

REFERENCE EVAPOTRANSPIRATION
PROGRAM

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REFERENCE EVAPOTRANSPIRATION PROGRAM

The program has been written to calculate daily reference crop (potential) evapotranspiration (ET_o) from data collected by a conventional weather station. Daily means and totals are used to calculate daily evapotranspiration (in mm/d). The results are written to a data file that can be printed, loaded into a spreadsheet or exported as a 'WaSim' climate data file. Additionally a daily summary of the input data can be viewed or saved.

The software may be installed on computers based on a single site within the department or section of a company, institute or organisation purchasing the software. Copies may be made for backup purposes only. It may not be copied for distribution, resale, hire or rental or any purpose other than the legitimate purposes above without the prior approval of Cranfield University.

Whilst every effort has been made to ensure the validity of the algorithms used in the calculation equations, the accuracy of the calculated evapotranspiration depends upon the accuracy of the input data measurement, siting of the weather station and relevance of the chosen evapotranspiration calculation method. Cranfield University takes no responsibility for matters arising from the application of the results of this program.

WaSim ET
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1. INTRODUCTION

1.1 Calculation methods

The program offers the user four alternative methods of evapotranspiration calculation by combination equations from various sources.

1.1.1 Penman-Monteith Method

This is based on the original form of the Penman-Monteith equation (Monteith, 1965 & 1981). The equations used are those recommended by the Food and Agriculture Organisation of the United Nations (FAO) using factors for a grass reference crop (Allen, et al. 1998)¹. The method should be appropriate in all parts of the world.

1.1.2 FAO Modified Penman Method

This uses the method of Doorenbos and Pruitt (1976). The equations used are those presented by Smith (1988) for a grass reference crop. The equation has widely used outside of UK, but has a tendency to overestimate ETo in temperate climates and is not generally recommended for use in the UK.

1.1.3 Penman Method

This uses the version of the Penman equation (Penman, 1948) for grass presented by MAFF (1967). The look-up tables used in that publication are substituted by equations presented by Mason (1978). The method is primarily intended for UK conditions. A spreadsheet version of the equations used can be found in Hess and Stephens (1993).

¹ Defined as ‘the rate of evapotranspiration from a hypothetical crop with an assumed height of 12cm, a fixed canopy resistance of 70 s m⁻¹, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water’.

2. INSTALLATION

The ET program must be installed on the hard disk of your computer.

- Run SETUP.EXE.
- This will create a sub-directory called Wasim\ET on your hard disk with the program file in it.

3. RUNNING THE PROGRAM

The main screen shows four menu options that are used to control the program.

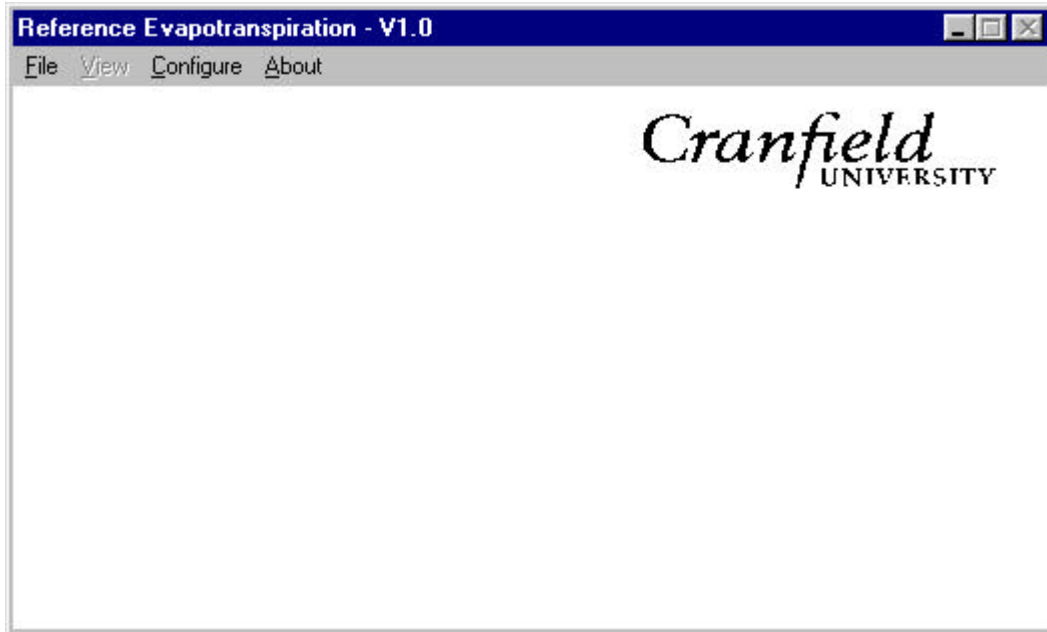


Figure 1 Main screen

Each of the menus can be activated by 'clicking' with the mouse pointer or typing the letter that is highlighted (or underlined) whilst holding down the <Alt> key. Additionally, the main functions also have short-cut keys to allow them to be accessed directly using the <Ctrl> keys.

