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Evaluation and generalization of radiation-based methods for calculating evaporation

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Abstract:

Eight radiation-based equations for determining evaporation were evaluated and expressed in five generalized forms. Five evaporation equations (Abtew, Hargreaves, Makkink, Priestley and Taylor and Turc), where each represents one generalized form, were then compared with pan evaporation measured at Changins station in Switzerland. The comparison was first made using the original constant values involved in each equation, and then using the recalibrated constant values. Evaluation of the Priestley and Taylor equation requires net radiation data as input, in this study, net radiation was estimated using Equation (16) owing to the lack of observation data. The results showed that when the original constant values were used, large errors resulted for most of the equations. When recalibrated constant values were substituted for the original constant values, four of the five equations improved greatly, and all five equations performed well for determining mean annual evaporation. For seasonal and monthly evaporation, the Hargreaves and Turc equations showed a significant bias, especially for cold months. With properly determined constant values, the Makkink and modified Priestley and Taylor equations resulted in monthly evaporation values that agreed most closely with pan evaporation in the study region. The simple Abtew equation can also be used when other meteorological data except radiation are not available. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS evaporation; radiation-based methods; pan evaporation; Switzerland

INTRODUCTION

Design and management of water resources systems require knowledge of the magnitude and variation of evaporative losses. There exist a multitude of methods for measurement and estimation of evaporation, which can be grouped into seven classes: (i) empirical (e.g. Kohler *et al.*, 1955), (ii) water budget (e.g. Guitjens, 1982), (iii) energy budget (e.g. Fritschen, 1966), (iv) mass transfer (e.g. Harbeck, 1962), (v) combination (e.g. Penman, 1948), (vi) radiation (e.g. Turc, 1961; Priestley and Taylor, 1972) and (vii) measurement (e.g. Young, 1947). Overviews of many of these methods, are found in review papers or books (e.g. Brutsaert, 1982; Singh, 1989; Jensen *et al.*, 1990; Morton, 1990, 1994). Most of the equations were developed for use in specific studies and are most appropriate for use in climates similar to where they were developed. It is not uncommon to use an equation for determination of evaporation from open water that was actually developed for determination of potential evapotranspiration from vegetated lands, and vice versa (see also Winter *et al.*, 1995).

The availability of many equations for determining evaporation, the wide range of data types needed and the wide range of expertise needed to use the various equations correctly, make it difficult to select the most appropriate evaporation method, even from a chosen group of methods for a given study. There is, therefore,

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a need to analyse and compare the various forms of existing popular evaporation models belonging to each group, and to develop a generalized model form from these methods.

Since 1996, a research programme has been underway with the main objective of evaluation and generalization of existing evaporation models. In an earlier study Singh and Xu (1997a) evaluated and compared 13 evaporation equations that belonged to the category of mass-transfer method, and a generalized model form for that category was developed. Singh and Xu (1997b) further examined the sensitivity of mass-transfer-based evaporation equations to errors in daily and monthly input data. More recently, Xu and Singh (1998) analysed the dependence of evaporation on various meteorological variables at different time-scales. This paper reports some of the results of the ongoing research. The objective here is to analyse and generalize the various popular evaporation equations that belong to the category of radiation-based methods. Included in the study is the discussion of existing methods, generalization of model forms, evaluation and comparison of the generalized equations with the original values of the constants involved in each equation, and evaluation and comparison of generalized equations with the recalibrated values of the constants.

RADIATION-BASED METHODS FOR ESTIMATION OF EVAPORATION

The radiation-based approach has had wide application in estimation of lake evaporation and potential evapotranspiration (ET) of land areas. Many empirical formulae have been derived based on this approach (Jensen *et al.*, 1990; Singh, 1989).

