*International Conference "Water, Environment, Energy and Society" (WEES–2009)*
*New Delhi, 12–16 January 2009*

# Comparison of Newly Proposed "Copais Approach" and Traditional Reference Evapotranspiration Equations in a Small Catchment

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**ABSTRACT:** Reference crop evapotranspiration ($ET_0$) is a key influential factor in many agricultural and hydrological projects. Alexandris and Kerkides (2003) and Alexandris *et al.* (2006) proposed a new empirical formula for hourly and daily estimations of reference evapotranspiration which requires data for three pertinent meteorological attributes, solar radiation $R_s$, air temperature $T$, and relative humidity $RH$. In this study, four reference evapotranspiration ($ET$) equations were compared using the weather data for five years (1995–1999) from a weather station at the Brue catchment, the United Kingdom. The Penman-Monteith equation standardized by the Food and Agriculture Organization (FAO56-PM) was used to compare with the California Irrigation Management Information System (CIMIS) Penman equation, the Penman–Monteith equation standardized by the American Society of Civil Engineers, and the new empirical equation (Copais Approach) with limited meteorological data. Yearly, monthly, daily and hourly comparisons of $ET_0$ were made using statistical terms like Linear Regression Correlation Coefficient ($R^2$) values, Root Mean Squared Differences (RMSE) and Standard Error of Estimates (SEE). The study showed that $ET_0$ values estimated by the other evaporation methods correlated very well with the corresponding values estimated by the standardized Penman–Monteith equations in both hourly and daily time steps. This study also demonstrated that the newly proposed empirical equation (Copais approach) for hourly reference evapotranspiration worked quite efficiently with a reasonably good accuracy.

**Keywords:** Evapotranspiration, FAO-PM, ASCE-PM, Copais Approach, UK.

## INTRODUCTION

Evapotranspiration, termed *ET* for short, is a natural phenomenon which is the combined process of plant transpiration and soil evaporation. *ET* is considered as the most significant component of the hydrologic budget apart from precipitation. Estimates of Reference Evapotranspiration ($ET_0$) are widely used in irrigation engineering to define crop water requirements. The accurate estimation of reference evaporation is very critical in the context of many scientific and management issues; for example, irrigation system design, irrigation scheduling and hydrologic and drainage studies crop production, management of water resources, evaluation of the effects of changing land use on water yields, and environmental assessment. The estimation of reference evapotranspiration depends on atmospheric variables, such as air temperature, solar radiation, wind speed, number of daylight hours, saturated vapour pressure and humidity. The Penman–Monteith approach recommended by FAO (FAO-PM) is considered as the standard to calculate reference evapotranspiration wherever the required input data are available (Allen *et al.,* 1998). Many researchers have made strong recommendations to consider FAO-PM as the standard method for evaluation of evapotranspiration through their comparative studies (Smith *et al.,* 1991; Allen *et al.,* 1998; Allen *et al.,* 2000; Howell *et al.,* 2000; Itenfisu *et al.,* 2000; Walter, 2000). Some studies also suggest that the *ET* estimation techniques are most appropriate for use in climatic regions similar to where they were developed (Penman, 1948; Jensen, 1973). The PM has two advantages over many other methods. First of all, it is a predominately physically based approach, indicating that the method can be used globally without any need for additional parameter estimations. Second, the method is well documented, implemented in a wide range of software, and has been tested using a variety of lysimeters. A major drawback to application of the PM, however, is the relatively high data demand.

Other modifications of the Penman equation to estimate evapotranspiration from a hypothetical grass $ET_0$, are the CIMIS Penman equation (George *et al.,* 1985; Snyder and Pruitt, 1985) and ASCE Penman equations. Pruitt and Doorenbos (1977) added some modifications to the Penman combination equation, with a wind function that was developed at the University of California, Davis. This modification adopted by California Irrigation Management Information System (CIMIS) for calculating hourly $ET_0$ and is popularly known as CIMIS Penman equation (Temesgen *et al.*, 2005). ASCE-PM is standardised of calculation of reference evapotranspiration (*ET*) as recommended by the Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of the American Society of Civil Engineers. Alexandris and Kerkides (2003, 2006) developed a new empirical equation for hourly and daily estimation of evapotranspiration, using a limited number of readily available weather parameters and demonstrated the estimation of hourly values of $ET_0$ with a satisfactory degree of accuracy compared with ASCE-PM estimation. The proposed equation is based on solar radiation, air temperature and relative humidity. The experiments had been conducted in experimental field of Agricultural University of Athens (Copais) in the central Greece, using surface polynomial regression analysis, therefore the model named as "Copais approach" for *ET* estimation. Even though, many equations have been developed and adapted for various applications based on available input data, there are still considerable amount of uncertainty among engineers and environmental managers to which method is to be adopted effectively in the calculation of reference evapotranspiration (Alkaeed *et al.*, 2006).

