Hydrology for Engineers | Lecture 4
EVAPOTRANSPIRATION

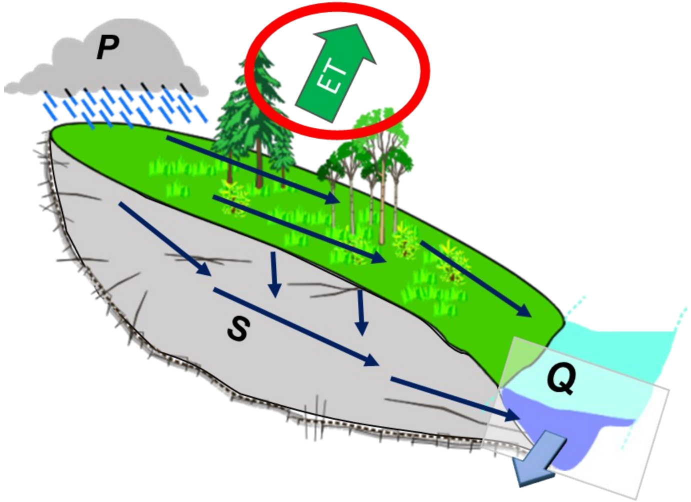
S. Bonetti

Evaporation and Evapotranspiration

S. Bonetti

- **Release of water from the catchment surface as water vapor.**
- When evaporation is produced by plant stomata, (i.e. it is mediated by vegetation in any form) it is conventionally termed **transpiration** (T).
- When both processes (evaporation from soil and plants) occur on the landscape (the large majority of the cases), we talk about **evapotranspiration** (ET)
- Globally, ET accounts for approximately **60-65% of the average precipitation over the Earth's land surface**. Of this, **~40% is transpiration** (and **~3% is open water evaporation**).
- Local **spatial and temporal variability** with respect to the mean can be very high! Hence the need for a thorough analysis and quantification.
- Here we are looking at **catchment scale** applications and we will introduce formulations relevant for the processes of interest (i.e. global features are not the interest of engineering hydrology).

60-65% of P over the Earth's surface



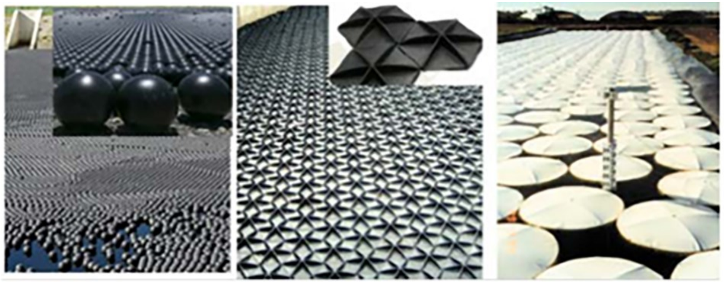
Computing evapotranspiration - relevance

- Relations between ET and ecosystem type are fundamental for predicting **ecosystem response to climate change**.

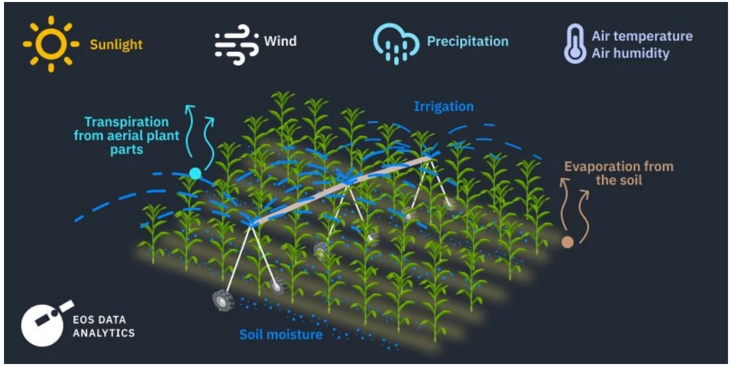
- Over the long term, the difference between continental precipitation and ET is the water available for direct human use and management. **Quantitative assessments of water resources** and the effects of climate and land-use change on those resources require a quantitative understanding of ET.

- Evaporation has a significant influence on the yield of **water-supply reservoirs**, and thus on the economics of building reservoirs of various sizes.

- The fraction of water falling in a given rain storm that contributes to streamflow and to groundwater recharge is in large part determined by the **antecedent soil moisture**; which depends on the amount of ET occurred since the previous storm.

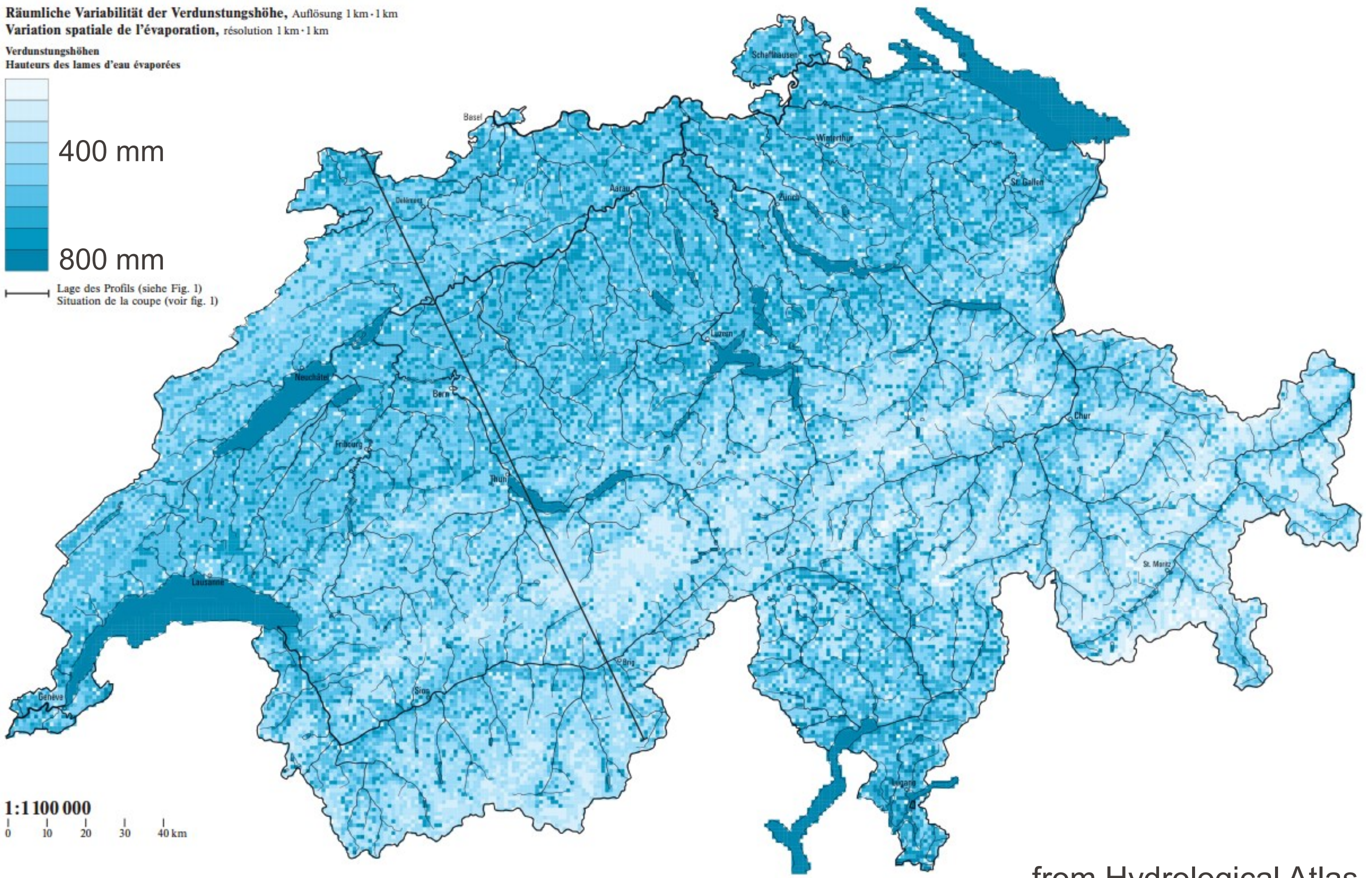


Example of covers for evaporation suppression: black plastic shade balls, floating black hexagons; floating white covers (from ethz.ch).



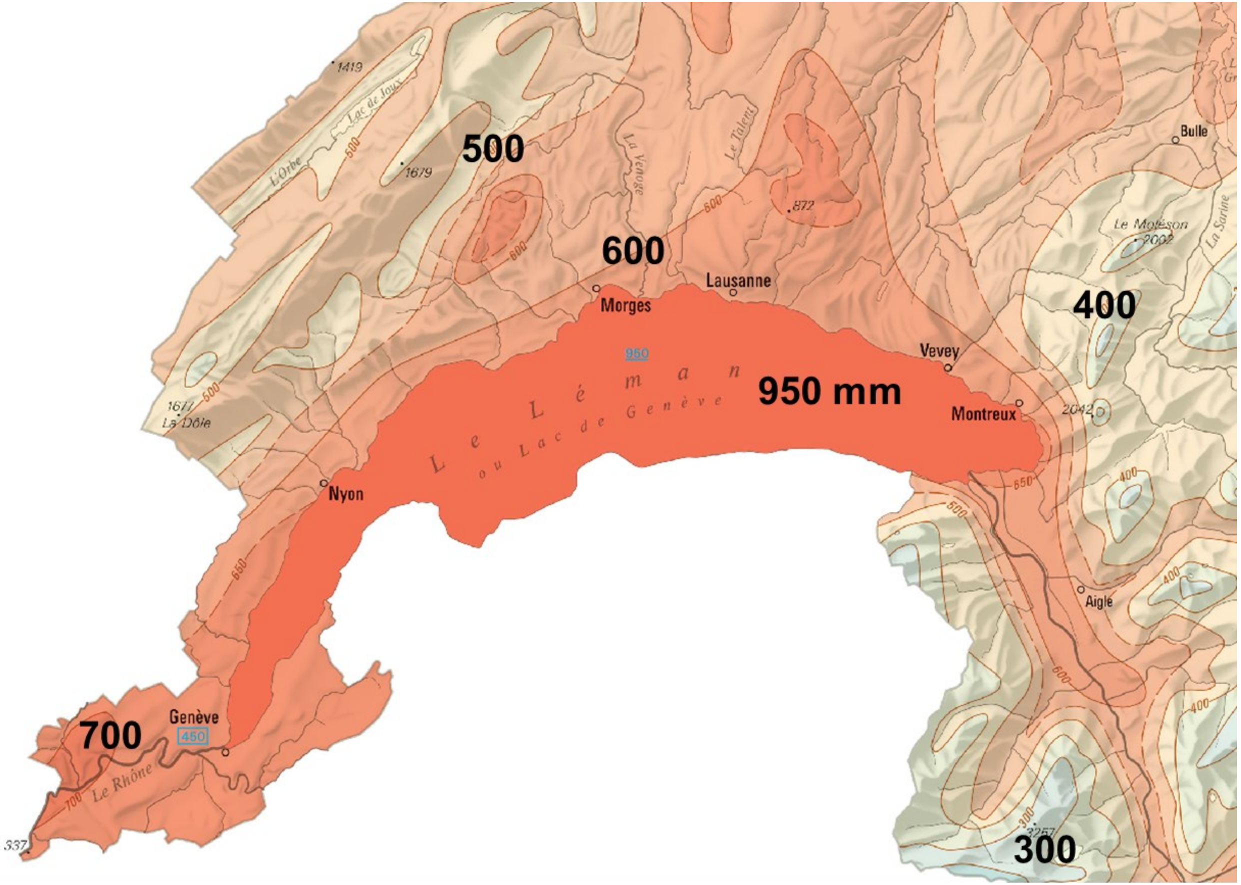
- Much of the world's food supply is grown on irrigated land (irrigation is one of the largest uses of water worldwide). Efficient irrigation requires knowledge of **crop water use** (transpiration).

