# Hydrology
# Evaporation

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FACH HOCHSCHULE LÜBECK

# Content

# Todo

- Jensen-Haise
- DVWK
- Turc
- Thorntwaite
- Leaf resistance concept
- Reduction by soil moisture
- Thorntwaite soil water balance
- Crop coefficient
- Modified Penman-Monteith
- Eddy-Correlation Method
- Lysimeters

# Objectives

To learn about ...

- types of evaporation
- estimation of evaporation
- measurement of evaporation

Basics to understand evaporation

- Physical background
- Hydrological Relevance
- Application

# Evaporation
## Relevance

Evaporation is a major component of the water balance accounting for about 60 to 70 % of the annual water balance in mid-latitudes and up to 99 % in arid climates. It is therefore of imminent importance to estimate evaporation for . . .

- irrigation projects
- management of water resources under changing climate
- management of reservoirs

Evaporation only plays a very minor in relation to floods. Only in very long rivers in arid zones evaporation has a significant effect on discharge along the river profile.

# Physical background

# Atmospheric parameters

with

$$\epsilon = \frac{\rho_v}{\rho_d}$$

$$q = \frac{\rho_v}{\rho}$$

$$rF = \frac{m}{m^*}$$

| | |
|---|---|
| $\epsilon$ | Mixing Ratio |
| $\rho_v$ | vapour density |
| $\rho_d$ | density of dry air |
| $\rho$ | $\rho = \rho_v + \rho_d$ |
| $q$ | specific moisture content |
| $m^*$ | Mixing ratio |
| $rF$ | specific moisture content |

# Barometric Pressure vs. Altitude

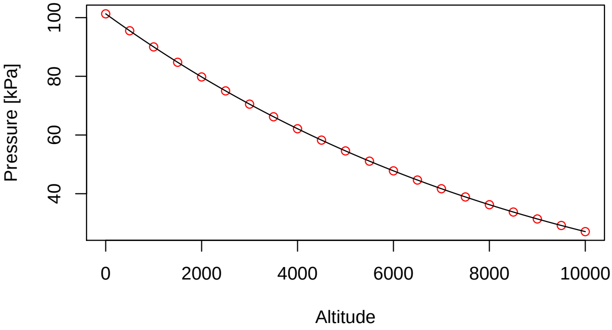
Equation:

$$P = 101.3 * \frac{(293 - 0.0065 * z)^{5.26}}{293} [kPa]$$

where

$$\begin{array}{r|l} P & \text{atmospheric pressure } [kPa] \\ z & \text{elevation above sea level } [m] \end{array}$$

# Pressure profile
# Altitude vs. Pressure



# International Barometric Function Altitude vs. Pressure

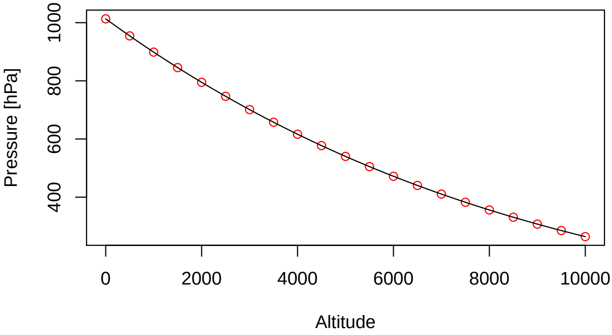
Equation:

$$
\begin{aligned}
P &= p_0 * \left[1 - \frac{0.0065\frac{K}{m} * h}{288.15 * K}\right]^{5.255} \quad [hPa] \\
p_0 &= 1013.25\mathrm{hPa}
\end{aligned}
$$

where

| | |
|---|---|
| $P$ | atmospheric pressure $[kPa]$ |
| $h$ | elevation above sea level $[m]$ |
| $K$ | temperature in $[K]$ |

# Pressure with International Barometric Equation



# Saturated Vapour Pressure
# Clasius-Clapeyron

$$e_s = 6.11 * 10^{(7.48 * T/(237+T))} \, [hPa] \quad (1)$$

$$e_a = rH * e_s \, [hPa] \quad (2)$$

$$(3)$$

| | |
|---|---|
| $e_s$ | saturated vapour pressure $[hPa]$ |
| $e_a$ | actual vapour pressure $[hPa]$ |
| $T$ | Temperature in degrees Celsius |

# Vapour pressure
# Magnus-Formula

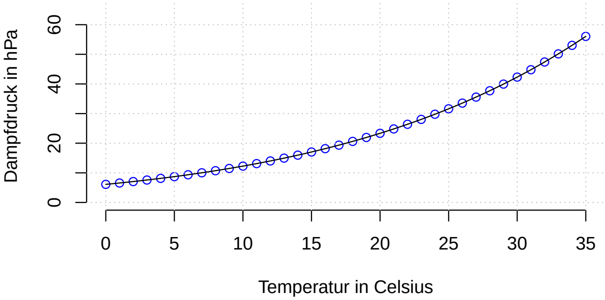



Figure: Vapour pressure calculated with Python

# Programming in Python

```
1: import numpy as np
2: import matplotlib.pyplot as plt
   # Create an array of 100
   # linearly-spaced points from 0 to 35
3: T = np.linspace(0,35,350)
4: es = 6.11*10^(7.48*T/(237+T))
5: plt.plot(T,es)
6: plt.savefig('figure/Tes.png')
```

# Saturated Vapour Pressure
# Clasius-Clapeyron

$$e_s = 0.6108 * exp(17.27 * T/(237.3 + T)) \, [kPa] \tag{4}$$

| | |
|---|---|
| $e_s$ | saturated vapour pressure $[kPa]$ |
| $T$ | Temperature in degrees Celsius |

# Programming in R

```
T<-seq(0,35,1.0)
es<-0.6108*exp(17.27*T/(237+T))
plot(T,es,xlab="Temperature in Celsius",
ylab="Vapour pressure in kPa",
xlim=c(0, 35), ylim=c(0, 10),
pch=1, lty=1, col="blue", axes=FALSE)
axis(1, seq(0,35,5))
axis(2, seq(0,10,2))
grid (NULL,NULL, lty = 3, col = "grey")
curve(0.6108*exp(17.27*x/(237.3+x)), add = TRUE)
```

# Vapour pressure
# Dependency on temperature

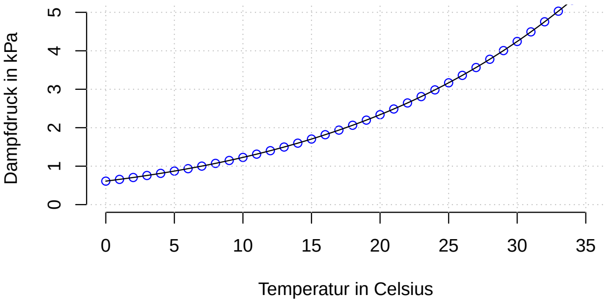



Figure: Vapour pressure as a function of temperature

# Relative Humidity

**Relative humidity** $rF$ is the percentage of actual humidity $e_a$ in relation to potential humidity $e_s$ at temperature $T$:

$$rF = e_a/e_s \; [\%]$$

The moisture **saturation deficit** $d$ is defined as:

$$d = (e_s - e_a) \text{ in } [hPa]$$

# Psychrometric Constant

$\gamma$

**Psychrometric constant** $\gamma$ is defined as:

$$\begin{aligned}\gamma &= \frac{c_p * P}{\lambda * \epsilon}\ [kPa] \\ &= 0.665 * 10^{-3} * P[kPa]\end{aligned}$$

with

| | |
|---|---|
| $\gamma$ | Psychrometric constant [] |
| $c_p$ | specific heat at const. pressure $[MJ\, kg^{-1}\, {}^\circ C^{-1}]$ |
| $\lambda$ | latent heat of vaporization $[MJ\, kg^{-1}]$ |
| $\epsilon$ | ratio of molecular weight of vapour dry air $[\epsilon = 0.622]$ |