Several studies have been conducted by researchers for comparative evaluation of most widely used and strongly recommended models for estimating hourly $ET_0$ like Penman–Monteith (FAO56-Penman–Monteith), CIMIS version of Penman (CIMIS-Penman), and the American Society of Civil Engineers version of Penman–Monteith (ASCE-PM) (Alexandris and Kerkides (2003), Itenfisu *et al.* (2000), Doorenbos and Pruitt (1977). In recent years several papers have evaluated hourly $ET_0$ equations (FAO-56 and ASCE Penman–Monteith, CIMIS Penman and Hargreaves) by comparing them with lysimetric measurements (Ventura *et al.*, 1999; Berengena and Gavila´n, 2005; Lo´pez-Urrea *et al.*, 2006). Alexandris and Kerkides (2003, 2006) compared their model (Copais approach) performance with that of FAO-PM, ASCE-PM and CIMIS-PM for hourly and daily values $ET_0$ estimation using statistics and scatter plots.

In this study the FAO-56 Penman–Monteith (FAO-56 PM), the American Society of Civil Engineers version of Penman–Monteith (ASCE PM), the California Irrigation Management Information System Penman equation equations (CIMIS PM) and Copais approach are evaluated to estimate hourly and daily $ET_0$ values in the Brue catchment in south west England of the United Kingdom. We followed the recommendation of FAO (Allen *et al.*, 1994a, b, 1998), the FAO56-Penman-Monteith equation was used as a comparison criterion for the selected other empirical equations. The main objective of this study is to compare $ET_0$ values estimated by FAO56-PM with the corresponding value of other models using 1995–1999 meteorological data from the study area.

## MATERIALS AND METHODS

### Study Area and Data Used

Hydrological Radar Experiment (HYREX) based data at the British Atmospheric Data Centre (BADC) was used for this study. The Hydrological Radar Experiment (HYREX) was a Special programme of UK Natural Environment Research Council (NERC) which ran from May 1993 to April 1997 (data collection was extended to 2000). The data were collected in the River Brue catchment in Somerset, south-west England, UK. The total area of the Brue catchment is about 135.2 km$^2$. The dense raingauge network comprises 49 Cassella 0.2 mm tipping bucket raingauges, and uniformly covers the whole region. An Automatic Weather Station (AWS) and Automatic Soil Water Station (ASWS) provide reliable and accurate measurements of meteorological parameters.

### Different Evapotranspiration Models Employed for the Study

#### *FAO-56 Penman–Monteith for Estimating Reference Evapotranspiration*

The FAO-56 PM equation for the hourly time step is,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{37}{T_{hr} + 273} u_2 (e^0(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \ldots (1)$$

where $ET_0$ is the reference evapotranspiration (*mm* h$^{-1}$); *D* the saturation slope vapour pressure curve at Thr (*kPa* °C$^{-1}$); $R_n$ the net radiation at the grass surface (MJm$^{-2}$ h$^{-1}$); *G* the soil heat flux density (MJm$^{-1}$h$^{-1}$); *g* the psychrometric constant (*kPa* °C$^{-1}$); $T_{hr}$ the mean hourly air temperature (°C); $u^2$, the average hourly wind speed at 2 m height (ms$^{-1}$); $e_0(T_{hr})$ the saturation vapour pressure at $T_{hr}$ (*kPa*); $e_a$ is the average hourly actual vapour pressure (*kPa*).

When $R_n > 0$ (i.e. day time),

$$G = 0.1\ R_n \qquad \ldots (2)$$

and for $R_n < 0$ (i.e. night time),

$$G = 0.5\, R_n \qquad \dots (3)$$

And that of daily time step is,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{hr} + 273} u_2 (e^0(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \dots (4)$$

where $ET_0$ is the reference evapotranspiration ($mm$ d$^{-1}$); $D$ the saturation slope vapour pressure curve at daily average $T_{hr}$ ($kPa$ °C$^{-1}$); $R_n$ the net radiation at the grass surface (MJm$^{-2}$ day$^{-1}$); $G$ the soil heat flux density (MJm$^{-1}$d$^{-1}$); $g$ the psychrometric constant ($kPa$ °C$^{-1}$); $T_{hr}$ the mean hourly air temperature (°C); U2 the average daily wind speed ($m$ s$^{-1}$); $e_0$ ($T_{hr}$) the saturation vapour pressure at $T_{hr}$ ($kPa$); $e_a$ is the average daily actual vapour pressure ($kPa$).

