Development of A Modified Penman's Method For Estimating Evaporation In Diwaniya

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Abstract

Evaporation equations which are developed and calibrated for one geographical region very often are not valid for different region and different climatic condition. In this paper the Penman original method is modified by using meteorological data from Diwaniya station to calibrate the three equations that were used in Penman's original method, i.e. incoming shortwave radiation equation, net longwave radiation equation, and wind function. Thus, new equations which are applicable to Diwaniya and are different from those originally suggested by Penman for England are presented so that computed evaporation is very close to the observed one.

Key words: Diwaniya; Evaporation, Penman's method; Angstrom's formula; Stefan-Boltzmann law; Wind function.

الخلاصة

ان معادلات التبخر التي تشتق وتعاير لمنطقة جغرافية معينة تكون غير ملائمة للاستخدام في منطقة اخرى وظروف مناخية مختلفة عن الظروف التي اشتقت فيها, وفي هذه الدراسة تم تطبيق وملائمة طريقة Penman الاصلية باستخدام بيانات مناخية من محطة الديوانية لمعايرة المعادلات الثلاثة التي تستخدم بطريقة Penman الاصلية وهذه المعادلات هي معادلة الاشعاع القصير الموجه المستلم, معادلة صافي الاشعاع الطويل الموجه, ودالة الريح. لذا تم ايجاد قيم ثوابت تختلف عن تلك الاصلية المقترحة من قبل Penman لكي يكون التبخر المحسوب من المعادلات التي تحتوي هذه الثوابت قريب جدا من الواقع.

1. Introduction

One of the major components of the hydrological cycle is evaporation. Estimation of evaporation is very important in many water resources studies such as water balance calculations and irrigation management, etc. Many organizations and researchers are derived methods to estimate evaporation. One of the famous methods that is widely used for estimating evaporation is Penman's method whereas Penman (1948) combined between two methods of estimation of evaporation to develop method to compute evaporation from free water surface in terms of four meteorological variables; these variables are net radiation, temperature, wind speed, and vapour pressure deficit of the air (Calder and Neal, 1984). In the present study Diwaniya meteorological data are used to modified Penman's original method so that evaporation in Diwaniya can be computed from equations different from those suggested by Penman for England. Thus, values of evaporation for Diwaniya which are computed from theses new equations can be utilized in studying two main problems in Diwaniya; theses two problems are irrigation management and dryness.

2. Objective of The Present Study

Modifying Penman's original method by using Diwaniya meteorological data to calibrate the three equations that were used by Penman, i.e. incoming shortwave radiation equation, net longwave radiation equation, and wind function. Comparison between Penman's original method and our modified method is also examined.

3. Mass Transfer Method

The simplest mass transfer method employs the following equation (Singh, 1992):

$E = f(u)\,(e'_s - e)$, ………………………………………………...(1)

where E (mm/day) is the evaporation from the water surface, e'_s (mm Hg) is the saturation vapour pressure at the water surface temperature (t'_s), e (mmHg) is the actual vapour pressure of the air which is equal to the saturation vapour pressure at the dew point, and f(u) (mm/day mmHg) is an empirical function of the wind speed.

The wind function *f(u)* is expressed by Penman in the following form (Jayawardena, 1991):

$f(u)= (a + b\ u_2)$, ……………………………………………………………………(2)

where a (mm/day mmHg) and b (mm s/day mmHg m) are empirical constants that depend chiefly on the height at which wind speed and air vapour pressure are measured, and u_2 (m/s) denotes wind speed at height of 2 m.

There is another form of Penman's wind function (Pereira et. al. 1996):

$f(u)= m\ (a_1 + b_1\ u_2)$, ………………………………………………………………….(3)

where m (mm/day mmHg), a_1 (dimensionless) and b_1 (s/m) are empirical constants that depend chiefly on the height at which wind speed and air vapour pressure are measured.

The equations that have been developed in the form of Equation 1 may be reliable in the areas and over the periods in which they were developed. However, large errors can be generated when these equations are extrapolated to other climatic areas without recalibration of the constants involved in the formula (Zhu, 2007).

