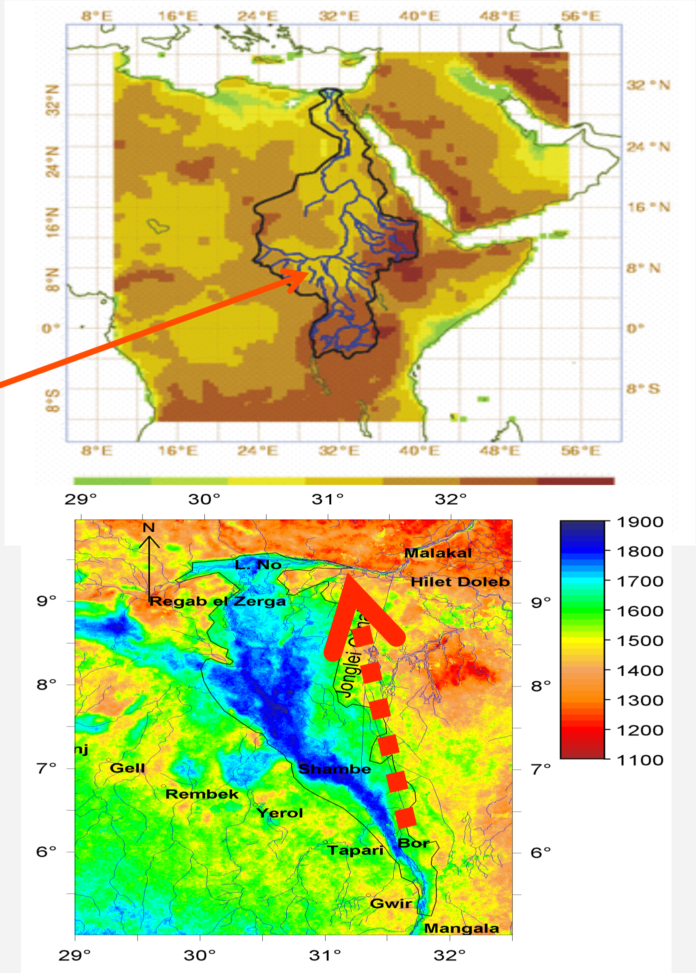
GWC 2: Evaporation

CTB3300WCx: Introduction to Water and Climate

Prof.dr.ir. Hubert H.G. Savenije

Importance of Evaporation

- Generally the largest outgoing flux
  - Particularly in dry climates
- Is often seen as a 'loss' (Sudd)
- But is an important supplier of continental precipitation (moisture recycling)



Types of Evaporation

- Direct evaporation *(physical process)*
  - Open water evaporation E_o
  - Soil evaporation E_s
  - Interception evaporation E_i
  - Sublimation of snow or ice E_{snow}
- Transpiration E_T *(bio-physical process)*
- Total evaporation $E = E_o + E_s + E_i + E_{snow} + E_T$

Evaporation or ‘evapotranspiration’

Avoid to use the term ‘Evapotranspiration’

- ‘Evapotranspiration’ is opaque jargon for **bulk evaporation,** masking that we do not know its composition

  → *Use (total) evaporation instead*

Potential Evaporation

Potential evaporation, E_p

- Would occur if there is no shortage of water,
- Or other factors that may limit transpiration *(temperature, solar radiation, humidity).*

Actual evaporation, E

- occurs if these stress factors are accounted for

Average (annual) evaporation

$$\bar{E} = \bar{P} - \bar{Q}$$

$\bar{Q}$ is the mean annual runoff [mm/a]
$\bar{P}$ is the mean annual precipitation [mm/a]
$\bar{E}$ is the mean annual evaporation [mm/a]