Discussion of existing methods

Empirical radiation-based equations for estimating potential evaporation generally are based on the energy balance (Jensen *et al.*, 1990). Most radiation-based equations take the form:

$$\lambda ET = C_r(wR_s) \quad \text{or} \quad \lambda ET = C_r(wR_n) \tag{1}$$

where λ is the latent heat of vaporization (in calories per gram), ET is the potential evapotranspiration (in millimetres per day), R_s is the total solar radiation (in calories per square centimetre per day), R_n is the net radiation (in calories per square centimetre per day), w is the temperature- and altitude-dependent weighting factor, and C_r is a coefficient depending on the relative humidity and wind speed. Eight popular radiation-based equations were evaluated and compared in this study: the Turc (1961), Makkink (1957), Jensen and Haise (1963), Hargreaves (1975), Doorenbos and Pruitt (1977), McGuinness and Bordne (1972), Abtew (1996) and Priestley and Taylor (1972) equations. For a more complete discussion, the reader is referred to the literature cited.

Turc method. Under general climatic conditions of western Europe, Turc (1961) computed ET in millimetres per day for 10-day periods as

$$ET = 0{\cdot}013\frac{T}{T+15}(R_s + 50) \quad \text{for} \quad RH \geqslant 50 \tag{2}$$

$$ET = 0{\cdot}013\frac{T}{T+15}(R_s + 50)\left(1 + \frac{50 - RH}{70}\right) \quad \text{for} \quad RH < 50 \tag{3}$$

where T is the air temperature in °C, R_s is the total solar radiation in cal/cm^2/day, and RH is the relative humidity in per cent.

Makkink method. Makkink (1957) estimated ET in millimetres per day over 10-day periods for grassed lands under cool climatic conditions of the Netherlands as:

$$ET = 0{\cdot}61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{58{\cdot}5} - 0{\cdot}012 \quad (4)$$

where R_s is solar radiation in equivalent millimetres of evaporation per day. Δ is the slope of the saturation vapour pressure curve (in mbar/ °C), γ (in mbar/ °C) is the psychromatic constant. These quantities are calculated as (see also Singh, 1989):

$$\Delta = 33{\cdot}8639[0{\cdot}05904(0{\cdot}00738T + 0{\cdot}8072)^7 - 0{\cdot}0000342] \quad (5)$$

$$\gamma \text{ (mbar/°C)} = \frac{c_p P}{0{\cdot}622\lambda} \quad (6)$$

$$\lambda \text{ (cal/g)} = 595 - 0{\cdot}51T \quad (7)$$

$$P = 1013 - 0{\cdot}1055EL \quad (8)$$

where EL is elevation (in metres), λ (in calories per gram) is latent heat, and P (in mbar) is atmospheric pressure. The specific heat of air c_p (in cal/g/ °C) varies slightly with atmospheric pressure and humidity, ranging from 0·2397 to 0·260. An average value of 0·242 is reasonable.

Jensen–Haise method. Jensen and Haise (1963) evaluated 3000 observations of ET as determined by soil sampling procedures over a 35-year period, and developed the following relation:

$$\lambda ET = C_t(T - T_x)R_s \quad (9)$$

where λ and R_s have the same meaning and units as before, ET is in millimetres per day, C_t (temperature constant) = 0·025, and $T_x = -3$ when T is in degrees Celsius. These coefficients were considered to be constant for a given area.

Hargreaves method. Hargreaves (1975) and Hargreaves and Samni (1982, 1985) proposed several equations for calculating potential evapotranspiration, ET (in mm/day). One of the equations is written as

$$\lambda ET = 0{\cdot}0135(T + 17{\cdot}8)R_s \quad (10)$$

All variables have the same meaning and units as before. The Hargreaves method was derived from 8 years of cool season Alta fescue grass lysimeter data from Davis, California.

Doorenbos and Pruitt method. Doorenbos and Pruitt (1977) presented a radiation method for estimating ET using solar radiation. The method is an adaptation of the Makkink (1957) method and was recommended over the Penman method when measured wind and humidity data were not available or could not be estimated with reasonable confidence.

$$ET = a\left(\frac{\Delta}{\Delta + \gamma} R_s\right) + b \quad (11)$$

where R_s is solar radiation in mm/day, $b = -0{\cdot}3$ mm/day and a is an adjustment factor that varies with mean relative humidity and daytime wind speed. The adjustment factor a was presented in graphic and tabular forms, and can also be calculated from

$$a = 1{\cdot}066 - 0{\cdot}13 \times 10^{-2} RH + 0{\cdot}045 U_d - 0{\cdot}20 \times 10^{-3} RH \times U_d - 0{\cdot}315 \times 10^{-4} RH^2 - 0{\cdot}11 \times 10^{-2} U_d^2 \quad (12)$$

where RH is the mean relative humidity in per cent and U_d is the mean daytime wind speed in metres per second.