# Gradient of saturated vapour pressure curve $\Delta$

$$\Delta = \frac{4098 * e_s}{237.3 + T} \tag{5}$$

| | |
|---|---|
| $\Delta$ | gradient of sat. vapour pressure curve |
| $e_s$ | saturated vapour pressure $[kPa]$ |
| $T$ | Temperature in degrees Celsius |

# Factors

Evaporation depends on . . .

- Air exchange, wind, advection
- Moisture saturation deficit of air
- Available energy as obtained from the energy balance

Key physical parameters are temperature and relative humidity. Wind speed is a parameter for air exchange and advection. Energy balances are only included in physical formulae, most empirical formulae rely on temperature, relative humidity and wind speed, some also on seasonal indices.

# Methods for the Estimation or Measurement of Evaporation

# Estimation Methods - Overview

**Calculation**

- Dalton-type
- Empirical formulae
  - Blaney-Criddle
  - Turc
  - Thorntwaite
  - Hargreaves
- Water balance of basins
- Energy balance
- Bowen ratio
- Penman-Monteith
- Priestley-Taylor

**Measurement**

- Class A-pan, evaporimeters
- Profile method: T, v, e profiles
- Sap flux measurements
- Eddy flux correlation
- Lysimeters
- Lake studies
- Basin studies
- Isotope methods

# Dalton Formula

One of the earliest approaches to estimate evaporation has been proposed by Dalton (1802) [1]. The formula proposed relates evaporation to saturation deficit $E_s - E_a$ and an advection term $a$.

$$E = f_D * (e_s - e_a)$$

with evaporation $E$ in mm, saturated vapour pressure $e_s$ and actual vapour pressure $e_a$. The factor $f_D$ depends on wind speed.

# Haude formula

Haude [2] proposed an adaption of the Dalton formula to regional conditions in Germany. The same author proposed advection term factors for Egypt. For the application of this formula measurements of temperature and relative humidity at 2 p.m. are needed.

$$E = f_H * [e_s(T_{14}) - rF_{14} * e_s(T_{14})]\,[mm/d] \tag{6}$$

For a green lawn in October $f_H = 0.2$.

Table: Haude Factors

| Month | pasture | lawn | corn | deciduous trees | pine trees |
|---|---|---|---|---|---|
| Jan | 0.2 | 0.2 | 0.11 | 0.01 | 0.08 |
| Feb | 0.2 | 0.2 | 0.11 | 0.01 | 0.04 |
| Mar | 0.25 | 0.23 | 0.11 | 0.04 | 0.14 |
| Apr | 0.29 | 0.24 | 0.17 | 0.10 | 0.35 |
| May | 0.29 | 0.29 | 0.21 | 0.23 | 0.30 |
| Jun | 0.28 | 0.29 | 0.24 | 0.28 | 0.34 |
| Jul | 0.26 | 0.28 | 0.25 | 0.32 | 0.31 |
| Aug | 0.25 | 0.26 | 0.26 | 0.26 | 0.25 |
| Sep | 0.23 | 0.23 | 0.21 | 0.17 | 0.20 |
| Oct | 0.22 | 0.20 | 0.18 | 0.10 | 0.13 |
| Nov | 0.20 | 0.20 | 0.11 | 0.01 | 0.07 |
| Dec | 0.20 | 0.20 | 0.11 | 0.005 | 0.05 |

# DVWK formula

The German Association of Hydrologists recomends the DVWK method:

$$E = B * f(v) * (e_s - e_a)\,[mm/d] \tag{7}$$

The saturated vapour pressure $e_s$ and actual vapour pressure $e_a$ are given in $hPa$. $B$ is a factor for surface roughness; $B = 0.135$. For rough surfaces with a fetch $< 20$ m, $B$ can increase to $B = 0.25$. The wind function is simply given by $f(v)$ in $m/s$.

# Temperature-based Methods

# Empirical formulae
# Blaney-Criddle

The Blaney-Criddle formula relies on day light percentage and temperature:

$$ET = p * (0.46 * T + 8.13)$$

with

| | |
|---|---|
| $ET$ | potentia evaporation in cm/month, |
| $T$ | air temperature in degrees Celsius |
| $p_i$ | annual daylight percentage of every month |

# Empirical formulae

## Hamon

The Hamon formula relies on day length and temperature:

$$E_p = K * 0.165 * 216.7 * N * \left(\frac{e_s}{T + 273.3}\right) \quad (8)$$

$$e_s = 0.6108 * exp\left(\frac{17.27 * T}{T + 237.3}\right) \quad (9)$$

where

| | |
|---|---|
| $ET$ | potential evaporation in mm/day, |
| $e_s$ | saturated vapour pressure mbar |
| $k$ | empirical coefficient = 1.0 [-] |
| $N$ | daylight hours [$h$] |
| $e_s$ | saturated vapour pressure in [$kPa$] |
| $T$ | average temperature in degree Celsius |

# Empirical formulae

## Hagreaves

The Hargreaves formula relies on temperature and extraterrestrial radiation:

$$ET = 0.0023 * R_a * (T + 17.8) * TR^{0.50} \tag{10}$$

where

| | |
|---|---|
| $ET$ | potential evaporation in mm/day |
| $R_a$ | extraterrestrial radiation $[MJm^2 day^1]$ |
| $T$ | average temperature in degree Celsius |
| $TR$ | temperature range in degree Celsius |

# Energy Balance & Lake Evaporation

# Energy Balance of a Lake

$$Q_0 = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w$$

where

| | |
|---|---|
| $Q_0$ | energy balance $[W/m^2]$ |
| $Q_s$ | energy from sun (short wave in) $[W/m^2]$ |
| $Q_r$ | energy reflected (short wave out) $[W/m^2]$ |
| $Q_a$ | energy from atmosphere (long wave in) $[W/m^2]$ |
| $Q_{ar}$ | energy reflected (long wave) $[W/m^2]$ |
| $Q_{bs}$ | energy emitted from water (long wave) $[W/m^2]$ |
| $Q_e$ | energy transferred by evaporation $[W/m^2]$ |
| $Q_h$ | energy transferred by sensible heat $[W/m^2]$ |
| $Q_v$ | energy advected $[W/m^2]$ |
| $Q_w$ | energy advected by evaporated water $[W/m^2]$ |