3.1 Configure

The configuration options allow description of the input data file format and the station parameters. Once set, these are automatically saved in two files called DEFAULT.FMT and STATION.PAR respectively. Files for different weather stations may be loaded (using the File, Open options) and saved with different names (using the File, Save As options), but the one that is to be used must have the above name.

Leaving either configuration screen using File, Exit will cause the currently displayed file to become the default and a copy of the file will be named DEFAULT.FMT or STATION.PAR as appropriate. Leaving by File, Close will not change the default files.

3.1.1 Data File Format

The data file format option allows the user to specify the format of the data file containing the automatic weather station data. The data file should be ASCII (i.e. not binary) and data should be in columns with one row for each day of the data.

- Number of columns Defines the number of columns of data in the data file.
- Separator Defines the way the columns are separated. There are three options;
- Space(multiple spaces are treated as a single separator)
 - Comma
 - Tab

The following check boxes allow specification of what sensors are used, the units in which data are recorded and the column in which the data are stored.

If the date is recorded in the form DD MM YY (i.e. separated by spaces) then you need only specify the column of the day and it is assumed that month and year are in the next two columns.

PARAMETER	UNITS	COLUMN
☒ Date	DD MM YY	1
☐ Time		
☒ Maximum Temperature	°C	4
☒ Minimum Temperature	°C	5
☐ Mean Temperature		
☐ Mean Rel. Humidity		
☒ Dry Bulb Temperature	°C	6
☒ Wet Bulb Temperature	°C	7
☐ Mean Vapour Pressure		
☒ Wind Speed	km	9
☒ Sunshine	hours	9
☐ Solar Radiation		
☐ Net Radiation		
☐ Soil heat flux		
☐ Air Pressure		
☒ Rainfall	mm	10

Figure 2 Data file format configuration

3.1.2 Station Parameters

The screenshot shows a Windows-style application window titled "D:\SILSOFT\ET\SILSOE.PAR". The window contains a "File" menu bar and several input sections. The "Station Name" field contains "Silsoe College". The "Location" section includes a "Latitude (°)" field with "52.1", a direction selector with "North" selected, and an "Altitude (m)" field with "60". The "Angstrom constants" section has fields for "a" (0.25) and "b" (0.50), each with a scroll bar. The "Anemometer" section has a "Height (m)" field with "2.0" and a scroll bar. The "ET Method" section has three radio buttons: "Penman-Monteith" (selected), "FAO Mod Penman", and "Penman".

Figure 3 Station parameter configuration

Before calculations can be made, it is necessary to set a number of station parameters and choose the calculation method to be used. Once set, these are written to a file (STATION.PAR) which is accessed each time you run the program. Therefore, the station parameters need only be written once for each station.

Each item on the form can be accessed using the mouse pointer and left mouse button, or pressing the letter shown by the highlight (or underlined in the Windows version) whilst holding down the Alt key.

3.1.2.1 Station Name

This is not used in calculations but is written to the output file (see below).

3.1.2.2 Latitude & Altitude

The latitude of the station (in degrees and minutes) and altitude (in metres) can be set using the 'scroll bar'. The scroll bar can be set using the mouse or the keyboard (see below).

3.1.2.3 Anemometer

The calculations of evapotranspiration are based on wind speed at 2.0m above ground level. Wind speeds measured at different heights are adjusted to an equivalent wind speed at 2.0, therefore the height of the anemometer (above ground level) should be entered.

3.1.2.4 ET method

Use the option buttons to select the appropriate evapotranspiration calculation method.

3.1.2.5 Angstrom constants

These are the constants used to estimate sunshine hours (if not measured) from solar radiation. The default values are $a = 0.25$ and $b = 0.50$ (Smith, 1990). Locally applicable values may be calibrated based on observations of sunshine duration and measured solar radiation. Doorenbos and Pruitt (1976, Appendix VI) present experimentally determined values of a and b for a range of locations world-wide.

3.2 File

Once the station parameters have been set, you may proceed to calculate evapotranspiration.

Select the data file to be processed by selecting Open from the File menu.