McGuinness and Bordne method. McGuinness and Bordne (1972) proposed a method for calculating potential evapotranspiration based on an analysis of a lysimeter data in Florida.

$$ET = \{(0{\cdot}0082T - 0{\cdot}19)(R_s/1500)\}2{\cdot}54 \quad (13)$$

where ET is in centimetres per day for a monthly period, T is in degrees Fahrenheit, and R_s is in cal/cm^2/day.

Abtew method. Abtew (1996) used a simple model that estimates ET from solar radiation as follows

$$ET = K\frac{R_s}{\lambda} \quad (14)$$

where ET is in millimetres per day, R_s is in MJ/m^2/day, λ is in MJ/kg, and K is a dimensionless coefficient.

Priestley and Taylor method. Priestley and Taylor (1972) proposed a simplified version of the combination equation (Penman, 1948) for use when surface areas generally were wet, which is a condition required for potential evaporation, ET. The aerodynamic component was deleted and the energy component was multiplied by a coefficient, $\alpha = 1{\cdot}26$, when the general surrounding areas were wet or under humid conditions.

$$ET = \alpha\frac{\Delta}{\Delta + \gamma}\frac{R_n}{\lambda} \quad (15)$$

where R_n is the net radiation (cal/cm^2 day), and other notations have the same meaning and units as in Equation (4). In this study, owing to a lack of observation data, R_n is estimated using an equation proposed by Linsley *et al.* (1982)

$$R_n = 7{\cdot}14 \times 10^{-3} R_s + 5{\cdot}26 \times 10^{-6} R_s(T + 17{\cdot}8)^{1{\cdot}87} - 3{\cdot}94 \times 10^{-6} R_s^2 - 2{\cdot}39 \times 10^{-9} R_s^2(T - 7{\cdot}2)^2 - 1{\cdot}02 \quad (16)$$

where R_n is in equivalent millimetres of evaporation per day.

Generalisation of the methods

Owing to the wide ranging inconsistency in meteorological data collection procedures and standards, many different evaporation equations, which have more or less the same model form, have been used by different authors. For example, by a proper transformation, Equations (9), (10) and (13) can be represented by the same model (form B in Table I). This has made it difficult, if not impossible, to use the various equations correctly. It is desirable to compare different model forms using the standard meteorological data measured at consistent heights and for the same periods. For this purpose, eight evaporation models, defined by Equations (2) through to (16), are generalized into five forms (Table I). This consideration has, at least, two advantages:

(1) for a specific site of interest, it is the form of a given model that is more important (useful) than the predetermined values of the constants using the meteorological data measured at different sites;

Table I. Five generalized radiation-based evaporation equations

Category	Generalized equation form[a,b]		Original equations
A	$ET = a\frac{R_s}{\lambda}$		Abtew (1996)
B	$ET = a(T+b)\frac{R_s}{\lambda}$		Hargreaves (1975), Jensen and Haise (1963), McGuinness and Bordne (1972)
C	$ET = a\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda}+b$		Makkink (1957), Doorenbos and Pruitt (1977)
D	$ET = a\frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda}+b$		Priestley and Taylor (1972)
E	$ET = a\left(\frac{T}{15+T}\right)(R_s+50)$	for $RH > 50$	Turc (1961)
	$ET = a\left(\frac{T}{15+T}\right)(R_s+50)\left(1+\frac{50-RH}{70}\right)$	for $RH \leqslant 50$	

[a] a and b are variables to be estimated; and other symbols have the same meaning as mentioned in the text.
[b] In Priestley and Taylor's equation R_n was calculated by Equation (16) owing to the lack of observation data.

