Cooperative Research Centre for
IRRIGATION FUTURES

Technical Report No. 09-1/08

An Analysis of Method and Meteorological Measurement for Evapotranspiration Estimation

Part 1: Results using weather data from Griffith, NSW

Annette B Barton and Wayne S Meyer

November 2008

BETTER IRRIGATION BETTER ENVIRONMENT BETTER FUTURE

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Part 1: Results using weather data from Griffith, NSW

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CSIRO Land & Water

CRC for Irrigation Futures

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Executive Summary

The National Evapotranspiration Project is being undertaken by the Cooperative Research Centre for Irrigation Futures. The focus of this project is the development of a standardised method for the computation of reference evapotranspiration (Et_{o}) within Australia and the collation of a set of associated crop coefficients (K_{c}) for different agro-ecological regions.

This report is the first of a two part series detailing research undertaken into the source of errors arising from the use of typical weather data to calculate Et_{o}. In this report two discrete weather datasets obtained at two proximate localities in Griffith, NSW, were compared. A typical Bureau of Meteorology (BoM) dataset was compared with a more comprehensive and precise weather dataset collected at the CSIRO research station.

Both the Penman combination equation and the FAO56 Penman–Monteith equation have been used for this analysis. The Penman equation has been used with coefficients optimised from measured Et_{o} values for Griffith (Penman–Griffith). The FAO Penman–Monteith equation has been used with the same variables and formulæ as adopted for the calculation of Et_{o} for the BoM "SILO" website.

Accepting that the optimised Penman combination method is the more accurate value of Et_{o} for Griffith conditions, then the calculation method is more critical than the data. When using the same dataset, the FAO Penman–Monteith method estimates a daily reference Et that is around 26% lower than the corresponding value given by the Penman–Griffith method. Annual totals of estimated daily Et_o calculated with the two methods, varied over four years from 23-26%, with the FAO56 value always being lower. Use of a default wind speed value of 2 ms^{-1} with the SILO dataset in the FAO equation increases this difference by around 4%.

It is concluded that use of the Penman–Griffith method is preferred because the daily Et_o value is closer to observed and because the Et_o value seems less sensitive to common estimates and errors in the input weather data. With either method, the critical influence of weather data is clear — the more accurate and descriptive the data, the more accurate will be the Et_{o} estimate.

Contents

1 Introduction

The National Evapotranspiration Project is being undertaken through the Cooperative Research Centre for Irrigation Futures. The focus of this project is the development of a standardised method for the computation of reference evapotranspiration (Et_o) and the collation of a set of associated crop coefficients (K_c) for different agro-ecological regions.

Numerous methods have been derived for estimating evapotranspiration. The first publication resulting from this project (Dodds et al., 2005) presented the much published basic energy equation for evaporation from a plant-soil system and the derivations for the various equations used to estimate evapotranspiration. All these equations require the input of weather data of one form or another, yet often the available weather data is limited to some very basic measurements. Errors will be introduced if the data are of poor quality (such as those obtained from poorly maintained weather stations) and variables are approximated from a limited set of observations.

As part of the Et project, research has been undertaken to investigate the source of errors arising from the use of typical weather data. During the 1980s and 1990s, extensive measurements of crop evapotranspiration were made at Griffith, NSW. As part of this study comprehensive and highly accurate weather data was collected to enable calibration of the Penman equation for south east Australian inland conditions. This more precise data set has been used, together with a typical Bureau of Meteorology (BoM) dataset from the SILO[1] site to compare reference evapotranspiration estimates and thereby identify the most significant sources of error.

Both the Penman combination equation and the FAO Penman–Monteith equation have been used for this analysis. The Penman combination equation has been used with coefficients optimised for irrigated crops grown at Griffith (Meyer et al., 1999). The FAO Penman–Monteith equation has been used with the same variables and formulæ as adopted for the calculation of Et_o for the SILO site.

This report is the first of a two part series detailing research undertaken into the source of errors arising from the use of typical weather data to calculate Et_o. In this report two discrete weather datasets obtained at two proximate localities in Griffith, NSW, were compared. A typical SILO dataset was compared with comprehensive and locally sited weather data collected at the CSIRO research station.

The second part of this series will examine the source of errors arising from the use of typical weather data to calculate Et_o from more humid tropical conditions. This will enable testing of the calibrated Penman calculation method in a very different environment to that of semi-arid Griffith and highlight reliability limits associated with different data sources and calculation methods.

[1] Specialised Information for Land Owners

2 The Weather Datasets

This research has focused on the outcomes resulting from the use of two weather datasets.

2.1 The CSIRO dataset

The first of these data sets is that generated from the meteorological observations taken at the CSIRO experimental site near Griffith, NSW (34.28^oS, 146.05^oE, 130 m above mean sea level) as part of a CSIRO project investigating the water balance of irrigated crops (Meyer, 1988). These observations were obtained by means of a standard meteorological station which provided measurements of the following variables:

- dry bulb temperature;
- wet bulb temperature;
- solar irradiance;
- rainfall amount;
- relative humidity;
- wind run (at 2 m); and
- evaporation from a screened Class A pan.

Details relating to the installation and maintenance of automatic weather stations and the collection of data are given in Shell et al. (1997). Weather observations for this dataset were recorded every 30 seconds and hourly means calculated. Measurements assigned to a given day were specific to the 24 hour period 00:00 hours to 24:00 hours for that day. On-going maintenance and calibration of measurement devices and the verification of results with those obtained from a second station at the site, ensured random and systematic errors were minimized and a high quality data set was obtained.

2.2 The SILO dataset

The second data set is a SILO Patched Point Dataset for the Bureau of Meteorology automatic weather station (AWS) located at Griffith Airport (Station No. 75041, 34.25^oS, 146.07^oE). This site is about 8 kilometers north of the CSIRO site with no significant difference in elevation although there is a low ridge ("Scenic Hill") between the two sites.

> *Combined with original measurements by the Bureau of Meteorology for a particular meteorological station and using interpolation methods to fill in any missing data values in the record, patched point datasets provide continuous historical meteorological data including daily rainfall, minimum and*

maximum temperatures, radiation, evaporation and vapour pressure.
(Bureau of Meteorology, 2005)

The daily dataset obtained included the following variables:

- maximum and minimum temperature;
- rainfall amount;
- evaporation (pan);
- radiation (modelled from cloud oktas observation data);
- average vapour pressure (calculated from 09:00 hours dry and wet bulb temperatures); and
- relative humidity (estimated) at maximum and minimum temperature.

Weather observations for the SILO data are taken at 09:00 hours and 15:00 hours each day. Rainfall and evaporation amounts are recorded at 09:00 hours each day and are the totals for the preceding 24 hour period. Rainfall measurements are assigned to the day on which they are recorded while evaporation measurements are assigned to the previous day. Daily maximum and minimum temperatures are also recorded at 09:00 hours. The daily maximum is shifted to the preceding day while the daily minimum is applied to the same day. SILO solar radiation values are based on cloud observations made at 09:00 hours and 15:00 hours of the day to which they are assigned. SILO vapour pressure is based on the 09:00 hours point observation of dry and wet bulb temperature and is also applied to the day of observation.

Of the variables listed above, only the temperature and rainfall values were directly measured at the locality. Evaporation, radiation and vapour pressure have been spatially interpolated by the Queensland Department of Natural Resources and Mines (Jeffrey et al., 2001). The values for relative humidity have been estimated (Jeffrey et al., 2001).