# Radiation Balance

$$\begin{aligned} R_f &= Q_s - Q_{sr} + Q_a - Q_{ar} - Q_{bs} \\ &= Q_s - \alpha_s * Q_s + Q_a - \alpha_l * Q_a - Q_{bs} \\ &= Q_s * (1 - \alpha_s) + Q_a * (1 - \alpha_l) - Q_{bs} \end{aligned}$$

where

| | |
|---|---|
| $R_f$ | radiation balance $[W/m^2]$ |
| $Q_s$ | energy from sun (short wave in) $[W/m^2]$ |
| $Q_{sr}$ | energy reflected (short wave out) $[W/m^2]$ |
| $Q_a$ | energy from atmosphere (long wave in) $[W/m^2]$ |
| $Q_{ar}$ | energy reflected (long wave) $[W/m^2]$ |
| $Q_{bs}$ | energy emitted from water (long wave) $[W/m^2]$ |
| $\alpha_s$ | short wave albedo [-] |
| $\alpha_l$ | long wave albedo [-] |

# Long Wave Emission

$$Q_{bs} = 0.97 * \sigma * T^4$$

| | |
|---|---|
| $Q_{bs}$ | energy emitted from water (long wave) $[W/m^2]$ |
| $\sigma$ | Stefan-Boltzmann Constant $5.67 * 10^{-8}$ $[W * m^{-2} * K^{-4}]$ |
| $T$ | Temperature in Kelvin [K] |

The value 0.97 results from the emissivity of water (which is very high for long wave radiation, namely 0.97).

# Advected Energy by Evaporation

$$Q_w = \frac{c_p * Q_e * (T_e - T_b)}{\lambda}$$

| | |
|---|---|
| $Q_w$ | energy advected by evaporation $[W/m^2]$ |
| $Q_e$ | latent energy transfer $[W/m^2]$ |
| $Q_h$ | sensible energy transfer $[W/m^2]$ |
| $c_p$ | specific heat of water 4186.8$[J/kgC]$ |
| | latent energy of evaporation 2260$[kJ/kg]$ |
| $T_e$ | temperature of water |
| $T_b$ | temperature of arbitrary datum |

# Bowen Ratio

$$B = \frac{Q_h}{Q_e}$$

| | |
|---|---|
| $B$ | Bowen ratio |
| $Q_e$ | latent heat transfer |
| $Q_h$ | sensible heat transfer |

# Energy for Evaporation

$$Q_e = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_0 + Q_v}{1 + B + c_p * (T_e - T_b)/\lambda}$$

| | |
|---|---|
| $Q_e$ | energy transferred by evaporation $[W/m^2]$ |
| $Q_s$ | energy from sun (short wave in) $[W/m^2]$ |
| $Q_r$ | energy reflected (short wave out) $[W/m^2]$ |
| $Q_a$ | energy from atmosphere (long wave in) $[W/m^2]$ |
| $Q_{ar}$ | energy reflected (long wave) $[W/m^2]$ |
| $Q_{bs}$ | energy emitted from water (long wave) $[W/m^2]$ |
| $Q_0$ | energy balance $[W/m^2]$ |
| $Q_v$ | energy advected $[W/m^2]$ |
| $B$ | Bowen ratio |
| $c_p$ | specific heat of water 4186.8$[J/kgC]$ |
| $T_e$, $T_b$ | current and reference temperature of water |
| $\lambda$ | latent energy of evaporation 2260$[kJ/kg]$ |

# Energy for Evaporation

$$E = \frac{Q_e}{\rho * \lambda} = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_0 + Q_v}{\rho * \lambda * (1 + B) + c_p * (T_e - T_b)}$$

| | |
|---|---|
| $Q_s$ | energy from sun (short wave in) $[W/m^2]$ |
| $Q_r$ | energy reflected (short wave out) $[W/m^2]$ |
| $Q_a$ | energy from atmosphere (long wave in) $[W/m^2]$ |
| $Q_{ar}$ | energy reflected (long wave) $[W/m^2]$ |
| $Q_{bs}$ | energy emitted from water (long wave) $[W/m^2]$ |
| $Q_0$ | energy balance $[W/m^2]$ |
| $Q_v$ | energy advected $[W/m^2]$ |
| $B$ | Bowen ratio |
| $c_p$ | specific heat of water 4186.8$[J/kgC]$ |
| $T_e, T_b$ | temperature of water |
| $\rho$ | density of water in kg/dm$^3$ |
| $\lambda$ | latent energy of evaporation 2260$[kJ/kg]$ |

# Integrated Aerodynamic and Energy Methods

# Energy Method for Terrestrial Surface

$$E_r = R_n/(\lambda * \rho) \quad (11)$$

$$\lambda = 2.501 - 0.002361 * T[MJ/kg] = \quad (12)$$

$$R_n = R_i * (1 - \alpha) - R_e \quad (13)$$

$$R_e = e * \sigma * T_p^4 \quad (14)$$

| | |
|---|---|
| $E_r$ | Evaporation by energy $[mm/d]$ |
| $R_n$ | incoming radiation $[W/m^2]$ |
| $\lambda$ | latent heat of evaporation in $[W]$ |
| $T$ | Temperature in degrees Celsius |
| $\rho$ | density of water in $[kg/dm^3]$ |
| $R_n, R_i$ | net and total incoming radiation $[W/m^2]$ |

# Calculation of Incoming Radiation

$$R_G = \frac{24 * 60}{\pi} * G_{sc} * d_r * [\omega * sin(\phi) * sin(\delta) + cos(\phi) * cos(\delta) * sin(\omega_s)]$$

| | |
|---|---|
| $R_G$ | extraterrestrial radiation $[MJ\, m^{-2}\, day^{-1}]$ |
| $G_{sc}$ | solar constant $= 0.0820\,[MJ\, m^{-2}\, min^{-1}]$ |
| $d_r$ | inverse relative distance earth-sun |
| $\omega_s$ | sunset hour angle $[rad]$) |
| $\phi$ | latitude $[rad]$ |
| $\delta$ | solar decimation $[rad]$ |

# Converting decimal degrees to radians

$$rad = \frac{\pi}{180} * d$$

The variable $d$ represents decimal degrees. For the northern hemisphere degrees in decimal degrees are positive for the southern hemisphere they are entered as negative values.

Table: Radians

| degrees | rad |
|---|---|
| 60 | 1.0472 |
| 50 | 0.8727 |
| 40 | 0.6981 |
| 30 | 0.5236 |
| 20 | 0.3491 |
| 10 | 0.1745 |
| 0 | 0.0000 |
| -10 | −0.1745 |
| -20 | −0.3491 |
| -30 | −0.5236 |
| -40 | −0.6981 |
| -50 | −0.8727 |
| -60 | −1.0472 |

# Inverse Relative Distance Earth-Sun

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

$J$ is the Julian day commencing with J=1 on the first of January and ending with J=365 on the $31^{st}$ of December.