The psychrometric constant, γ, can be calculated using Eqn. 5,

$$\gamma = 0.665 \times 10^{-3} P \qquad \dots (5)$$

where γ Psychometric constant [$kPa$ °C$^{-1}$]; and $P$ atmospheric pressure [$kPa$],

The actual vapour pressure ($e_a$) is calculated by,

$$e_a = e^0(T_{hr}) \frac{RH_{hr}}{100} \qquad \dots (6)$$

$RH_{hr}$ is the average hourly relative humidity (%)

$e^0(T_{hr})$ The saturation vapour pressure at $T_{hr}$, which can calculate from the following equations,

$$e^0(T_{hr}) = 0.6108 \exp\left[\frac{17.27T_{hr}}{T_{hr} + 237.3}\right] \qquad \dots (7)$$

where $e^0(T_{hr})$ is the saturation vapour pressure at $T_{hr}$ ($kPa$); $T_{hr}$ the mean hourly air temperature (°C);

Δ Slope of saturation vapour pressure curve ($kPa$ °C$^{-1}$) at mean air temperature ($T_{hr}$), (Tetens, 1930; Murray, 1967) calculated by,

$$\Delta = \frac{4098\left[0.6108 \exp\left(\dfrac{17.27T_{hr}}{T + 237.3}\right)\right]}{(T + 237)^2} \qquad \dots (8)$$

## ASCE Penman–Monteith Equation for Estimating Reference Evapotranspiration

The manner and form of the standardized ASCE-PM equation is very much like that of the FAO-56-PM equation The standardization of this equation assumes that weather parameters are over the grass having a height of 0.1 to 0.2 m for both grass and alfalfa reference applications. The ASCE standardized reference equation (ASCE-PM) is listed in Eqn. 9,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T_{hr} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \dots (9)$$

where:

$ET_0$ = standardized reference crop evapotranspiration for short surfaces ($mm$ h$^{1}$) for daily time steps or mm h$^{-1}$for hourly time steps),

$R_n$ = calculated net radiation at the crop surface (MJm$^{-2}$ d$^{-1}$for daily time steps or MJm$^{-2}$ h$^{-1}$ for hourly time steps),

$G$ = soil heat flux density at the soil surface (MJm$^{-2}$ d$^{-1}$ for daily time steps or MJm$^{-2}$ h$^{-1}$ for hourly time steps),

$T$ = mean daily or hourly air temperature at 1.5 to 2.5 m height (°C),

$u_2$ = mean daily or hourly wind speed at 2 m height (m s$^{-1}$),

$e_s$ = saturation vapor pressure at 1.5 to 2.5 m height ($kPa$), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature

$e_a$ = mean actual vapor pressure at 1.5 to 2.5 m height ($kPa$),

Δ = slope of the saturation vapor pressure-temperature curve ($kPa$ °C$^{-1}$),

γ = psychrometric constant ($kPa$ °C$^{-1}$),

Units for the 0.408 coefficient are m$^2$ mm MJ$^{-1}$

$C_d$ is also known as bulk surface resistance and aerodynamic resistance coefficient the value of which varies with day and night. Variation of $C_n$ and $C_d$ is detailed in Table 1.

**Table1:** Variation of $C_d$ and $C_n$ in Eqn. 9.

| *Time Step* | *Reference crop (Short)* | | *Reference crop (Tall)* | | *Units of $ET_0$* |
|---|---|---|---|---|---|
| | $C_d$ | $C_n$ | $C_d$ | $C_n$ | |
| Daily | 0.34 | 900 | 0.38 | 1,600 | mmd$^{-1}$ |
| Hourly (Day) | 0.24 | 37 | 0.25 | 66 | mmh$^{-1}$ |
| Hourly (Night) | 0.96 | 37 | 1.7 | 66 | mmh$^{-1}$ |

## CIMIS–Penman for Estimating Reference Evapotranspiration (hourly time step)

This model is a modification of the Penman equation to represent hourly evapotranspiration from a hypothetical grass, $ET_0$ ($mm$ h$^{-1}$), is known as the