$$\frac{\bar{E}}{\bar{P}} = 1 - \frac{\bar{Q}}{\bar{P}} = 1 - C_R$$

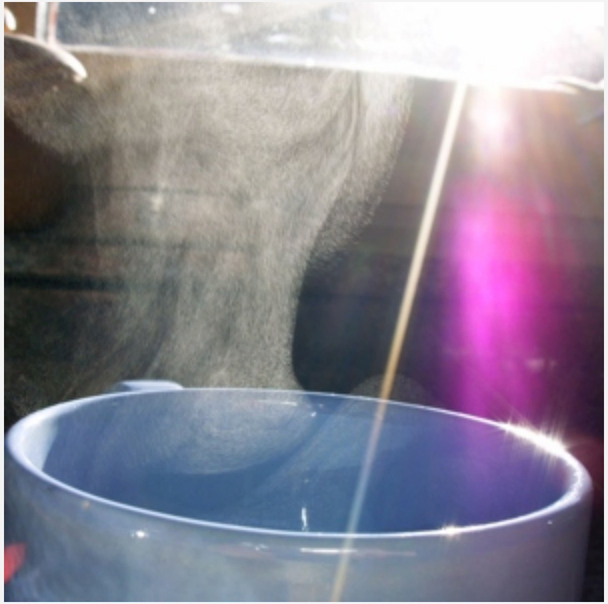
Actual evaporation

$$E \leq E_p$$

Energy constraint

$$\bar{E} \leq \bar{P}$$

Moisture constraint

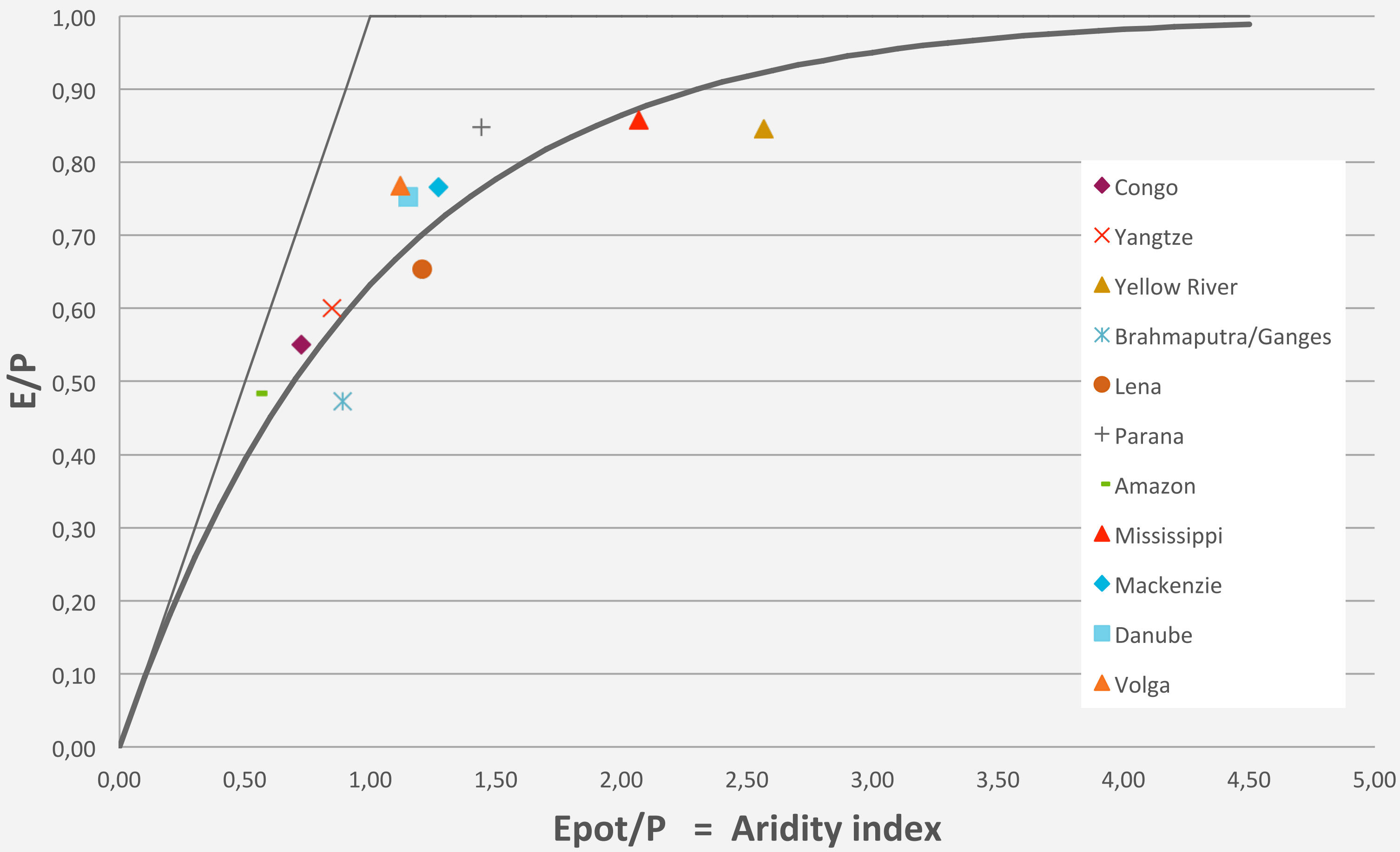


Budyko Curve

$$\frac{\bar{E}}{\bar{P}} = \left(1 - \exp\left(-\frac{\bar{E}_p}{\bar{P}}\right)\right) = 1 - C_R$$

- If P $\rightarrow 0$, $\boldsymbol{E = P}$
- If P $\rightarrow \infty$, $\boldsymbol{E = E_p}$

Budyko (1920-2001)


1,00
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
0,10
0,00
E/P
0,00
0,50
1,00
1,50
2,00
2,50
3,00
3,50
4,00
4,50
5,00
Epot/P = Aridity index
Congo
Yangtze
Yellow River
Brahmaputra/Ganges
Lena
Parana
Amazon
Mississippi
Mackenzie
Danube
Volga