Table: Inverse Distance Earth Sun

| Month | Julian Day | relative inverse distance earth sun |
|---|---|---|
| January | 1 | 1.033 |
| February | 31 | 1.028 |
| March | 60 | 1.017 |
| April | 91 | 1.000 |
| May | 121 | 0.9838 |
| June | 152 | 0.9714 |
| July | 182 | 0.967 |
| August | 213 | 0.9714 |
| September | 244 | 0.9838 |
| October | 274 | 1.000 |
| November | 305 | 1.017 |
| Dezember | 335 | 1.029 |
| New Year | 365 | 1.033 |

# Inverse Relative Distance Earth-Sun

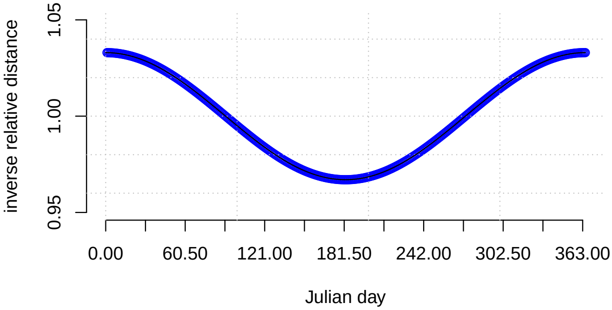



Figure: Relative inverse distance earth-sun

# Solar Declination

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

$J$ is the Julian day commencing with J=1 on the first of January and ending with J=365 on the $31^{st}$ of December.

Table: Solar Declination

| Month | Julian Day | solar declination |
|---|---|---|
| January | 1 | −0.401 |
| February | 31 | −0.309 |
| March | 60 | −0.143 |
| April | 91 | 0.07181 |
| May | 121 | 0.2613 |
| June | 152 | 0.385 |
| July | 182 | 0.403 |
| August | 213 | 0.3113 |
| September | 244 | 0.133 |
| October | 274 | −0.07527 |
| November | 305 | −0.2693 |
| Dezember | 335 | −0.3862 |
| New Year | 365 | −0.4023 |

# Solar Declination

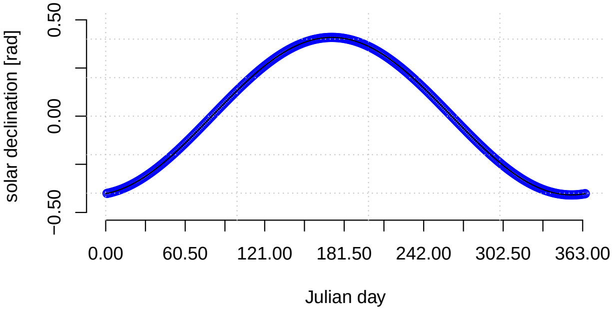



Figure: Solar declination

# Sunset Hour Angle

$$\omega = arccos\left[-tan(\phi) * tan(\delta)\right] \quad (15)$$

$$\omega = \frac{\pi}{2} - arctan\left(\frac{-tan(\phi) * tan(\delta)}{\sqrt{X}}\right) \quad (16)$$

$$N = \frac{24}{\pi} * \omega_s \quad (17)$$

| | |
|---|---|
| $N$ | daylength |
| $\omega$ | sunset hour angle (radians) |
| $\phi$ | latitude (radians) |
| $\delta$ | declination (radians) |
| $X$ | $1 - [tan(\phi)]^2 * [tan(\delta)]^2$ |
| $N$ | Day length (max. sunshine hours |

Table: Sunshine hours

| Month | Julian Day | sunshine hours |
|---|---|---|
| January | 1 | 7.240 |
| February | 31 | 8.525 |
| March | 60 | 10.476 |
| April | 91 | 12.758 |
| May | 121 | 14.879 |
| June | 152 | 16.520 |
| July | 182 | 16.790 |
| August | 213 | 15.505 |
| September | 244 | 13.415 |
| October | 274 | 11.206 |
| November | 305 | 9.023 |
| Dezember | 335 | 7.463 |
| New Year | 365 | 7.220 |

# Sunshine Hours

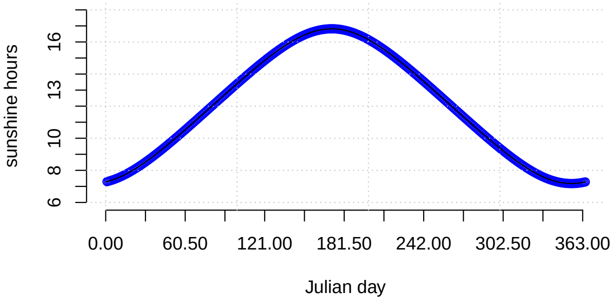



Figure: Sunshine hours

# Extraterrestrial Radiation

$$R_a = \frac{24 * (60)}{\pi} * G_{sc} * d_r * [\omega_s * sin(\phi) + cos(\phi) * cos(\delta) * sin(\omega_s)]$$

where

| | |
|---|---|
| $R_a$ | extraterrestrial radiation $[MJm^{-2}day^{-1}]$ |
| $G_{sc}$ | solar constant $= 0.0820$ $[MJm^{-2}min^{-1}]$ |
| $d_r$ | inverse relative distance earth-sun |
| $\omega_s$ | sunset hour angle (radians) |
| $\phi$ | latitude (radians) |
| $\delta$ | declination (radians) |

# Extraterrestrial Radiation

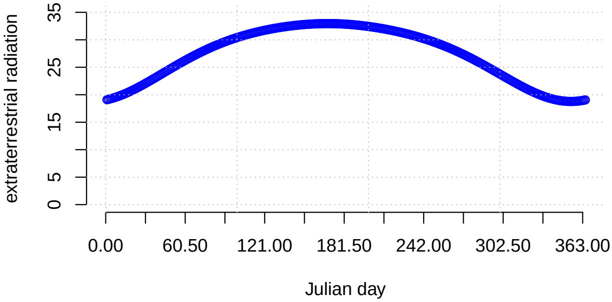



Figure: Extraterrestrial radiation

# Conversion factors

Table: convert

| | $\frac{MJ}{m^2*d}$ | $\frac{J}{m^2*d}$ | $\frac{cal}{m^2*d}$ | $\frac{W}{m^2}$ | $\frac{mm}{d}$ |
|---|---|---|---|---|---|
| $\frac{MJ}{m^2*d}$ | 1 | 100 | 23.09 | 11.6 | **0.408** |
| $\frac{cal}{m^2*d}$ | $4.1868 * 10^{-2}$ | 4.1868 | 1 | 0.485 | 0.171 |
| $\frac{W}{m^2}$ | 0.0864 | 8.64 | 2.06 | 1.0 | 0.035 |
| $\frac{mm}{d}$ | 2.45 | 245 | 28.4 | 28.4 | 1.000 |

Multiplication with 0.408 converts $\frac{MJ}{m^2*d}$ to $\frac{mm}{d}$ which is the equivalent amount of water $\frac{mm}{d}$ that can be evaporated by the energy $\frac{MJ}{m^2*d}$.