CIMIS PM equation (George *et al.*, 1985; Snyder and Pruitt, 1985, 1992),

$$ET_0 = \frac{\dfrac{\Delta(R_n - G)}{(\Delta+\gamma)} + 0.268\dfrac{\Delta}{(\Delta+\gamma)}(a_w + b_w u_2)VPD}{\lambda} \quad \dots (10)$$

where $ET_0$ is the evapotranspiration ($mm$ h$^{-1}$), $u_2$ wind speed at 2 m ($m$ s$^{-1}$), $R_n$ net radiation (MJ m$^{-1}$ h$^{-1}$), $G$ set equal to zero with standard CIMIS usage, $\gamma$ psychrometric constant ($kPa$ °C$^{-1}$) calculated from,

$$\gamma = 0.000646(1 + 0.000946T_{hr})P \quad \dots (11)$$

where $P$ is barometric pressure ($kPa$) at the study area,

$$VPD = e^0(T_{hr}) - e_a \quad \dots (12)$$

where $VPD$ is vapour pressure deficit ($kPa$) and the $e_a$ and $e^0(T_{hr})$ are from Eqns. (6) and (7) respectively, $\Delta$ slope of saturation vapour pressure curve ($kPa$ °C$^{-1}$) at mean air tempreature, ($T_{hr}$) from Eqn. (8), $\lambda$ the latent heat of vaporization (MJ kg$^{-1}$), using Eqn. (13),

$$\lambda = 2.501 - (2.361 \times 10^{-3})T_{hr} \quad \dots (13)$$

Doorenbos and Pruitt, 1977 developed coefficients $a_w$ and $b_w$ for predicting hourly reference $ET_0$,

They suggested the coefficients as,

$a_w = 0.29$ and $b_w = 0.53$, for $Rn > 0$ (day time)

$a_w = 1.14$ and $b_w = 0.40$, for $Rn < 0$ (night time)

Hourly estimations of $ET_0$ can be estimated by applying these values to the modified form of the Penman equation (CIMIS PM), Eqn. (10).

### *"Copais Approach" for Estimating Reference Evapotranspiration (hourly time step)*

(Alexandris and Kerkides, 2003) developed Copais equation for estimating $ET_0$ on an hourly basis ($mm$ h$^{-1}$) is,

$$\begin{aligned} ET_0 &= C_0 + C_1 RH + C_2 T + C_3 RH^2 + C_4 T^2 \\ &\quad + C_5 R_s + \left(\frac{R_s}{2}\right)(C_6 RH + C_7 T) + C_8 T^2 \end{aligned} \quad \dots (14)$$

where $R_s$ is the solar radiation flux density in (MJ m$^{-2}$ h$^{-1}$), $T$ the mean hourly air temperature (°C), $RH$ the relative humidity (%).

Other coefficients are identified as,

$C_0 = 0.1396$, $C_1 = -3.019 \times 10^{-3}$,
$C_2 = -1.2109 \times 10^{-3}$, $C_3 = 1.626 \times 10^{-5}$,
$C_4 = 8.224 \times 10^{-5}$, $C_5 = 0.1842$,
$C_6 = -1.095 \times 10^{-3}$, $C_7 = 3.655 \times 10^{-3}$ and
$C_8 = -4.442 \times 10^{-3}$

Having the appropriate dimensions implied by Eqn. (14).

Alexandris and Kerkides (2006) also developed another equation for estimating $ET_0$ on a daily basis ($mm$ d$^{-1}$), which is,

$$ET_0 = m_1 + C_2 m_2 + C_1 m_3 + m_4 C_1 C_2 \quad \dots (15)$$

where $m_1 = 0.057$, $m_2 = 0.227$, $m_3 = 0.643$ and $m_4 = 0.0124$ and $C_1$ and $C_2$ can estimated by following equations,

$$C_1 = a_1 + a_2 RH + a_3 R_s + a_4 R_s RH \quad \dots (16)$$

where $a_1 = 0.6416$, $a_2 = -0.00784$, $a_3 = 0.372$ and $a_4 = -0.00264$.

$$C_2 = b_1 + b_2 T + b_3 R_s + b_4 T R_s \quad \dots (17)$$

In these equations $C_1$ and $C_2$ represent evapotranspiration in mm day$^{-1}$.

The dimensions of the parameters $a_1$, $a_2$, $b_1$ are in mm day$^{-1}$, $a_3$, $a_4$, $b_3$, in $10^6 \times$ mm$^3$ MJ, $m_1$ in mm day$^{-1}$, $m_2$, $m_3$ dimensionless and $m_4$ in day mm$^{-1}$.