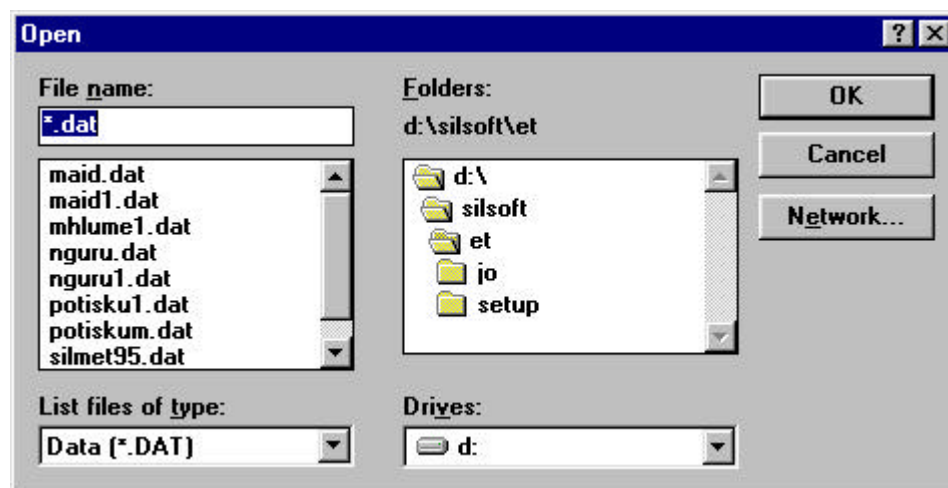


Figure 4 File Open dialog box for single data files

A dialog box will be displayed that allows you to browse directories to locate the required file. By default only files with the extension '.DAT' will be displayed. Other filters may be applied by selecting from the 'List of file type' menu. To display all files type '*.*' in the File Name box (or any other extension filter). As the calculations are being done, the current date and daily evapotranspiration (mm/day) are shown on the form.

When all data have been processed, a results file will be created with the same file name as the input data file but the extension '.ETO'.

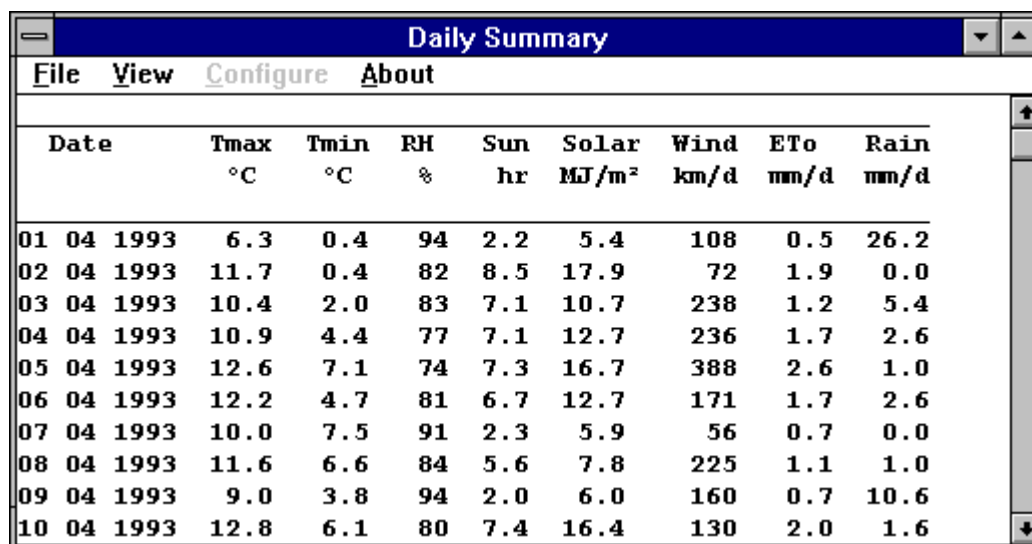
3.2.1 Output

The output file (*.ETO) is an ASCII format file consisting of;

- the station name on the first line, then,
- for each day: day, month, year, rainfall (mm/day), ETo (mm/day)

3.3 View

A summary of the daily weather data can be viewed by selecting from the View menu. The outputs can be saved to a file by selecting Save As from the File menu. Alternatively, a WaSim climate data file (.CLD) can be created by selecting 'Export as Wasim CLD file'. These options will not be available until calculations have been done.



The screenshot shows a window titled "Daily Summary" with a menu bar containing "File", "View", "Configure", and "About". Below the menu bar is a table with 10 columns: "Date", "Tmax", "Tmin", "RH", "Sun", "Solar", "Wind", "ETo", and "Rain". The units for these columns are °C, °C, %, hr, MJ/m², km/d, mm/d, and mm/d respectively. The table displays data for the first 10 days of April 1993. The window has a scrollbar on the right side.