Since it is difficult to measure the temperature at the air-water interface, e'_s in Equation 1 has often been replaced by the saturation vapour pressure at the air temperature, e_s, or the saturation vapour pressure at the mean water temperature, e_w (Pochop et. al., 1985a; Pochop et. al., 1985b; Jayawardena, 1991; Prereira, 1996). Hence, the following approximate equation is used instead of Equation 1:

$E_{th} = f(u)\ (e_s - e)$, ……………………………………………………………….(4)

In 1948 Penman calibrated Equation 4 for UK to obtain the following equation:

$E_{th}=0.35\ (1 +0.54\ u_2)\ (e_s - e)$, …………………………………………………..(5)

where E_{th} (mm/day) is theoretical water-surface evaporation. Sometime later Penman (1956) revised his equation and proposed that the parameter a_1 equals 0.5 would give a better description of lake evaporation (Prereira, 1996). Therefore, the following equation is suggested:

$E_{th}=0.35\ (0.5 + 0.54\ u_2)\ (e_s - e)$, ……………………………………………..(6)

4. Energy Budget Method

The principal quantities which are employed in the energy budget theorem are incoming shortwave radiation, net shortwave radiation, net longwave radiation, and net radiation. The description of theses quantities are as follows:

(i) <u>Incoming Shortwave Radiation</u>

The incoming solar shortwave radiation (R_s), which is arrived at the earth surface, can be computed using the famous empirical formula of Angstrom (Wales-Smith, 1980):

$R_s = R_A\ (c + d\ (\frac{n}{N}))$, …………………………………………………….. (7)

where R_s (cal/cm^2 day) is the incoming shortwave solar radiation actually received at the earth from sun and sky, R_A (cal/cm^2 day) is the total possible solar radiation (extraterrestrial radiation) for the latitude and time of year in the absence of an atmosphere and is obtainable from equation or standard tables, n (hr/day) is the measured daily duration of bright sunshine, N (hr/day) is the total possible daily duration of bright sunshine for the latitude and time of year which is obtainable from equation or standard tables, and c and d are regression constants. The values of c and d which were suggested by Penman (1948) 0.18 and 0.55 respectively. Then, Equation 7 could be written in the following form:

$R_s = R_A (0.18 + 0.55 \times (\frac{n}{N}))$, ……………………………………………….(8)

(ii) Net Shortwave Radiation

Part of R_s is reflected as a shortwave solar radiation. The remaining energy, R_I, is given by:

$R_I = R_s - r\ R_s$, …………………..…………………………………………………(9)

where R_I (cal/cm^2 day) is the net shortwave solar radiation and r is the albedo or reflection coefficient which is equal to 0.06 for free water surface (Wilson, 1983).

(iii) Net Longwave Radiation

Some of the net amount of radiation absorbed at the earth surface is reradiated by the earth as longwave radiation. This net outward flow may be expressed according to the Stefan-Boltzmann law as follows (Meyer, 1999; Meyer et. al., 1999; Allen et. al., 2005):

$R_B = \varepsilon_w\ \sigma\ T_a^4\ (\varepsilon_{at} - 1)\ f_{cd}$, …………………………………………………...(10)

where R_B (cal/cm^2 day) is the net longwave radiation received at the surface, ε_w (dimensionless) is the emissivity of the water surface and it is equal to 0.97 in clear sky condition (Eaglson, 1970, Jayawardena, 1991), σ (=117×10^{-9} (cal/cm^2 day k^4) is a universal constant called the Stefan-Boltzmann constant, T_a (°k) is the absolute temperature of the surface (absolute temperature (°k)=temperature (°C)+273), ε_{at} (dimensionless) is the atmospheric emissivity, and f_{cd} (dimensionless) is the cloudiness function.

The atmospheric emissivity, ε_{at}, is computed as follows:

$\varepsilon_{at} = f + v\ \sqrt{e}$, ………………………………………………………………..(11)

where f (dimensionless) and v (mmHg$^{-0.5}$) are empirical constants. The values of constants f and v are (0.43-0.68) and (0.033-0.095 mmHg$^{-0.5}$) respectively (singh, 1992).