## Performance Analysis of Different Methods Relative to FAO56-PM

The meteorological data of 5 years from the Hydrological Radar Experiment (HYREX) based at the British Atmospheric Data Centre (BADC) covering the period of January 1995–December 1999 were analyzed for calculating evapotranspiration by the different methods.

In this study, FAO-56 PM method was considered as the benchmark method and the performance of other three $ET_0$ estimation methods (ASCE PM, CIMIS PM and COPAIS Approach) were compared. A Matlab based program module was developed for use in this study, which uses climate variables and calculates hourly and daily $ET_0$ mm/day by all the aforementioned empirical equations.

Variations in performance of other equations with FAO-56 PM method were estimated using graphics, simple linear regression and statistical terms like the standard error of estimate SEE statistic, Root Mean Squared Differences, coefficient of determination $R^2$, and slope $S$ of a linear regression fit (through (0, 0) coordinate). Comparisons between the different equations were made in hourly and daily time steps. Comparisons in hourly and daily steps were demonstrated using the suggested equations and these values accumulated for estimating longer time steps (monthly and yearly). All empirical equations except CIMIS PM were compared for hourly and daily values.

Summed hourly values of $ET_0$ were used for daily estimation.

Irmak *et al.* (2003) computed the SEE using the following the equation,

$$SSE = \sqrt{\left[\frac{1}{\{n(n-2)\}}\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2 - \frac{\left[n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\times\left(\sum_{i=1}^{n} y_i\right)\right]^2}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\right]} \quad \ldots (18)$$

where, $x_i$ = $ET_0$ estimated using the FAO56-PM ($mm$ $h^{-1}/mm$ $d^{-1}$) and $y_i$ = $ET_0$ estimated using other equations ($mm$ $h^{-1}/mm$ $d^{-1}$).

Root Mean Squared Differences (RMSE) can be estimated using following equation,

$$RMSD = \sqrt{\left[\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}\right]} \quad \ldots (19)$$

where $n$ is number of observations $x_i$ and $y_i$ are same as above.

## RESULTS AND DISCUSSIONS

### Hourly $ET_0$ Comparison

This section describes the regressive comparison between hourly $ET_0$ values calculated using FAO56-PM equation and those calculated by the hourly equations like ASCE-PM, CIMIS-PM and "Copais approach" for five years in the Brue Catchment. Plots of the hourly reference evapotranspiration, FAO56-PM versus ASCE- PM, FAO56-PM versus CIMIS-PM FAO56-PM versus FAO56 PM $ET_0$ for five year period (1995–1999), are shown in Figures 1 to 3 respectively. The comparison results based on various performance statistics between $ET_0$ estimates for individual years of record for the different methods are shown in Table 2.

**Table 2:** Slopes, Correlation Coefficients ($R^2$) and Root Mean Squared Differences (RMSD), Standard Errors of Estimate (SEE) of Hourly Reference Evapotranspiration ($ET_0$) Comparisons between the Different Methods (CIMIS PM, ASCE PM, and Copais Approach with FAO56-PM) during 1995–1999 period

| Year | *ASCE-PM vs FAO56-PM* | | | | *CIMIS-PM vs FAO56-PM* | | | | *COPAIS vs FAO56-PM* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Slopes* | *$R^2$* | *RMSD* | *SEE* | *Slop* | *$R^2$* | *RMSD* | *SEE* | *Slop* | *$R^2$* | *RMSD* | *SEE* |
| 1995 | 1.05 | 0.99 | 0.007 | 0.0028 | 1.27 | 0.93 | 0.043 | 0.0316 | 0.98 | 0.97 | 0.015 | 0.0129 |
| 1996 | 1.06 | 0.99 | 0.0066 | 0.0027 | 1.22 | 0.96 | 0.028 | 0.0185 | 0.97 | 0.96 | 0.016 | 0.0140 |
| 1997 | 1.07 | 0.99 | 0.0068 | 0.0019 | 1.17 | 0.97 | 0.021 | 0.0114 | 0.97 | 0.96 | 0.017 | 0.0111 |
| 1998 | 1.06 | 0.99 | 0.0061 | 0.0025 | 1.15 | 0.98 | 0.018 | 0.0120 | 0.95 | 0.96 | 0.015 | 0.0117 |
| 1999 | 1.05 | 0.99 | 0.0046 | 0.0023 | 0.92 | 0.95 | 0.014 | 0.0127 | 1.01 | 0.95 | 0.014 | 0.0137 |