# Short-Wave Radiation on Earth
# After travelling through atmosphere and clouds

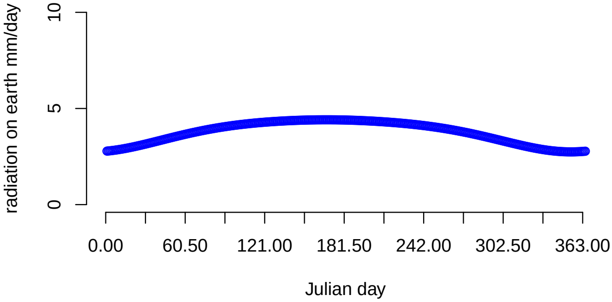



Figure: Short wave radiation at earth surface in mm/d

# Net Long Wave Radiation

$$
\begin{aligned}
R_l &= (0.34 - 0.14 * \sqrt{e_a}) * \sigma * \left[\frac{T^4_{max,K} - T^4_{min,K}}{2}\right] \\
&\quad *(1.35 - (n/N) * 0.35)
\end{aligned}
$$

$$
e_a = 0.6108 * exp(17.27 * T/(237.3 + T))
$$

| | |
|---|---|
| $R_{nl}$ | Net long wave outgoing radiation $[MJm^{-2}day^{-1}]$ |
| $e_a$ | actual vapour pressure $[kPa]$ |
| $T_{min,K}$ | Temperature in Kelvin (min. and max. measured during day) |

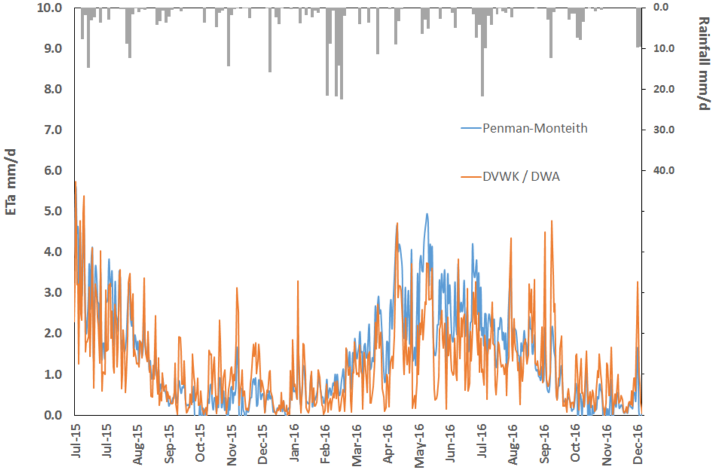
# Soil Heat Flux

$$G = c_s * \left[\frac{T_i - T_{i-1}}{\Delta\, t}\right] * \Delta\, z$$

| | |
|---|---|
| $G$ | soil heat flux in $[MJm^{-2}day^{-1}]$ |
| $c_s$ | soil heat capacity $[MJm^{-3\circ}C^{-1}]$ |
| $T_i$ | air Temperature in $^\circ$ *Celsius* |
| $\Delta\, t$ | time step $[day]$ |
| $\Delta\, z$ | soil depth $[m]$ |

# Combined Equations

# Verdunstung Jahresgang



# Aerodynamic Method

$$E_a = B * (e_s - e_a) \, [mm/day] \tag{18}$$

$$e_s = 6.11 * 10^{(7.48 * T/(237+T))} \, [hPa] \tag{19}$$

$$e_a = rH * e_s \, [hPa] \tag{20}$$

$$B = \frac{0.0102 * {u_2}^2}{ln\left(z_2/z_0\right)} \tag{21}$$

| | |
|---|---|
| $E_a$ | Evaporation by energy $[mm/d]$ |
| $e_s$ | saturated vapour pressure $[hPa]$ |
| $e_a$ | actual vapour pressure $[hPa]$ |
| $T$ | Temperature in degrees Celsius |
| $u_2$ | wind speed at 2m height $[m/s]$ |
| $z_2$ | height 2m $[m]$ |
| $z_0$ | roughness height 0.01 - 0.06 m $[m]$ |

# Combined Method
## Energy and Aerodynamic Term

$$E_c = \left(\frac{\Delta}{\Delta + \gamma}\right) * E_r + \left(\frac{\gamma}{\Delta + \gamma}\right) * E_a \, [mm/d] \qquad (22)$$

$$\Delta = \frac{4098 * e_s}{237.3 + T} \qquad (23)$$

| | |
|---|---|
| $E_c$ | Evaporation from combined method [hPa] |
| $E_a$ | Evaporation from aerodynamic method [hPa] |
| $E_r$ | Evaporation from energy method |
| $\Delta$ | gradient of sat. vapour pressure curve |
| $\gamma$ | psychrometric constant 66.8 $Pa/(^\circ C)$ |
| $T$ | Temperature in degrees Celsius |

# Combined Method
# Energy Term

$$
\begin{aligned}
E_r \;=\; & \left(0.25 + 0.5 * \frac{n}{N}\right) * S_0 - \left(0.9 * \frac{n}{N} + 0.1\right) \\
& (0.34 - 0.14 * \sqrt{e_d}) * \sigma * T^4
\end{aligned}
$$

| | |
|---|---|
| $E_r$ | Evaporation from energy method |
| $n$ | sunshine hours |
| $N$ | potential sunshine hours |
| $e_d$ | vapour pressure |
| $\sigma$ | Boltzmann-Constant |
| $T$ | Temperature in degrees Celsius |

# Priestley & Taylor

$$
\begin{aligned}
E_{PT} &= \alpha * \left(\frac{\Delta}{\Delta + \gamma}\right) * R_n \\
R_n &= R_s * (1 - \alpha) - R_e \\
R_e &= e * \sigma * T_p^4 \\
E_r &= R_n / (\lambda * \rho) \\
\lambda &= 2.501 - 0.002361 * T [MJ/kg]
\end{aligned}
$$

| | |
|---|---|
| $E_{PT}$ | Evaporation by Priestley & Taylor $[mm/d]$ |
| $\alpha$ | 1.3 |
| $R_n$ | net radiation $[W/m^2]$ |
| $R_s$ | total short wave incoming radiation $[W/m^2]$ |
| $\lambda$ | latent heat of evaporation in $[W]$ |
| $T$ | Temperature in degrees Celsius |
| $\rho$ | density of water in $[kg/dm^3]$ |

# Makkink

$$ET = \alpha * \left(\frac{\Delta}{\Delta + \gamma} * \frac{R_s}{\lambda}\right) - \beta$$

| | |
|---|---|
| $ET$ | Evaporation by Makkink $[mm/d]$ |
| $R_s$ | solar radiation in $[MJm^{-2}day^{-1}]$ |
| $\alpha$ | 0.61 |
| $\beta$ | 0.12 |
| $\lambda$ | latent heat of evaporation in $MJkg^{-1}$ |
| $\Delta$ | slope of the vapour pressure curve in $[kPa^\circ C^{-1}]$ |
| $\gamma$ | psychrometric constant $[kPa^\circ C^{-1}]$ |

# Doorenbos & Pruitt

$$
\begin{aligned}
ET &= a + b * \left( \frac{\Delta}{\Delta + \gamma} * \frac{R_s}{\lambda} \right) \\
a &= 1.066 - 0.13 * 10^{-2} * rH + 0.45 * u_z - 0.2 * 10^{-3} * rH * u_z \\
&\quad -0.315 * 10^{-4} * rH^2 - 0.11 * 10^{-2} * u_z^2 \\
b &= -0.3
\end{aligned}
$$

| | |
|---|---|
| $ET$ | Evaporation $[mm/d]$ |
| $R_s$ | solar radiation in $[MJm^{-2}day^{-1}]$ |
| $\lambda$ | latent heat of evaporation in $MJkg^{-1}$ |
| $\Delta$ | slope of the vapour pressure curve in $[kPa^\circ C^{-1}]$ |
| $\gamma$ | psychrometric constant $[kPa^\circ C^{-1}]$ |
| $u_z$ | wind speed at 2m in $[m/s]$ |
| $rH$ | relative humidity in $[\%]$ |