Table II. Monthly averages of the main climatic variables and evaporation for station Changins in Switzerland (1990–1994)

Month	Temperature (°C)	Wind speed (m/s)	Vapour pressure deficit (mbar)	Humidity (%)	Radiation ($cal/cm^2/day$)	E_{pan} (mm/day)
January	2·19	2·44	1·52	80·50	88·16	0·94
February	2·77	2·45	1·79	78·25	159·33	1·15
March	7·47	2·61	3·50	69·22	266·14	2·18
April	8·98	2·71	4·29	67·76	346·34	2·78
May	14·30	2·60	5·89	68·19	457·92	3·44
June	16·70	2·54	6·37	70·74	462·61	3·47
July	20·14	2·42	9·08	66·08	513·29	4·72
August	20·53	2·40	9·90	63·84	445·13	4·90
September	15·28	2·18	4·91	75·05	295·72	2·75
October	10·03	2·35	2·45	81·16	160·04	1·41
November	6·04	2·21	1·69	82·65	84·70	0·95
December	2·75	3·08	1·52	80·37	71·98	1·02

2. it permits comparison of all model forms using standard meteorological data measured at the same sites and for the same periods.

STUDY REGION AND DATA

The Changins climatological station in the state of Vaud in Switzerland was used in this study. This station is located at a latitude of 46°24′N and a longitude of 06°14′E. Several hydrometeorological variables, including air temperature, wind speed, relative humidity, solar radiation, vapour pressure and corrected pan evaporation, among others, have been recorded continuously for the period 1990 to 1994. The hourly data were selected and subsequently integrated to daily values for use in the study. The monthly averages of the main climatic variables and the amount of evaporation are given in Table II.

RESULTS AND DISCUSSIONS

In the first stage of the comparative study, evaporation calculated by all eight methods with their original constant values was evaluated against the pan evaporation records. For illustrative purposes, results from five models, where each represents one generalized form, are discussed in this section. In the case where there are more models than one in the selected form, the model that gives the best results will be selected. This consideration results in the following five models: Abtew (Equation 14) for form A, Hargreaves (Equation 10) for form B, Makkink (Equation 4) for form C, Priestley and Taylor (Equations 15 and 16) for form D and Turc (Equations 2 and 3) for form E.

Correlation between methods

The monthly evaporation values computed using the different methods for 5 years (1990–1994) were analysed in order to correlate with pan evaporation using a linear regression equation:

$$Y = mX + c \tag{17}$$

where Y represents E_{Pan} and X is the ET estimated from the above-mentioned five methods, and m and c are constants representing the slope and intercept, respectively. The results of regression together with the cross-correlation (r^2) between pan evaporation and the evaporation computed using other methods are presented in Figure 1.

As can be expected, using the original constant values of empirical formulae applicable to other climatic areas leads to large errors. It is seen from Figure 1 that four of the five selected models yield large errors. In these regression equations, either the slopes are significantly different from 1 (e.g. Figure 1C) or the intercepts are significantly different from 0 (e.g. Figure 1B and E) or both (e.g. Figure 1D). This particular case study shows that the simplest model (the Abtew method, Figure 1A) best fits the measured ET when the original constant values of the equations are used. Systematic underestimation found in Figure 1B, C and E means that the constant values of 0·0135, 0·61 and 0·013 used in the Hargreaves, Makkink and Turc equations are too small for this station. The high value of intercept c (−1·05 mm/day) found in Figure 1D (calculated by Equation 15) is due to the negative R_n values calculated by Equation (16) during winter months.

