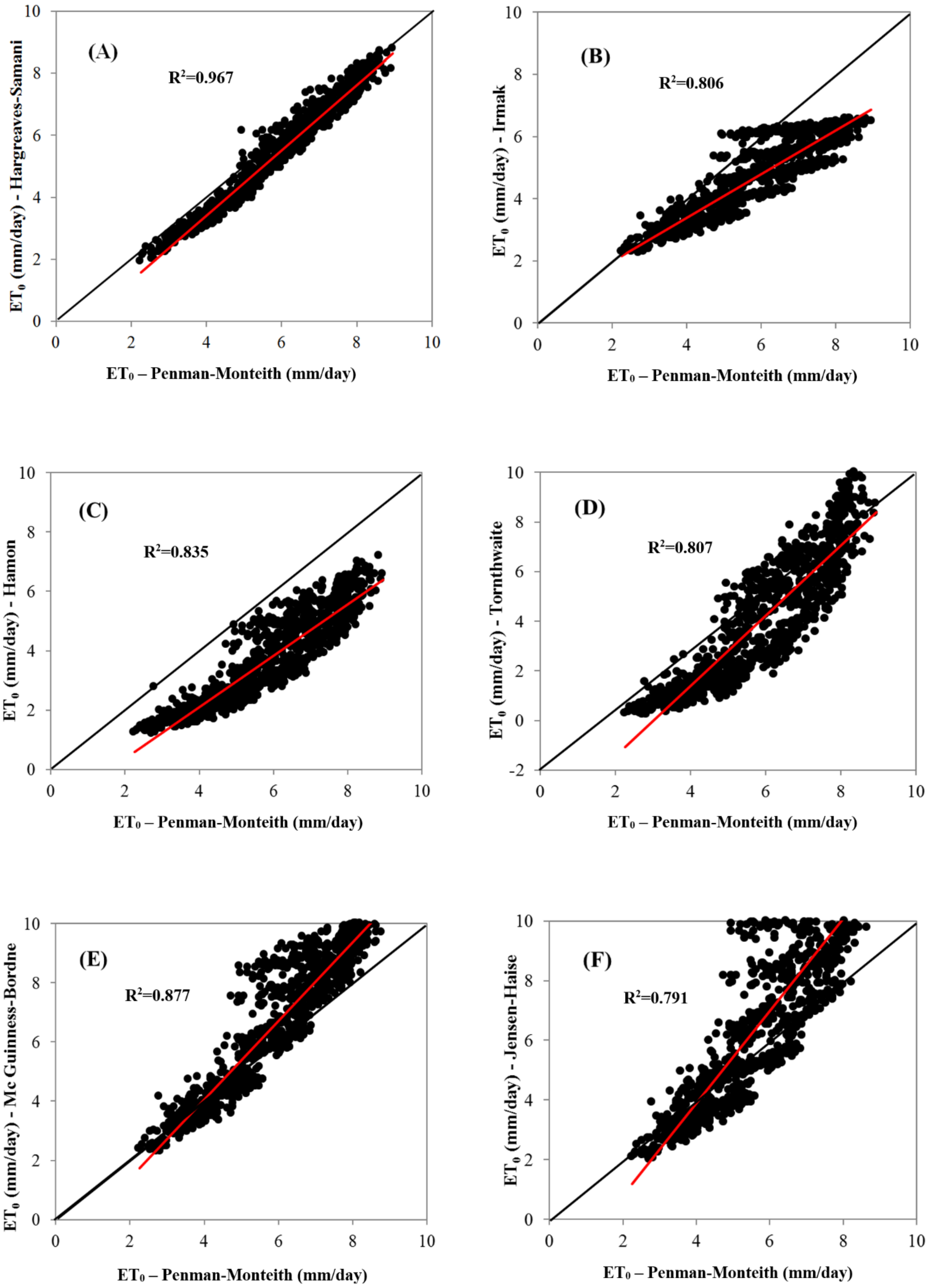
$$ET_0 = 0.34R_a + 0.182T\left(1 - \frac{RH}{100}\right) - 1.55 \qquad (11)$$

$$ET_0 = 0.369R_a + 0.139T_{max}\left(1 - \frac{RH}{100}\right) - 1.95 \qquad (12)$$

The statistical parameters for these equations as well as the six commonly used equations are presented in Table 5. Also, Fig. 3 shows plots of the estimated ET_0 values from the six commonly used methods as well as Eqs. (11) and (12) versus the FAO56-PM.