The cloudiness function, f_{cd}, is computed as follows:

$f_{cd} = h + q\ \frac{R_s}{R_{so}}$, ……………………………………………………………(12)

where h and q are empirical constants and R_{so} (cal/cm^2 day) is a clear sky incoming shortwave solar radiation; the amount of the incoming shortwave solar radiation (R_s) that would be received at the weather measurement site under conditions of clear sky.

The value of f_{cd} equals one in a perfectly clear day where the ratio $\frac{R_s}{R_{so}}$ equals one (Meyer, 1999; Meyer et. al., 1999; Allen et al., 2005).

In 1948 Penman showed that the ratio $\frac{R_s}{R_{so}}$ can be replaced in $\frac{n}{N}$ (Singh, 1992). Hence, Equation 12 is written as follows:

$f_{cd} = h + q\ \frac{n}{N}$, …………………………………...……………………………(13)

In the same year (1948) Penman calibrated Equation 10 for England and obtained:

$R_B = \sigma\ T_a^4\ (0.092\ \sqrt{e} - 0.56)\ (0.1 + 0.9\ (\frac{n}{N}))$, ………………………………..(14)

Sometime later he gave another form of Equation 10 (Wilson, 1983):

$R_B = \sigma\ T_a^4\ (0.077\ \sqrt{e} - 0.47)\ (0.2 + 0.8\ (\frac{n}{N}))$, …………………………………..(15)

(iv) Net Radiation (H_n)

The amount of energy, i.e. net radiation, finally remaining at a free water surface that is denoted by H_n is equal to the algebraic sum of net shortwave radiation and net longwave radiation (Meyer, 1999; Meyer et. al., 1999; Dodds et. al., 2005; Allen et al., 2005):

$H_n = R_I + R_B$, ……………………………………………………………………(16)

5. Penman's Method

Penman showed that by combining the energy budget and the mass transfer theorem which are described in the previous sections of this paper it can be shown that:

$$E = \frac{\Delta H + \gamma E_{th}}{\Delta + \gamma},$$

……………………………………………………………………………(17)

where γ (=0.495 mmHg/°C) is a psychrometric constant and Δ (mmHg/°c) is the slope of saturation vapour pressure-temperature curve at air temperature t.

Equation 17 is the Penman equation in Penman's original form. E_{th} is obtained from aerodynamic equation (Equation 5 or 6). H (mm/day) is computed as follows:

$H=10\ H_n/\ \rho_w\ \lambda_v$, ……………………………………………………………………(18)

where ρ_w (g/cm^3) is the mass density of water, and λ_v (cal/g) is the latent heat of vaporization which is computed as follows (Meyer, 1999; Dingman, 1994):

$\lambda_v = 597.3 - 0.564\ t$, ……………………………………………………………(19)

The typical value of λ_v is 590 cal/g (Dingman, 1994). Thus, some writers assume λ_v equal to this value for small range of air temperature.

The slope of saturation vapour pressure temperature curve, Δ in mmHg/°C, may be estimated by firstly computing e_s as follows (Meyer, 1999; Meyer et. al., 1999; Dingman, 1994; Allen et al., 2005):

$$e_s = 4.582\exp\left(\frac{17.27\,t}{t+237.3}\right) \quad , \quad \text{……………………………………………..(20)}$$

Then Δ is found by taking the derivative of Equation 19 with respect to temperature. Therefore,

$$\Delta = \frac{18777}{(t+237.3)^2}\exp[17.27\,t/(237.3+t)],$$

………………………………………..(21)

6. Modification of Penman's Method for Diwaniya

In this section we calibrate Equations 2, 7, 11, and 13 using the average values of meteorological data from Diwaniya Meteorological Station (see Table 1) so that the Penman method may be followed to estimate evaporation in Diwaniya as accurately as possible. The calibration procedure is described as follows:

1) The constants in Equation 2 both vary from 0 to 1. We choose a=b=0 as starting values.
2) The constants in Equation 7 vary from 0 to 1. We choose c=d=0 as starting values.
3) The constant f in the atmospheric emissivity equation (Equation 11) varies from 0.43 to 0.68 while v varies from 0.033 to 0.095 mmHg$^{-0.5}$. Therefore, We choose f=0.43 and v=0.033 mmHg$^{-0.5}$ as starting values.