Date	Tmax °C	Tmin °C	RH %	Sun hr	Solar MJ/m²	Wind km/d	ETo mm/d	Rain mm/d
01 04 1993	6.3	0.4	94	2.2	5.4	108	0.5	26.2
02 04 1993	11.7	0.4	82	8.5	17.9	72	1.9	0.0
03 04 1993	10.4	2.0	83	7.1	10.7	238	1.2	5.4
04 04 1993	10.9	4.4	77	7.1	12.7	236	1.7	2.6
05 04 1993	12.6	7.1	74	7.3	16.7	388	2.6	1.0
06 04 1993	12.2	4.7	81	6.7	12.7	171	1.7	2.6
07 04 1993	10.0	7.5	91	2.3	5.9	56	0.7	0.0
08 04 1993	11.6	6.6	84	5.6	7.8	225	1.1	1.0
09 04 1993	9.0	3.8	94	2.0	6.0	160	0.7	10.6
10 04 1993	12.8	6.1	80	7.4	16.4	130	2.0	1.6

Figure 5 Example view of daily summary

Selecting Close from the View menu will clear the display.

4. DAILY CALCULATION METHODS

Evapotranspiration is calculated on a daily basis from;

- maximum air temperature, °C
- minimum air temperature, °C
- mean daily vapour pressure, kPa
- net radiation, MJ m⁻² d⁻¹
- wind run, km d⁻¹

The following input data required by the Penman equation for each time step;

- ☒ Maximum and minimum (or mean) air temperature (required)
- ☒ Mean vapour pressure (calculated from relative humidity or wet & dry² bulb temperatures). If no humidity measurements are available, daily mean vapour pressure is estimated from the saturation vapour pressure at the minimum air temperature.
- ☒ Mean wind speed (required).
- ☒ One of net radiation, solar (global) radiation or sunshine ratio (required).
If net radiation is not available, longwave radiation is estimated from air temperature, sunshine ratio and humidity.
If solar radiation is not available, it is estimated from the sunshine duration, time of year and latitude. If sunshine ratio (actual sunshine / potential sunshine duration) is not available, it is estimated from the solar radiation, time of year and latitude.

The following data are optional and will be used if present, if not they will be estimated;

- ☐ Barometric pressure. If not available, this is estimated from the altitude (m) of the station.
- ☐ Soil heat flux. If soil heat flux is not available, it is estimated as a fraction of net radiation.
- ☐ Rainfall. This is **not** used in the calculation, but if available it is written to the output file for subsequent use.

4.1 Humidity variables

4.1.1 Mean vapour pressure

If vapour pressure for each time step is given, this is averaged and used as input to the evapotranspiration equation.

² If a wet and dry bulb psychrometer is present, the ambient air temperature will be used for the dry bulb temperature.

4.1.2 Relative humidity

If relative humidity for each time step is given, then for each timestep,

$$ed = \frac{RH}{100} \left[\frac{ea_{T_{\max}} + ea_{T_{\min}}}{2} \right] \quad (\text{Allen et al., 1998}) \quad (19)$$

4.1.3 Wet and dry bulb temperature

If wet and dry bulb temperatures for each time step are given, then for each timestep.

$$ed = ea_{T_{\text{wet}}} - g(T_{\text{dry}} - T_{\text{wet}})P \quad (1)$$

4.1.4 Saturation vapour pressure

$$e_a = 0.61078e^{\left(\frac{17.27T}{T+237.3}\right)} \quad (\text{Tetens, 1930}) \quad (2)$$

4.1.5 Mean air pressure

$$P = P_0 \left(\frac{T_{k0} - h(A - A_0)}{T_{k0}} \right)^{\frac{g}{hR}} \quad (\text{Burman et al., 1987}) \quad (3)$$

4.1.6 Wind speed at 2 m

The wind speed measured at height z , m, is converted to an equivalent 2 m wind speed (assuming that wind speed is measured above a reference grass surface) using

4.2 Convert wind speed to 2m equivalent

$$\frac{U_2}{U_z} = \frac{4.87}{\ln(67.8z - 5.42)} \quad (\text{Allen et al. 1989}) \quad (4)$$

Symbol	Description	Unit	Value
γ	psychrometric constant for natural ventilation	kPa °C ⁻¹	0.0008
η	constant lapse rate	K m ⁻¹	0.0065K m ⁻¹
A	altitude	m	
A ₀	altitude at sea level	m	0m
ea _T	saturation vapour pressure at temperature T	kPa	
ed	actual vapour pressure	kPa	
g	gravitational acceleration	m s ⁻²	9.8 m s ⁻²
P	atmospheric pressure	kPa	
P ₀	atmospheric pressure at sea level	kPa	101.3kPa
R	specific gas constant	J kg ⁻¹ K ⁻¹	287 J kg ⁻¹ K ⁻¹
RH	relative humidity	%	
T _{dry}	dry bulb temperature	°C	
T _{k0}	reference temperature at sea level	K	293.16K
T _{wet}	wet bulb temperature	°C	