Table 5 Summary statistics of daily ET_0 estimating methods compared with calculated FAO56-PM method

Method	MBE (mm day^{-1})	RMSE (mm day^{-1})	RE (%)	R^2
Hargreaves-Samani	-0.487	0.583	10.00	0.967
Thornthwaite	-1.846	2.252	38.63	0.807
Jensen-Haise	0.898	1.788	30.66	0.791
Hamon	-2.145	2.241	38.44	0.835
Mc Guinness-Bordne	0.669	1.169	20.04	0.877
Irmak	-1.159	1.368	23.47	0.806
Equation 11	-0.054	0.301	5.17	0.968
Equation 12	-0.118	0.290	4.97	0.974


(A)
R²=0.967
ET₀ (mm/day) - Hargreaves-Samani
ET₀ – Penman-Monteith (mm/day)
0
2
4
6
8
10
(B)
R²=0.806
ET₀ (mm/day) - Irmak
ET₀ – Penman-Monteith (mm/day)
(C)
R²=0.835
ET₀ (mm/day) - Hamon
ET₀ – Penman-Monteith (mm/day)
(D)
R²=0.807
ET₀ (mm/day) - Tornthwaite
ET₀ – Penman-Monteith (mm/day)
-2
(E)
R²=0.877
ET₀ (mm/day) - Mc Guinness-Bordne
ET₀ – Penman-Monteith (mm/day)
(F)
R²=0.791
ET₀ (mm/day) - Jensen-Haise
ET₀ – Penman-Monteith (mm/day)

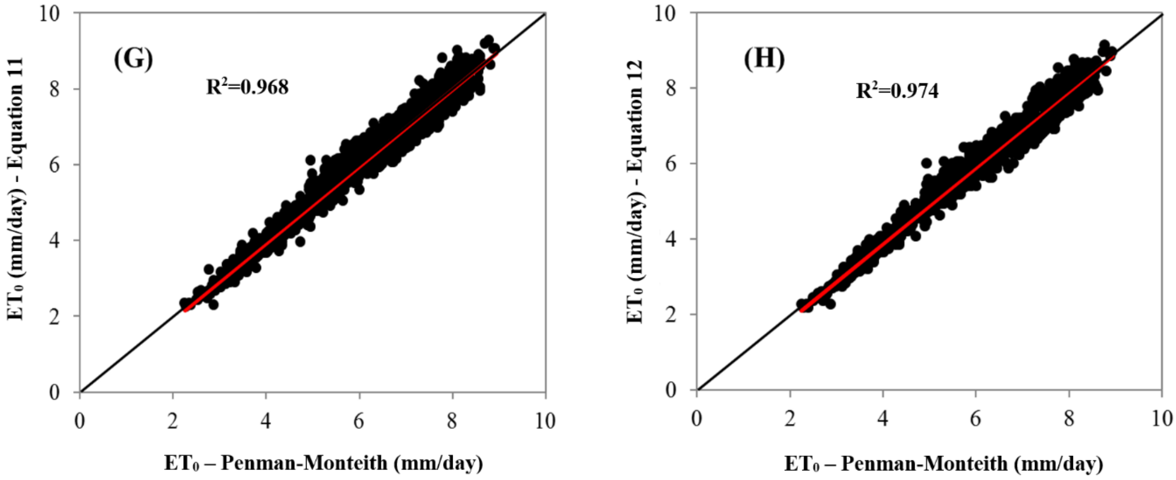


Fig. 3 Estimated ET_0 from Six equations and new equations versus FAO56-PM (A-H)

It can be noted that the optimized Eqs. (11) and (12) have performed better than all other methods considered in this study. The coefficient of determinations for all commonly used equations, except the Hargreaves-Samani method, are less than 0.90. The Hargreaves-Samani equation has $R^2=0.967$, which is slightly lower than the values for the proposed Eqs. (11) and (12). Other methods such as Hamon, underestimates the values of evapotranspiration (MBE=-2.145), while the Jensen-Haise method relatively overestimates ET_0 (MBE=0.898). Tornthwaite method has the poorest performance with RMSE =2.252 mm day^{-1} and RE =38.63% with a coefficient of determination ($R^2=0.835$) slightly higher than the Jensen-Haise method. The estimated statistical parameters for the Jensen-Haise method are: $R^2=0.791$, RMSE =2.241 mm day^{-1} and RE=30.66%.