Meteorological factors affecting evaporation

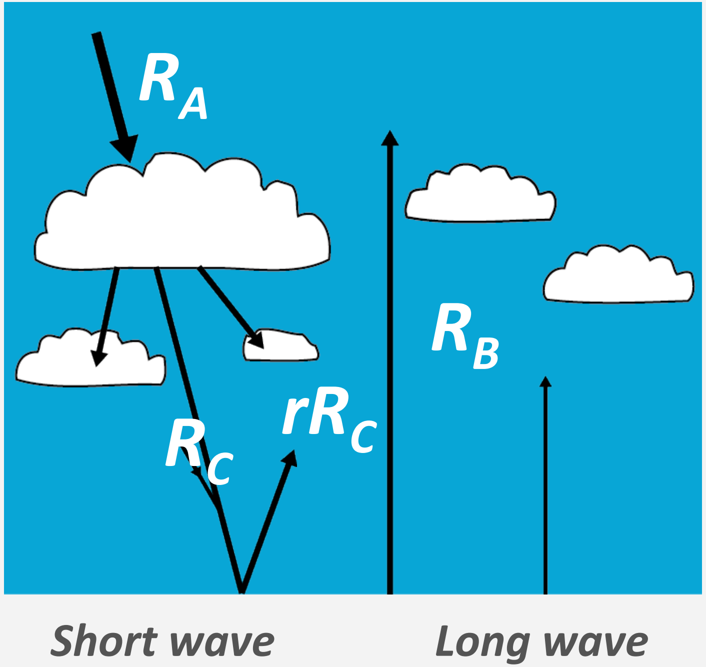
- Energy balance
- Radiation
- Humidity
- Aerodynamic resistance

Radiation Balance

$$R_N = (1 - r)R_C - R_B$$

R_N : Net short wave radiation [W/m^2]
R_C : Incoming short wave radiation
R_B : Outgoing long wave radiation
r : Albedo or whiteness

Surface	Albedo (r)
Open water	**0.06**
Grass	**0.24**
Bare soil	**0.10 – 0.30**
Fresh snow	**0.90**



Radiometer

Sunshine Recorder

- R_C can be determined empirically by the theoretical sun hours and n/N
- n/N is the ratio of recorded sun hours to the theoretical (potential) sun hours

Netherlands	$R_C = (0.20 + 0.48\ n/N)R_A$
Average	$R_C = (0.25 + 0.50\ n/N)R_A$
New Delhi	$R_C = (0.31 + 0.60\ n/N)R_A$
Singapore	$R_C = (0.21 + 0.48\ n/N)R_A$