Evapotranspiration: typical values (mean annual ET in CH)



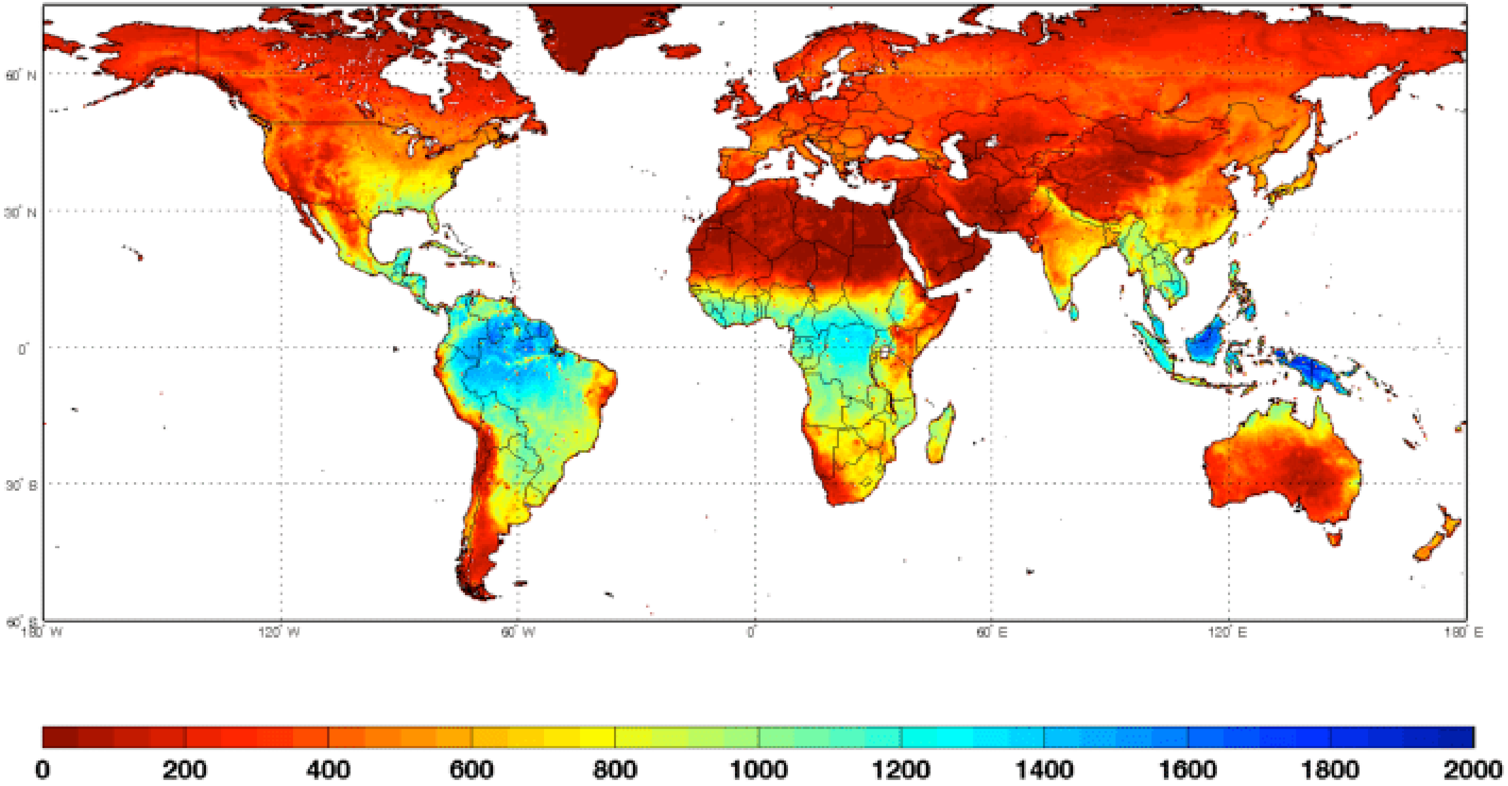
from Hydrological Atlas of Switzerland

Evapotranspiration: typical values (mean annual ET in CH)



from Hydrological Atlas of Switzerland

Evapotranspiration: typical values (mean annual ET, global)



Map of global evapotranspiration (in **mm**) distribution for the year 2006. Data are from Global Land-surface Evaporation: Amsterdam Method (GLEAM). From Wang et al. (2012).

Lecture outline

1. **Evaporation**:
- Intro on basic concepts, definitions, terminology
- Energy budget method
- Aerodynamic method
- Combined method: the Penman equation

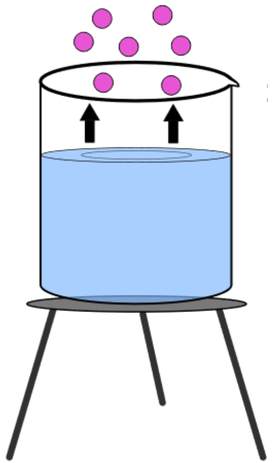
2. **Transpiration**:
- Intro on basic concepts, definitions, terminology
- Penman equation for T

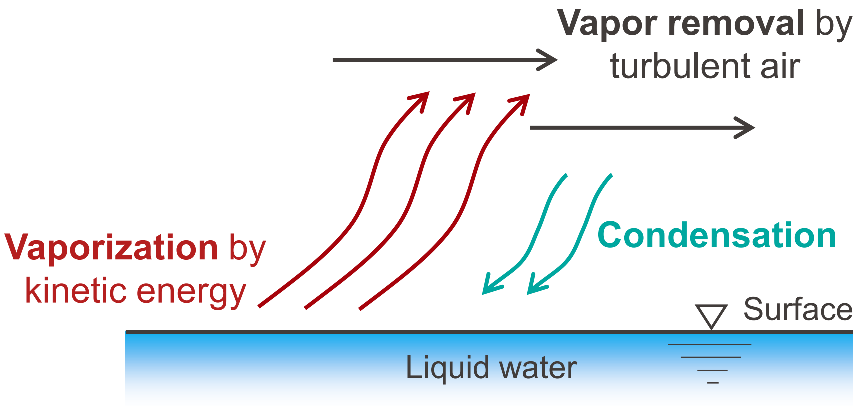
3. **Evapotranspiration (for engineers)**:
- The Penman-Monteith equation
- The Blaney-Criddle equation
- Balance closure methods

Evaporation

The **transition of water from the liquid to the vapor phase**.

Such transition requires:
i) energy supply to provide water molecules the necessary kinetic energy to escape from the liquid surface;
ii) suitable mechanisms to **transport** away escaped molecules from the immediate vicinity of the liquid surface thus preventing their return to condense





The system therefore may be **supply-limited** (when energy transfer limits E or ET) or **transport-limited** (when air turbulence does).

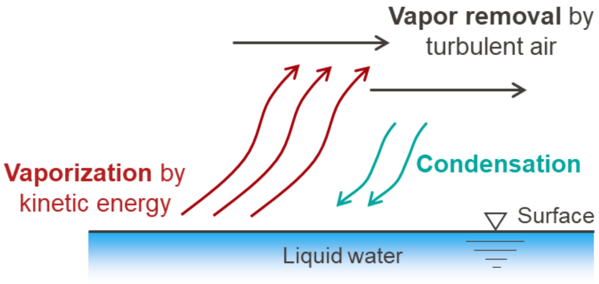
It is almost impossible to have the two mechanisms in isolation.

Evaporation

The two requirements (enough energy & turbulence) have given raise to two main classes of methods to describe evaporation:

i) Energy budget formulations (say, supply-limited) where the main focus is on the energy supply aspects of the phenomenon.

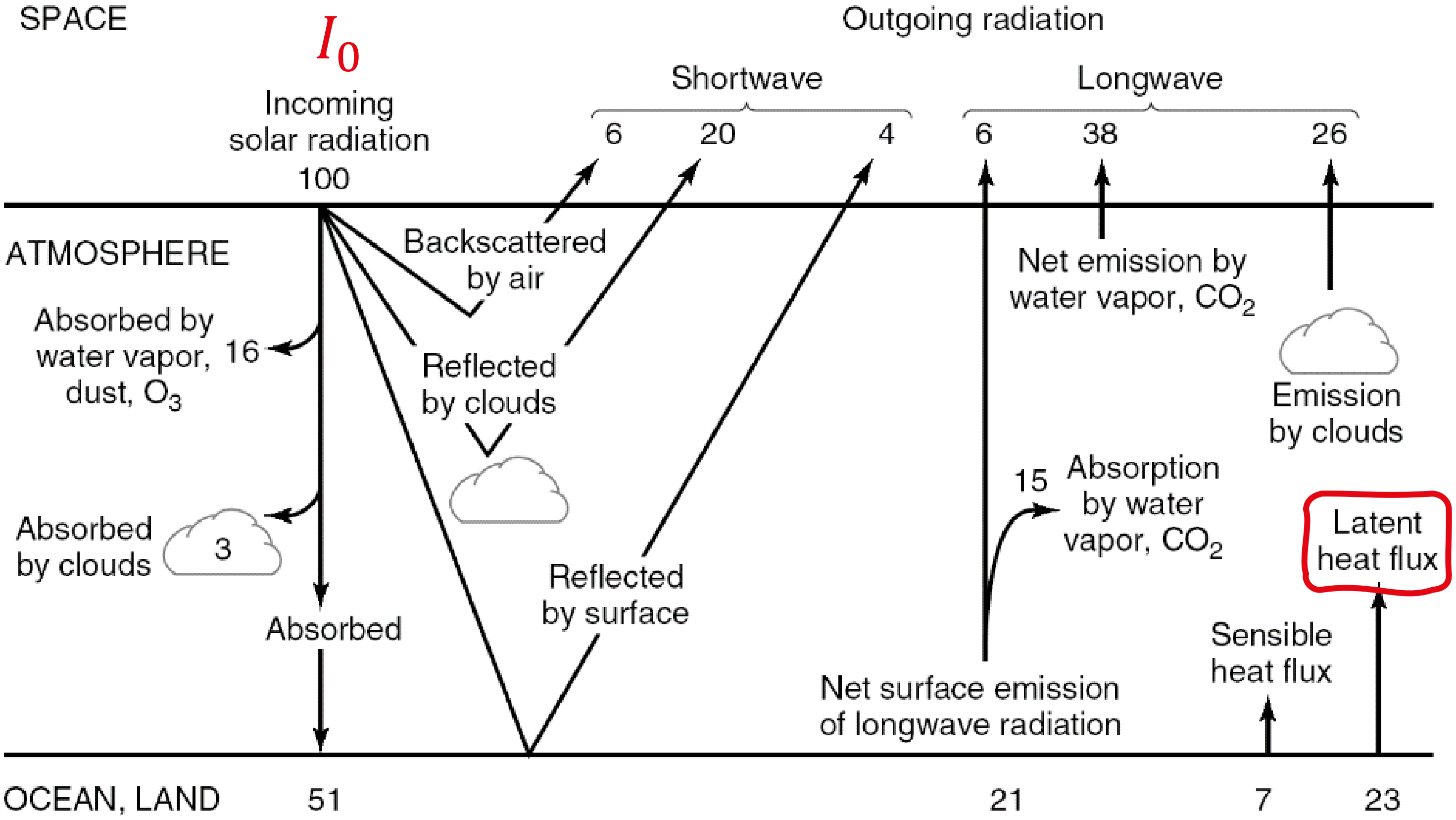
ii) Aerodynamic or mass-transfer formulations (say, transport-limited) which constist primarily of the description of water vapor transport mechanisms near the surface.