4.3 Radiation variables

4.3.1 Maximum solar radiation

$$d = 0.4093 \sin\left(\frac{2p}{365} J - 1.405\right) \quad (5)$$

$$w = \arccos(-\tan(L) * \tan(d)) \quad (\text{Duffie \& Beckman, 1980}) \quad (6)$$

$$d_r = 1 + 0.033 \cos\left(\frac{2p}{365} J\right) \quad (\text{Duffie \& Beckman, 1980}) \quad (7)$$

$$R_a = \frac{G_{sc}}{p} d_r [w \sin(L) \sin(d) + \cos(L) \cos(d) \sin(w)] \quad (\text{Duffie \& Beckman, 1980}) \quad (8)$$

4.3.2 Day length

$$N = \frac{24}{p} w \quad (\text{Duffie \& Beckman, 1980}) \quad (9)$$

4.3.3 Incoming solar radiation

If no solar radiation data are available, then

$$R_s = R_a \left(a_s + b_s \frac{p}{N}\right) \quad (10)$$

4.3.4 Actual sunshine duration

If no sunshine data are available, then

$$n = \frac{1}{b_s} \left(\frac{R_s}{R_a} - a_s\right) \quad (11)$$

4.3.5 Soil heat flux

$$G = 0.38(T_i - T_{i-1}) \quad (\text{Wright \& Jensen, 1972}) \quad (12)$$

Symbol	Description	Unit	Value
δ	solar declination	rad	
ω	sunset hour angle	rad	
a_s	Ångström constant	-	
b_s	Ångström constant	-	
G	soil heat flux	$\text{MJ m}^{-2} \text{d}^{-1}$	
G_{sc}	solar constant	$\text{MJ m}^{-2} \text{d}^{-1}$	118.08 $\text{MJ m}^{-2} \text{d}^{-1}$
J	Julian day number (Jan 1 = 1)	-	
L	latitude	rad	
n	daylight hours	h d^{-1}	
N	maximum daylight hours	h d^{-1}	
R_a	extra-terrestrial radiation	$\text{MJ m}^{-2} \text{d}^{-1}$	
R_s	incoming shortwave radiation	$\text{MJ m}^{-2} \text{d}^{-1}$	
T_i	mean air temperature on day I	$^{\circ}\text{C}$	

4.4 Evapotranspiration calculation methods

4.4.1 Penman-Monteith³

4.4.1.1 Net radiation

If net radiation is not measured it is estimated from;

$$R_{ns} = (1 - a) R_s \quad (13)$$

$$f = \left(a_c \frac{b_s}{a_s + b_s} \right) \frac{n}{N} + \left(b_c + \frac{a_s}{a_s + b_s} a_c \right) \quad (14)$$

$$e' = a_l + b_l \sqrt{ed} \quad (15)$$

$$R_{nl} = -fe's \left(\frac{Tk_{\max}^4 + Tk_{\min}^4}{2} \right) \quad (16)$$

$$R_n = R_{ns} + R_{nl} \quad (17)$$

4.4.1.2 Evapotranspiration

$$T = \left(\frac{T_{\max} + T_{\min}}{2} \right) \quad (18)$$

³ Methods are taken from Allen et al. (1998).

$$l = 2.501 - 0.002361T \quad (19)$$

$$ea = \frac{ea_{T_{\max}} + ea_{T_{\min}}}{2} \quad (20)$$

$$\Delta = \frac{4098ea}{(T + 237.3)^2} \quad (21)$$

$$ra = \frac{\ln\left(\frac{Zw-d}{Zom}\right) \times \ln\left(\frac{Zs-d}{Zoh}\right)}{k^2 U_z} \quad (22)$$

$$g = \frac{cpP}{el} \times 10^{-3} \quad (23)$$

$$g^* = g \left(1 + \frac{rc}{ra}\right) \quad (24)$$

$$T_{kv} = T_k \left(1 - 0.378 \frac{ed}{P}\right)^{-1} \quad (25)$$

$$r = \frac{P}{T_{kv} \frac{R}{1000}} \quad (26)$$

$$ET_{aero} = \frac{86.4}{l} \frac{1}{\Delta + g^*} \frac{rcp}{ra} (ea - ed) \quad (27)$$

$$ET_{rad} = \frac{\Delta}{\Delta + g^*} \frac{(R_n - G)}{l} \quad (28)$$

$$ET_o = ET_{rad} + ET_{aero} \quad (29)$$

Symbol	Description	Unit	Value
λ	latent heat of vapourisation	MJ kg ⁻¹	
Δ	slope of vapour pressure curve	kPa °C ⁻¹	
γ	psychrometric constant	kPa °C ⁻¹	
ρ	atmospheric density	kg m ⁻³	
α	albedo	-	0.23 for grass
κ	von Karman constant	-	0.41
ε	ratio of molecular weight of water to dry air	-	0.622
σ	Stefan Boltzman constant	MJ m ⁻² K ⁻⁴ d ⁻¹	4.903 x 10 ⁻⁹ MJ m ⁻² K ⁻⁴ d ⁻¹
ε'	net emissivity	-	