Maximum amount of sun hours per day N

North Lats. / South Lats.	Jan / July	Feb. / Aug.	Mar. / Sept	Apr. / Oct.	May / Nov.	June / Dec.	July / Jan.	Aug. / Feb.	Sept / Mar.	Oct. / Apr.	Nov. / May	Dec. / June
60	6.7	9.0	11.7	14.5	17.1	18.6	17.9	15.5	12.9	10.1	7.5	5.9
58	7.2	9.3	11.7	14.3	16.6	17.9	17.3	15.3	12.8	10.3	7.9	6.5
56	7.6	9.5	11.7	14.1	16.2	17.4	16.9	15.0	12.7	10.4	8.3	7.0
54	7.9	9.7	11.7	13.9	15.9	16.9	16.5	14.8	12.7	10.5	8.5	7.4
52	8.3	9.9	11.8	13.8	15.6	16.5	16.1	14.6	12.7	10.6	8.8	7.8
50	8.5	10.0	11.8	13.7	15.3	16.3	15.9	14.4	12.6	10.7	9.0	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.4	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.9	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	12.0	10.6	10.8
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	12.0	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	12.0	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	12.0	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	12.0	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
Equator 0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Short wave radiation expressed in terms of evaporation RA/λ in kg m-2day-1

	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
	NORTHERN HEMISPHERE												
	60	1.4	3.6	7.0	11.1	14.6	16.4	15.6	12.6	8.5	4.7	2.0	0.9
	52	3.2	5.5	8.8	12.5	15.4	16.6	16.0	13.6	10.2	6.7	3.9	2.6
	50	3.7	6.0	9.2	12.7	15.5	16.6	16.1	13.7	10.4	7.1	4.4	3.1
	40	6.2	8.4	11.1	13.8	15.9	16.7	16.3	14.7	12.1	9.3	6.8	5.6
	30	8.1	10.5	12.8	14.7	16.1	16.5	16.2	15.2	13.5	11.2	9.1	7.9
	20	10.8	12.4	14.0	15.2	15.7	15.8	15.8	15.4	14.4	12.9	11.3	10.4
	10	12.8	13.9	14.8	15.2	15.0	14.8	14.9	15.0	14.8	14.2	13.1	12.5
Equator	0	14.6	15.0	15.2	14.7	13.9	13.4	13.6	14.3	14.9	15.0	14.6	14.3
	10	15.9	15.7	15.1	13.9	12.5	11.7	12.0	13.1	14.4	15.4	15.7	15.8
	20	16.8	16.0	14.5	12.5	10.7	9.7	10.1	11.6	13.6	15.3	16.4	16.9
	30	17.2	15.8	13.5	10.9	8.6	7.5	7.9	9.7	12.3	14.8	16.7	17.5
	40	17.3	15.1	12.2	8.9	6.4	5.2	5.6	7.6	10.7	13.8	16.5	17.8
	50	16.9	14.1	10.4	6.7	4.1	2.9	3.4	5.4	8.7	12.5	16.0	17.6
	60	16.5	12.6	8.3	4.3	1.8	0.9	1.3	3.1	6.5	10.8	15.1	17.5
	SOUTHERN HEMISPHERE												