However, it is almost never possible to have the two mechanisms in isolation.
Thus, most methods use a **combination** of these two approaches.

iii) A third class of methods considers **water-budget formulations**, in which evaporation is treated as the unknown term in the continuity equation. Conceptually the most obvious and appealing, but they require detailed independent estimates of all other components of the water budget (thus often unsuitable, especially when the objective is closure of the hydrologic cycle).

Energy balance



Radiation and heat balance in the atmosphere and at the Earth's surface

Latent and sensible heat fluxes

Latent (= invisible) heat vs. *sensible* (= that can be sensed) heat

Latent heat:

- ***Latent heat*** is the heat given up or absorbed when a phase (solid, liquid or gas) changes.
- The ***latent heat of vaporization*** ($l_v$or λ) is the energy needed to break inter-molecular $\mathrm{H_2O}$ bounds and allow vaporization. It is expressed in joule/kilogram [J/kg]. At standard pressure, $\ell_v = 2.26 \times 10^6$ J/kg.
- Actually, l_v decreases as the temperature T [ºC] of the evaporating surface increases, as

$$l_v[J/kg] = 2.501 \cdot 10^6 - 2370 \cdot T$$

- The product between latent heat of vaporization,ℓ_v, (Joule/kg) and the evaporation flux, E, (kg/day or mm*area*density/day) is the vaporization heat flux (in Joule/day).

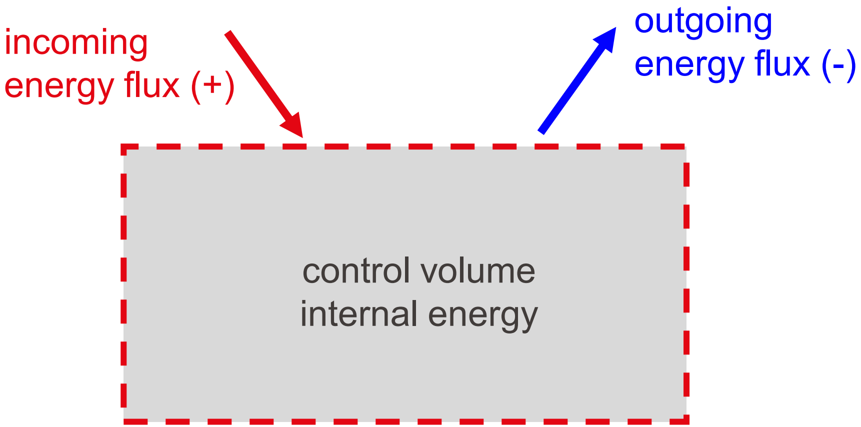
Sensible heat is the heat exchanged by a system, which results in a change in the temperature of the system.

The energy balance method

Consider a **control volume** (e.g., a layer of surface material - this may consist of water, or some substrate like soil, plant canopy or snow).

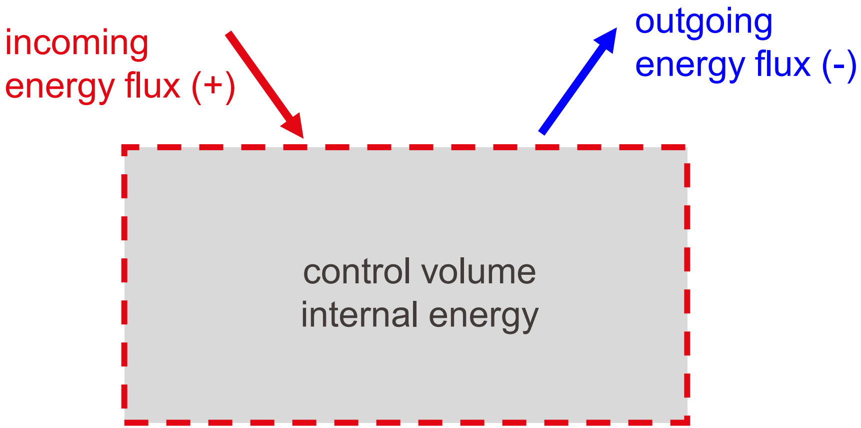
The control volume may be infinitesimally thin, or be finite and large (like a lake or an assemblage of vegetation over its entire depth).

Incoming and outgoing energy fluxes are balanced and equal the rate of increase of energy stored in the control volume (signs are such that incoming fluxes are positive, negative outgoing).



The energy balance method

Overall, the principle is to balance the rate of change of energy storage in the control volume (possibly per unit horizontal area) **to include input** (net radiative flux R_n supplied at the upper surface of the control volume) **and outgoing** (latent heat of vaporization, $\ell_v E$, and the sensible heat flux H_s) **fluxes**.



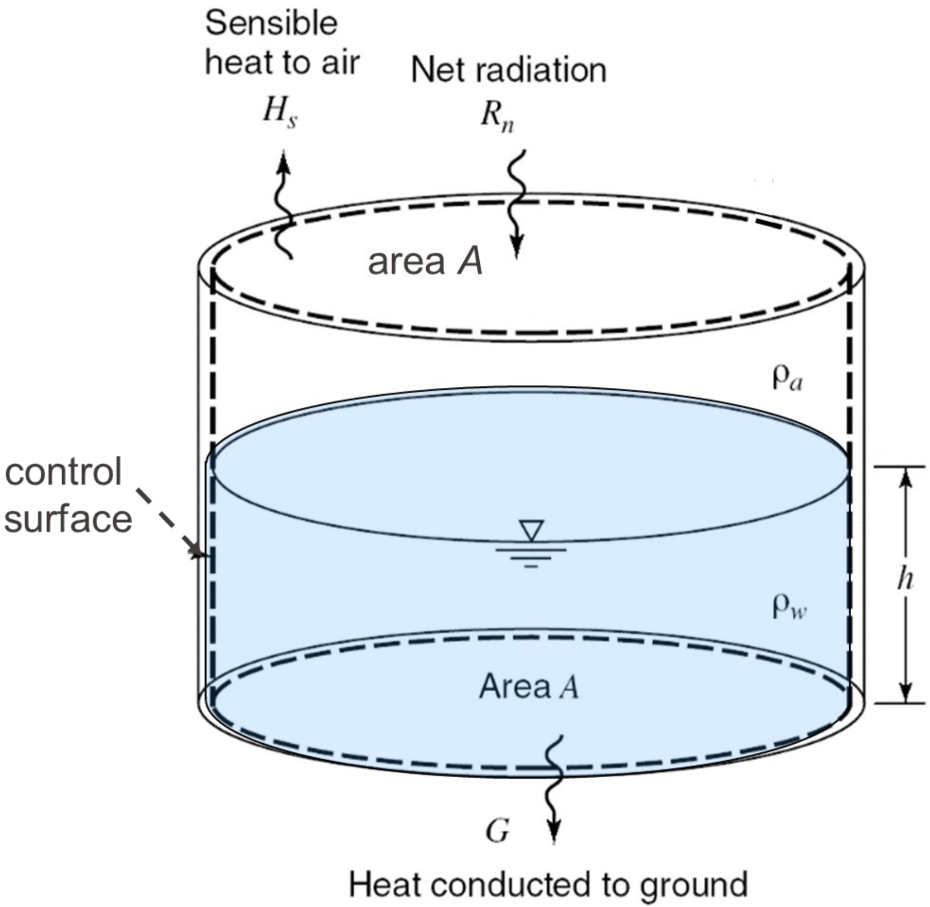
Note that there are processes that may or may not be parametrized and that we neglect:

- Carbon dioxide fixation.
- Presence of ice/snow and energy loss due to fusion and sublimation.
- Lateral advective heat fluxes.
- Vertical heat exchanges with lower ground layers (usually termed *G*).

The energy balance method

Formulate an energy balance for a still, shielded liquid surface of area A, where:

- the control volume includes the air that is on top of the liquid
- evaporation E occurs within the control volume
- the pan has impermeable sides (there is no flow of liquid water across the control surface)



The energy balance method

S. Bonetti

Let dH/dt be the change in internal energy in the control volume. Given that **no work is done by the system**, the energy balance equation simplifies to:

$$\frac{dH}{dt} = R_n - H_s - G$$

where:

- R_n is the net radiation flux
- H_s is the sensible heat to the air stream supplied by the water
- G is the ground heat flux to the lower ground layers

If we **assume that the temperature of the water in the control volume is constant in time**, the only change in the heat stored within the control volume is the change in the internal energy of the water evaporated $l_v \dot{m}_v$, where $\dot{m}_v = \rho_w A E$. Assuming unitary areas ($A = 1$ m^2), we have:

$$R_n - H_s - G = l_v \dot{m}_v = l_v \rho_w E$$

The energy balance method

The energy balance equation for evaporation E is thus obtained as:

$$E = \frac{1}{l_v \rho_w}(R_n - H_s - G)$$

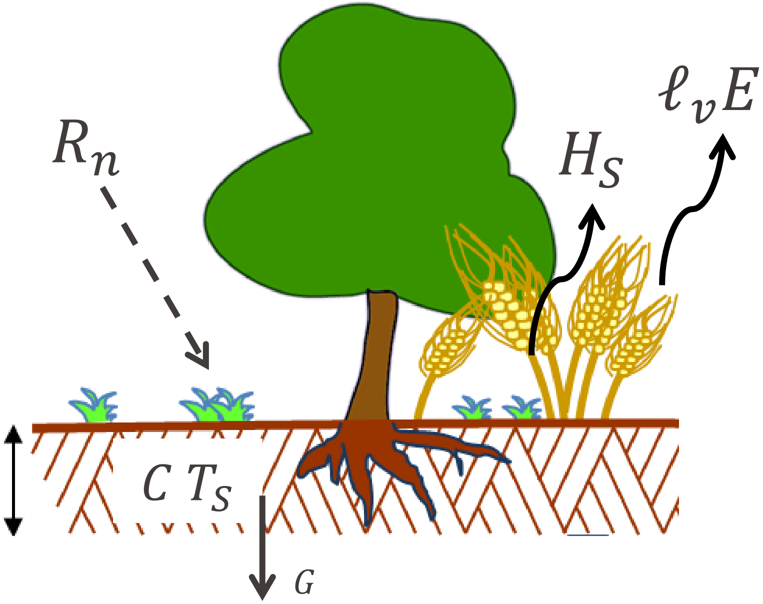
If we further assume that $H_S \sim G \sim 0$, a **reference evaporation rate** E_r (for which all incoming radiation is absorbed by evaporation) is calculated as:

$$E_r = \frac{R_n}{l_v \rho_w}$$

The energy balance method: more general example

S. Bonetti

Consider a soil control volume



C : thermal capacity of the active soil layer
T_S: soil temperature (state variable that changes over time)
(thus $C\ T_S$ *is* energy stored as heat)