γ^*	modified psychrometric constant	kPa °C ⁻¹	
a_c	empirical constant	-	1.35
a_l	empirical constant	-	0.34
a_s	Ångström constant	-	
b_c	empirical constant	-	-0.35
b_l	empirical constant	-	-0.14
b_s	Ångström constant	-	
cp	specific heat of moist air	kJ kg ⁻¹ °C ⁻¹	1.013 kJ kg ⁻¹ °C ⁻¹
d	zero plane displacement of wind profile	m	0.08m for grass
ea	mean saturation vapour pressure	kPa	
ed	actual vapour pressure	kPa	
ETaero	aerodynamic term	mm d ⁻¹	
ETo	reference crop evapotranspiration	mm d ⁻¹	
ETrad	radiation term	mm d ⁻¹	
f	cloudiness factor	-	
G	Soil heat flux	MJ m ⁻² d ⁻¹	
n	bright sunshine hours	h d ⁻¹	
P	atmospheric pressure	kPa	
R	specific gas constant	J kg ⁻¹ K ⁻¹	287 J kg ⁻¹ K ⁻¹
ra	aerodynamic resistance	s m ⁻¹	
rc	bulk surface resistance	s m ⁻¹	70 s m ⁻¹ for reference grass
R_n	net radiation	MJ m ⁻² d ⁻¹	
R_n	net radiation	MJ m ⁻² d ⁻¹	
R_{nl}	net longwave radiation	MJ m ⁻² d ⁻¹	
R_{ns}	net shortwave radiation	MJ m ⁻² d ⁻¹	
R_s	incoming solar radiation	MJ m ⁻² d ⁻¹	
T_i	mean air temperature for day i	°C	
T_k	mean air temperature	K	
T_{kv}	virtual temperature	K	
T_{max}	maximum air temperature	°C	
T_{min}	minimum air temperature	°C	
Uz	windspeed at height z	m s ⁻¹	
Zoh	roughness parameter for heat and water vapour	m	0.0015m for grass
Zom	roughness parameter for momentum	m	0.01476m for grass
Zs	screen height	m	1.2m
Zw	height of windspeed measurement	m	2m

4.4.2 Penman (1967)⁴

4.4.2.1 Net radiation

$$l = 4.1868(597.31 - 0.565T) \quad (\text{Mason, 1978}) \quad (30)$$

$$R_{ns} = (1 - a) \frac{100R_s}{10l} \quad (31)$$

$$f(T) = s T_k^4 \quad (32)$$

$$f(ed) = 0.47 - 0.075\sqrt{0.75(10ed)} \quad (33)$$

$$f(n) = 0.17 + 0.83\frac{n}{N} \quad (34)$$

$$R_{nl} = f(T) \cdot f(ed) \cdot f(n) \quad (35)$$

$$R_n = R_{ns} - R_{nl} \quad (36)$$

4.4.2.2 Evapotranspiration

$$T = \left(\frac{T_{\max} + T_{\min}}{2} \right) \quad (37)$$

$$f(U) = 0.26252156 \left(1 + 0.01 \frac{U}{1.609334} \right) \quad (\text{Mason, 1978}) \quad (38)$$

$$Ea = f(U)10(ea - ed) \quad (39)$$

$$\Delta = \frac{10ea}{T_k} \left(\frac{6970}{T_k} - 5.028 \right) \quad (40)$$

$$g = \frac{2.4P}{0.62196l} \quad (\text{Mason, 1978}) \quad (41)$$

$$ET_o = \frac{Rn \frac{\Delta}{g} + Ea}{\frac{\Delta}{g} + 1} \quad (42)$$

⁴ Methods are based on Hess and Stephens, 1993.