# Abtew

$$ET = \alpha * \left(\frac{R_s}{\lambda}\right)$$

| | |
|---|---|
| $ET$ | Evaporation $[mm/d]$ |
| $\alpha$ | 0.53 |
| $R_s$ | solar radiation in $[MJm^{-2}day^{-1}]$ |
| $\lambda$ | latent heat of evaporation in $MJkg^{-1}$ |

# Penman-Monteith Method, FAO version

$$E_{T_0} = \frac{0.408 * (R_n - G) + \gamma * \frac{900}{T+273} * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)} \quad (24)$$

| | |
|---|---|
| $E_{T_0}$ | reference evaporation $[mm/d]$ |
| $R_n$ | net radiation at the crop surface $[MJ/m^{-2}day-1]$ |
| $G$ | soil heat flux $[MJ/m^{-2}day-1]$ |
| $T$ | mean daily temperature at 2m height $[^\circ Celsius]$ |
| $u_2$ | wind speed at 2m height $[ms^{-1}]$ |
| $e_s$ | saturation vapour pressure $[kPa]$ |
| $e_a$ | actual vapour pressure $[kPa]$ |
| $\Delta$ | slope of vapour pressure curve $[kPa^\circ Celsius^{-1}]$ |
| $\gamma$ | psychrometric constant $[kPa^\circ Celsius^{-1}]$ |

# Instruments and Methods

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# Measurement Methods
# Water Balance

| Water budget measurements | | Brief Description | Assumptions |
|---|---|---|---|
| | Evaporation pan | Directly measures change in water level over time for a sample of open water in a "pan" with well-specified dimensions and siting. | Assumes relationship between measured evaporation from pans and actual evaporation from adjacent area can be calibrated, and calibration is transferable between locations and climates. |
| | Water balance of basin | The unmeasured difference between other measured components of the basin water balance, including incoming precipitation, surface and groundwater outflow, and soil water storage. | Assumes all other components of the basin water balance can be measured as spatial averages with sufficient accuracy for evaporation to be reliably calculated as the difference between them. |
| | Lysimetry | Measures change in weight of an isolated, preferably undisturbed, soil sample with overlying vegetation (if present) while measuring precipitation to and drainage from the sample. | Assumes the sample of soil and overlying vegetation on which measurements are made are representative in terms of soil water content and vegetation growth and vigor of the plot or field in question. |
| | Soil moisture depletion | Measures change in water content of a representative sample of undisturbed soil and vegetation while measuring precipitation and run-on/runoff and estimating deep drainage for the sample plot. | Assumes that soil water measuring devices (resistance blocks, tensiometers, neutron probes, time-domain reflectometers, capacitance sensors) adequately determine change in soil water, the effects of deep roots and sensor placement are small, and deep drainage can be estimated adequately. |

Figure: Water Balance-based methods to determine evaporation, source: Shuttleworth (2008)

# Measurement Methods
# Vapour Transport

| | | | |
|---|---|---|---|
| Water vapor transfer methods | **Bowen Ratio - Energy Budget** | Calculates evaporation as latent heat from the surface energy budget using the ratio of sensible to latent heat (Bowen ratio) derived from the ratio between atmospheric temperature and humidity gradients measured a few meters above vegetation. | Assumes the turbulent diffusion coefficient for sensible heat and latent heat are the same in the lower atmosphere in all conditions of atmospheric stability, and that plot-scale measurements of energy budget components (net radiation, soil heat) are representative of upwind conditions. |
| | **Eddy correlation (also called eddy covariance)** | Calculates evaporation as 20- to 60-minute time averages from the correlation coefficient between fluctuations in vertical windspeed and atmospheric humidity measured at high frequency (~10 Hz) at the same location, a few meters above vegetation. | Assumes only turbulent transfer of water vapor at sample point, and that corrections for water vapor transfer in turbulence at time scales less than ~0.1 seconds or greater than the selected averaging time are acceptable. |
| Components of evaporation | **Transpiration measurement by porometry or monitoring sap flow** | Porometry: measured from humidity increase in a chamber temporarily enclosing transpiring leaves/shoots. Sap Flow: measured from rate of sap flow in trunk, branches, or roots using heat as a tracer, with an estimate of the area of wood through which flow occurs. | Porometry assumes the enclosure of leaves and shoots in the chamber does not significantly alter transpiration rate. Sap Flow assumes installation of sensors does not alter sap flow rate, and cross-sectional area over which flow occurs can be determined accurately. |
| | **Rainfall interception loss from tall vegetation** | Measured as difference between cumulative rainfall above/below tall (usually forest) canopy. Requires careful below-canopy sampling with gauges/troughs that sample at spatial scale of canopy features, preferably randomly relocated after each measurement interval. | Assumes below-canopy sampling is adequate, a requirement rarely met for a typical 1-2 week measurement interval. It becomes feasible over several measurement intervals if gauges are regularly and randomly relocated. |
| | **Soil evaporation** | A small-scale, shallow implementation of lysimetry or soil moisture depletion methods for a near-surface soil sample below vegetation using several "microlysimeters" or sequential gravimetric multisampling. | Assumes the average of all small soil samples, regardless of their below-canopy location, are representative of the entire soil surface. |

Figure: Vapour transport-based methods to determine evaporation, source: Shuttleworth (2008)

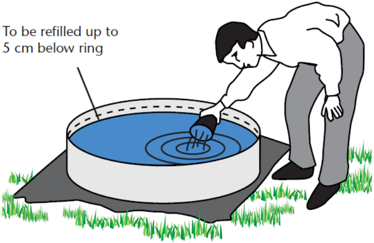
# Measurement Methods
# Large Scale

| | | | |
|---|---|---|---|
| Large-scale evaporation | **Scintillometer measurements** | Uses theoretical relationship between sensible and latent heat fluxes and atmospheric scintillation introduced into a beam of electromagnetic radiation between source and detector by temperature and humidity fluctuations. | Applies strictly in an ideal turbulent field close, but not too close, to a surface with uniform aerodynamic roughness. However, field experiments suggest a worthwhile measurement is possible over a mixture of vegetation covers. |
| | **Remote sensing estimates** | Evaporation is deduced indirectly from the surface energy balance, with sensible heat calculated from the difference between air temperature and the temperature of the evaporating surface, along with an estimate of the aerodynamic exchange resistance between these two. | Assumes the "aerodynamic" surface temperature (that which controls sensible heat transfer from the surface), is the same as (or can be estimated from) the "radiometric" surface temperature (that which can be measured using an airborne or satellite radiometer). |
| | **LIDAR (LIght Detection And Ranging) method** | The local time-average vertical gradient of water vapor is sampled remotely using LIDAR. Local evaporation flux is calculated from this using similarity theory and supplementary measurements of friction velocity and atmospheric stability. | Assumes Monin-Obukov similarity theory applies and the supplementary measurements of friction velocity and atmospheric stability are locally applicable within the measurement field of the LIDAR. |

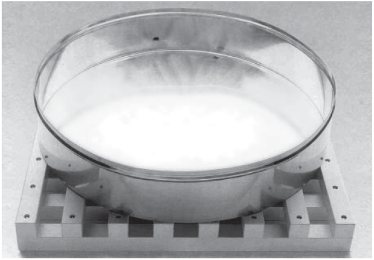
Figure: Large scale methods to determine evaporation, source: Shuttleworth (2008)