R_n : net solar radiative flux on the surface
H_S : sensible heat flux outgoing the surface
ℓ_v : latent heat of vaporization
E : evaporation (evapotranspiration)
G : ground heat losses to lower depths

$$C\frac{dT_S}{dt} = R_n - H_S - G - \ell_v E \rho_w$$

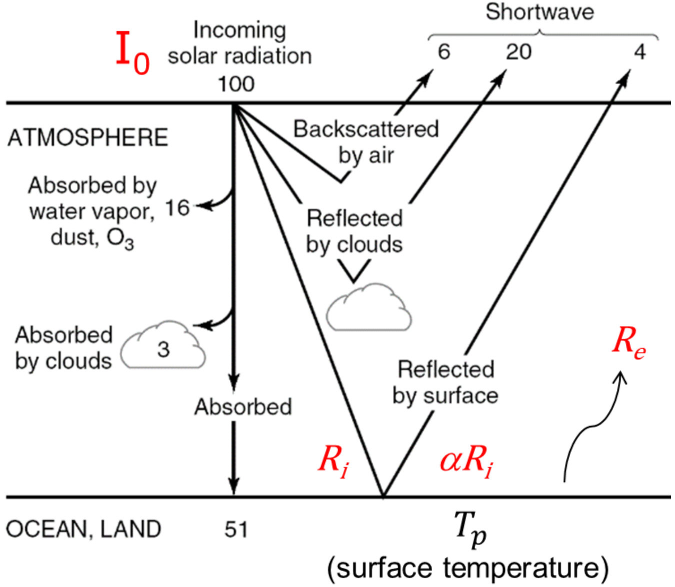
Note: we are neglecting CO_2 fluxes/conversions

Net radiation

The net radiation flux R_n at the Earth surface (like for any pan experiment) is the fundamental energy input necessary for the water evaporation. This is defined as:

$$R_n = R_i(1-\alpha) - R_e$$

which is the difference between the **absorbed** ($R_i(1-\alpha)$) and the **emitted** (R_e) radiation.



- The absorbed radiation is the incident radiation R_i minus the fraction αR_i which is reflected by the surface (α is called **albedo**).
- The emitted radiation R_e depends on the temperature of the body according to **Stefan-Boltzmann law**: $R_e = e\,\sigma\,T_p^4$, where e is emissivity ($e \cong 0.97$ for water), σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4) and T_p is the absolute temperature of the surface in degrees Kelvin.

S. Bonetti

The energy balance method: example

For a particular location the average net radiation is 185 W/m², air temperature is 28.5 ºC, relative humidity is 55 percent, and wind speed is 2.7 m/s at a height of 2m (we will need this info later). Determine the open water evaporation rate in mm/d using the energy method.

Solution:

- Note that the latent heat of vaporization as a function of temperature is given (in J/kg) by $l_v = 2.501 \cdot 10^6 - 2370 \cdot T = 2.433 \cdot 10^6$ J/kg
- Recall that $\rho_w = 996.3$ kg/m³
- Assume $H_s \sim G \sim 0$

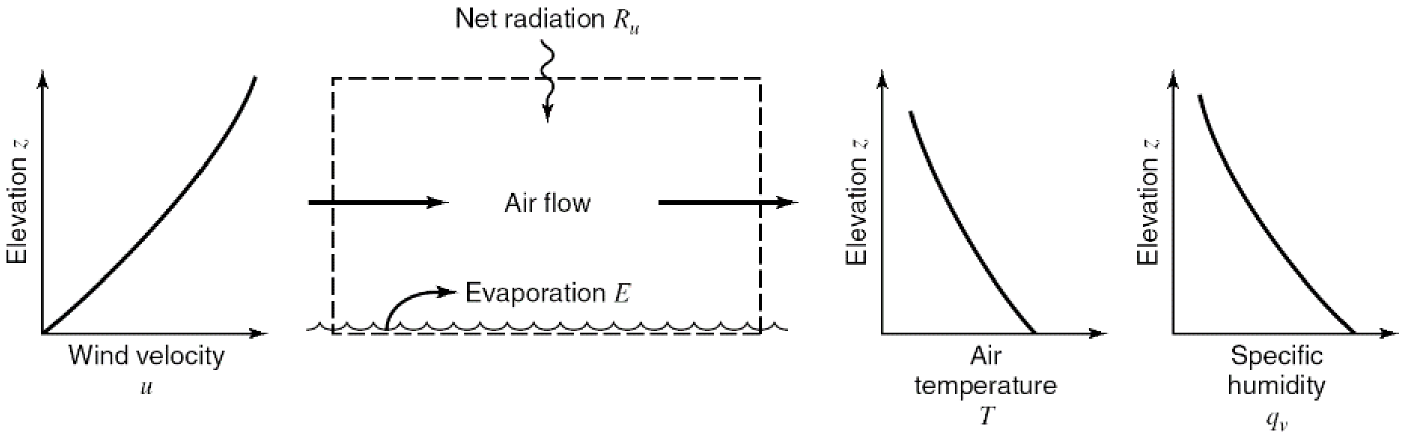
- $E_r = \frac{185}{2.433 \cdot 10^6 \cdot 996.3} = 7.63 \cdot 10^{-8}$m/s = 6.6 mm/day

- (recall that W=J/s)

The aerodynamic method

The aerodynamic method considers the **ability to transport water vapor away from the water surface**. This is generated by the **humidity gradient** in the air near the surface and the **wind speed** across the surface.

These processes can be analyzed by coupling the equation for mass and momentum transport in the air. Considering the control volume below, the vapor flux passing upward by convection can be defined along with the momentum flux (as a function of the humidity gradient and the wind velocity gradient, respectively).



(We will skip the details of the derivation here)

The aerodynamic method

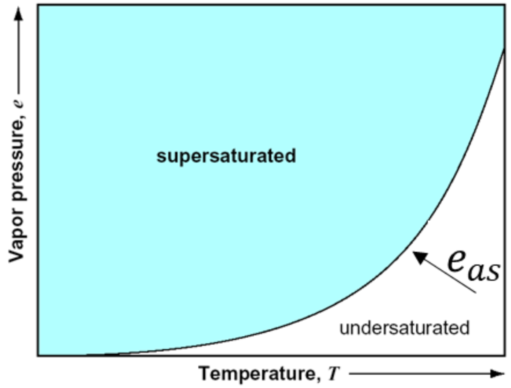
Thornthwaite-Holzman equation (1939) for transport-limited evaporation.

The main idea is that evaporation E_a [mm/day] is **proportional to the vapor pressure deficit** (VPD):

$$E_a = B \cdot VPD = B \cdot (e_{as} - e_a)$$

where:

- B [mm/day/Pa] is a vapor transfer coefficient
- e_{as} [Pa=N/m^2] is vapor pressure at the surface, i.e. the saturation vapor pressure at ambient air temperature (when the rate of evaporation and condensation are equal)
- e_a [Pa] is the ambient vapor pressure in the air.



- The dependence of the saturation vapor pressure on **temperature** can be expressed, in Pa, as (T in the equation is in ºC):

$$e_{as} = 611 \cdot \exp\left(\frac{17.27 \cdot T}{237.3 + T}\right)$$

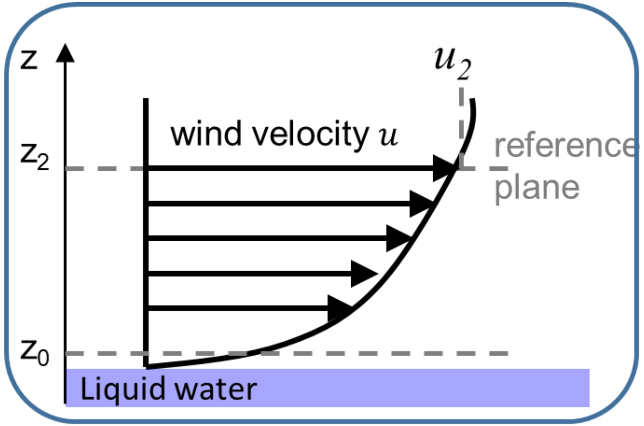
- The ambient vapor pressure can be related to saturation vapor pressure through **relative humidity** R_h $(0 < R_h \leq 1)$:

$$e_a = R_h \cdot e_{as}$$

The aerodynamic method

- B [mm/day/Pa] is expressed as a function of the wind speed as

$$B = \frac{0.102\, u_2}{\left(\ln \frac{z_2}{z_0}\right)^2}$$



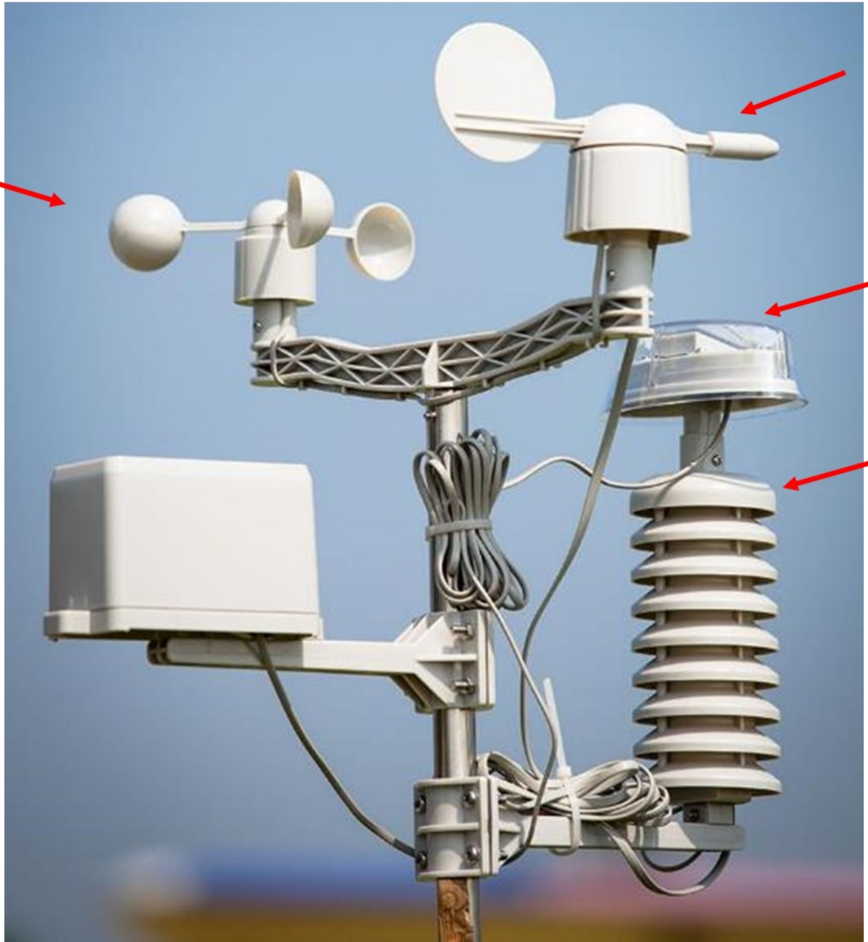
where u_2 is the **wind velocity** [m/s] measured at a reference height z_2 [cm] and z_0 [cm] is the **roughness height** of the water surface.