4) The constants in the cloudiness function (Equation 13) both vary from 0 to 1. Our trial values are h=0 and q=1−h= 1.0.
5) The evaporation for each month is computed using computer program. This estimated value of evaporation is compared with the observed one and the difference between them is detected. The sum of squared differences for all months is also computed.
6) A large number of different sets of constant values are tried using the computer program. The set of constants which corresponds to minimum sum of squared differences between computed and measured evaporation is considered to be the best set in representing climate and location of Diwaniya city.

Calculation of daily mean evaporation (mm/day) for each month according to the Penman original method and our modified method using the set of constants corresponding to the minimum squared differences are shown in Table 2 and 3 respectively. Graphical comparisons are also given as Figure 1 and 2 which show very clearly that the modified method agrees with Diwaniya observed evaporation observed better than the Penman original method. This is expected because the constants which are used by Penman are appropriate for England rather than for other locations.

Table 1: List of weather elements of Diwaniya Meteorological Station which are used to calibrate Penman's original methods.

Element	Symbol	Unit	Time period
Air temperature *	t	ºC	1971-2002
Relative humidity *	RH	%	1971-2005
Actual vapour pressure *	e	mmHg	1988-2002
Wind speed *	u	m/s	1971-2005
Actual sun shine duration *	n	hr	1980-2007
Observed evaporation †	E_a	mm/month	1971-2006

Source: Iraqi Meteorological Organization, * The data are daily mean (unit/day), † The data are monthly (mm/month).

Table 2: Computed evaporation in Diwaniya according to Penman's original method (Equations 6, 8, 15, 16, 17, 18, 19, and 21).

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
t (°C) *	10.773	13.265	17.719	24.413	30.052	33.870	35.606	34.900	31.545	25.974	18.055	12.607
u_2 (m/s) *	2.298	2.564	2.805	2.830	2.634	3.292	3.371	2.784	2.155	1.913	1.941	2.076
n (hr/day) *	6.365	7.310	7.994	8.518	9.531	11.692	11.704	11.370	10.415	8.557	7.311	6.449
N (hr/day) ‡	10.241	11.021	11.980	12.959	13.839	14.278	14.059	13.319	12.420	11.441	10.481	10.041
R_A (cal/cm^2/day) ‡	467.432	641.018	726.334	873.857	922.785	979.354	929.375	860.637	773.916	612.980	504.829	430.639
RH% *	0.702	0.605	0.515	0.419	0.315	0.268	0.267	0.291	0.315	0.401	0.562	0.687
e_s (mmHg) †	10.217	11.788	15.829	23.919	32.371	40.813	45.348	44.340	37.343	26.903	16.525	11.410
e (mmHg) *	7.172	7.132	8.152	10.022	10.197	10.938	12.108	12.903	11.763	10.788	9.287	7.839
Observed E_a (mm/day) *	1.987	2.924	4.537	6.585793	9.438	11.956	13.275	12.135	9.187	6.324	3.391	2.080
n/N †	0.622	0.663	0.667	0.657	0.689	0.819	0.832	0.854	0.839	0.748	0.698	0.642
Δ (mmHg/°c) †	0.646	0.746	0.959	1.373	1.830	2.208	2.400	2.320	1.971	1.489	0.977	0.719
(λ_v) (cal/g) †	591.224	589.819	587.307	583.531	580.351	578.197	577.218	577.616	579.509	582.651	587.117	590.190
E_{th} (mm/day) †	1.855	3.071	5.413	9.865	14.919	23.816	26.995	22.043	14.895	8.647	3.922	2.026
R_s (cal/cm^2/day) †	243.923	349.229	397.307	473.209	515.641	617.370	592.821	558.999	496.244	362.491	284.548	229.637
R_I (cal/cm^2/day) †	229.288	328.275	373.469	444.816	484.703	580.328	557.252	525.459	466.469	340.741	267.475	215.859
R_B (cal/cm^2/day) †	139.539	151.760	153.417	150.325	166.093	191.051	185.700	179.569	180.475	162.014	149.790	141.380
H_n (cal/cm^2/day) †	89.749	176.515	220.051	294.491	318.610	389.277	371.551	345.889	285.994	178.727	117.684	74.479
H (mm/day) †	1.518	2.993	3.747	5.047	5.490	6.733	6.437	5.988	4.935	3.067	2.004	1.262
Computed E (mm/day) †	1.664	3.024	4.314	6.324	7.497	9.861	9.952	8.811	6.934	4.460	2.649	1.574
$E-E_a$ (mm/day) †	-0.323	0.100	-0.223	-0.262	-1.941	-2.095	-3.323	-3.324	-2.253	-1.864	-0.742	-0.506
$(E-E_a)^2$ †	0.104	0.010	0.050	0.069	3.767	4.388	11.041	11.048	5.075	3.476	0.550	0.256
$ER = \sum(E-E_a)^2$ †	39.834											