Clearly, this second dataset will be less precise than the first, and any derived values from the SILO dataset would be expected to have greater variability than those derived from the CSIRO dataset.

2.3 The period of analysis

The authors elected to analyse the evapotranspiration estimates obtained using the weather datasets, for a two year period. The period commencing January 1989 and ending December 1990 was selected.

3 The Penman-type Methodologies

The derivation of four Penman-type equations can be perused in Dodds et al. (2005). Two of the Penman-type methods were selected for this research assignment:

- Penman combination method;
- FAO Penman–Monteith method.

Coefficient values for the Penman equation which have been used in this research are those derived by Meyer (1988) and Meyer et al. (1999) for the Griffith area and is subsequently referred to as the Penman–Griffith method. In the case of the FAO equation, variable values are those adopted in the SILO calculations which are those given in FAO56 (Allen et al., 1998).

For completeness the formulæ and coefficients corresponding to each of these methods is provided below.

3.1 The Penman–Griffith method

3.1.1 The equation

Penman (1948) combined the energy balance equation with the Dalton ærodynamic equation to produce the Penman combination equation:

$$Et_o = \left[\left(\frac{\Delta}{\Delta + \gamma} \right) (R_n - G) + \left(\frac{\gamma}{\Delta + \gamma} \right) f(u)(e_o - e_a) \right] / L \quad (1)$$

where Et_o daily reference evapotranspiration (mm day^{-1}),
Δ slope of saturation pressure curve (kPa ^{o}C^{-1}),
R_n net radiant energy to the soil-plant system (MJ m^{-2} day^{-1}),
G soil heat flux (MJ m^{-2} day^{-1}),
γ psychrometric constant (0.066 kPa ^{o}C^{-1}),
$f(u)$ wind function (MJ m^{-2}kPa^{-1} day^{-1}),
e_o mean daily saturation vapour pressure (kPa),
e_a actual mean daily vapour pressure (kPa), and
L latent heat of vaporisation of water (MJ kg^{-1}).

3.1.2 Calculation of input variables

Formulæ and values for the input variables are given below. Additional information can be sourced from Meyer et al. (1999) and Dodds et al. (2005).

Latent heat of vapourisation:

$$L = 2.50025 - (0.002365 T_{mean}) \quad (2)$$

Saturation vapour pressure:

$$e_o = 0.6108 \exp\left(\frac{17.27T_{mean}}{T_{mean} + 237.3}\right) \tag{3}$$

where T_{mean} (^{o}C) is the daily mean dry bulb temperature.

Actual vapour pressure:

$$e_a = 0.6108 \exp\left(\frac{17.27T_{dew}}{T_{dew} + 237.3}\right) \tag{4}$$

where T_{dew} (^{o}C) is the daily mean dew point temperature.

Or, where T_{dew} is not available (Allen et al., 1998):

$$e_a = \left[\left(e_o(T_{min}) \times \frac{RH_{max}}{100}\right) + \left(e_o(T_{max}) \times \frac{RH_{min}}{100}\right)\right]/2 \tag{5}$$

where

$$e_o(T_{min}) = 0.6108 \exp\left(\frac{17.27T_{min}}{T_{min} + 237.3}\right) \tag{6}$$

and

$$e_o(T_{max}) = 0.6108 \exp\left(\frac{17.27T_{max}}{T_{max} + 237.3}\right) \tag{7}$$

Wind function:

$$f(u) = a' + b'(u) \tag{8}$$

where a' and b' are constants and u is wind run (km day^{-1}). Meyer has calibrated the constants for Griffith as follows (Meyer et al., 1999):

$$\begin{aligned} a' &= 17.8636 \\ b' &= 0.044 \end{aligned}$$

Slope of the saturation vapour pressure curve:

$$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27T_{mean}}{T_{mean}+237.3}\right)\right]}{(T_{mean} + 237.3)^2} \tag{9}$$

Soil heat flux:
Meyer (1988) measured the soil heat flux at Griffith and applied regression analysis to give the following equation:

$$G = 0.12(T_{mean} - T_{av}) \tag{10}$$

where T_{av} is the average air temperature of the *preceding* 3 days:

$$T_{av} = (T^{i-1}_{mean} + T^{i-2}_{mean} + T^{i-3}_{mean})/3 \tag{11}$$

Net radiant energy:
Meyer (1999) presents a methodology to calculate the net radiant energy which has been calibrated for Griffith:

$$R_n = R_{ns} - R_{nl} \tag{12}$$

where R_n net radiant energy to the soil-plant system (MJ m^{-2} day^{-1}),
R_{ns} net incoming shortwave radiation (MJ m^{-2} day^{-1}), and
R_{nl} net outgoing longwave radiation (MJ m^{-2} day^{-1}).

$$R_{ns} = (1 - \alpha) R_s \tag{13}$$

and

$$R_{nl} = \left(a \frac{R_s}{R_{so}} + b \right) \varepsilon' \sigma (T_a + 273)^4 \tag{14}$$

where α albedo of the surface in question,
R_s incoming shortwave solar energy (MJ m^{-2} day^{-1}),
R_{so} incoming shortwave energy on a totally clear day (MJ m^{-2} day^{-1}),
a, b constants which sum to unity,
ε' effective emissivity,
σ Stefan-Boltzmann constant (4.896×10^{-9} MJ m^{-2} day^{-1} K^{-4}), and
T_a air temperature (^{o}C).

The albedo, α, is assumed to be 0.23 for green vegetation, with the exception of wheat, for which Meyer et al. (1999) use a value of 0.184 based on local measured values.

The incoming shortwave solar energy, R_s, and the air temperature (usually mean daily), T_a, are measured values.

Meyer (1999) developed an empirical equation to calculate the incoming shortwave energy on a totally clear (non-cloudy) day, based on fitting a curve to measurements over a number of years:

$$R_{so} = 22.357 + 11.0947 \cos D - 2.3594 \sin D \tag{15}$$

where

$$D = 2\pi \frac{DOY}{365.25} \tag{16}$$

and *DOY* is the day number of the year.

Equation 16 is calibrated for Griffith and requires alteration to calculate R_{so} at other latitudes and altitudes.

The constants a and b have been calibrated for Griffith as follows (Meyer, 1999):

$$a = 0.92$$
$$b = 0.08$$

The effective net emissivity, ε' is given by:

$$\varepsilon' = c + d\sqrt{e_a} \tag{17}$$

where e_a mean daily water vapour pressure in the air, and
c, d constants with values 0.34 and -0.139 respectively.

3.2 The FAO Penman–Monteith method

3.2.1 The equation

The FAO Irrigation and Drainage Paper 56 Allen et al. (1998), produced by the Food and Agricultural Organisation of the United Nations, provides guidelines for estimating crop evapotranspiration based on the Penman–Monteith combination equation. This method is termed the "FAO Penman-Monteith". Additional information can be sourced from Allen et al. (1998) and Dodds et al. (2005).

This method has been adopted by the Bureau of Meteorology for the calculation of reference evapotranspiration values which are published as part of the SILO datasets. The basic equation is as follows:

$$Et_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{mean}+273}\right)u_2(e_o - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{18}$$

where Et_o daily reference evapotranspiration (mm day^{-1}),
Δ slope of saturation pressure curve (kPa ^{o}C^{-1}),
R_n net radiant energy to the soil-plant system (MJ m^{-2} day^{-1}),
G soil heat flux (MJ m^{-2} day^{-1}),
γ psychrometric constant (0.066 kPa ^{o}C^{-1}),
u_2 daily mean wind speed at 2 m height (m s^{-1}),
e_o mean daily saturation vapour pressure (kPa),
e_a actual mean daily vapour pressure (kPa), and
T_{mean} mean air temperature (^{o}C).