The roughness height usually takes values **between 0.01 and 0.06 cm**, while the reference elevation for wind speed measurements is generally **2 m**.

Thus, with the aerodynamic method, evaporation can be computed as:

$$E_a = B\,(e_{as} - e_a) = \frac{0.102\, u_2}{\left(\ln \frac{z_2}{z_0}\right)^2} VPD$$

The aerodynamic method: the need for meteorological data



The aerodynamic method: example

For a particular location the average net radiation is 185 W/m², air temperature is 28.5 ºC, relative humidity is 55%, and wind speed is 2.7 m/s at a height of 2 m. Determine the open water evaporation rate in mm/d using the aerodynamic method.

Assume the roughness height $z_0 = 0.03$ cm.

Solution:

- $e_{as} = 611 \cdot \exp\left(\frac{17.27 \cdot 28.5}{237.3+28.5}\right) = 3893$ Pa
- $e_a = R_h \cdot e_{as} = 0.55 \cdot 3893 = 2141$ Pa
- $B = \frac{0.102\, u_2}{\left(\ln\frac{z_2}{z_0}\right)^2} = \frac{0.102 \cdot 2.7}{\left(\ln\frac{200}{0.03}\right)^2} = 0.0036$ mm/(Pa·day)
- $E_a = B \cdot VPD = B \cdot (e_{as} - e_a) = 0.0036 \cdot (3893 - 2141) = 6.31$ mm/d

(quite similar to the energy balance method, but ONLY for that set of parameters)

Combined methods

When the energy supply is not limiting, the aerodynamic method can be used, and when the vapor transport is not limiting, the energy balance method can be used. However, both of these factors are not normally limiting, so a combination of these methods is usually required.
Thus, combined formulas are a **weighted sum of the energy balance and aerodynamic method**:

Energy balance term

$$E = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_a$$

Aerodynamic term

where:

- $\gamma =$ *psychrometric constant* (~66.8 Pa/ºC), although slight pressure and temperature dependence
- $\Delta = \frac{de_{as}}{dT} =$ *gradient of the saturated vapor pressure curve* $= \frac{4098\, e_{as}}{(237.3+T)^2}$, according to the formula shown before

Combined method: example

Solve the previous example via the combined method.

Solution:

- Evaluate $\Delta = \frac{4098\, e_{as}}{(237.3+T)^2} = \frac{4098 \cdot 3893}{(237.3+28.5)^2} = 225.8$ Pa/ºC
- Assume $\gamma = 66.8$ Pa/ºC
- $E = \frac{\Delta}{\Delta+\gamma} E_r + \frac{\gamma}{\Delta+\gamma} E_a = \frac{225.8}{225.8+66.8} 6.6 + \frac{66.8}{225.8+66.8} 6.31 = 6.53$ mm/day

Combined methods: Priestley-Taylor equation

The combination method is best for application to small areas with detailed climatological data including net radiation, air temperature, humidity, wind speed, and air pressure.

For very large areas, energy largely governs evaporation. Priestley and Taylor (1972) discovered that the aerodynamic term in the previous equation is approximately 30% of the energy term, so that the equation for the combined method can be simplified to:

$$E = 1.3\left(\frac{\Delta}{\Delta+\gamma}\right)E_r$$

Exercise (continued): solve the previous example via the Priestley-Taylor method.

Solution: $E = 1.3\left(\frac{\Delta}{\Delta+\gamma}\right)E_r = 1.3\,\frac{225.8}{225.8+66.8}\,6.6 = 6.62$ mm/day

Combined methods: Penman equation

By combining the evaporation and heat constitutive laws with the energy balance, one can derive the Penman equation for the evaporation flux, E, from a saturated surface:

$$l_v E = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} f_u VPD$$

where f_u is a "wind function' that can take various forms. One possible expression is $f_u = 6.43(1 + 0.563\, u_2)$, where u_2 is wind speed (m/s) 2 meters above the ground. In this case R_n is in MJ/m²/day, VPD in kPa, l_v in MJ/kg, and E in mm/day.

(here we implicitly assume division by $\rho_w = 1000$ kg/m³ to obtain E in units of mm/day)

Exercise (continued): solve the previous example via the Penman method.

Solution:

- $f_u = 6.43(1 + 0.563 \cdot 2.7) = 16.2$
- $E = \dfrac{\frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} f_u VPD}{l_v} = \dfrac{\frac{225.8}{225.8+66.8} 185 \cdot 86400 \cdot 10^{-6} + \frac{66.8}{225.8+66.8} 16.2 \cdot 1752 \cdot 10^{-3}}{2.43} = 7.73$ mm/day

Combined methods: Penman equation

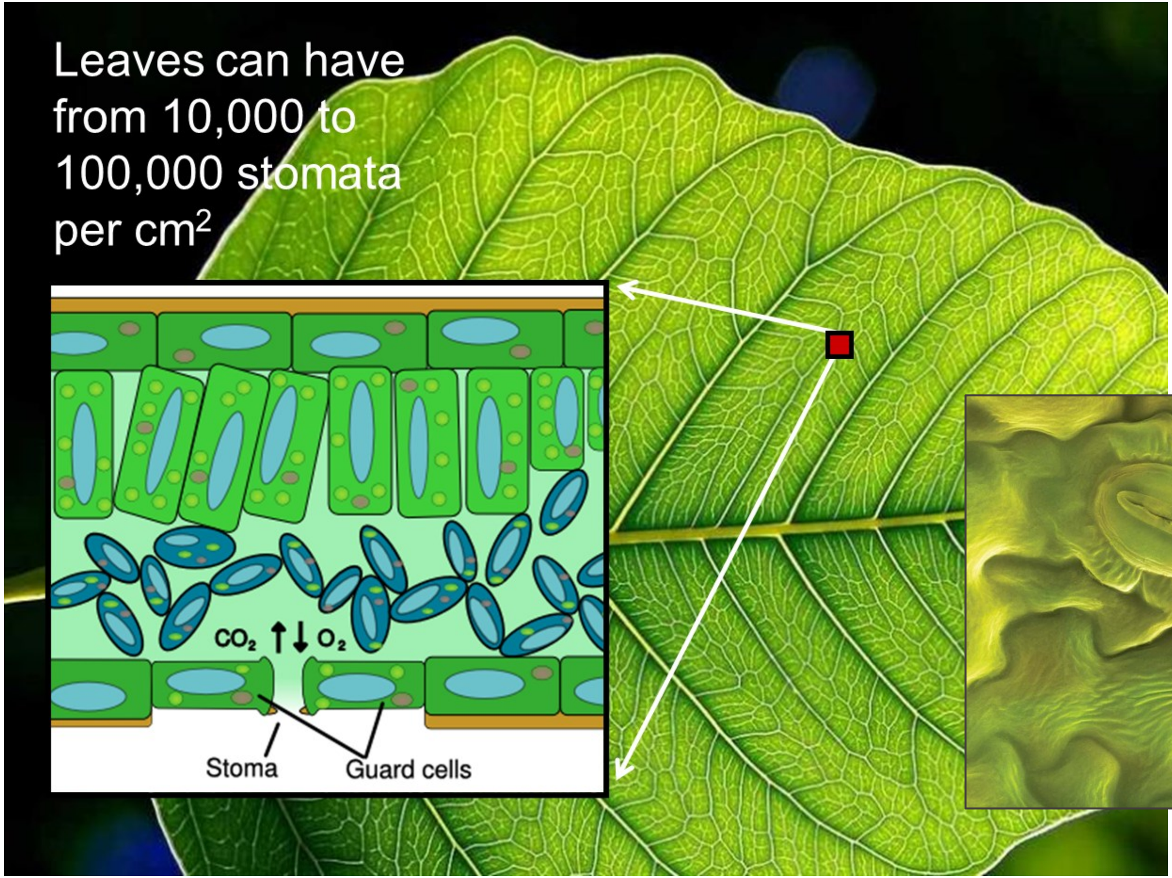
The Penman equation is often expressed in an equivalent form where the **aerodynamic resistance** r_a is used instead of the wind function:

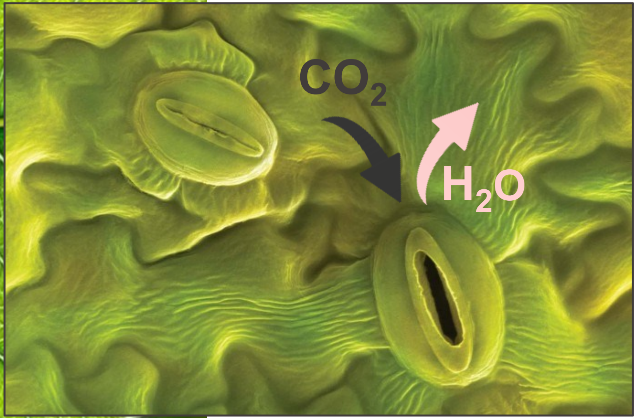
$$l_v E = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\rho \, {}^{c_p}/_{r_a}}{\Delta + \gamma} VPD$$

where $c_p = 0.622\, \ell_v\, \gamma\, /p$ is the heat capacity of moist air (approx. 1.013 KJ / Kg / °C), p is the atmospheric pressure (constant) and ρ is the air density.

Note that possible ground losses G (neglected so far) are usually expressed as a fraction of R_n.