Symbol	Description	Unit	Value
λ	latent heat of vapourisation	J g^{-1}	
α	albedo	-	0.25 for grass
σ	Stefan Boltzman constant	$\text{mm K}^{-4} \text{d}^{-1}$	$1.9885 \times 10^{-9} \text{mm K}^{-4} \text{d}^{-1}$
Δ	slope of vapour pressure curve	$\text{mb } ^\circ\text{C}^{-1}$	
γ	psychrometric constant	$\text{mb } ^\circ\text{C}^{-1}$	
λ	latent heat of vapourisation	J g^{-1}	
ea	mean saturation vapour pressure	kPa	
ed	actual vapour pressure	kPa	
Ea	aerodynamic term	mm d^{-1}	
ETo	reference crop evapotranspiration	mm d^{-1}	
f(ed)	humidity factor	-	
f(n)	cloudiness factor	-	
f(T)	temperature term	mm d^{-1}	
f(U)	wind function	$\text{mm mb}^{-1} \text{d}^{-1}$	
n	bright sunshine hours	h d^{-1}	
N	maximum daylight hours	h d^{-1}	
P	atmospheric pressure	kPa	
R_n	net radiation	mm d^{-1}	
R_{ns}	net shortwave radiation	mm d^{-1}	
R_s	incoming solar radiation	$\text{MJ m}^{-2} \text{d}^{-1}$	
T	mean air temperature	$^\circ\text{C}$	
T_k	mean air temperature	K	
$T_{\max}$	maximum air temperature	$^\circ\text{C}$	
$T_{\min}$	minimum air temperature	$^\circ\text{C}$	
U	wind speed	km d^{-1}	

4.4.3 FAO Modified Penman⁵

4.4.3.1 Net radiation

$$R_{ns} = (1 - a) \frac{R_s}{2.45} \quad (43)$$

$$R_{nl} = s T_k^4 (7.723 - \sqrt{10ed}) (0.1 + 0.9 \frac{n}{N}) \quad (44)$$

$$R_n = R_{ns} - R_{nl} \quad (45)$$

4.4.3.2 Evapotranspiration

$$f(U) = 0.27 \left(1 + \frac{U}{100} \right) \quad (46)$$

$$g = 0.006595P \quad (47)$$

$$\Delta = \frac{10ea}{T_k} \frac{6790}{T_k - 5.028} \quad (48)$$

$$W = \frac{\Delta}{\Delta + g} \quad (49)$$

$$U_d = \frac{U}{1 + \frac{1}{43.2}} \quad (50)$$

$$RH_{\max} = \left(\frac{ed}{ea_{T_{\min}}} \right) \times 100\% \quad (51)$$

$$c = a_0 + a_1 RH_{\max} + a_2 R_s + a_3 U_d + a_4 k + a_5 U_d k + a_6 RH_{\max} R_s U_d + a_7 RH_{\max} R_s k \quad (52)$$

(Frevert *et al.*, 1983)

$$ET_o = c [WR_n + (1 - W) f(U) 10(ea - ed)] \quad (53)$$

⁵ Methods are based on Smith (1988).

Symbol	Description	Unit	Value
α	albedo	-	0.25 for grass
σ	Stefan Boltzman constant	mm K ⁻⁴ d ⁻¹	8.727 x 10 ⁻¹² mm K ⁻⁴ d ⁻¹
Δ	slope of vapour pressure curve	mb °C ⁻¹	
γ	psychrometric constant	mb °C ⁻¹	
a_0	constant in estimation of c	-	0.6817
a_1	constant in estimation of c	-	0.0027864
a_2	constant in estimation of c	-	0.0181768
a_3	constant in estimation of c	-	-0.0682501
a_4	constant in estimation of c	-	0.0126514
a_5	constant in estimation of c	-	0.0097297
a_6	constant in estimation of c	-	0.43025 E ⁻⁴
a_7	constant in estimation of c	-	-0.92118 E ⁻⁷
ea	mean saturation vapour pressure	kPa	
ed	actual vapour pressure	kPa	
ET _o	reference crop evapotranspiration	mm d ⁻¹	
f(U)	wind function	mm mb ⁻¹	
k	day - night wind ratio	-	
n	bright sunshine hours	h d ⁻¹	
N	maximum daylight hours	h d ⁻¹	
P	atmospheric pressure	kPa	
RH _{max}	maximum relative humidity	%	
R _n	net radiation	mm d ⁻¹	
R _{nl}	net longwave radiation	mm d ⁻¹	
R _{ns}	net shortwave radiation	mm d ⁻¹	
R _s	incoming solar radiation	MJ m ⁻² d ⁻¹	
T _k	mean air temperature	K	
U	wind speed	m s ⁻¹	
U _d	daytime wind speed	km d ⁻¹	
W	weighting factor	-	

4.4.4 Penman open water

4.4.4.1 Net radiation

Net radiation, R_n , is calculated as in section 4.4.1.1 above except that an albedo, a , of 0.05 is used for open water.

