สูตรและสมการประกอบของ Penman Monteith

Penman-Monteith Equation and components

[ ] Recommended combination formula is :

$$ETo = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$

where :

ETo	:	reference crop evapotranspiration [mm d^{-1}]
R_n	:	net radiation at crop surface [MJ m^{-2} d^{-1}]
G	:	soil heat flux [MJ m^{-2} d^{-1}]
T	:	average temperature [°C]
Δ	:	slope vapour pressure curve [kPa $°C^{-1}$]
γ	:	psychrometric constant [kPa $°C^{-1}$]
U_2	:	windspeed measured at 2m height [m s^{-1}]
e_s	:	saturation vapour pressure [kPa]
e_a	:	actual vapour pressure [kPa]
(e_s-e_a)	:	saturation vapour pressure deficit [kPa]
900	:	conversion factor

When no measured radiation data are available, the net radiation can be estimated as follows:

$$R_n = R_{ns} - R_{nl}$$

$$R_{ns} = 0.77\left(0.25 + 0.50\frac{n}{N}\right)R_a$$

$$R_{nl} = 2.45x10^{-9}\left(0.9\frac{n}{N} + 0.1\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left(T_{kx}^4 + T_{kn}^4\right)$$

$$G = 0.14\left(T_{month\ n} - T_{month\ n-1}\right) \approx 0$$

where :

R_n	:	net radiation [MJ m^{-2} d^{-1}]
R_{ns}	:	net shortwave radiation [MJ m^{-2} d^{-1}]
R_{nl}	:	net longwave radiation [MJ m^{-2} d^{-1}]
R_a	:	extraterrestrial radiation [MJ m^{-2} d^{-1}]
n/N	:	relative sunshine fraction
T_{kx}	:	maximum temperature [K]
T_{kn}	:	minimum temperature [K]
e_a	:	actual vapour pressure [kPa]
G	:	soil heat flux [MJ m^{-2} d^{-1}]

Parameter Used in Equations :-

[ ] Latent Heat of Vaporization (λ)

$$\lambda = 2.501 - \left(2.361x10^{-3}\right)T$$

where : λ = latent heat of vaporization [MJ kg^{-1}]
T = air temperature [°C]

[ ] Slope Vapour Pressure Curve (Δ)

$$\Delta = \frac{4098e_s}{(T+237.3)^2}$$

where : Δ = slope vapour pressure curve [kPa $°C^{-1}$]
T = air temperature [°C]
e_s = saturation vapour pressure at temperature T [kPa]

[ ] Psychometric Constant (γ)

$$\gamma = 0.00163\frac{P}{\lambda}$$

where : γ = psychrometric constant [kPa $°C^{-1}$]
P = Atmospheric pressure [kPa]
λ = latent heat of vaporization [MJ kg^{-1}]

[ ] Atmospheric Pressure (P)

$$P = P_o\left(\frac{T_{ko} - \alpha\left(z - z_o\right)}{T_{ko}}\right)^{\frac{g}{\alpha R}}$$

where: P = atmospheric pressure at elevation z [kPa]
P_o = atmospheric pressure at sea level [kPa]
Z = elevation [m]
Z_o = elevation at reference level [m]
g = gravitational acceleration = 9.8 [m s^{-2}]
R = specific gas constant = 287 [J kg^{-1} K^{-1}]
T_{ko} = reference temperature [K] at elev. $Z_o \approx 273+T$ [°C]
α = conatant lapse rate saturated air = 0.0065 [K m^{-1}]

Recommended :

P_o = 101.3 [kPa] at Z_o = 0 m.
T_{ko} = (Tmean + 273) [K] when T in °C

$$P = 101.3\left(\frac{(T_{mean}+273)-0.0065Z}{T_{mean}+273}\right)^{5.26}$$

[ ] Saturation Vapour Pressure at the Air Temperature (e°(T))

$$e^{\circ}(T) = 0.6108 \quad \exp\left[\frac{17.27\ T}{T + 237.3}\right]$$

where :

e°(T)	=	saturation vapour pressure at the air temperature T [kPa]
T	=	air temperature [°C]
exp[..]	=	2.7183 (base of natural logarithm) raised to the power [..]