Mean annual and seasonal values

The mean annual and seasonal values of evaporation were computed using various methods and pan evaporation for the period of 1990–1994 and the calculated values are shown in Table III. It is seen that the mean annual differences among the pan evaporation and the five estimation methods range from 2·9 to

Table III. Mean annual and seasonal estimated evaporation using selected methods[a] with original constant values

Season[c]	E_{Pan} (mm)	E_{Abt} (mm)	Error[b] (%)	E_{Har} (mm)	Error (%)	E_{Mak} (mm)	Error (%)	E_{Prt}[d] (mm)	Error (%)	E_{Tur} (mm)	Error (%)
Winter	1·04	0·96	−7·69	0·49	−52·88	0·48	−53·85	0·15	−85·58	0·30	−71·15
Spring	2·80	3·24	15·71	2·41	−13·93	2·15	−23·21	2·36	−15·71	2·18	−22·14
Summer	4·37	4·33	−0·92	4·13	−5·49	3·41	−21·97	4·71	7·78	3·83	−12·36
Autumn	1·71	1·67	−2·34	1·29	−24·56	1·13	−33·92	0·95	−44·44	1·30	−23·98
Annual	2·48	2·55	2·82	2·08	−16·12	1·79	−27·82	2·04	−17·74	1·90	−23·39

[a]Subscripts Abt = Abtew method, Har = Hargreaves methods, Mak = Makkink method, Prt = Priestley and Taylor method and Tur = Turc method.
[b]Percentage error = 100 × [(estimated − E_{Pan})/E_{Pan}].
[c]Winter is December, January and February, spring is March, April and May, summer is June, July and August and autumn is September, October and November.
[d]In Priestley and Taylor's equation net radiation was calculated by Equation (16) owing to the lack of observation data.