# Measurement Methods

## Pans




United States Class A pan



GGI-3000 pan

Figure: Pans

# Measurement of Evaporation
## Class A pan

- Wood as support 15 cm
- Defined diameter 120.7 cm
- Water level 5-7 cm below rim
- Water depth ca. 25 cm
- Measurement of rainfall
- Wave protection
- Protection against animals (grid)

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# Measurement of Evaporation
## Correction Factors

| Class A pan | Case A: Pan placed in short green cropped area | | | | Case B: Pan placed in dry fallow area | | | |
|---|---|---|---|---|---|---|---|---|
| RH mean (%) ® | | low < 40 | medium 40 - 70 | high > 70 | | low < 40 | medium 40 - 70 | high > 70 |
| Wind speed (m $s^{-1}$) | Windward side distance of green crop (m) | | | | Windward side distance of dry fallow (m) | | | |
| Light | 1 | .55 | .65 | .75 | 1 | .7 | .8 | .85 |
| < 2 | 10 | .65 | .75 | .85 | 10 | .6 | .7 | .8 |
| | 100 | .7 | .8 | .85 | 100 | .55 | .65 | .75 |
| | 1000 | .75 | .85 | .85 | 1000 | .5 | .6 | .7 |
| Moderate | 1 | .5 | .6 | .65 | 1 | .65 | .75. | .8 |
| 2-5 | 10 | .6 | .7 | .75 | 10 | .55 | .65 | .7 |
| | 100 | .65 | .75 | .8 | 100 | .5 | .6 | .65 |
| | 1000 | .7 | .8 | .8 | 1000 | .45 | .55 | .6. |
| Strong | 1 | .45 | .5 | .6 | 1 | .6 | .65 | .7 |
| 5-8 | 10 | .55 | .6 | .65 | 10 | .5 | .55 | .65 |
| | 100 | .6 | .65 | .7 | 100 | .45 | .5 | .6 |
| | 1000 | .65 | .7 | .75 | 1000 | .4 | .45 | .55 |
| Very strong | 1 | .4 | .45 | .5 | 1 | .5 | .6 | .65 |
| > 8 | 10 | .45 | .55 | .6 | 10 | .45 | .5 | .55 |
| | 100 | .5 | .6 | .65 | 100 | .4 | .45 | .5 |
| | 1000 | .55 | .6 | .65 | 1000 | .35 | .4 | .45 |

- $E_{pot} = f_c * E_{pan}$
- correction factor depends on wind and humidity and surrounding

source: FAO, paper 24 65

# Measurement of Evaporation
## Example

Type of pan: Class A evaporation pan
Water depth in pan on day 1 = 150 mm
Water depth in pan on day 2 = 144 mm (after 24 hours)
Rainfall (during 24 hours) = 0 mm
K pan = 0.75
Formula: $ET_o$ = K pan × E pan
Calculation: E pan = 150 - 144 = 6 mm/day
$ET_o$ = 0.75 × 6 =4.5 mm/day

# Measurement of Evaporation
## Sunken pan

- $E_{pot} = f_c * E_{pan}$
- correction factor 0.83-0.98

source: John Rich, www.perrylakes.info

# Measurement of Evaporation

## Sunken pan

| Location | Class *A* Pan | BPI sunken 6 ft, diameter, 2 ft. deep. | Colorado sunken 3 ft. square 2 ft. deep. | Screened sunken (young) 2 ft. diameter, 3 ft. deep. |
|---|---|---|---|---|
| Denver, Colorado (12 ft. pan 3 ft. deep) | 0.67 | | | |
| Fullerton, California (» ») | 0.77 | 0.94 | 0.89 | 0.98 |
| Ft. Mc Intosh, Texas (» ») | 0.73 | | | 0.88 |
| Falcon Dam, Texas (» ») | 0.68 | | | 0.91 |
| Dryden, Texas (» ») | 0.73 | | | 0.96 |
| Lake Elsinor, California | 0.77 | | | 0.98 |
| Red Bluff Reservoir, Texas | 0.68 | | | |
| Lake Okeechobee, Florida | 0.81 | | 0.98 | |
| Lake Hefner, Oklahoma | 0.69 | 0.91 | 0.83 | 0.91 |
| Felt Lake, California | 0.77 | 0.90 | 0.84 | 0.98 |
| Lake Colorado City, Texas | 0.72 | | | |