* Oberved values (Source: Iraqi Meteorological Organization–Diwaniya Meteorological Station), ‡ From standard tables according to the latitude of Diwaniya (31° 59' N), † Computed values

Table 3: Computed evaporation in Diwaniya according to our modified method with a=0.675, b=0.3, c=0.0, d=0.45, f=0.58, h=1.0, q=0.0, and v=0.095 as well as using Equation 19.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
t (°C) *	10.773	13.265	17.719	24.413	30.052	33.870	35.606	34.900	31.545	25.974	18.055	12.607
u_2 (m/s) *	2.298	2.564	2.805	2.830	2.634	3.292	3.371	2.784	2.155	1.913	1.941	2.076
n (hr/day) *	6.365	7.310	7.994	8.518	9.531	11.692	11.704	11.370	10.415	8.557	7.311	6.449
N (hr/day) ‡	10.241	11.021	11.980	12.959	13.839	14.278	14.059	13.319	12.420	11.441	10.481	10.041
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E_{th} (mm/day) †	4.155	6.724	11.642	21.179	32.489	49.670	56.053	47.476	33.804	20.126	9.100	4.634
R_s (cal/cm^2/day) †	130.734	191.328	218.100	258.475	285.987	360.889	348.164	330.614	292.041	206.308	158.464	124.463
R_I (cal/cm^2/day) †	122.890	179.849	205.014	242.967	268.828	339.236	327.274	310.777	274.519	193.930	148.956	116.996
R_B (cal/cm^2/day) †	121.860	126.739	120.596	105.893	111.653	106.488	92.060	80.327	91.940	97.904	106.277	116.306
H_n (cal/cm^2/day) †	1.029	53.110	84.418	137.074	157.175	232.747	235.214	230.450	182.579	96.026	42.679	0.690
H (mm/day) †	0.017	0.900	1.437	2.349	2.708	4.025	4.075	3.990	3.151	1.648	0.727	0.012
Computed E (mm/day) †	1.812	3.223	4.912	7.339	9.047	12.385	12.963	11.636	9.303	6.259	3.544	1.897
$E-E_a$ (mm/day) †	-0.175	0.299	0.375	0.753	-0.391	0.429	-0.312	-0.499	0.116	-0.065	0.153	-0.183
$(E-E_a)^2$ †	0.031	0.089	0.141	0.567	0.153	0.184	0.098	0.249	0.014	0.004	0.023	0.033
$ER=\sum(E-E_a)^2$ †	1.585											

* Oberved values (Source: Iraqi Meteorological Organization–Diwaniya Meteorological Station), ‡ From standard tables according to the latitude of Diwaniya (31° 59' N), † Computed values