3.2.2 Calculation of input variables

Formulæ and values for the input variables are given below. The formulæ and variables presented here are those adopted for the calculation of Et_o for the SILO evapotranspiration estimates (see Appendix A, Fitzmaurice and Beswick, 2005).

Saturation vapour pressure:
The saturation vapour pressure at air temperature, T is:

$$e^0(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{19}$$

and the mean daily saturation vapour pressure is calculated as:

$$e_o = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \tag{20}$$

Actual vapour pressure:
Values for average daily vapour pressure are provided in the SILO dataset. For the CSIRO dataset, Equations 4 or 5 can be applied.

Daily mean wind speed:
Only the CSIRO dataset includes values for daily mean wind speed, calculated by aggregating wind run measurements. A default value of 2 ms^{-1} has been used for the SILO evapotranspiration estimates.

Slope of the saturation vapour pressure curve:
As for the Penman combination method, Equation 9 is applicable here.

Soil heat flux:
For the SILO evapotranspiration estimates a default value of 0 MJ m^{-2} day^{-1} has been adopted. Allen et al. (1998, p.54) states that, for "day and ten-day" periods, soil heat flux beneath the grass reference surface is relatively small and may therefore be ignored.

Net radiant energy:
As for the Penman combination method, R_n is the difference between net incoming shortwave radiation and net outgoing longwave radiation (Equation 12).

Net incoming shortwave radiation, R_{ns}, is calculated similarly as for the Penman combination equation (Equation 13).

Net outgoing longwave radiation, R_{nl}, is calculated as[2]:

$$R_{nl} = \sigma \left[\frac{T^4_{max,K} + T^4_{min,K}}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \tag{21}$$

where R_s incoming shortwave solar energy (MJ m^{-2} day^{-1}),
R_{so} incoming shortwave energy on a totally clear day (MJ m^{-2} day^{-1}),
σ Stefan-Boltzmann constant (4.896×10^{-9} MJ m^{-2} day^{-1} K^{-4}),
$T_{max,K}$ maximum absolute daily temperature (K),
$T_{min,K}$ minimum absolute daily temperature (K), and
e_a actual mean daily vapour pressure (kPa).

The clear sky radiation, R_{so}, is calculated as:

$$R_{so} = (0.75 + 2 \times 10^{-5} h) R_a \tag{22}$$

where R_a extraterrestrial radiation (MJ m^{-2} day^{-1}), and
h station altitude (m).

[2]This equation is almost identical to Equation 14 for the Penman combination equation, however in this instance T_{max} and T_{min} are used instead of T_{mean} and the coefficients in the last term have not been calibrated.

The extraterrestrial radiation, R_a, is given by:

$$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (23)$$

where G_{sc} solar constant (0.0820 MJ m^{-2} min^{-1}),
d_r inverse relative distance Earth–Sun,
δ solar declination (rad),
φ latitude (rad), and
ω_s sunset hour angle (rad).

The terms in this equation can be calculated as follows:

$$d_r = 1 + 0.033 \cos\left(J \frac{2\pi}{365}\right) \quad (24)$$

where J is the number of the day in the year (between 1 and 365 or 366).

$$\omega_s = \arccos(-\tan(\varphi) \tan(\delta)) \quad (25)$$

and

$$\delta = 0.409 \sin\left(J \frac{2\pi}{365} - 1.39\right) \quad (26)$$

4 Analysis Results

MS Excel spreadsheets and GenStat were used to manipulate the data and perform the calculations. The results are presented here.

4.1 Results for the Penman–Griffith equation

The CSIRO and SILO weather datasets were compared using the Penman–Griffith equation. For the SILO weather dataset the following three variations were considered:

- Variation A: *For the SILO dataset*,(SILO0) soil heat flux (G) has been calculated as for the Penman–Griffith equation and the CSIRO dataset wind speed values have been used in the wind function ($f(u)$).
- Variation B: *For the SILO dataset* (SILO1), soil heat flux (G) has been set to zero and the CSIRO dataset wind speed values have been used in the wind function ($f(u)$).
- Variation C: *For the SILO dataset* (SILO2), soil heat flux (G) has been set to zero and a default wind speed value of 2 ms^{-1} (or 172.8 km/day) has been used in the wind function ($f(u)$).

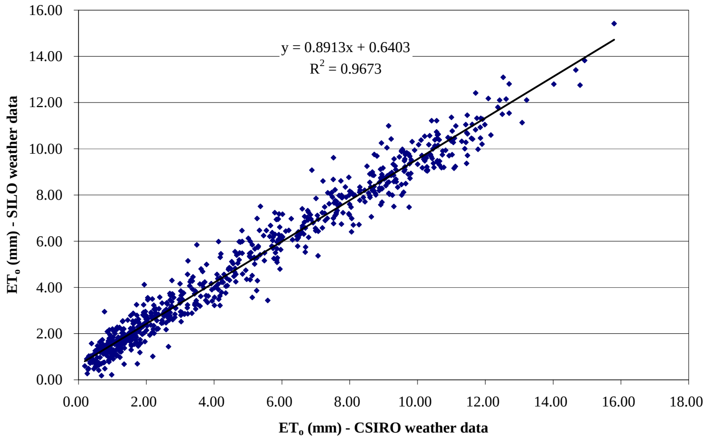
Reference evapotranspiration calculated using the SILO dataset were plotted against Et_o calculated using the CSIRO dataset and the regression relationship obtained (refer Figure 1). The results are summarised in Table 1. The regression value for which $x = y$ [or $Et_o(CSIRO) = Et_o(SILO)$] is also given.

Table 1: Summary of results for the Penman–Griffith equation.

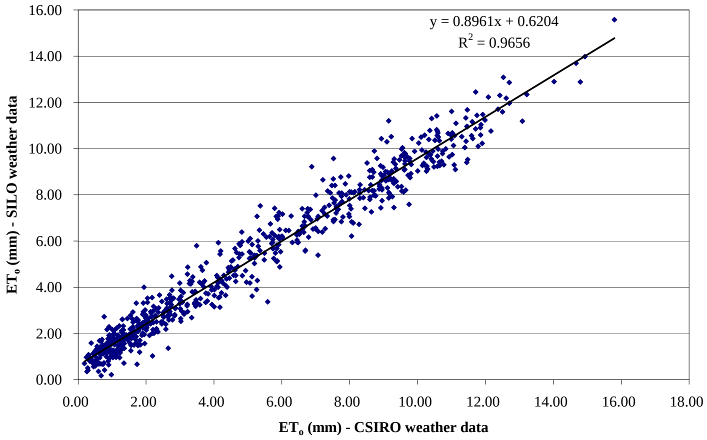
Variation	Regression Equation[a]	R^2	$x = y$	Aunual Aggregate Et_o (mm) 1989 CSIRO	1989 SILO	1990 CSIRO	1990 SILO
A	$y = 0.89x + 0.64$	0.97	5.89		1834		1927
B	$y = 0.90x + 0.62$	0.97	5.97	1798	1836	1898	1929
C	$y = 0.84x + 0.77$	0.95	4.90		1764		1913