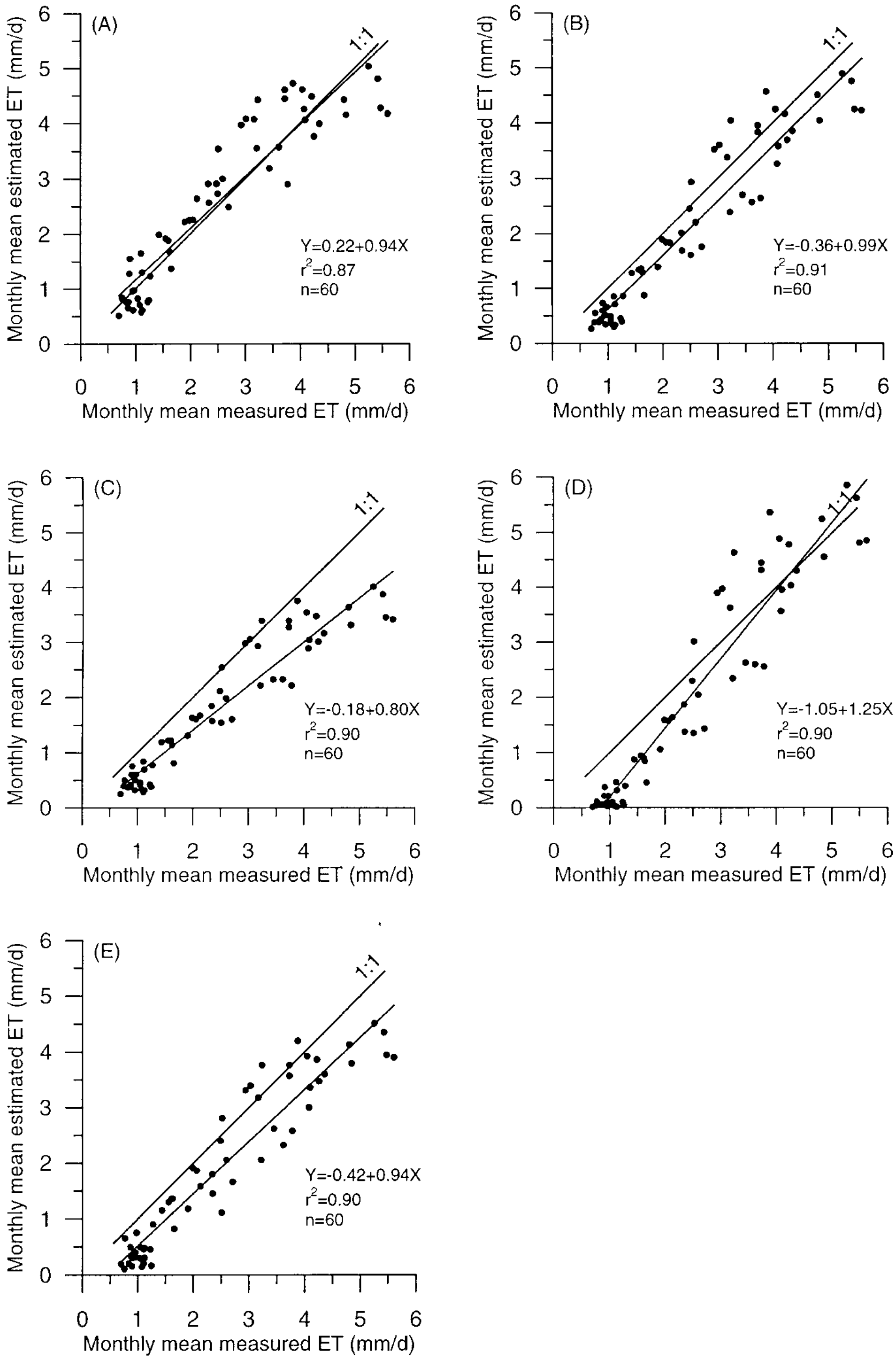

Figure 1. Comparison of pan *ET* with estimated *ET* for (A) the Abtew equation (Equation 14), (B) Hargreaves equation (Equation 10), (C) Makkink equation (Equation 4), (D) Priestley and Taylor equation (Equations 15 and 16) and (E) Turc equation (Equations 2 and 3). The original constant values were used in the calculation

Table IV. Comparison of parameter values before and after recalibration

Category	Generalized equation form[a,b]	Representative equation	Parameter values Original	Recalibrated
A	$ET = a\frac{R_s}{\lambda}$	Abtew (1996)	$a = 0{\cdot}53$	$a = 0{\cdot}53$
B	$ET = a(T+b)\frac{R_s}{\lambda}$	Hargreaves (1975)	$a = 0{\cdot}0135, b = 17{\cdot}8$	$a = 0{\cdot}0145, b = 17{\cdot}8$
C	$ET = a\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda} + b$	Makkink (1957)	$a = 0{\cdot}61$, $b = -0{\cdot}012$	$a = 0{\cdot}77, b = 0{\cdot}2$
D	$ET = a\frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda} + b$	Priestley and Taylor (1972)	$a = 1{\cdot}26, b = 0$	$a = 0{\cdot}98, b = 0{\cdot}94$
E	$ET = a\left(\frac{T}{15+T}\right)(R_s + 50)$ for $RH > 50$; $ET = a\left(\frac{T}{15-T}\right)(R_s + 50)\left(1 + \frac{50 - RH}{70}\right)$ for $RH \leqslant 50$	Turc (1961)	$a = 0{\cdot}013$	$a = 0{\cdot}015$

[a]All symbols have the same meaning as mentioned in the text.
[b]In Priestley and Taylor's equation R_n was calculated by Equation (16) owing to the lack of observation data.

27·8%, with the best estimates obtained by the Abtew method and the worst by the Makkink method. As far as the mean seasonal values for each method were concerned, the differences among the pan evaporation and last four methods became even larger, with the estimation methods giving values for evaporation that were much too low, especially in winter.

Modifications to equations

The previous discussion shows that empirical formulae, as used in this study, may be reliable in the areas and over the periods for which they were developed, but large errors can be expected when they are extrapolated to other climatic areas without recalibrating the constants involved in the formulae. Accordingly, modifications were made to the original equations used here to improve results. The constant values of 0·0135 and 0·013 used in the Hargreaves and Turc equations, respectively, were recalibrated and the new values obtained were 0·0145 and 0·015, respectively. The two constant values, i.e. 0·61 and −0·012, used in the Makkink equation were changed to 0·77 and 0·20, respectively. In the original form of the Priestley and Taylor equation, one constant value was used, i.e. 1·26. In order to overcome the problem of a high intercept value in the regression equation (Figure 1D), a second constant was found necessary (see the general form D in Table I). Recalibration led to $a = 0{\cdot}98$ and $b = 0{\cdot}94$ when the value for R_n was calculated by Equation (16). The only equation that could not be improved further by recalibration is that for the Abtew method and the same constant value of 0·53 was therefore retained. A comparison of the original model parameter values with the recalibrated values is shown in Table IV.