source: Gangopadhyaya

# Actual Evaporation
# Soil Moisture Reduction

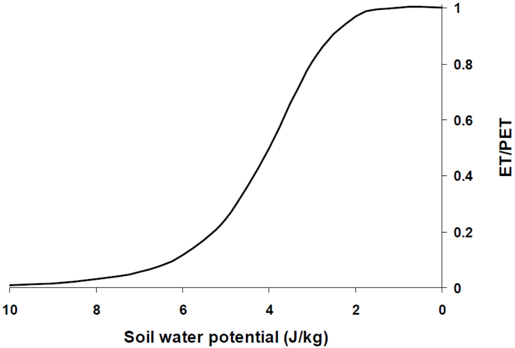



Figure: Reduction of evaporation by limited soil moisture

# Actual Evaporation
## Soil Function

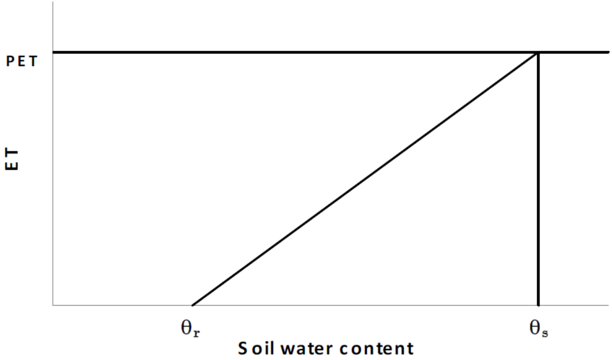



Figure: Reduction of evaporation by limited soil moisture

# Actual Evaporation
# Water Table Reduction

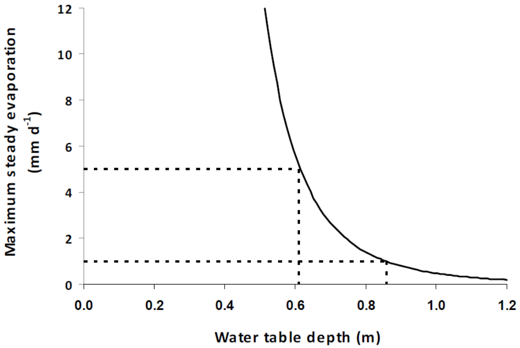



Figure: Reduction of evaporation by deep water table

# Bagrov-Gugla Verfahren

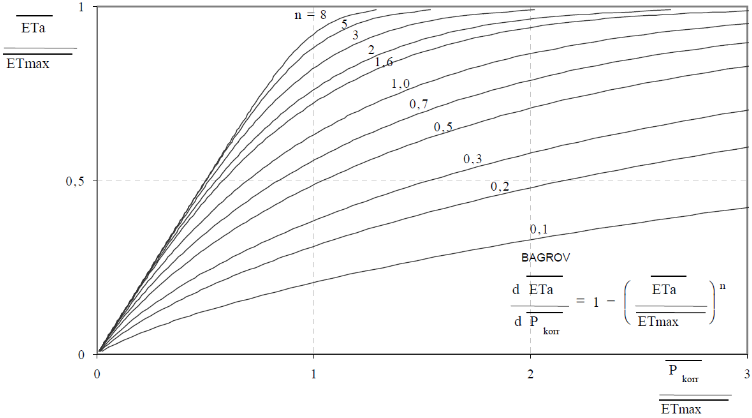
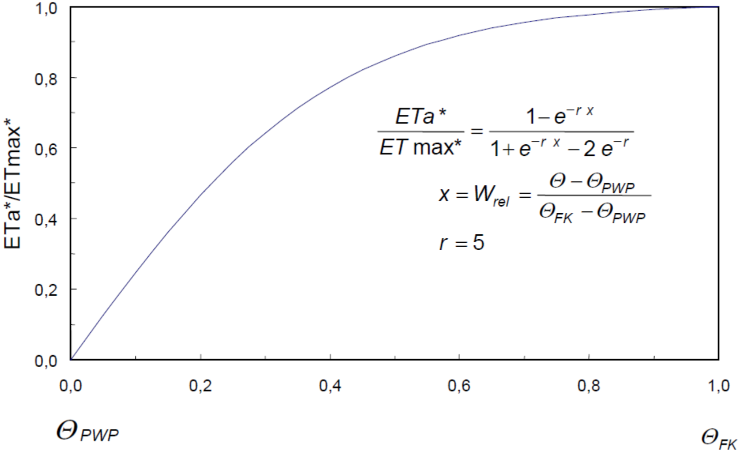



Figure: Reduction of evaporation by (BfG, 2003) [3]

# Bagrov-Gugla Bodenfeuchte



# Actual Evaporation

# Reduction by resistance

$$\lambda * ETo = \frac{\frac{\Delta}{\lambda} * (R_n - G) + \frac{\rho * c_p}{\lambda} * \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma * \left(1 + \frac{r_s}{r_a}\right)} \quad (25)$$

where as in [4]

| | |
|---|---|
| $ETo$ | reference evaporation $[mm/d]$ |
| $R_n$ | net radiation at the crop surface $[MJ/m^{-2} day-1]$ |
| $G$ | soil heat flux $[MJ/m^{-2} day-1]$ |
| $T$ | mean daily temperature at 2m height $[^\circ Celsius]$ |
| $u_2$ | wind speed at 2m height $[ms^{-1}]$ |
| $e_s$ | saturation vapour pressure $[kPa]$ |
| $e_a$ | actual vapour pressure $[kPa]$ |
| $\Delta$ | slope of vapour pressure curve $[kPa^\circ Celsius^{-1}]$ |
| $\gamma$ | psychrometric constant $[kPa^\circ Celsius^{-1}]$ |

# Actual Evaporation
# Reduction by resistance

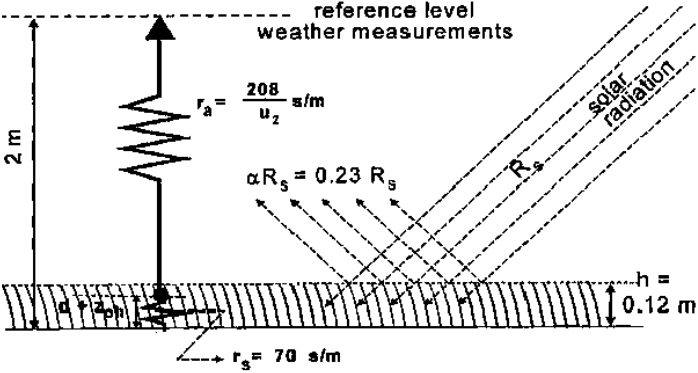



Figure: Reduction of evaporation by resistance

# Actual Evaporation
## Reduction with Crop Coefficient

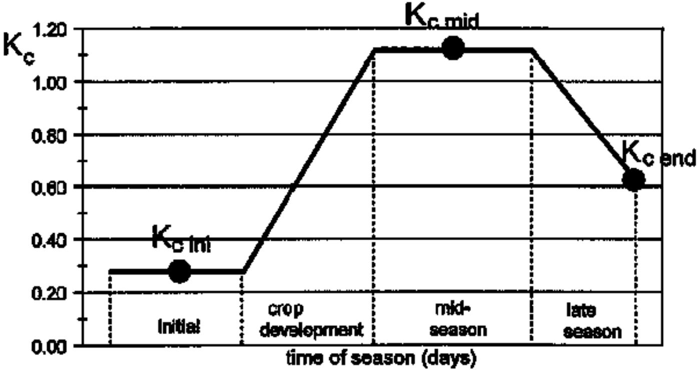



Figure: Reduction of evaporation by crop coefficient

# Actual Evaporation
# Reduction after Infiltration

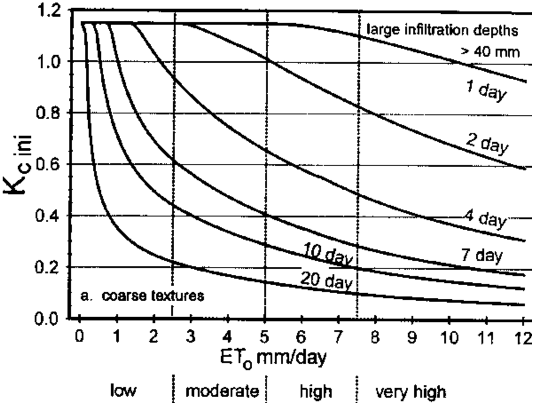
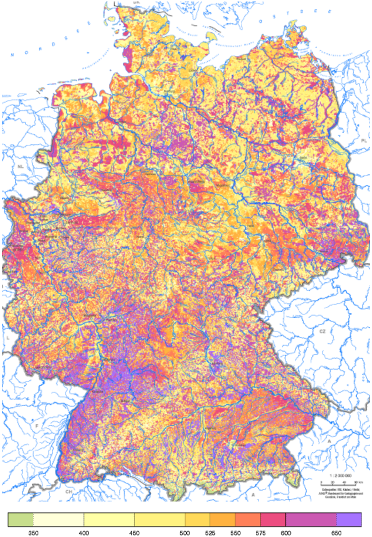
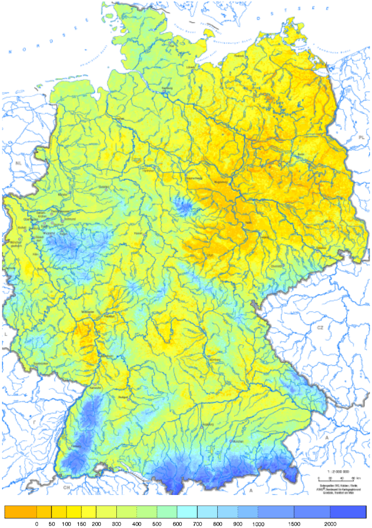



Figure: Reduction of evaporation by crop coefficient

# Abfluss


350 400 450 500 525 550 575 600 650


0 50 100 150 200 300 400 500 600 700 800 900 1000 1500 2000

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