[a] $y = Et_o$ (SILO) and $x = Et_o$ (CSIRO)

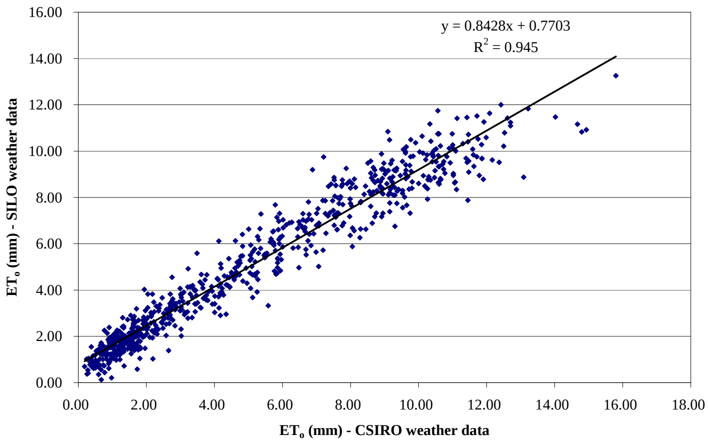
The above results indicate only minor differences between Variations A and B. This is not surprising when the values for G — as calculated using the CSIRO data and the Meyer soil heat flux equation — are examined. The average value for the assessment period is 0.00, with a minimum value of -1.28 and a maximum value of 1.42. Hence approximating G with a default value of zero, is not likely to introduce significant error.



(a) Variation A.



(b) Variation B.



(c) Variation C.

Figure 1: Calculation of Evapotranspiration using the Penman–Griffith equation.

Annual Et_o totals for all events analysed are given columns 5–8 of Table 1. Interestingly Variations A and B show a consistent difference between the two datasets. Where wind is not a factor of difference between the two datasets, the annual difference is approximately 2%, with the SILO dataset overestimating Et_o. When SILO wind is assumed to be a default value of 2 ms^{-1}, the differences become variable; for 1989 the difference was -2% and for 1990 the difference was almost 1%.

In Figure 2 the absolute difference between Et_o calculated using the CSIRO dataset and Et_o calculated using the SILO2 dataset (Var. C) has been plotted on a time scale. This plot shows that the difference between the two estimates is partially related to time with $Et_o(SILO)$ on average being greater than $Et_o(CSIRO)$ during the winter months (March – September) and less than $Et_o(CSIRO)$ during the summer months (September – March). From this graph it can be appreciated that while *on an annual basis* the differences between the two datasets is only small, on a seasonal basis the differences may be far more significant.

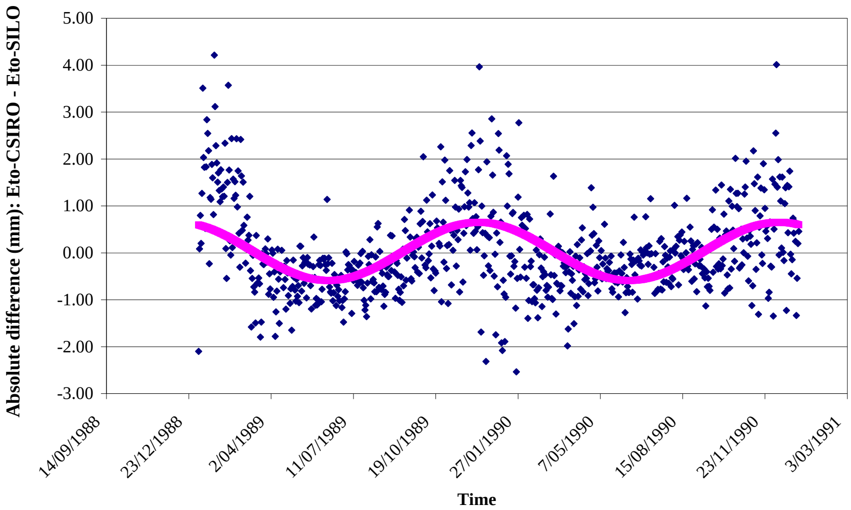


Figure 2: Absolute difference between Et_o calculated using the CSIRO dataset and the SILO2 dataset.

In Figures 3 and 4 the vapour pressure variables (e_o, e_a and $e_o - e_a$) and radiation variables (R_s, R_{nl} and R_n) have been plotted for Variation B and lines of best fit shown. The first graph shows there is very little difference, on average, between the saturated vapour pressure values which are based on daily mean temperature. More significant differences — as indicated by slope coefficients less than one, and lower R^2 values — occur with respect to the actual vapour pressure values. With the radiation variables also, the significant difference in incoming shortwave solar energy (R_s) values is also reflected in the differences in the R_{nl} and R_n values, which are both functions of R_s.

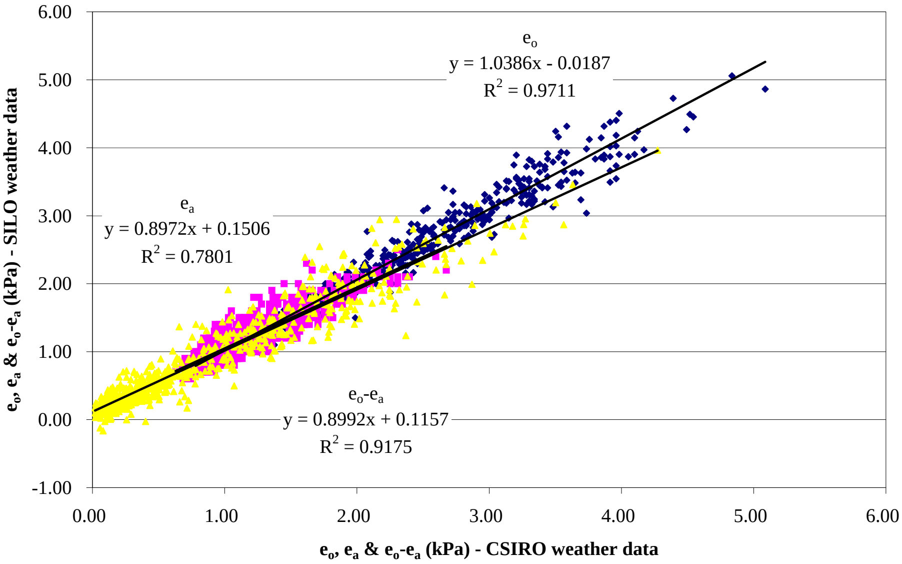


Figure 3: Penman–Griffith equation (Var. B) vapour pressure variables.