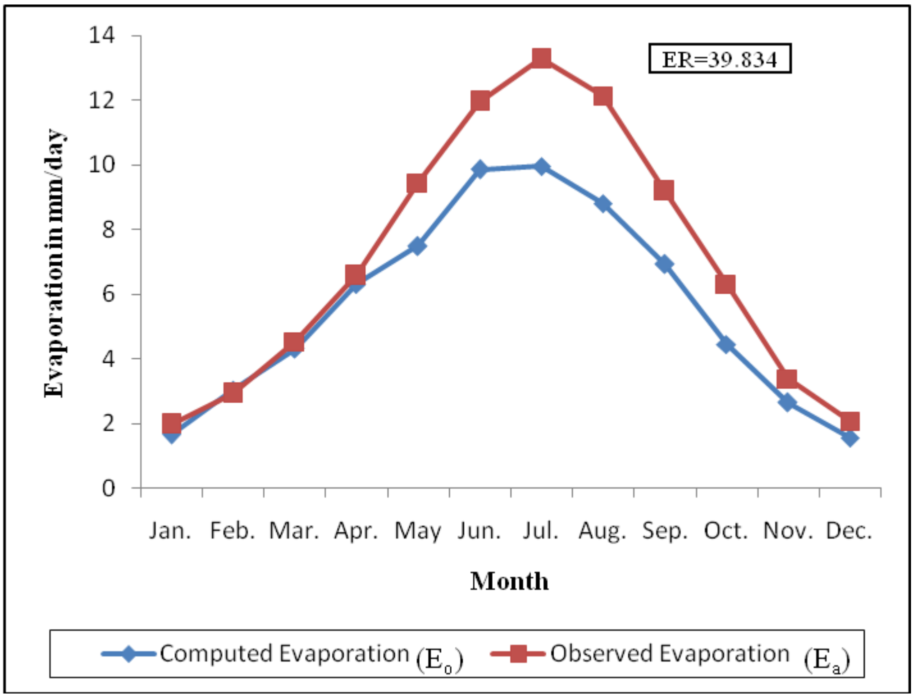

Figure 1: Comparison of evaporation in Diwaniya as computed by Penman's original method (1956) with observed evaporation (Equations 6, 8, 15, 16, 17, 18, 19, and 21).

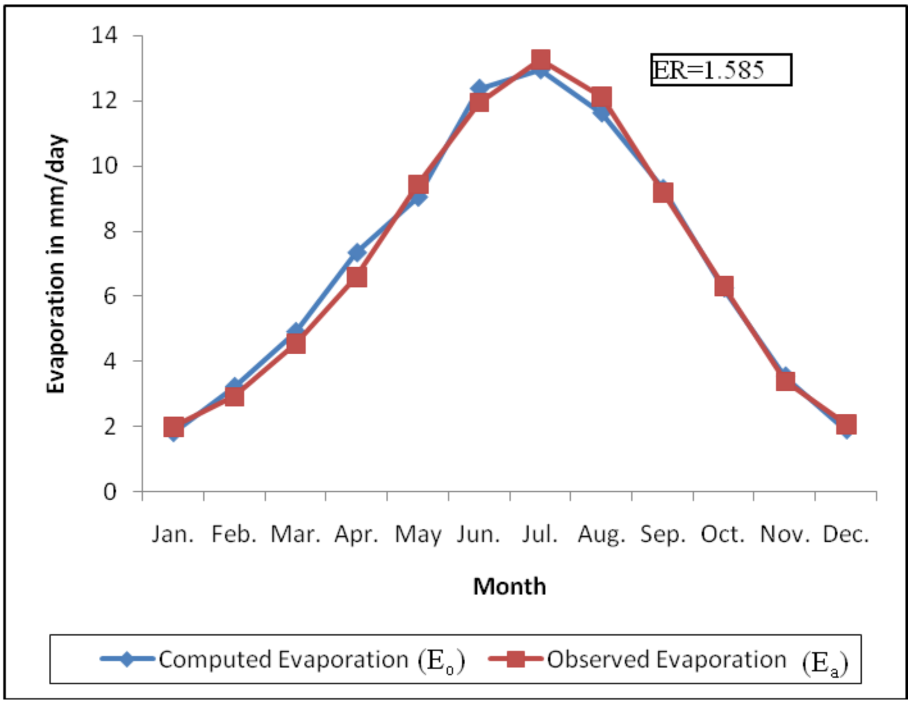

Figure 2: Comparison of evaporation in Diwaniya as computed by our modified method with observed evaporation (a=0.675, b=0.3, c=0, d=0.45, f=0.58, h=1.0, q=0, and v=0.095 as well as using Equation 19).