Comparison of the statistical parameters including MBE, RMSE and RE for Eqs. (11) and (12) with those for the Hargreaves-Samani equation show that the proposed equations have performed better.

3.2 Validation of New Equations

Eqs. (11) and (12) were validated using climatic data from 10 stations located in New South Welles, Victoria, Northern Territory, South Australia and Queensland. The validation was performed for the same period of data as the equations were developed (2001 to 2011). The estimated ET_0 values from the proposed equations versus the FAO56-PM are presented in Fig. 4.

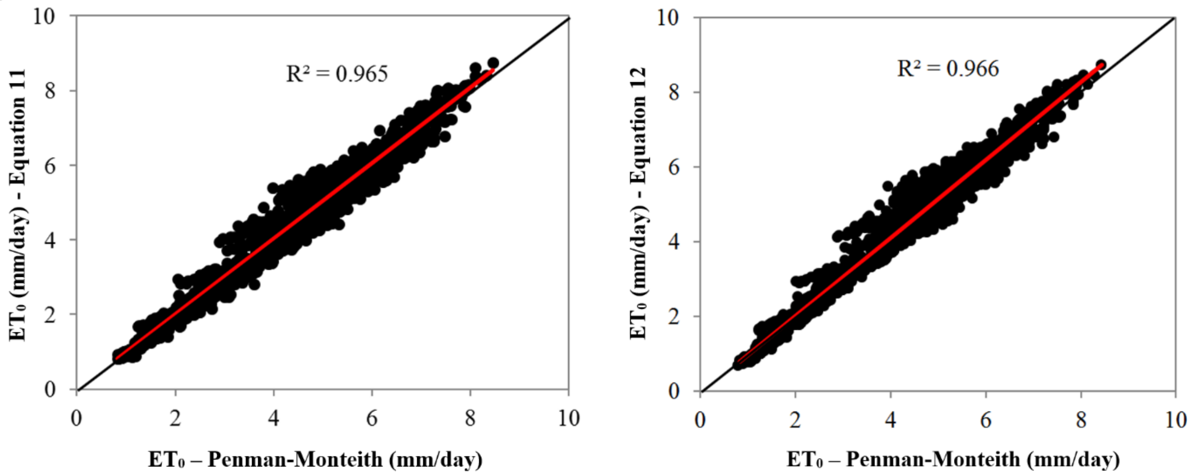


Fig. 4 Validation of Eq. 11 and 12 using data from other states of Australia

Yet again, Eqs. (11) and (12) performed well with RMSE of 0.355 mm day^{-1} and 0.375 mm day^{-1}, and the coefficient of determination of 0.965 and 0.966, respectively.

3.3 Comparison of New Equations with Calibrated Hargreaves-Samani for Data Across Australia

A high R^2 value for the Hargreaves-Samani method as well as similarity of its input parameters (R_a, T_{mean}, T_{min}, and T_{max}) with Eqs. (11) and (12) encouraged the authors to calibrated Hargreaves-Samani equation for Australia using the MHBMO algorithm. Figure 5 presents the estimated ET_0 from Eqs. (11) and (12) as well as the original and calibrated Hargreaves-Samani versus the FAO56-PM method for all 18 stations across Australia. The results show poor performances of Hargreaves-Samani equation both before and after the calibration compared with the proposed equations having higher RMSE and lower R^2 across Australia.