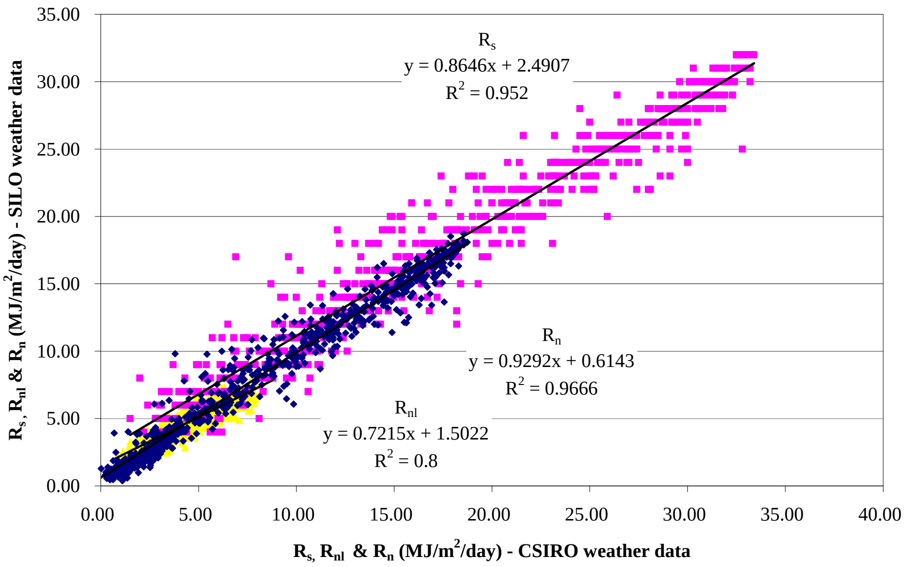


Figure 4: Penman–Griffith equation (Var. B) radiation variables.

4.2 Results for the FAO Penman–Monteith equation

Results for the FAO Penman–Monteith equation are shown in Figure 5 and Table 2. For the SILO weather dataset the following variations were considered:

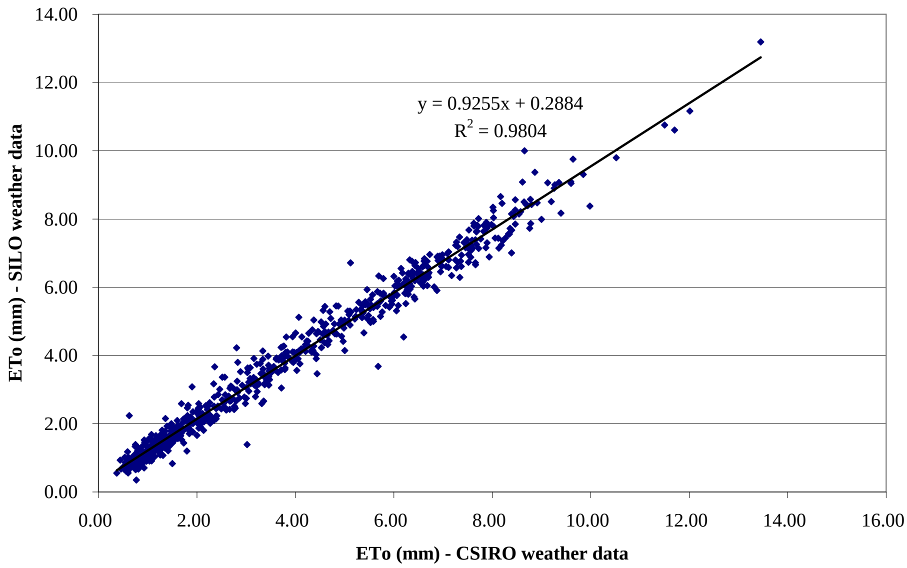
- Variation A: *For the SILO dataset* (SILO1), the CSIRO dataset wind speed values have been used.
- Variation B: *For the SILO dataset* (SILO2), a default wind speed value of 2 ms^{-1} (or 172.8 km/day) has been used.

As discussed in Section 3.2, a default value of zero has been adopted for soil heat flux, G — both for the CSIRO and SILO datasets.

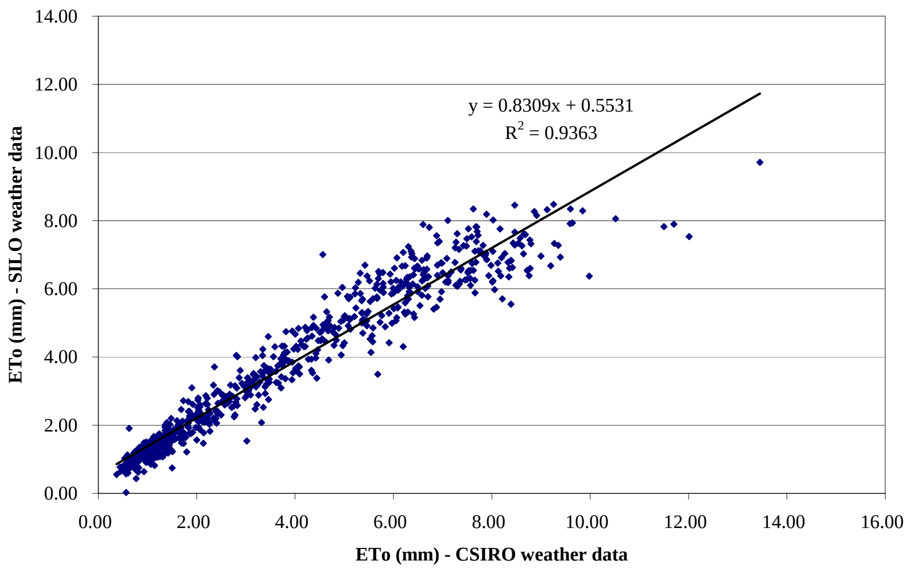
Table 2: Summary of results for the FAO Penman–Monteith equation.

Variation	Regression Equation[a]	R^2	$x = y$	Annual Aggregate Et_o (mm)			
				1989		1990	
				CSIRO	SILO	CSIRO	SILO
A	$y = 0.92x + 0.29$	0.98	3.87	1380	1383	1400	1400
B	$y = 0.83x + 0.55$	0.94	3.27		1315		1399

[a] $y = Et_o$ (SILO) and $x = Et_o$ (CSIRO)



(a) Variation A.



(b) Variation B.

Figure 5: Calculation of Evapotranspiration using the FAO Penman–Monteith equation.

Table 2 shows that for Variation A the annual ET_o totals are almost identical for both datasets. Where wind is assumed to be a default value of 2 ms^{-1} (Var. B) the differences become more variable (-5% for 1989 and 0% for 1990). This same phenomenon was also observed in the case of the Penman–Griffith equation.

Again the absolute difference between Et_o calculated using the CSIRO dataset and Et_o calculated using the SILO dataset (Var. B) when plotted on a time scale (refer Figure 6) show a seasonal trend. $Et_o(SILO)$ on average is greater than $Et_o(CSIRO)$ during the winter months and less than $Et_o(CSIRO)$ during the summer months, hence while *annual differences* between the two datasets may not be great, on a seasonal basis the differences may be far more significant.

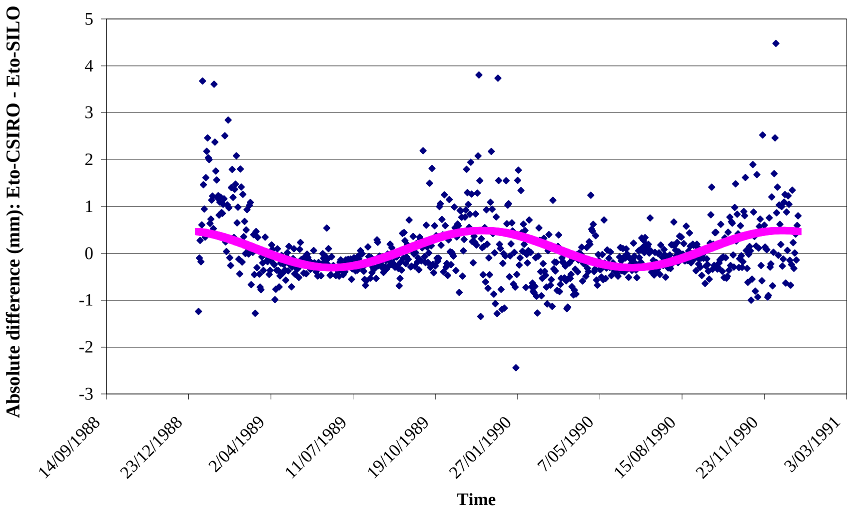


Figure 6: Absolute difference between Et_o calculated using the CSIRO dataset and the SILO2 dataset (Var. B).

