APPENDIX V

CALCULATION OF REFERENCE EVAPOTRANSPIRATION ACCORDING TO PENMAN-MONTEITH COMBINATION EQUATION

The calculation of reference evapotranspiration (ET_o), i.e., the rate of evapotranspiration from a hypothetic reference crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70ms^{-1} and an albedo of 0.23 (closely resembling the evapotranspiration from an extensive surface of green grass), is done according to the Penman-Monteith equation (Monteith, 1965, 1981; FAO, 1992b). The calculation procedure uses a standardized set of input parameters, as follows:

$T_{\max}$ ... maximum daily temperature (ºC)
$T_{\min}$ ... minimum daily temperature (ºC)
RH ... mean daily relative humidity (%)
U2 ... wind speed measurement (ms^{-1})
SD ... bright sunshine hours per day (hours)
A ... elevation (m)
L ... latitude (deg)
J ... Julian date, i.e., number of day in year

The *Penman-Monteith combination equation* can be written in terms of an aerodynamic and a radiation term (FAO, 1992b):

$$ET_o = ET_{ar} + ET_{ra} \qquad (1)$$

where the *aerodynamic term* can be approximated by

$$ET_{ar} = \frac{g}{J + g^*} \cdot \frac{900}{T_a + 273} \cdot U2 \cdot (e_a - e_d) \qquad (2)$$

and the *radiation term* by

$$ET_{ra} = \frac{J}{J + g^*} \cdot (R_n - G) \cdot \frac{1}{l} \qquad (3)$$

where variables in (2) and (3) are as follows:

g ... psychrometric constant (kPa ºC^{-1})
g^* .. modified psychrometric constant (kPa ºC^{-1})
J ... slope of vapor pressure curve (kPa ºC^{-1})
T_a ... average daily temperature (ºC)
e_a ... saturation vapor pressure (kPa)
e_d ... vapor pressure at dew point (kPa)
$(e_a - e_d)$ vapor pressure deficit (kPa)
U2 ... wind speed measurement (ms^{-1})
R_n ... net radiation flux at surface (MJ m^{-2} d^{-1})
G ... soil heat flux (MJ m^{-2} d^{-1})
l ... latent heat of vaporization (MJ kg^{-1})

In the calculation procedure for the reference crop we use the following relationships to define terms in (2):

Average daily temperature:

$$T_a = 0.5(T_{\max} + T_{\min}) \tag{4}$$

Latent heat of vaporization:

$$l = 2.501 - 0.002361\,T_a \tag{5}$$

Atmospheric pressure (kPa) at elevation A:

$$P = 101.3\left(\frac{293 - 0.0065\,A}{293}\right)^{5.256} \tag{6}$$

Psychrometric constant:

$$g = 0.0016286 \cdot \frac{P}{l} \tag{7}$$

Aerodynamic resistance:

$$r_a = \frac{208}{U2} \tag{8}$$

Crop canopy resistance:

$$r_c = \frac{R_l}{0.5\,LAI} \tag{9}$$

where under ambient CO_2 concentrations the average daily stomata resistance of a single leaf, R_l (sm^{-1}), is set to R_l = 100, and leaf area index of the reference crop is assumed as $LAI = 24 \cdot 0.12 = 2.88$.

Modified psychrometric constant:

$$g^* = g\left(1 + \frac{r_c}{r_a}\right) \tag{10}$$

Saturation vapor pressure e_a for given temperatures $T_{\min}$ and $T_{\max}$

$$e_{ax} = 0.6108\exp\left(\frac{17.27\,T_{\max}}{237.3 + T_{\max}}\right) \tag{11}$$

$$e_{an} = 0.6108\exp\left(\frac{17.27\,T_{\min}}{237.3 + T_{\min}}\right) \tag{12}$$

$$e_a = 0.5(e_{ax} + e_{an}) \tag{13}$$

Vapor pressure at dew point, e_d:

$$e_d = \frac{RH}{100} \cdot \frac{0.5}{\left(\frac{1}{e_{ax}} + \frac{1}{e_{an}}\right)} \tag{14}$$

Slope of vapor pressure curve, J, for given temperatures $T_{\max}$ and $T_{\min}$:

$$J_x = \frac{4096\, e_{ax}}{(237.3 + T_{\max})^2} \tag{15}$$

$$J_n = \frac{4096\, e_{an}}{(237.3 + T_{\min})^2} \tag{16}$$

$$J = \left(J_x + J_n\right) \tag{17}$$

Using (4)-(17) all variables in (2) can be calculated from the input parameters of the ET_o computer subroutine. To determine the remaining variables R_n and G used in the radiation term ET_{ra} of equation (3), we proceed with the following calculation steps:

Latitude expressed in rad:

$$j = \frac{Lp}{180} \tag{18}$$

Solar declination (rad):

$$d = 0.4093 \cdot \sin\left(\frac{2p}{365} J - 1.405\right) \tag{19}$$

Relative distance Earth to Sun:

$$d = 1 + 0.033 \cos\left(\frac{2p}{365} J\right) \tag{20}$$

Sunset hour angle (rad):

$$y = arc\cos\,(-\tan j \ \tan d) \tag{21}$$

Extraterrestrial radiation (MJ m^{-2} d^{-1}):

$$R_a = 37.586\, d\,(y \sin j \sin d + \cos j \cos d \sin y) \tag{22}$$

Maximum daylight hours:

$$DL = \frac{24}{p}\, y \tag{23}$$

Short-wave radiation R_s (MJ m^{-2} d^{-1})

$$R_s = \left(0.25 + 0.5 \frac{SD}{DL}\right) R_a \tag{24}$$

For a reference crop with an assumed albedo coefficient $a = 0.23$ *net incoming short-wave radiation* R_{ns} (MJ m^{-2} d^{-1}) is:

$$R_{ns} = 0.77\ R_s \tag{25}$$

Net outgoing long-wave radiation R_{nl} (MJ m^{-2} d^{-1}) is estimated using:

$$R_{nl} = 4.903 \cdot 10^{-9} \left(0.1 + 0.9 \frac{SD}{DL}\right)\left(0.34 - 0.139\sqrt{e_d}\right) \frac{\left(273.16 + T_{\max}\right)^4 + \left(273.16 + T_{\min}\right)^4}{2} \tag{26}$$

Using (25) and (26), *net radiation flux* at surface, R_n, becomes

$$R_n = R_{ns} - R_{nl} \tag{27}$$

Finally, *soil heat flux* is approximated using

$$G = 0.14\,(T_{a,n} - T_{a,n-1}) \tag{28}$$

where $T_{a,n}$ and $T_{a,n-1}$ are average monthly temperatures of current and previous month, respectively. With equations (5), (10), (17), (27) and (28) all variables in (3) are defined and can be calculated from the input parameters described at the beginning of this Appendix.