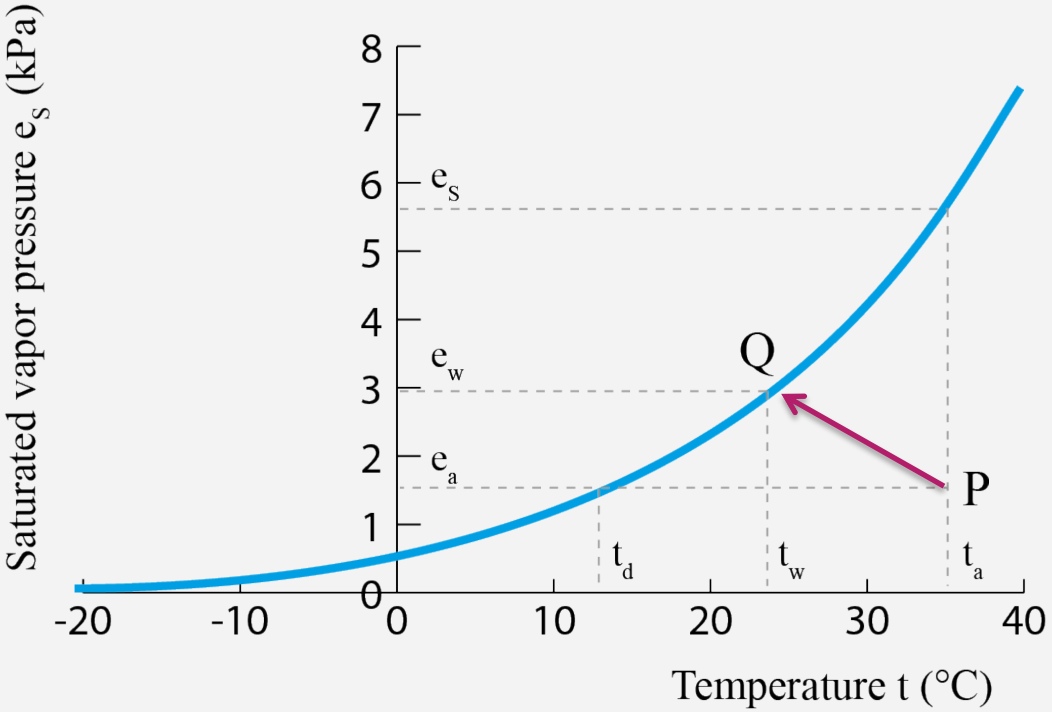
Outgoing Long wave radiation

- R_B is calculated through an empirical equation

$$R_B = \sigma(273 + t_a)^4 \left(0.47 - 0.21\sqrt{e_a}\right)\left(0.2 + 0.8\frac{n}{N}\right) \ [\mathrm{Jd^{-1}m^{-2}}]$$

left middle right

Humidity



$$e_s = 0.61\exp\left(\frac{19.9t_a}{273+t_a}\right)$$

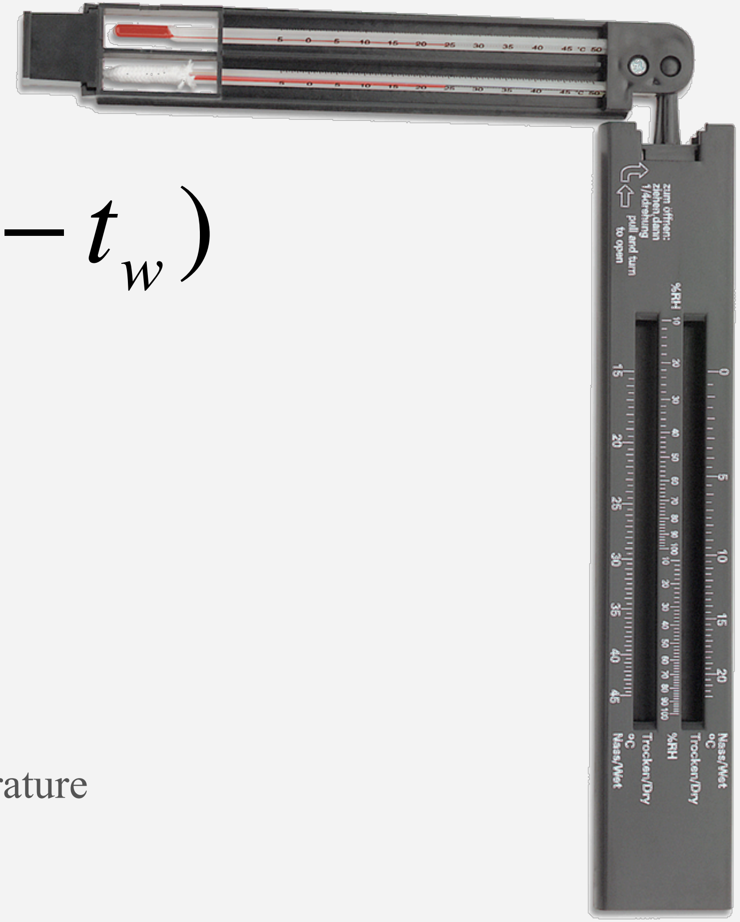
$$s = \frac{\mathrm{d}e_s}{\mathrm{d}t} = \frac{5430e_s}{\left(273+t_a\right)^2}$$

$$e_a(t_a) = e_s(t_w) - \gamma(t_a - t_w)$$

Psychrometer

$$e_a(t_a) = e_s(t_w) - \gamma(t_a - t_w)$$

$$h = \frac{e_a(t)}{e_s(t)}$$



t_a is the dry bulb temperature
t_w is the wet bulb temperature
$e_s(t_w)$ is the saturation pressure at the wet bulb temperature
γ is the psychrometer constant (0.066 kPa/^{o}C
h is the relative humidity