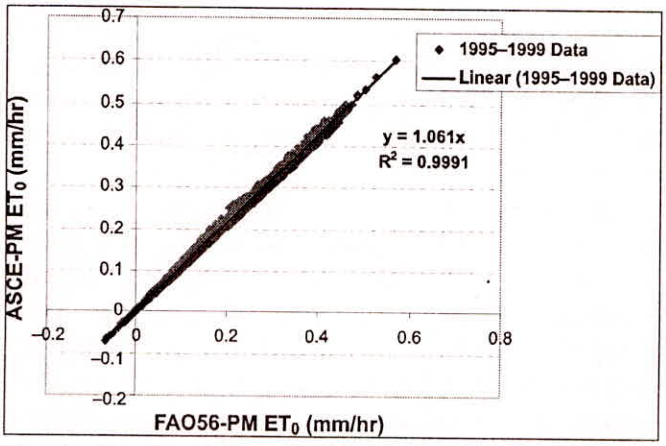

**Fig. 1:** Hourly reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the standardized ASCE Penman–Monteith equation (ASCE-PM $ET_0$) for Brue Catchment. During the year 1995–1999

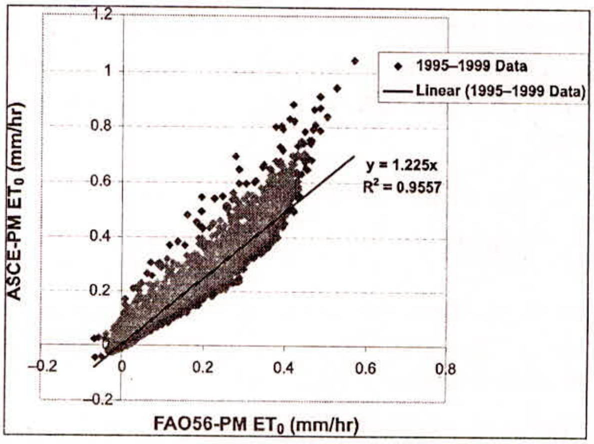

**Fig. 2:** Hourly reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the standardized CIMIS Penman–Monteith equation (CIMIS-PM $ET_0$) for Brue Catchment. During the year 1995–1999

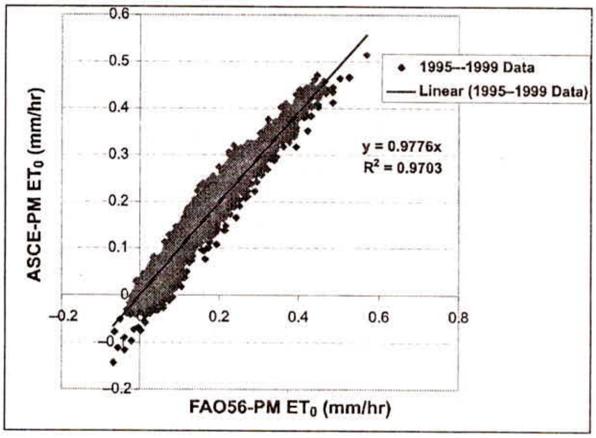

**Fig. 3:** Hourly reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the COPAIS Approach empirical equation (ASCE-PM $ET_0$) for Brue Catchment. During the year 1995–1999

The lower value of SEE implies the better performance of the empirical equation. From Table 2, the calculated average SEE in the hourly time step for all the methods indicating the low values such as 0.00244, 0.01724 and 0.01268 mm $h^{-1}$ for the ASCE-PM,IS-PM and Copais Approach methods, respectively. From these SEE values we can infer that ASCE-PM has shown the best performance, since it has the least SEE value, followed by Copais and CIMIS-PM respectively.

The five year mean values of slope, $R^2$, and RMSD between CIMIS $ET_0$ and FAO56 PM $ET_0$ are 1.058, 0.99, and 0.0062 mm $h^{-1}$, respectively. Even though, the slope of those plots higher than 1:1 ratio, the CIMIS Penman equation keeps a very good linear relation with the standardized Penman Monteith equations. In the case of CIMIS-PM, the mean values of slope, $R^2$, and RMSD in comparison with FAO56-PM are 1.15, 0.958 and 0.0248 respectively. From Table 2, we can also learn that CIMIS-PM model over predicting the $ET_0$ values compared with all other models in all of the yeas except year 1999. One reason for this overestimation could be the simplification of CIMIS equation considering soil heat flux equals zero.