4.4.4.2 Evaporation

$$Ea = 0.35 \left(0.5 + \frac{0.621375 U}{100} \right) 7.500638 (ea - ed) \quad (\text{Penman, 1963}) \quad (54)$$

$$Eo = \frac{R_n / l \frac{\Delta}{g} + Ea}{\frac{\Delta}{g} + 1} \quad (55)$$

λ , Δ and γ are calculated as in section 4.4.1.2 above.

Symbol	Description	Unit	Value
λ	latent heat of vapourisation	MJ kg ⁻¹	
Δ	slope of vapour pressure curve	kPa °C ⁻¹	
γ	psychrometric constant	kPa °C ⁻¹	
α	albedo	-	0.05 for open water
ea	mean saturation vapour pressure	kPa	
ed	actual vapour pressure	kPa	
Ea	aerodynamic term	mm d ⁻¹	
Eo	open water evaporation	mm d ⁻¹	
R_n	net radiation	MJ m ⁻² d ⁻¹	

5. USING VISUAL BASIC CONTROLS

5.1 Command Buttons

Command buttons can be activated by either;

- moving the mouse pointer to the button and 'clicking' the left mouse button, or,
- pressing the letter shown by the highlight (or underlined in the Windows version) whilst holding down the Alt key.

5.2 Scroll Bars

Effect	Mouse action	Keyboard action
Small change	Click on left (decrease) or right (increase) arrows.	Use left (decrease) or right (increase) cursor keys.
Large change	Click between 'slider' and the end of the scroll bar.	Use Page Up (decrease) or Page Down (increase) cursor keys.
Variable change	Drag the slider to any position on the scroll bar.	

5.3 Option Buttons

Option buttons are used to select from mutually exclusive options. The option may be selected by clicking on the option with the mouse or pressing the letter shown by the highlight (or underlined in the Windows version) whilst holding down the Alt key. Selecting one option will automatically de-select the others.

6. REFERENCES

- Allen, R. G., Jensen, M. E., Wright, J. L. and Burman, R. D., (1989) Operational estimates of evapotranspiration. *Agronomy Journal* 81:650-662.
- Allen, R. G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome. 300pp.
- Doorenbos, J. and Pruitt, W. O. (1976) *Guidelines for predicting crop water requirements*. FAO Irrigation and Drainage Paper 24, 2nd ed. Rome. 156pp.
- Duffie, J. A. and Beckman, W. A. (1980) *Solar engineering of thermal processes*. John Wiley & Sons, New York. pp1-109.
- Frevert, D. K., Hill, R. W. and Braaten, B. C. (1983) Estimation of FAO evapotranspiration coefficients. *J. of Irrig. and Drainage Eng.* 109:265-270
- Hess, T. M. and William Stephens (1993) The Penman equation. In *Spreadsheets in Agriculture*, Eds. D. H. Noble and C. P. Course. Longman Scientific and Technical, pp184-194.
- Martínez-Lozano J. A., Tena, F., Onrubia, J. E. and De La Rubia, J., (1984) The historical evolution of the Ångström formula and its modifications: review and bibliography. *Agricultural and Forest Meteorology*, 33:109-128.
- Mason, D. J. (1978) *Input parameters for combination equation*. MSc thesis, Silsoe College, Silsoe, Bedford. Unpubl.
- Monteith, J. L. (1965) *Evaporation and the environment*. In: The state and movement of water in living organisms. XIXth Symposium. Soc for xp. Biol., Swansea. Cambridge University Press. pp. 205-234.
- Monteith, J. L. (1981) Evaporation and temperature. *Q. J. Royal Meteo. Soc.* 107:1-27.
- Penman, H. L. (1948) Natural evaporation from open water, bare soil and grass. *Proc. Royal Soc., London, Series (A)* 193:120-145.
- Penman, H. L. (1963) Vegetation and hydrology. Tech. Comm. no. 53. CAB, Farnham, England. pp124
- Smith, M. (1988) *Calculation procedures of modified Penman equation for computers and calculators*. FAO, Land and Water Development Division, Rome.
- Smith, M. (1991) *Expert consultation on revision of FAO methodologies for crop water requirements*. FAO, Land and Water Development Division, Rome.
- Thompson, N., Barrie, I. A. and Ayles, M. (1981). The meteorological office rainfall and evaporation calculation system: (MORECS). Hydrological Memorandum No. 45. The Met Office. Bracknell, UK.
- Tetens, O. (1930) Über einige meteorologische Begriffe. *Z. Geophys.* 6:297-309
- Wright, J. L. and Jensen M. E. (1972) Peak water requirements of crops in Southern Idaho. *J. Irrig. and Drain. Div., ASCE.* 96(IR1):193-201.

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