Transpiration



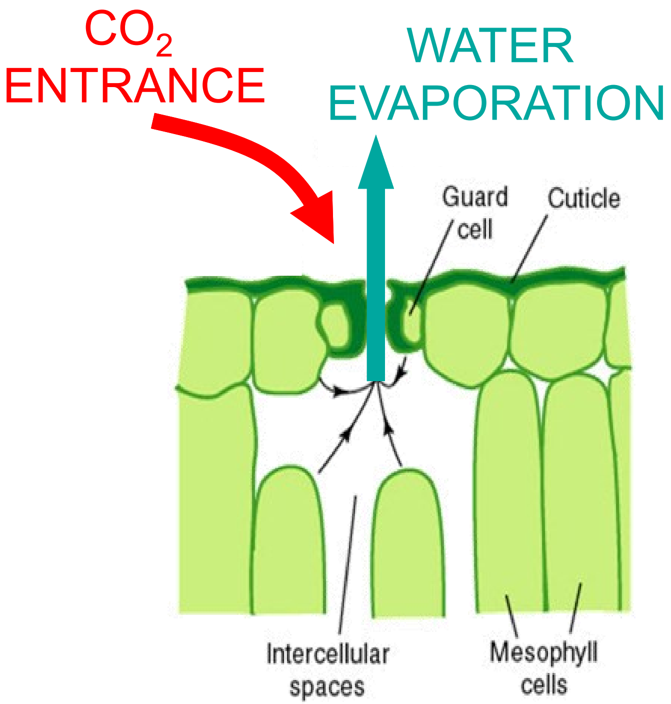


nature.com

http://en.wikipedia.org/wiki/Image:Leaf_anatomy.svg

Transpiration

STOMATA: small intracellular openings (~µm) in the epidermic tissue of the leaves (mostly located in the lower leaf surface), regulated by guard cells, through which water vapor is released, and $C0_2$ is incorporated by plants



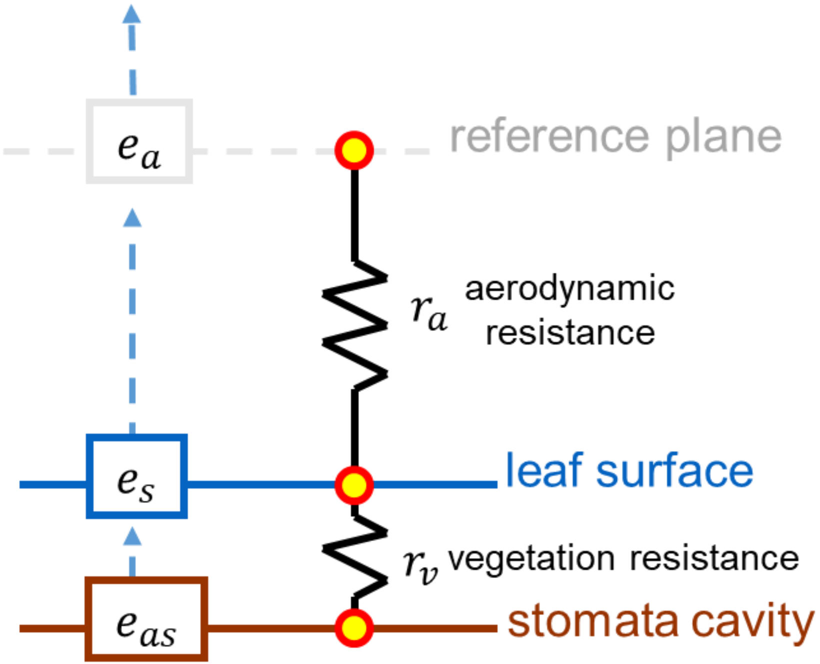
REGULATION = plants are able to regulate the opening degree of the stomata....

COMPROMISE:
high (low) water losses
vs.
high (low) carbon assimilation

Transpiration: physical differences between E and T

1) we need to **include the control exerted by vegetation** on the vapor flux

2) we need to take into account the fact that the source of water is inside the leaves, and thus **the air above transpiring canopies is NOT SATURATED** (differently from evaporation from a water body, above which the air is almost saturated)



Transpiration: Penman equation

The **Penmann equation remains valid** for the transpiration flux, provided that the psychometric constant γ is replaced by $\gamma(1 + r_v/r_a) > \gamma$ to take into account for the non-saturated conditions above the canopy.

$$\ell_v \, Tr = \frac{\Delta}{\Delta + \gamma\,(1 + r_v/r_a)} R_n + \frac{\rho\, c_p/r_a}{\Delta + \gamma\,(1 + r_v/r_a)} VPD$$

However, this approach in unpractical because the vegetation resistance r_v is very difficult to estimate.

We need to find more empirical and application-oriented approaches.

Evapotranspiration (for engineers)

The **combined effect** of vaporisation from liquid or wet surfaces and due to the role of vegetation stomata is usually termed **evapotranspiration** and is generally indicated with the term ET.

ET is a key element for hydrological evaluations of water fluxes subtracted to the rainfall-runoff transformations and depends on the resistance to evaporation exerted by distributed and various assemblages of vegetation types.

Evaporation by plants occurs in conjunction with **photosynthesis**.

It should be clear that <u>**our treatment skips entire disciplines**</u> to come up with reasonable empirical estimates of the rates of daily water loss from large surfaces hosting diverse assemblages of vegetation – fundamental to engineering hydrology.

Evapotranspiration: methods

Table 6.35
Methods for Estimating Evapotranspiration

Classification	Method	References
Combination	Penman-Monteith	Monteith (1965); Allen (1986); Allen et al. (1989)
	Penman	Penman (1963)
	1972 Kimberly-Penman	Wright and Jensen (1972)
	1982 Kimberly-Penman	Wright (1982)
	FAO-24 Penman	Doorenbos and Pruitt (1975; 1977)
	FAO-PPP-17 Penman	Frére and Popov (1979)
	Businger-van Bavel	Businger (1956); van Bavel (1966)
Radiation	Jensen-Haise	Jensen and Haise (1963); Jensen et al. (1971)
	FAO-24 Radiation	Doorenbos and Pruitt (1975; 1977)
	Priestly-Taylor	Priestly and Taylor (1972)
	Turc	Turc (1961); Jensen (1966)
Temperature	NRCS Blaney-Criddle	USDA (1970)
	FAO-24 Blaney-Criddle	Doorenbos and Pruitt (1977); Allen and Pruitt (1986)
	Hargreaves	Hargreaves et al. (1985); Hargreaves and Samani (1985)
	Thornthwaite	Thornthwaite (1948); Thornthwaite and Mather (1955)
Evaporation-pan	Christiansen	Christiansen (1968); Christiansen and Hargreaves (1969)
	FAO-24 Pan	Doorenbos and Pruitt (1977)

Source: ASCE, 1990. *Evapotranspiration and Irrigation Water Requirements.* p. 165. Reprinted by permission of ASCE.

still ongoing research – yet very important applications

ET: Penman-Monteith equation

The idea is to apply the PM equation for transpiration using effective values of the climate parameters (T, u, e_s...) and replacing the vegetation resistance with an effective surface resistance r_s embedding the resistances to soil evaporation and grass transpiration.

$$\ell_v \, ET = \frac{\Delta(R_n - G) + \rho \, c_p / r_a VPD}{\Delta + \gamma \, (1 + r_s / r_a)}$$

But we further need a **STANDARD** methodology that can be used and compared across landscapes worldwide.

This standard has been provided by **FAO** (the UN Food and Agriculture Organization) in **1990**.

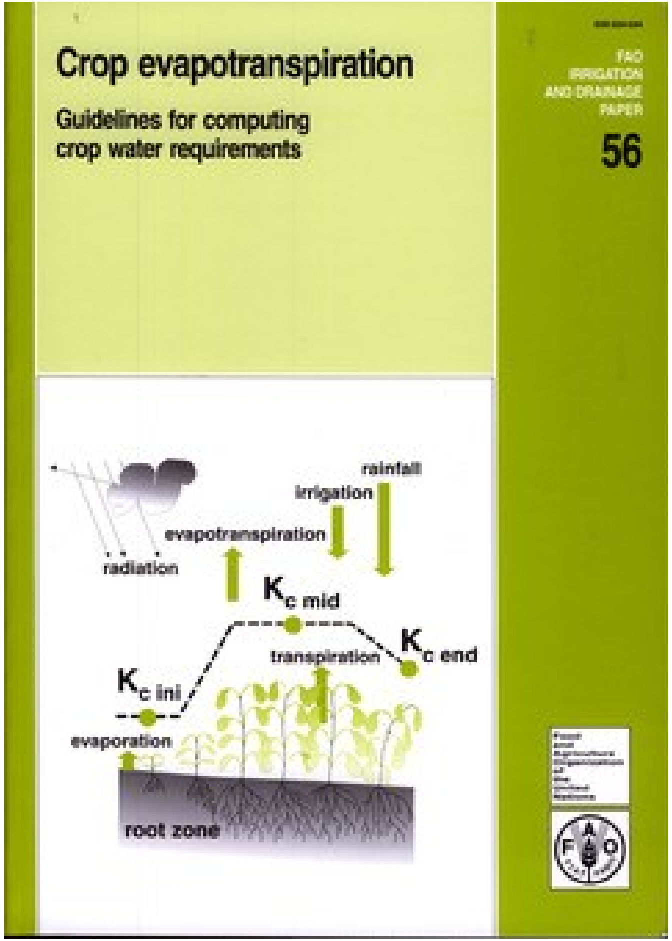
See: https://www.fao.org/3/x0490e/x0490e06.htm#formulation%20of%20the%20penman%20monteith%20equation

ET: the FAO approach

A large number of more or less empirical methods have been developed by numerous scientists and specialists worldwide to estimate ET from different climatic variables.

Relationships were often subject to rigorous local calibrations and proved to have limited global validity. Testing the accuracy of the methods under a new set of conditions is laborious, time-consuming and costly, and yet ET data are frequently needed at short notice for project planning or irrigation scheduling design.

To meet this need, guidelines were developed and published in the FAO Irrigation and Drainage Paper No. 24 'Crop water requirements'.



https://www.fao.org/3/X0490E/x0490e00.htm

The FAO approach: a three-step procedure

1. Compute the evapotranspiration that a **reference crop** (an active grassfield) would produce during its growing season in the absence of limitations induced by water stress (**well-watered conditions**), under the actual CLIMATE CONDITIONS

   → **Reference potential evapotranspiration (ET_0)**

2. Compute the evapotranspiration that the **actual crop** during its **actual LIFE CYCLE**, would produce in the absence of limitations induced by water stress

   → **Potential evapotranspiration (ET_c)**

3. Compute the actual evapotranspiration of the actual crop, under the **actual environmental conditions and WATER AVAILABILITY**

   → **Actual evapotranspiration (ET)**

The FAO approach: STEP 1 (ET_0)

Step 1: Reference potential evapotranspiration (ET_0)

The reference crop is a hypothetical grass crop with an assumed crop height h of 0.12 m (which implies aerodynamic resistance $r_a = 208/u_2$ [s/m]), a fixed surface resistance r_s of 70 s/m and an albedo α of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s/m implies a moderately dry soil surface resulting from about a weekly irrigation frequency.

By using the reference crop and standard values for the equation constants, the $\boldsymbol{ET_0}$ simplifies to:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\dfrac{900}{T+273}\,u_2\,VPD}{\Delta + \gamma(1 + 0.34\,u_2)}$$

Note: the units of the constants do not appear explicitly in the equation (so the dimensions may appear inconsistent). Thus, **the following units should be used strictly**:
R_n [MJ/m^2/d], Δ [kPa/degC], γ [kPa/degC], T [degC], u_2 [m/s], VPD [kPa].