The major drawback of Copais approach is the exclusion of wind speed from the empirical equation. To investigate the effect of the wind speed on the calculation of reference evapotranspiration, the absolute deviation between Copais approach and FAO56-PM hourly $ET_0$ estimates are plotted against the wind speed for the selected five years. That plot for year 1998 is shown in Figure 4. Such plots have shown that there is a positive correlation between the wind speed and $ET_0$ deviations. The effect of wind velocity could be the reason for the underestimation of Copais approach. However in this case the underestimation level is much low (slope of the curves are near to 1:1 ratio), so we can say Copais approach is also equally strong for reference $ET_0$ estimation in our study area.

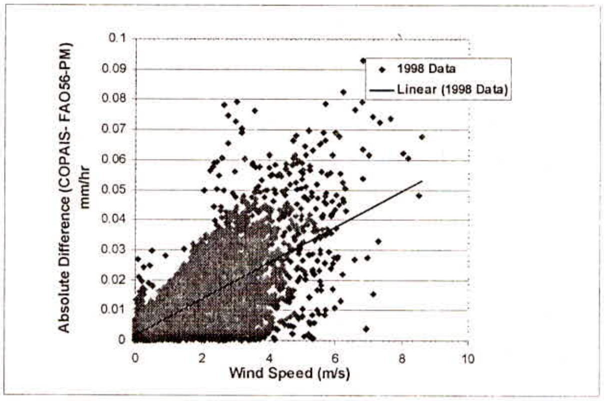

**Fig 4:** Absolute Difference of the hourly $ET_0$ values estimated according to Copais and FAO56-PM-PM vs. wind speed for year 1998

## Daily $ET_0$ Comparison

Figures 5 and 6 shows daily reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the standardized ASCE Penman–Monteith equation (ASCE-PM $ET_0$) for the Brue Catchment for 1995. This comparison of the estimated daily $ET_0$ visualises the reliability of the proposed daily Copais model. The plot of daily Copais approach against daily FAO56–PM at the Brue catchment revealed practically reasonable agreement (slope = 1.15 and intercept $R^2 = 0.92$) between the two methods. It is obvious from Figure 5 that daily ASCE-PM performs best with $R^2$ value of 0.99. RMSD based daily comparisons were also performed between the different methods and these values observed relatively small.

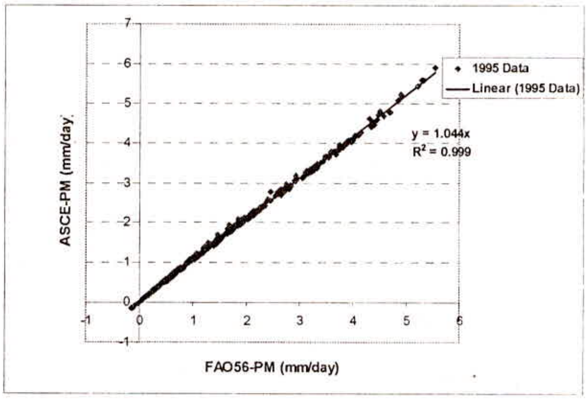

**Fig. 5:** Daily reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the standardized ASCE Penman–Monteith equation (ASCE-PM $ET_0$) for Brue Catchment for year 1995

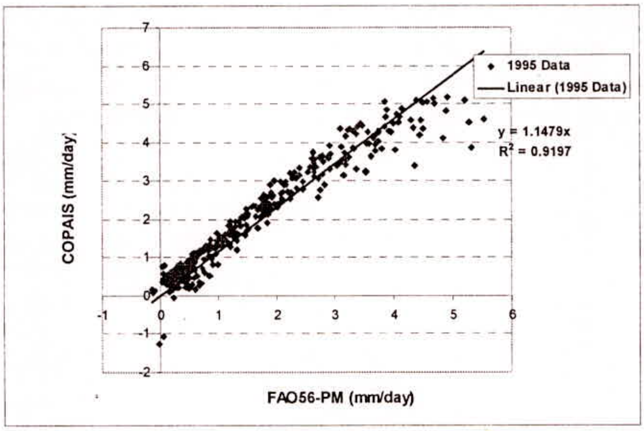

**Fig. 6:** Daily reference evapotranspiration comparison between the FAO56 Penman equation (FAO56-PM $ET_0$) and the Copais Approach based Empirical Equation (COPAIS $ET_0$) for the year 1995

## Monthly and Yearly $ET_0$ Comparison

In Figure 7 the variation of monthly (summed hourly) $ET_0$ by all tested methods is presented. This figure gives a clear picture of the variation of the mean monthly percentage of over/underestimation at the study area. In the first instance, one can note that CIMIS-PM $ET_0$ values are higher than FAO56 PM $ET_0$ by 40%–60% for peak months during the study period (1995–1999). In comparison to FAO56–PM, Copais method slightly overestimates throughout the study duration at the Brue catchment. However the maximum values of overestimation were found in 16–20% range in the hottest and driest months. In comparison with FAO56–PM, on a monthly basis, ASCE-PM showed underestimation at the Brue catchment and one can learn it from the graph.