The mean seasonal and annual values calculated by these equations with the calibrated constant values are shown in Table V and the same regression analysis was carried out for the monthly values of evaporation (Figure 2). A comparison of Tables III, and V and Figures 1 and 2 shows a significant improvement in four of the five models. The mean annual errors produced by the Hargreaves, Makkink, Priestley and Taylor and Turc equations reduced from −16·1, −27·8, −17·7 and −23·3%, respectively, to −10·0, 0·0, and 0·0 and −11·6%, respectively. Although the seasonal bias is still a major problem for the Hargreaves and Turc methods, the Makkink and Priestly and Taylor methods, which have a more physical basis by taking into

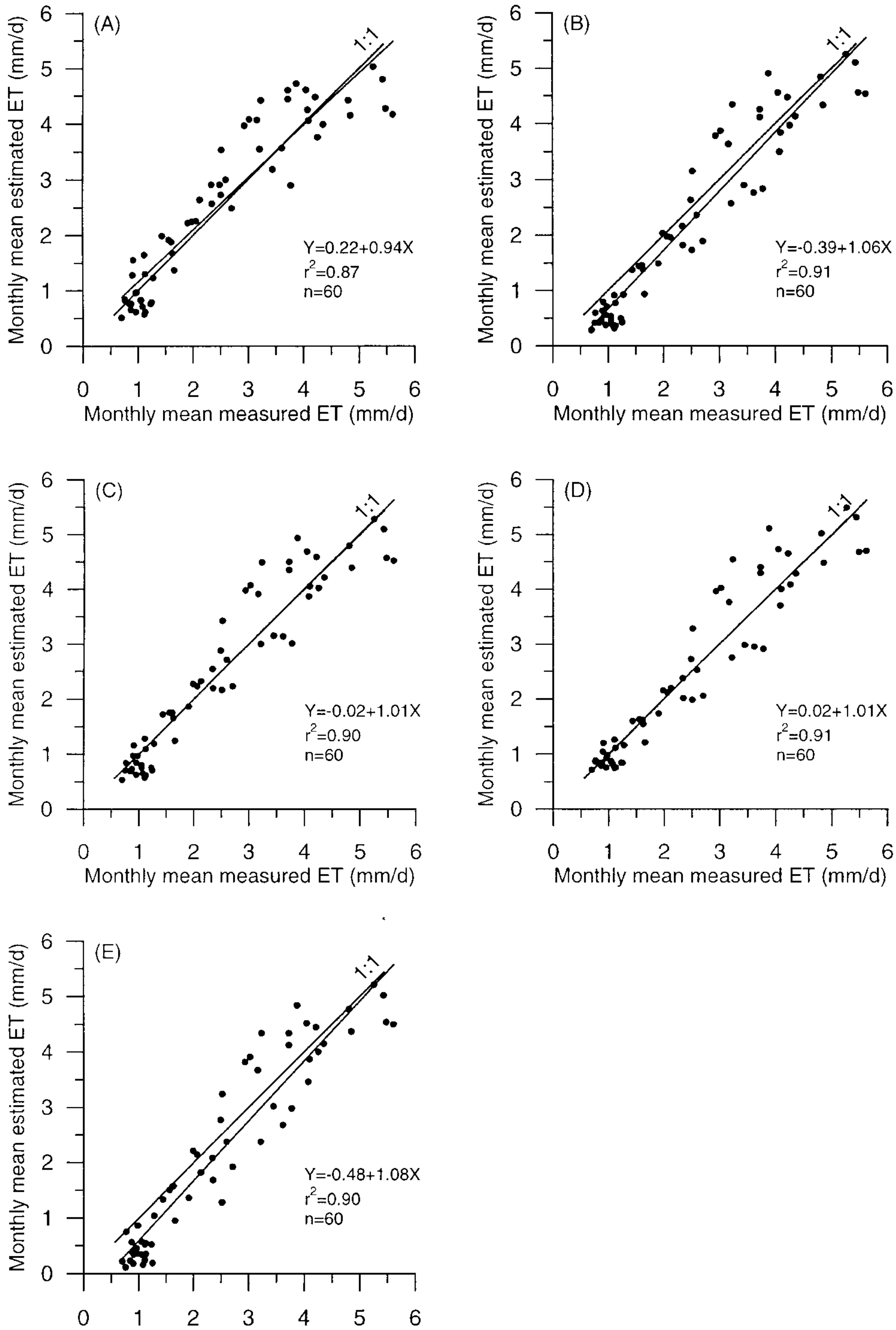

Figure 2. Comparison of pan *ET* with estimated *ET* for (A) the Abtew equation (Equation 14), (B) Hargreaves equation (Equation 10), (C) Makkink equation (Equation 4), (D) Priestly and Taylor equation (Equations 15 and 16) and (E) Turc equation (Equations 2 and 3). The recalibrated constant values were used in the calculation

Table V. Mean annual and seasonal estimated evaporation using selected methods[a] with calibrated constant values

Season[c]	E_{Pan} (mm)	E_{Abt} (mm)	Error[b] (%)	E_{Har} (mm)	Error (%)	E_{Mak} (mm)	Error (%)	E_{Prt} (mm)	Error (%)	E^{d}_{Tur} (mm)	Error (%)
Winter	1·04	0·96	−7·69	0·53	−49·04	0·83	−20·19	0·93	−10·58	0·35	−66·34
Spring	2·80	3·24	15·71	2·58	−7·85	2·93	4·64	2·77	−1·07	2·51	−10·35
Summer	4·37	4·33	−0·91	4·43	1·37	4·51	3·20	4·60	5·26	4·42	1·14
Autumn	1·71	1·67	−2·33	1·39	−18·71	1·64	−4·09	1·60	−6·43	1·50	−12·28
Annual	2·48	2·55	2·82	2·23	−10·00	2·48	0·00	2·48	0·00	2·19	−11·69

[a]Subscripts Abt = Abtew method, Har = Hargreaves method, Mak = Makkink method, Prt = Priestley and Taylor method and Tur = Turc method.
[b]Percentage error = $100 \times [(\text{estimated} - E_{Pan})/E_{Pan}]$.
[c]Winter is December, January and February, spring is March, April and May, summer is June, July and August and autumn is September, October and November.
[d]In Priestley and Taylor's equation net radiation was calculated by Equation (16) owing to the lack of observation data.