Energy balance

$$\frac{\Delta S_E}{\Delta t} = R_N - H - A - \rho\lambda E \quad [\mathrm{Wm}^{-2}]$$

Assume:
$\Delta S/\Delta t = 0,\ A = 0$

On daily basis !!

$$E = \frac{\left(R_N - H\right)}{\rho\lambda} = \frac{(1-r)R_C - R_B - H}{\rho\lambda} \quad [\mathrm{m/d}]$$

Penman (1948)

- Open water evaporation based on the energy balance,
- but making use of empirical relations
- 4 standard meteorological variables:
  - *air temperature*
  - *relative humidity*
  - *wind velocity*
  - *net radiation*

Penman Formula

$$E_o = \frac{\left(\frac{sR_N}{\rho\lambda} + \frac{c_p \rho_a}{\rho\lambda} \frac{e_s - e_a}{r_a} \right)}{s + \gamma} \text{ [m/d]}$$

$$r_a = \frac{245}{(0.54u_2 + 0.5)} \frac{1}{86400} \text{[d/ m]}$$

R_N	net radiation at the Earth surface	[J day^{-1} m^{-2}]
λ	heat of evaporation (λ = 2.45 MJ/kg)	[J kg^{-1}]
s	slope of the saturation pressure curve	[kPa K^{-1}]
c_p	specific heat of air (1004 J kg^{-1} K^{-1})	[J kg^{-1} K^{-1}]
ρ_a	density of air (1.205 kg/m3)	[kg m^{-3}]
ρ	density of water (1000 kg/m3)	[kg m^{-3}]
e_a	actual vapour pressure of the air at 2 m elevation	[kPa]
e_s	saturation vapour pressure for the temp. at 2 m elevation	[kPa]
γ	psychrometer constant (γ = 0.066 kPa/^{o}C)	[kPa K^{-1}]
r_a	aerodynamic resistance	[day m^{-1}]

Penman-Monteith

$$E_a = \frac{\left(\frac{sR_N}{\rho\lambda} + \frac{c_p \rho_a}{\rho\lambda} \frac{e_s - e_a}{r_a} \right)}{s + \gamma \left(1 + \frac{r_c}{r_a} \right)} \quad [\text{m/d}]$$

Crop resistance r_c

- Provides a constraint on the transpiration of vegetation
- Depends on the opening of stomata in leaves, as a function of:
  - *Soil moisture availability*
  - *Relative humidity*
  - *Sunlight*
  - *Temperature*

Evaporation of the World

Earth Syst. Dynam. Discuss., 5, 203-279, 2014
www.earth-syst-dynam-discuss.net/5/203/2014/
doi:10.5194/esdd-5-203-2014

Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Simple Terrestrial Evaporation to Atmosphere Model

Review Status

This discussion paper is under review for the journal Earth System Dynamics (ESD).

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Abstract. Terrestrial evaporation consists of biophysical (i.e., transpiration) and physical fluxes (i.e., interception, soil moisture, and open water). The partitioning between them depends on both climate and the land surface, and determines the time scale of evaporation. However, few land-surface models have analysed and evaluated evaporative partitioning based on land use, and no studies have examined their subsequent paths in the atmosphere. This paper constitutes the first of two companion papers that investigate the contrasting effects of interception and transpiration in the hydrological cycle. Here, we present STEAM (Simple Terrestrial Evaporation to Atmosphere Model) used to produce partitioned evaporation and analyse the characteristics of different evaporation fluxes on land. STEAM represents 19 land-use types (including irrigated land) at sub-grid level with a limited set of parameters, and includes phenology and stress functions to respond to changes in climate conditions. Using ERA-Interim reanalysis forcing for the years 1999–2008, STEAM estimates a mean global terrestrial evaporation of 73 800 km^3 $year^{-1}$, with a transpiration ratio of 59%. We show that the terrestrial residence time scale of transpiration (days to months) has larger inter-seasonal variation and is substantially longer than that of interception (hours). Furthermore, results from an offline land-use change experiment illustrate that land-use change may lead to significant changes in evaporative partitioning even when total evaporation remains similar. In agreement with previous research, our simulations suggest that the vegetation's ability to transpire by retaining and accessing soil moisture at greater depth is critical for sustained evaporation during the dry season. Despite a relatively simple model structure, validation shows that STEAM produces realistic evaporative partitioning and hydrological fluxes that compare well with other global estimates over different locations, seasons and land-use types. We conclude that the simulated evaporation partitioning by STEAM is useful for understanding the links between land use and water resources, and can with benefit be employed for atmospheric moisture tracking.