In Figures 7 and 8 the vapour pressure variables (e_o, e_a and $e_o - e_a$) and radiation variables (R_s, R_{nl} and R_n) have been plotted for Variation A and lines of best fit shown.

4.3 Conclusions

From the above comparisons of the CSIRO and SILO weather datasets using the Penman–Griffith and FAO methodologies the following conclusions can be drawn. Assuming the calibrated Penman–Griffith equation together with the CSIRO dataset give the more reliable estimate of Et_o:

- Larger values of Et_o calculated using the SILO dataset (greater than 5–6mm for the Penman–Griffith equation and 3–4mm for the FAO equation) are underestimated while smaller values are overestimated.
- Where a default wind run value of 2 ms^{-1} is adopted for the SILO dataset, larger Et_o values are more significantly underestimated.

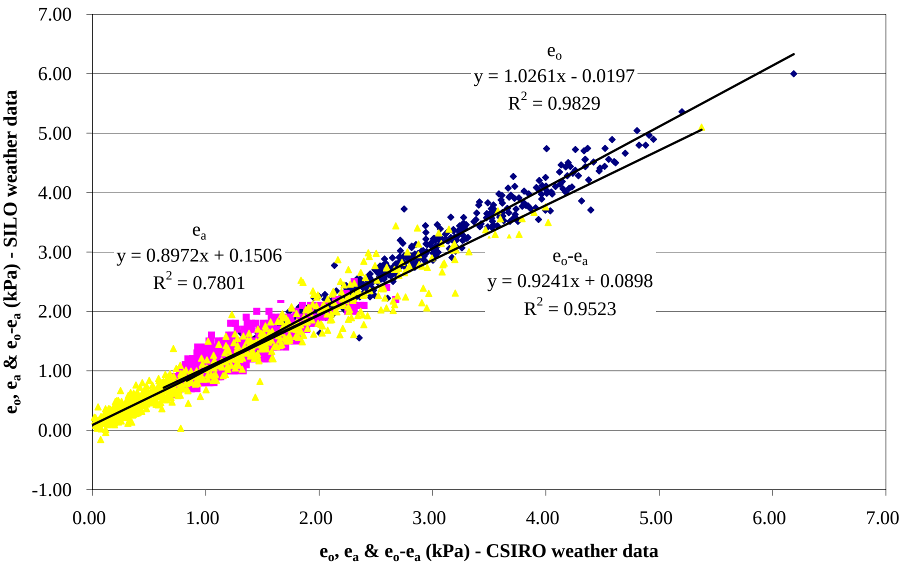


Figure 7: FAO Penman-Monteith equation (Var. A) vapour pressure variables.

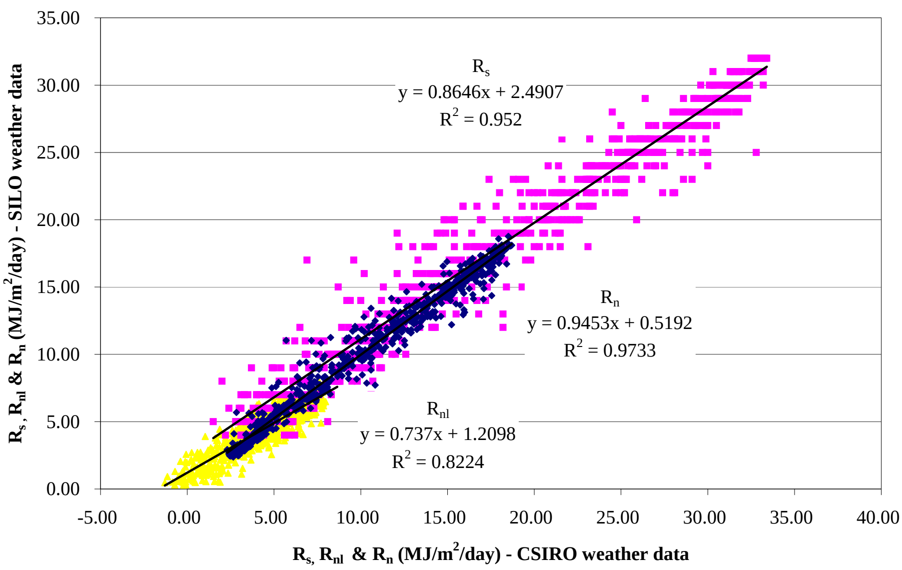


Figure 8: FAO Penman-Monteith equation (Var. A) radiation variables.

- Differences in daily vapour pressure and radiation measurement contribute to the errors in $Et_o(SILO)$. This may be due to the process of interpolation, which is used for the generation of the SILO values, resulting in a smoothing of occasional exceptional daily high or low values and some seasonal variation.

- Underestimation and overestimation of values is cyclic with underestimation occurring in the summer (high radiation; more advective) season and overestimation occurring in the winter (low radiation; less advective) season.

- Where accurate wind values are adopted with the SILO dataset, the annual summation of Et_o is not affected by the less accurate dataset.

5 Comparison of Methods

In the preceding sections the differences in the Et_o values calculated using two different datasets have been compared using two evapotranspiration methods. The first of these methods, the Penman–Griffith formula, has been locally calibrated using experimental data specific to Griffith; hence it can be considered to be the more precise method for the Griffith locality. The second method, the FAO Penman–Monteith, is the standard recommended by the Food and Agriculture Organisation of the United Nations which is presently being used for calculation of the reference evapotranspiration values displayed on the SILO site.

Graphs comparing the two methods are presented in Figures 9 and 10. In both figures Et_o calculated using the FAO method has been plotted against values calculated using the Penman–Griffith method. In Figure 9 the CSIRO dataset has been used for both methods. In Figure 10 the CSIRO dataset has been used with the Penman–Griffith method while the SILO2 datset (SILO values including a default wind speed of 2 ms^{-1}) has been used with the FAO method.

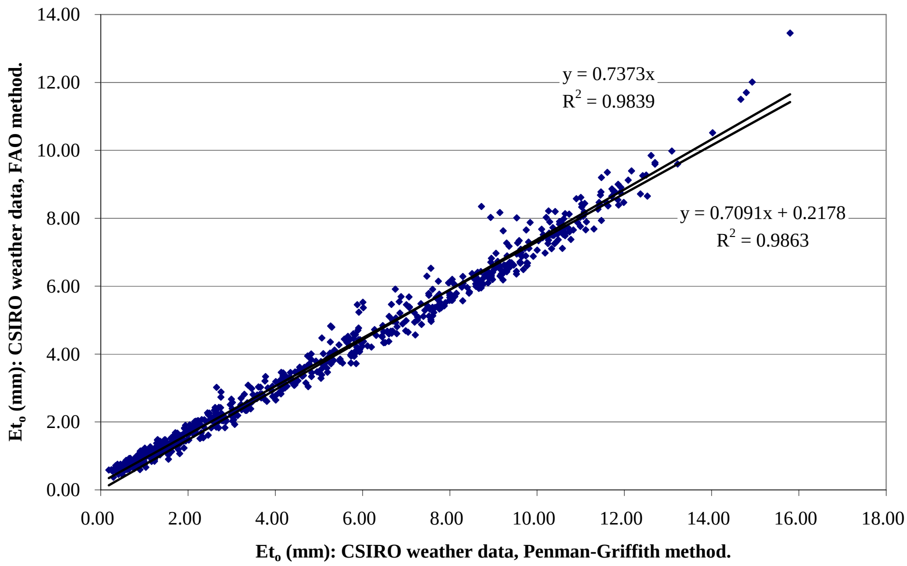


Figure 9: A comparison between the Penman–Griffith and FAO Methods (CSIRO data only). Full regression and regression through the origin shown.