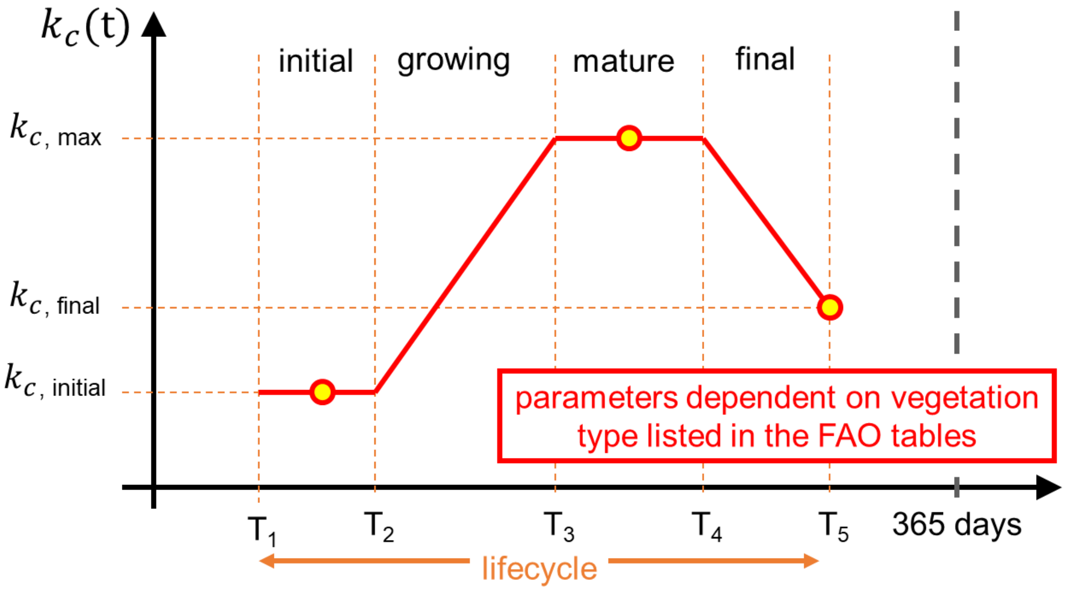
This results in ET_0 in kg/m^2/d, which is equivalent to mm/d.

The FAO approach: STEP 2 (ET_c)

Step 2: Crop potential evapotranspiration (ET_c)

Use of crop coefficients $k_c(t)$ that relate the actual crop in the actual growing season to the reference evapotranspiration:

$$ET_c = k_c\, ET_0$$

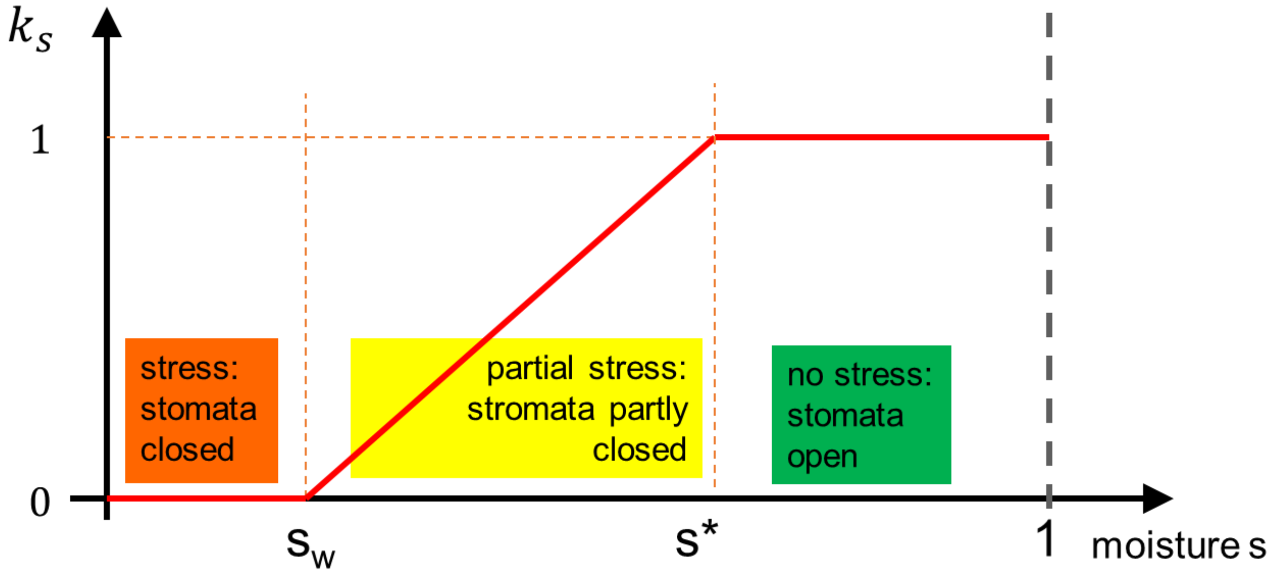


The FAO approach: STEP 3 (ET)

Step 3: Actual evapotranspiration (ET)

Use of stress coefficients $k_s(t)$ that relate the potential evapotranspiration to the actual water availability:

$$ET = k_s\, ET_c = k_s\, k_c\, ET_0$$



The FAO approach: example from South Africa

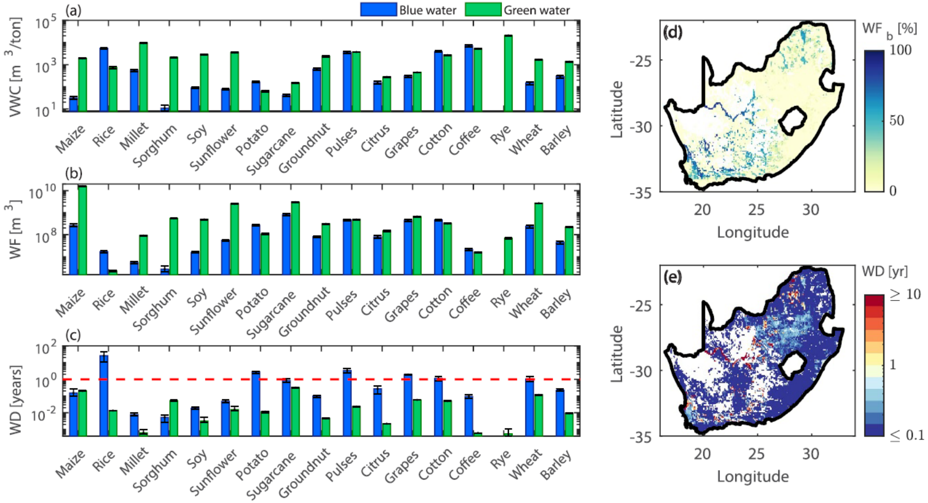
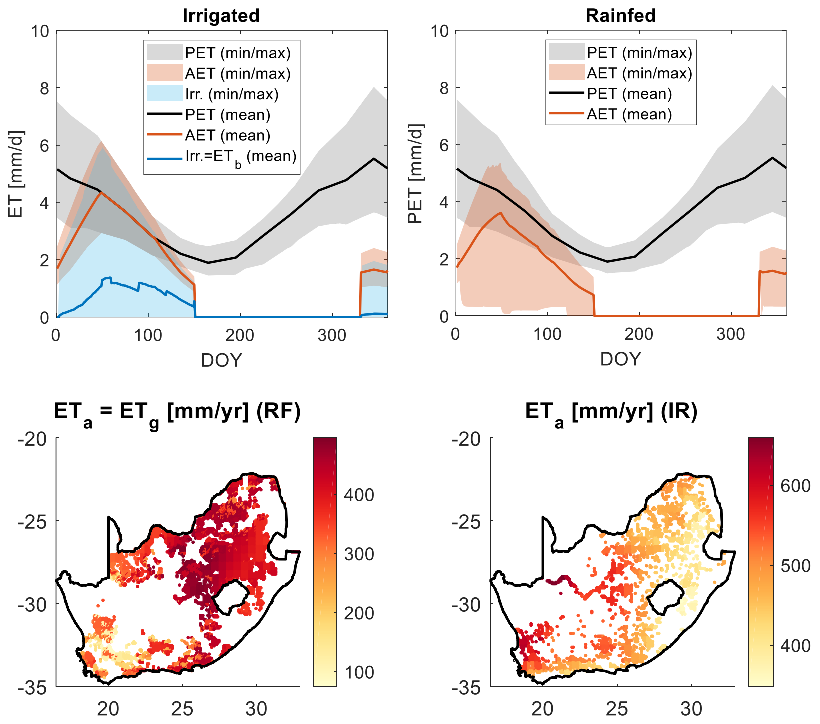


Figure 2. Water sustainability of current South African crop production. Country level values of green and blue (a) average VWC (i.e. production-weighted average), (b) total WF (i.e. sum over all cells), and (c) average WD (i.e. production-weighted average) for the reference year 2000. Box plots were obtained as averages from the five climate models, error bars show the maximum and minimum values obtained from the different climate models. The red dashed line in panel (c) marks the value of WD = 1 year. Spatial distribution of (d) percentage of blue WF and (e) WD values at the grid level (considering all crops, average across five climate models). The colorbar in panel (e) was truncated between 0.1 and 10 yr to favor comparison.



[Bonetti et al. (2022)](#)

ET: the Blaney-Criddle equation

Simplified method for the estimation of the **reference crop evapotranspiration ET_0 [mm/day]**:

$$ET_0 = p \cdot (0.46T + 8.13)$$

where:

- T [degC] is the mean daily temperature **over the month considered**
- p is the daily percentage of total annual daytime hours (given as a function of the month of the year under study and the latitude of the location where ET needs to be evaluated – see next slide)

Note: **this is applied at MONTHLY timescale**!

ET: the Blaney-Criddle equation (example)

S. Bonetti

Given:
- Latitude: 35º North
- Mean T_{max} in April = 29.5 ºC
- Mean T_{min} in April = 19.4 ºC

Question: determine, for the month of April and at the given location, the mean ET_0 in mm/day using the Blaney-Criddle method

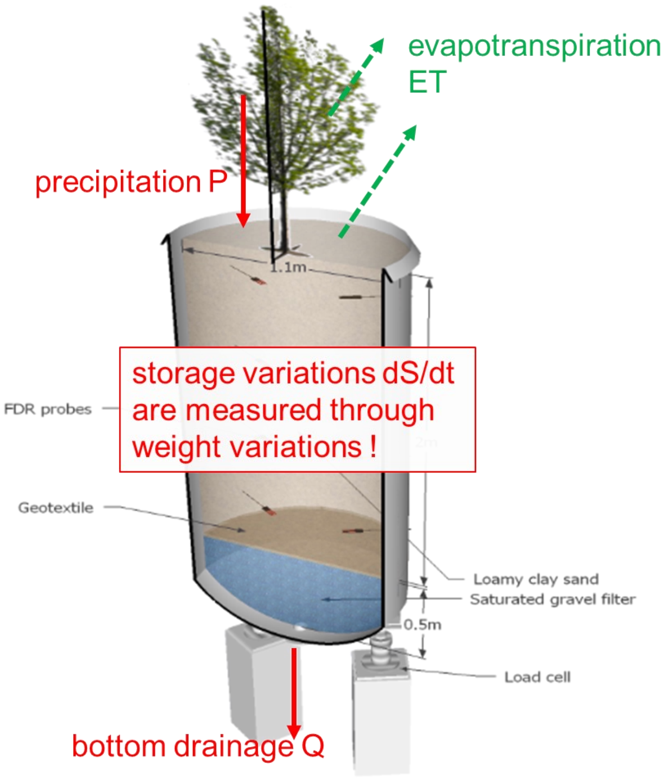
Table 4 MEAN DAILY PERCENTAGE (p) OF ANNUAL DAYTIME HOURS FOR DIFFERENT LATITUDES

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°		.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
55		.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
50		.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
45		.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
40		.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35		.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30		.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25		.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20		.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15		.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10		.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5		.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0		.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

https://www.fao.org/3/S2022E/s2022e07.htm#3.1.3%20blaney%20criddle%20method

Solution:
- Determine $T_{mean} = \frac{T_{max}+T_{min}}{2} = \frac{29.5+19.4}{2} = 24.5$ ºC
- From the table (given latitude, month of April): $p = 0.29$
- Compute $ET_0 = p \cdot (0.46T + 8.13) = 0.29 \cdot (0.46 \cdot 24.5 + 8.13) = 5.6$ mm/day

ET: water balance approach



Certain experimental setups provide an **indirect estimate of** ET.