7. Conclusions

Application of some equations which are used in Penman's original method for open water-surface evaporation in England to compute evaporation in Diwaniya city leads to results which are substantially different from measured values. Therefore, adjustment of the constants in these equations is necessary. In this paper, a set of values of these constants are determined based on meteorological data from Diwaniya Observing Station. Hence, it is concluded that the following equations give better results than the original equations which are applicable to England only:

1. Wind function

$f(u) = (0.675 + 0.3\ u_2)$, ………………………………………………………….(22)

or

$f(u) = 0.75\ (0.9 + 0.4\ u_2)$, ……………………………………………………(23)

2. Incoming shortwave radiation

$R_S = 0.45\ R_A\ (\frac{n}{N})$, ……………………………………………………….(24)

3. Net longwave radiation

$R_B = 0.97\ \sigma\ T_a^4\ (0.58 + 0.095\ \sqrt{e})$, …………………………………………..(25)

Therefore, the general form of equation of our modified method from which the evaporation in Diwaniya can be computed as accurately as possible is as follows:

$$E = \frac{\Delta\,((1-r)\,0.45 R_A + 0.97\,\sigma\,T_a^4\,(0.58 + 0.095\sqrt{e})) + \gamma\,((0.675 + 0.3\ u2)(e_S - e))}{\Delta + \gamma}, \ldots .(26)$$

or

$$E = \frac{\Delta\,((1-r)\,0.45 R_A + 0.97\,\sigma\,T_a^4\,(0.58 + 0.095\sqrt{e})) + \gamma\,(0.75(0.9 + 0.4\ u2)\,(e_S - e))}{\Delta + \gamma}, .(27)$$

It is found that the sum of squared different between computed and observed evaporation for all months is 39.834 when using the original equations in Penman's method for evaporation in England. There is a considerable difference between this values and the value of 1.585 which is obtained using the above new equations.

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Notations

Δ	Slope of saturation vapour pressure curve at air temperature t.
ε_{at}	Atmospheric emissivity.
ε_w	Water emissivity.
γ	Psychrometric constant.
λ_v	Latent heat of vaporization.
ρ_w	Mass density of water.
σ	Stefan-Boltzman constant.
a, a_1	Empirical constants of Penman's wind function.
b, b_1	Empirical constants of Penman's wind function.
c, d	Empirical constants of incoming shortwave radiation.
e	Actual or observed vapour pressure.
e_s	Saturation vapour pressure at the air temperature.
e'_s	Saturation vapour pressure at the surface temperature.
e_w	Mean water temperature.
E	Evaporation from free water surface.
E_{th}	Theoretical evaporation from water surface.
f	Empirical constant of atmospheric emissivity.
f_{cd}	Cloudiness function.
$f(u)$	Wind function.
h	Empirical constants of cloudiness function.
H	Net radiation in mm/day.
H_n	Net radiation.
m	Empirical constant of Penman's wind function.
n	Actual sunshine duration.
N	Total or possible sunshine duration.
q	Empirical constants of cloudiness function.
r	Albedo or reflection coefficient.
R_A	Extraterrestrial solar radiation.
R_B	Net longwave solar radiation.
R_I	Net shortwave solar radiation.

R_s	Incoming shortwave solar radiation.
R_{so}	Clear sky incoming shortwave solar radiation (cal/cm^2 day).
t	Air temperature.
t'_s	Water surface temperature.
T_a	Absolute air temperature.
v	Empirical constant of atmospheric emissivity.
u_2	Wind speed at height of two meters.