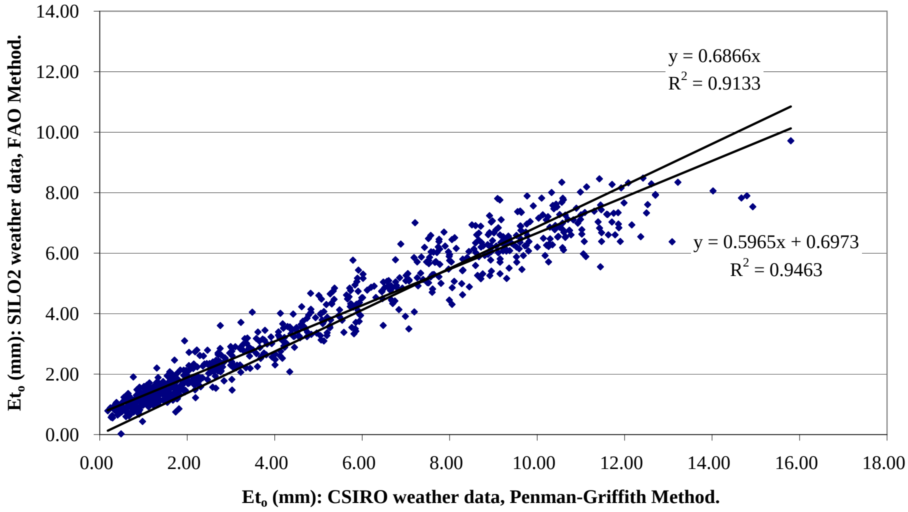


Figure 10: A comparison between the Penman–Griffith (CSIRO data) and FAO (SILO2 data) Methods. Full regression and regression through the origin shown.

In order to confirm these results the procedure discussed in Section 4 was repeated using CSIRO and SILO datasets for a second two year period: 2001–2002. The graphs for this period, Figures 11 and 12, which correspond to those given in Figures 9 and 10, are given below. These graphs verify the results obtained for the period 1989–1990.

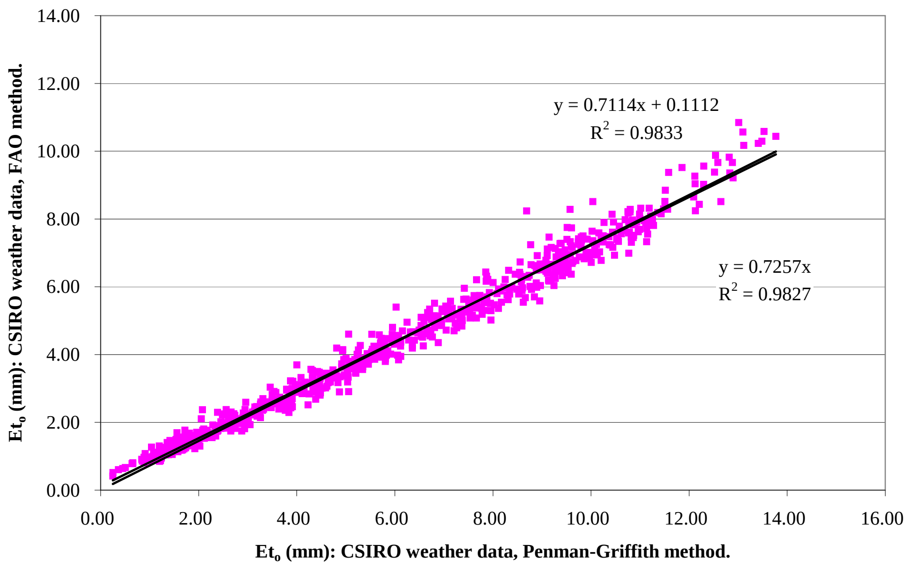


Figure 11: A comparison between the Penman–Griffith and FAO Methods (CSIRO data only) for the period 2001–2002. Full regression and regression through the origin shown.

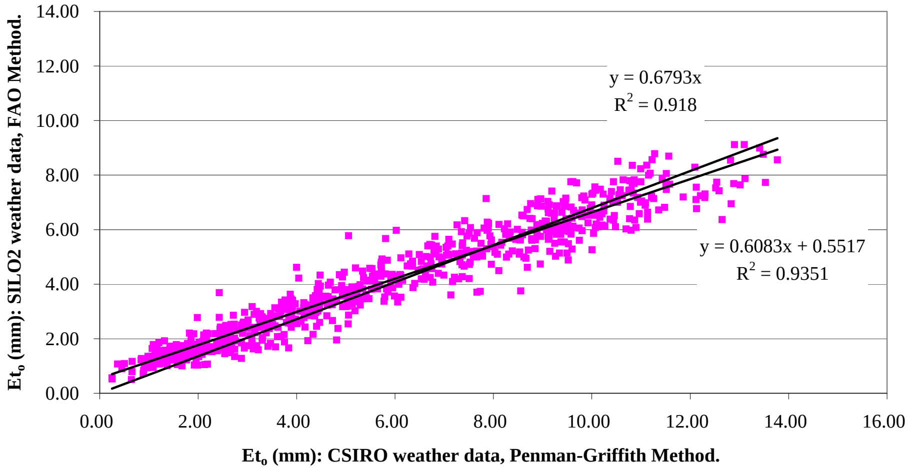


Figure 12: A comparison between the Penman–Griffith (CSIRO data) and FAO (SILO2 data) Methods for the period 2001–2002. Full regression and regression through the origin shown.

A summary of results is given in Table 3.

Table 3: Summary of results.

Equ.	Data	Regression Equation[a]		R^2	Aggregate Et_o (mm/yr)			
		1989-98	2001-02		1989	1990	2001	2002
P–G	CSIRO	—	—		1798	1898	2001	2228
FAO	CSIRO	$y = 0.71x + 0.22$	$y = 0.71x + 0.11$	0.99	1385	1391	1473	1612
FAO	SILO1	$y = 0.66x + 0.49$		0.97	1383	1400	1493	1665
FAO	SILO2	$y = 0.60x + 0.70$	$y = 0.61x + 0.55$	0.95	1315	1399	1430	1546

[a] $y = Et_o$ (FAO) and $x = Et_o$ (P–G)

The results show that where the CSIRO dataset is used in the FAO Et_o calculations, the y-axis intercept for the line of best fit is relatively small. While statistically significant, the measure of improvement on the regression line placed though the origin is very small — less than 0.5%. Hence it can be generalised, that the FAO method consistently under-estimates Et_o in comparison to the Penman–Griffith method by around 26%. Figure 13 shows that this difference peaks at more than 2.5 mm per day in mid-summer. Use of the SILO dataset in the FAO Et_o calculations results in an increase in the y-axis intercept and a decrease in slope. This means that daily Et_o values calculated using the SILO weather data and FAO method will tend to be greater than the daily Et_o values calculated using CSIRO weather data and Penman–Griffith method at lower Et_o and the opposite at high daily Et_o.