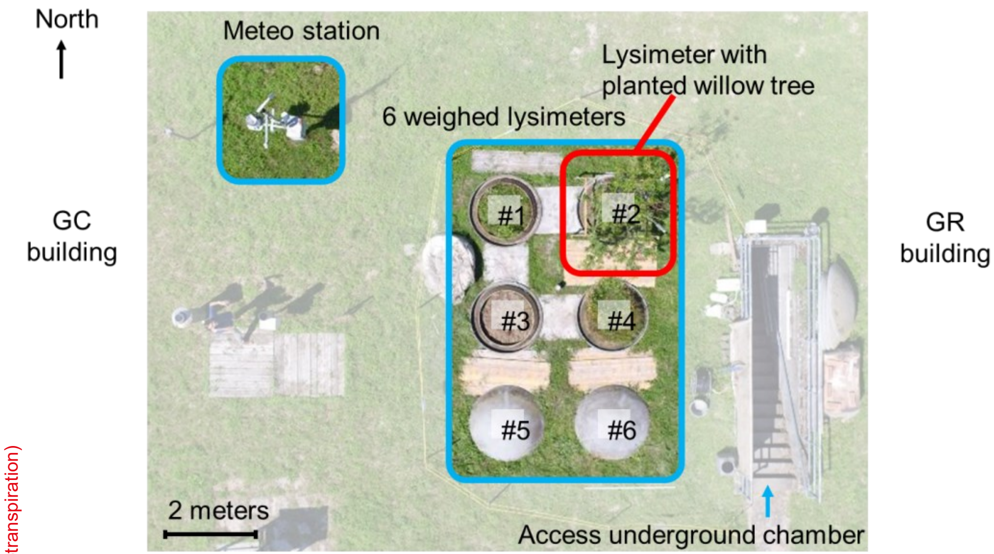
This is the case of **lysimeters** where the water budget is allowed by direct measurement of the weight of the system.

Thus, by measuring input and output fluxes and the state variable (the weight → the volume of stored water), the outgoing vaporization flux E is treated as the unknown closure of the continuity for the control volume that includes the land-surface-atmosphere interface as a boundary:

$$\frac{dS}{dt} = P - Q - ET$$

S. Bonetti

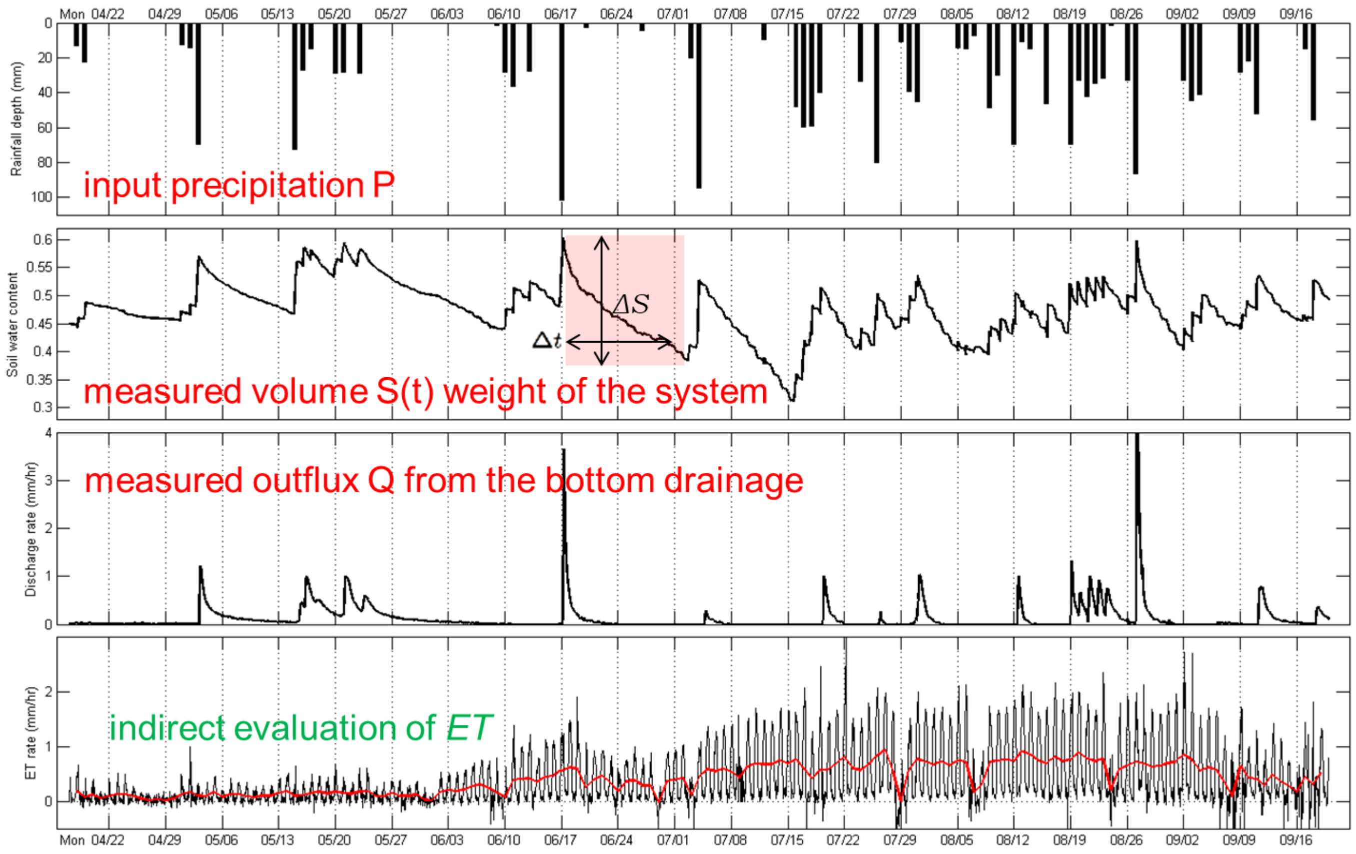
Water balance approach: lysimeters



- A lysimeter is an artificially enclosed volume of soil, usually planted with grass or similar vegetation, for which the inflows and outflows of liquid water can be measured and changes in storage can be monitored by weighing.
- Lysimeters range from 1 m^2 or less to over 150 m^2 in size.
- ET evaluated in conditions identical to those of the surrounding area.
- Carefully obtained lysimeter measurements are usually considered to give the best determinations of actual ET or, if well-watered conditions are maintained, ET_0 or ET_c, and are often taken as standards against which other methods are compared

- Lysimeters must be carefully constructed to reproduce surrounding soil and vegetation. They must have provisions for drainage that closely mimic drainage in the natural soil so that the water-content profile, and hence the evapotranspiration rate, are similar to those in the surrounding soil. It is virtually impossible to use this technique for forest vegetation.

ET: water balance approach



$$\frac{dS}{dt} = P - Q - ET \quad \rightarrow \quad ET \sim P - Q - \frac{dS}{dt}$$

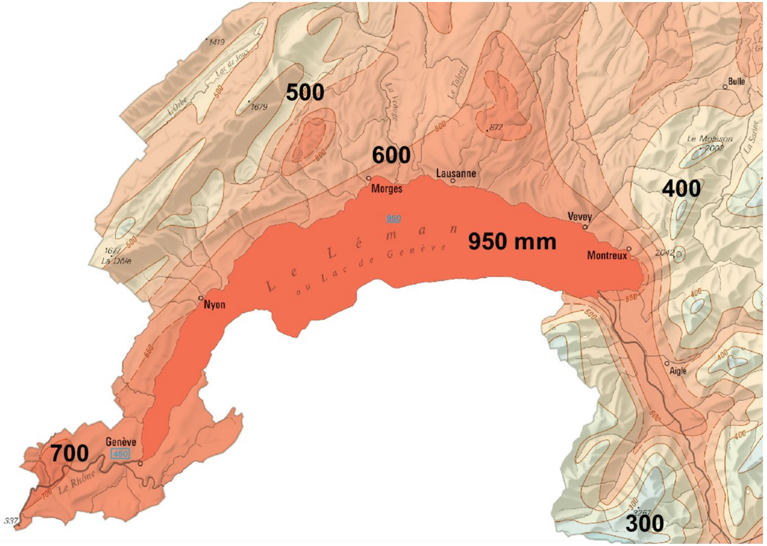
Water balance approach: practical considerations

The water balance approach can be used also for the assessment of E, ET, or T from any control volume.

However, while the water-balance approach is simple in concept, it is generally far from simple in application, because the measurement of all water inputs and outputs is generally a formidable task.

For example, for evaporation from a *lake*:

- All major **streams** entering the body and the outlet stream must be continuously gauged, and some method must be devised for estimating the amount of **any non-channelized surface-water flow inputs**.
- It is difficult to **assess ground-water inflows and outflows** to lakes. At best, these are usually estimated from gradients observed in a few observation wells and assumptions about the saturated thickness and hydraulic conductivity of surrounding geologic formations, perhaps supplemented by scattered observations with seepage meters.
- If the lake is large and the surrounding topography irregular, it may be difficult to obtain **precise measurements of precipitation**.
- **Changes in storage** can be estimated from careful observations of water levels if one has good information on the lake's bathymetry, and if corrections are made for changes in water density.



References and questions

- **Dingman**, Physical Hydrology **(Ch. 2 and 6)**
- **Brutsaert**, Hydrology An Introduction **(Ch. 4)**
- **Mays**, Water Resources Engineering **(Ch. 7)**

(Non-exhaustive) list of possible questions on Lecture IV:

- Explain the difference between mass balance, aerodynamic, and combined approaches for the estimation of evaporation.
- When is ET transport-limited? And supply-limited?
- What is the difference between potential and actual ET?
- How is ET measured via the water balance method? Draw the control volume for the case of a lysimeter, the fluxes involved, and write the bass balance equation. What are the practical difficulties in water balance-based ET estimations?
- See examples and exercises in the slides.