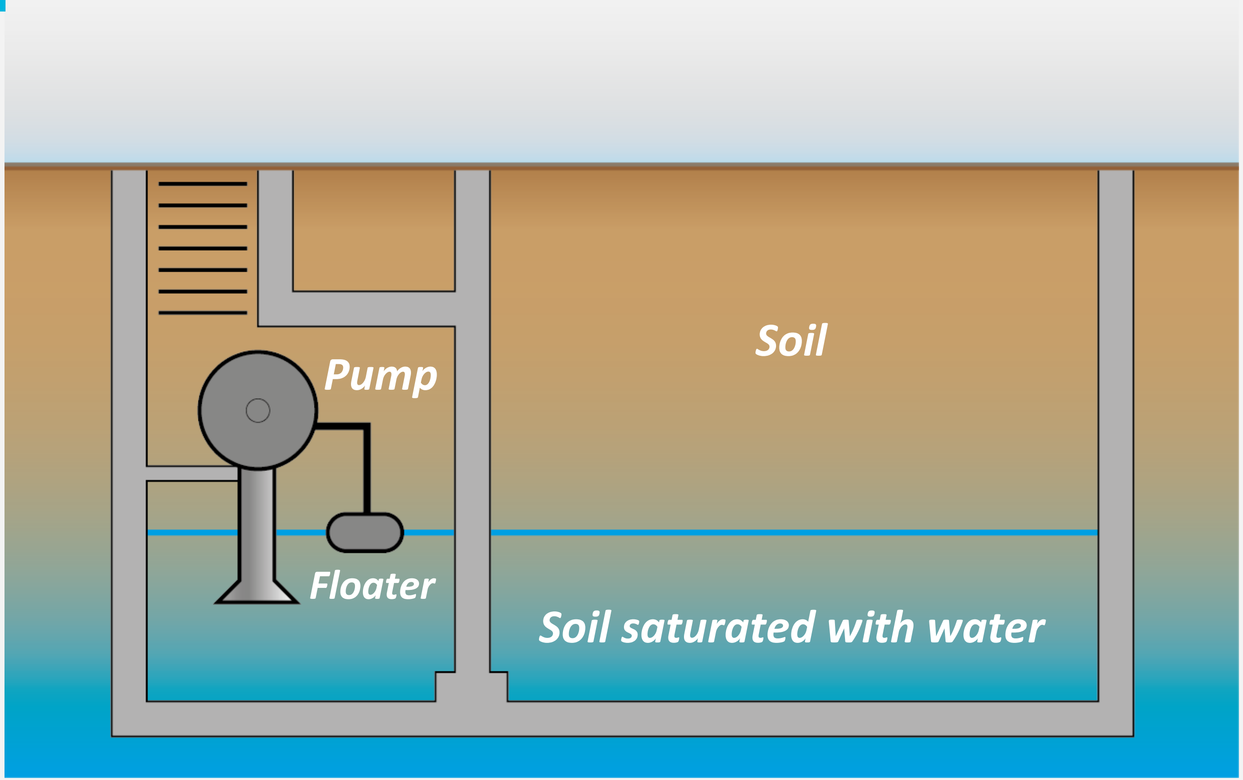
Direct measurement of evaporation

- Water balance: $$E = P - \frac{Q}{A} - \frac{\mathrm{d}S}{\mathrm{d}t}$$ [L/T]
- Evaporation pan
- Lysimeter
- Shallow Lysimeter