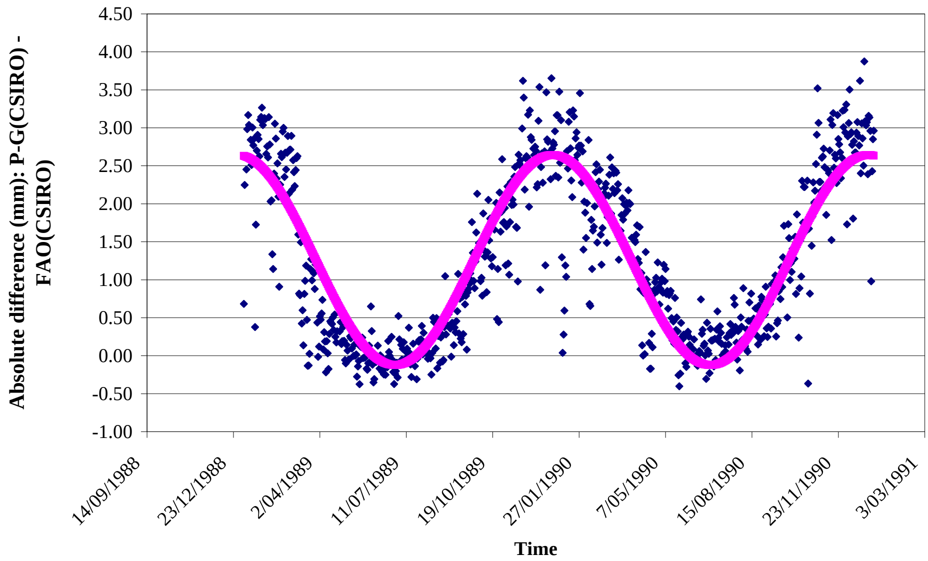


Figure 13: Absolute difference between Et_o calculated using the Penman–Griffith and FAO equations (CSIRO data).

In Figures 9 and 11, where the CSIRO dataset has been used for the FAO Et_o calculations, a relatively tight grouping of points occurs along the line of best fit. More scattering occurs where the SILO dataset is used in the FAO Et_o calculations, indicating an increase in the standard error deviation.

Figure 14 shows the absolute difference between the two methods, where the SILO2 data has been used with the FAO equation. In comparison with Figure 13 it can be seen that the amplitude of the sine curve has increased and the difference between the two methods in mid-summer is more than 3 mm. The standard error at this point is also greater.

This under-estimation of Et_o by the FAO equation is also evident from the annual aggregates given in Table 3. Where CSIRO data or SILO data with CSIRO wind values are used with the FAO equation, the annual summations vary between 23–26%. Where SILO data is used with the 2 ms^{-1} default wind speed with the FAO equation, this difference rises to between 26–31%. On average, use of the default wind speed increases the difference by 4%.

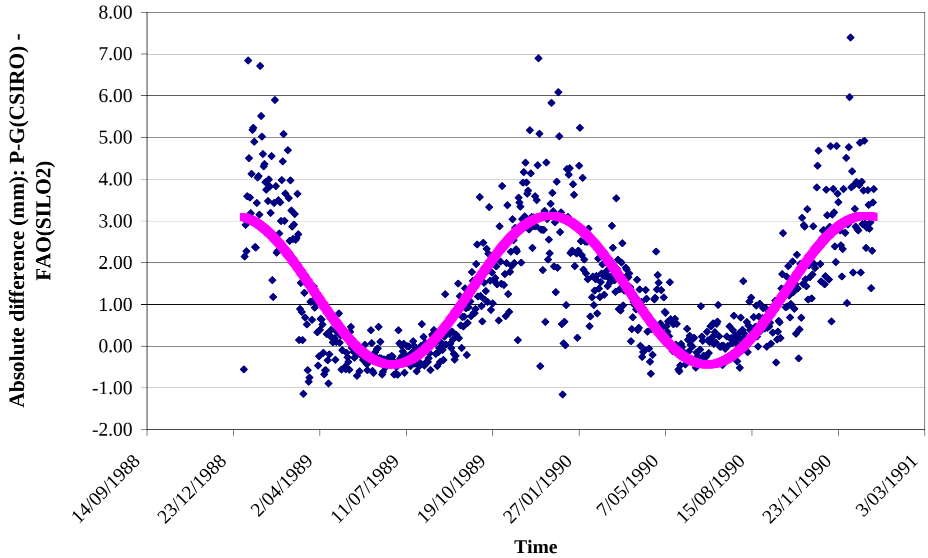


Figure 14: Absolute difference between Et_o calculated using the Penman–Griffith (CSIRO data) and FAO equations (SILO2 data).

6 Discussion and Conclusions

One of the aims of the National Evapotranspiration Project is the development of a standardised method for the computation of reference evapotranspiration (Et_o) using the limited weather data typically available at weather stations across Australia. The analyses described in this report have made an important contribution to this endeavour.

The SILO website provides limited meteorological datasets Australia-wide. These datasets are currently being used with the FAO Penman–Monteith method to calculate local reference evapotranspiration. Calculations use a default wind speed of 2 ms^{-1}.

During the 1980s and 1990s, research was undertaken into evapotranspiration at the CSIRO station at Griffith, NSW. This work involved the collection of highly accurate weather data and led to the calibration of the Penman combination equation (Penman–Griffith) for the Griffith region.

This more precise methodology and dataset — the Penman–Griffith equation and CSIRO weather data — have been compared with the FAO methodology and SILO dataset. This work has shown that both the method and the dataset can contribute to differences in the results.

When comparing the the two datasets, with either the Penman–Griffith or FAO equations, the absolute difference between the results is found to be cyclic with the CSIRO dataset giving a higher value in summer (values greater than 5–6 mm) and the lower value in winter (values less than 5–6 mm). When the annual aggregates are compared, differences are not more than $\pm 2\%$ — even where a default wind speed of 2 ms^{-1} is adopted with the SILO dataset — due to the cancelling effect of the seasonal differences. Hence it can be concluded that any error in Et_o estimation arising from the use of the SILO dataset will depend on the period of interest. While annual estimates are not likely to be impacted, seasonal estimates may.

Results indicate, however, that the methodology is more critical than the dataset. When the two methods are compared using the one, CSIRO, dataset, Et_o values obtained using the FAO method are around 26% less than those obtained using the Penman–Griffith method. Use of the SILO dataset (including the default wind speed value) with the FAO equation, leads to increased differences particularly during the mid-summer period.

These differences are also reflected in the annual aggregates. Where CSIRO data or SILO data with CSIRO wind values are used with the FAO equation, the annual summations vary between 23–28%. Where SILO data is used with the 2 ms^{-1} default wind speed with the FAO equation, this difference rises by approximately 3%. This increase would be greater during the summer season and less during the winter season.

It is acknowledged that the results presented here relate to a single Australian locality — Griffith, NSW. In order to ascertain whether these result are applicable for Australia in general, further research is required. Investigations and results relating to other localities will follow in the Part 2 of this report.

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