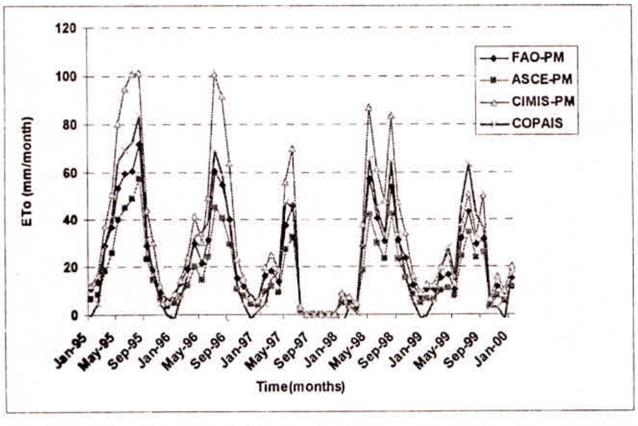

**Fig. 7:** Monthly variation of different reference evapotranspiratiom methods at brue catchment during the study period (1995–1999)

Figure 8 shows the comparisons of the annual $ET_0$ estimations. The years 1997 and 1999 were excluded from the graph due to insufficient data. Although the trends of the estimated $ET_0$ were in better agreements among the applied methods in lower time steps, these methods didn't exhibited the same results. In the present calculations, the annual sum of $ET_0$ estimations based on CIMIS-PM showed the highest value among the tested methods having the values ranged from 585 mm yr$^{-1}$ in 1995 and 469 mm yr$^{-1}$ in 1998. The $ET_0$ estimations by ASCE-PM has the lowest values ranged from 298 mm yr$^{-1}$ in 1995 and 222 mm yr$^{-1}$ in 1998 whereas Copais approach method was very close with FAO56-PM having the values ranged from 415 mm yr$^{-1}$ in 1995 and 308 mm yr$^{-1}$ in 1998.

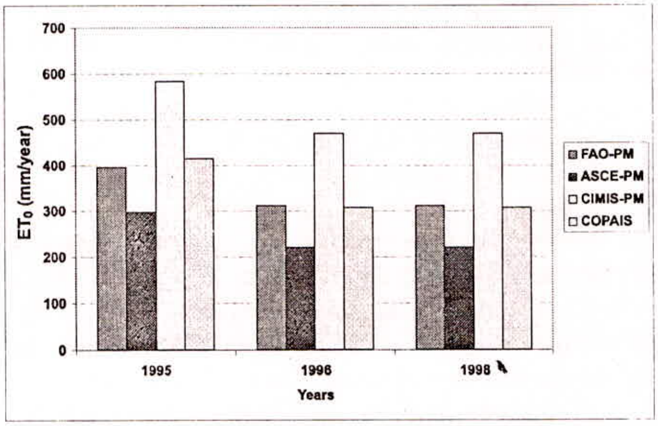

**Fig. 8:** Annual evapotranspiration estimates given by the different methods at brue catchment, UK

## SUMMARY

This study evaluated the relative performance of several commonly used penman empirical equations (FAO56-PM, ASCE-PM, CIMIS-PM) and a newly proposed empirical equation(Copais Approach) with limited meteorological data for calculation of reference evapotranspiration in the Brue catchment. It is demonstrated that $ET_0$ values estimated by ASCE PM, CIMIS Penman and Copais approach equations correlate well with that of FAO56-PM for both hourly and daily time steps within the study area.

The study once again emphasised FAO56-PM and ASCE-PM as the standard and desirable methods for estimating $ET_0$ if accurate and extensive climatic data available. The new Copais empirical formula approach also provides satisfactorily results for hourly and daily estimates compare with FAO-PM method of estimation. The study has shown that the omission of wind speed as a factor from "Copais approach" directly affecting $ET_0$ estimation but was at a minimal level in our study area. But this could raise some concerns in windy places. We encourage more investigation of this

"Copais Approach" in arid and sub arid regions of Indian subcontinent, so that the approach can be further explored for its suitability and applicability.

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