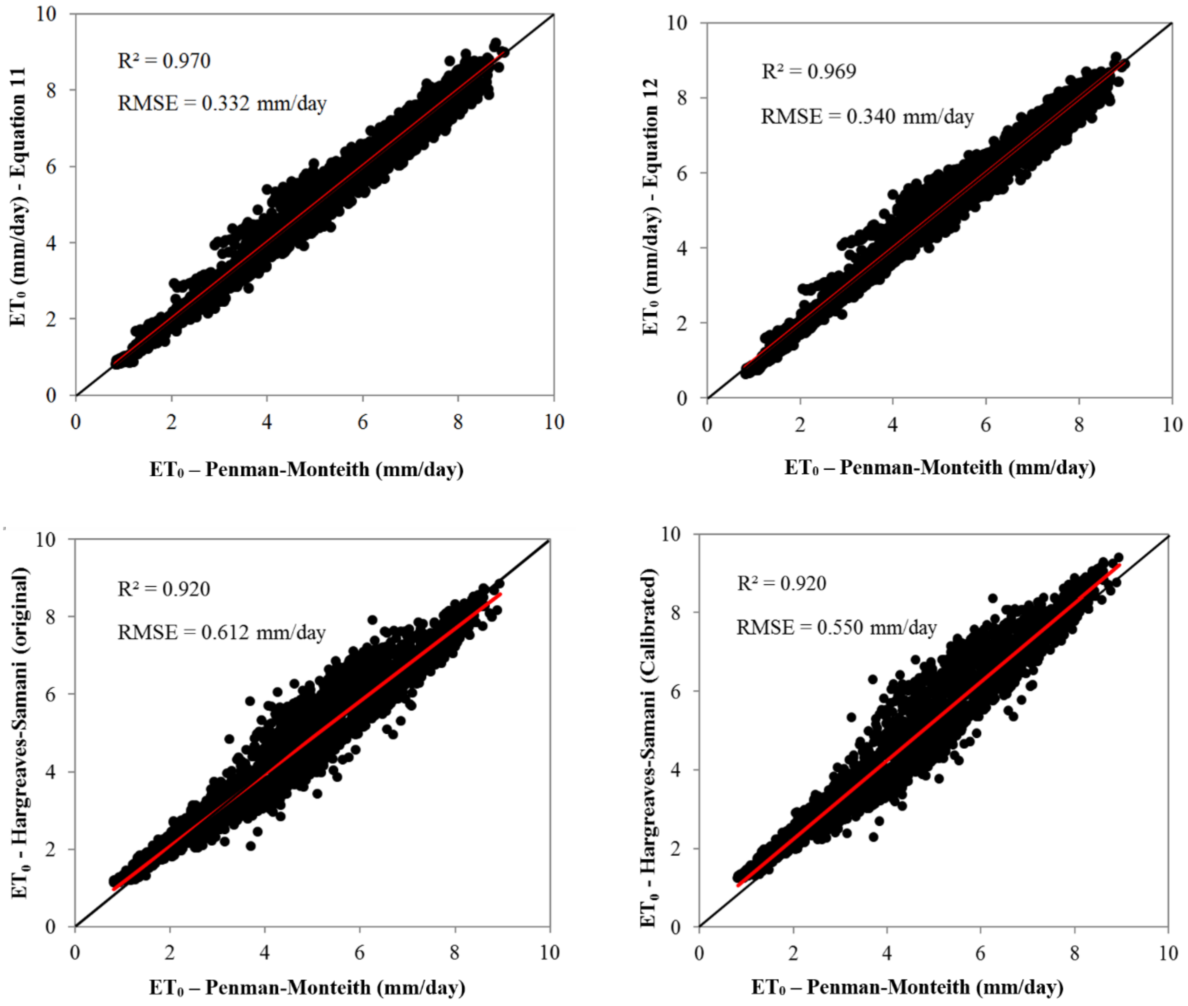


Fig. 5 Comparison Eq. 11 and 12 with original and calibrated Hargreaves-Samani (2001-2011)

Through the optimization process, the coefficient of 0.0023 in the original Hargreaves-Samani equation was replaced with 0.00247. This did not improve the coefficient of determination (R^2=0.92). All in all, the results of this study are suggesting that Eqs. (11) and (12) , with R^2 of 0.970 and 0.969, can be used to calculate ET_0 values with a high level of accuracy across Australia.

4 Conclusion

Six commonly-used equations for estimating reference evapotranspiration (ET_0) were evaluated using meteorological data from weather stations located in Western Australia. Two new equations were derived and tested for estimating reference evapotranspiration (ET_0) using the surface polynomial regression technique. Moreover, these equations were optimized using modified version of Honey-Bee Mating Optimization (MHBMO) algorithm. The results showed that the estimated ET_0 values from the two new equations are well-correlated with those from the FAO56-PM across Australia. Considering the limitation of available and reliable climate data in Australia, these equations are suggested as practical techniques for estimating ET_0. Also, the Hargreaves-Samani method was calibrated using the MHBMO algorithm; however the results did not improved and use of Eqs. (11) and (12) are recommended over the other methods tested in this study.

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