[ ] Saturation Vapour Pressure (e_s)

$$e_s = \frac{e^{\circ}(T_{\max}) + e^{\circ}(T_{\min})}{2}$$

where :

e°(T)	=	saturation vapour pressure at the air temperature T [kPa]
T_{max}, T_{min}	=	air temperature [°C]

[ ] Actual vapour pressure (e_a) derived from relative humidity data

For RH_{max} and RH_{min} :

$$e_a = \frac{e^{\circ}(T_{\min})\frac{RH_{\max}}{100} + e^{\circ}(T_{\max})\frac{RH_{\min}}{100}}{2}$$

For RH_{mean} :

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^{\circ}(T_{\max}) + e^{\circ}(T_{\min})}{2}\right]$$

where :

e_a = actual vapour pressure [kPa]
$e°(T_{min})$ = saturation vapour pressure at daily minimum temperature [kPa]
$e°(T_{max})$ = saturation vapour pressure at daily maximum temperature [kPa]
RH_{max} = maximum relative humidity [%]
RH_{min} = minimum relative humidity [%]

[ ] Vapour Pressure Deficit (VPD)

$$VPD = e_s - e_a$$

where :

VPD = vapour pressure deficit [kPa]

[ ] Soil Heat Flux (G)

$$G = 0.14 \left(T_{month\ n} - T_{month\ n-1} \right) \approx 0$$

where :

$T_{month\ n}$ = temperature [°C] on month n
$T_{month\ n-1}$ = temperature [°C] in preceding on month n-1

[ ] Extraterrestrial Radiation (R_a)

$$R_a = 37.6\, d_r \left(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s \right)$$

where :

R_a = extraterrestrial radiation [MJ m^{-2} d^{-1}]
d_r = relative distance Earth – Sun
δ = solar declination [rad]
φ = latitude [rad]
ω_s = sunset hour angle [rad]

$$d_r = 1 + 0.033 \cos (0.0172\, J)$$
$$\delta = 0.409 \sin (0.0172\, J - 1.39)$$
$$J = \text{integer} (30.42\, M - 15.23)$$

where : J = number of the day in the year
M = month number (1 – 12)

[ ] Daylight Hours (N)

$$N = 7.64\, \omega_S$$

where : N = maximum day light hours [h]

[ ] Windspeed (U_2)

$$U_2 = U_Z \frac{4.87}{\ln(67.8z - 5.42)}$$

where :

U_z = windspeed measurement at height z [m s^{-1}]
U_2 = windspeed at 2 m height [m s^{-1}]
z = height of wind vane or height of windspeed measurements [m]

[ ] Day Wind (U_{day})

$$U_{day} = \frac{2\,U\left(U_{day}/U_{night}\right)}{\left(1 + U_{day}/U_{night}\right)}$$

where :

U_{day} = windspeed during day time (07.00 – 19.00 hrs) [m s^{-1}]
U_{night} = windspeed during night time (19.00 – 07.00 hrs) [m s^{-1}]
U = average windspeed over 24 hours [m s^{-1}]

For average conditions :

$$U_{day} / U_{night} \approx 2$$

$$U_{day} = 1.33U$$

$$U_{2\,day} = 1.33\,U_2$$

[ ] Conversions : Cloundiness --→ n/N ratio

cloundiness oktas	0	1	2	3	4	5	6	7	8
n/N ratio	.95	.85	.75	.65	.55	.45	.30	.15	-

cloundiness tenths	0	1	2	3	4	5	6	7	8	9	10
n/N ratio	.95	.85	.80	.75	.65	.55	.50	.40	.30	.15	-

[ ] Conversions SI – C.G.S. system

Pressure :	1 mbar	=	0.1 kPa (kiloPascal)
Radiation :	1 cal cm^{-2} d^{-}	=	0.041868 MJ m^{-2} d^{-1}
	1 MJ m^{-2} d^{-1}	=	23.884 cal cm^{-2} d^{-1}
		=	0.408 mm d^{-1}
	1 mm d^{-1}	=	2.45 MJ m^{-2} d^{-1}
		=	58.6 cal cm^{-2} d^{-1}
	1 W m^{-1}	=	0.0864 MJ m^{-2} d^{-1}
		=	2.064 cal cm^{-2} d^{-1}
Velocity :	1 knot	=	0.515 m s^{-1}
		=	1.85 km hr^{-1}
		=	44.5 km d^{-1}
Degree :	1 Radian	=	π /180 Decimaldegrees