consideration the slope of the saturation vapour pressure curve and elevation, etc., gave the best estimate of evaporation, provided that the constant values were properly calibrated using local meteorological data. The simple Abtew equation, which needs only solar radiation as input, can be used in the situation where other meterological data are unavailable.

SUMMARY AND CONCLUSIONS

Eight radiation-based equations for calculating evaporation were evaluated using meteorological data from Changins station in Switzerland. These eight equations were then expressed in five generalized forms, which are represented by the Abtew, Hargreaves, Makkink, Priestley and Taylor and Turc equations, respectively. The evaluation and comparison were made based on both the original constant values involved in each equation and the recalibrated constant values. When using the original constant values, of the five original equations evaluated, the simple Abtew equation resulted in monthly and annual evaporation values that agreed most closely with pan evaporation values. Large errors resulted for the other four methods. Underestimation was the common problem, especially for cold months. By substituting recalibrated constant values for the original constant values, four of the five equations improved greatly, and all five equations worked well for determining the mean annual evaporation values. As far as the seasonal and monthly values were concerned, the Hargreaves and Turc equations showed a significant bias when compared with pan evaporation. With properly determined constant values, the Makkink and Priestley and Taylor equations are good choices for calculating evaporation in the study region as far as radiation-based methods are concerned. The simple Abtew equation can also be used when other meteorological data except radiation are not available. It should be noted that because there were no measurements of net radiation available in this study, the evaluation of the Priestley–Taylor equation was in fact a joint evaluation of that equation (Equation 15) and the equation selected to estimate net radiation (Equation 16).

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