Pan evaporation

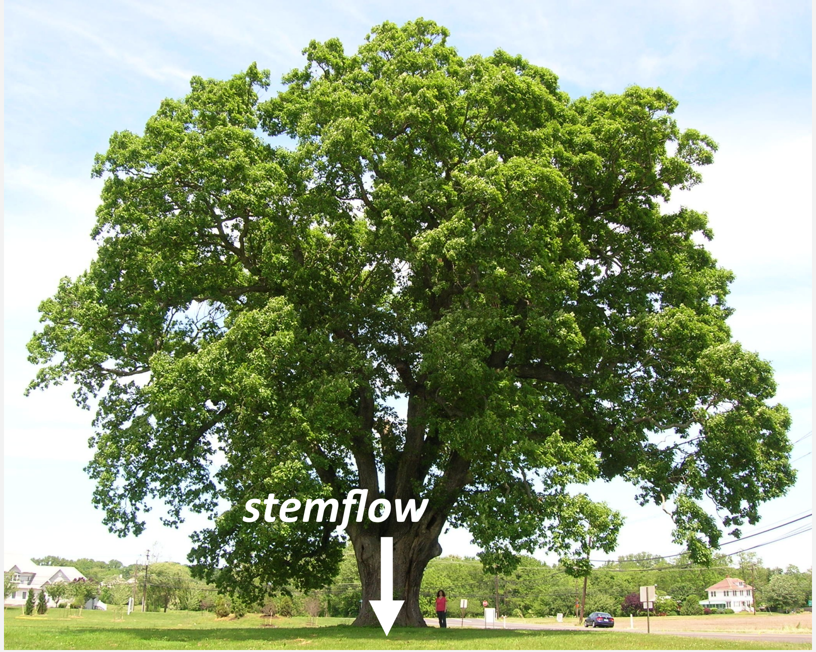
$$E_0 = k_{pan} E_{pan} \quad [\text{mm/d}]$$

Lysimeter



Interception measurement

Precipitation



Canopy interception

throughfall

Forest floor interception

Infiltration

Shallow Lysimeter

Hydrol. Earth Syst. Sci., 11, 695–701, 2007
www.hydrol-earth-syst-sci.net/11/695/2007/

Hydrology and Earth System Sciences

New technique to measure forest floor interception – an application in a beech forest in Luxembourg

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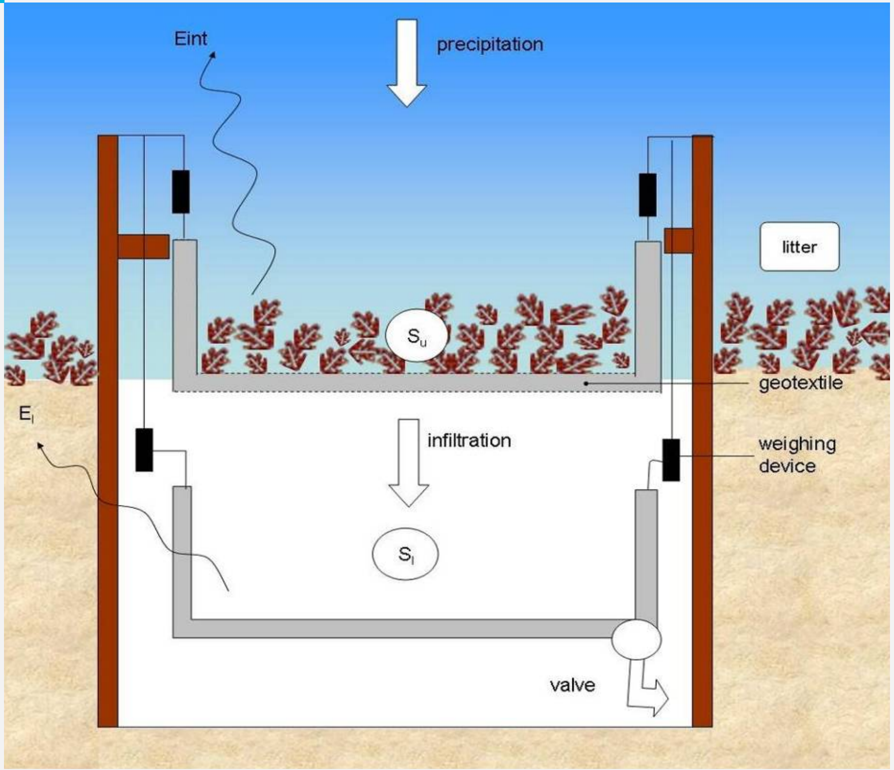
Shallow Lysimeter



$$\frac{dS_{upper}}{dt} + \frac{dS_{lower}}{dt} = P - E - \frac{Q}{A}$$

The evaporation tower

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Hydrology and Earth System Sciences
Open Access

A new method to measure Bowen ratios using high-resolution vertical dry and wet bulb temperature profiles

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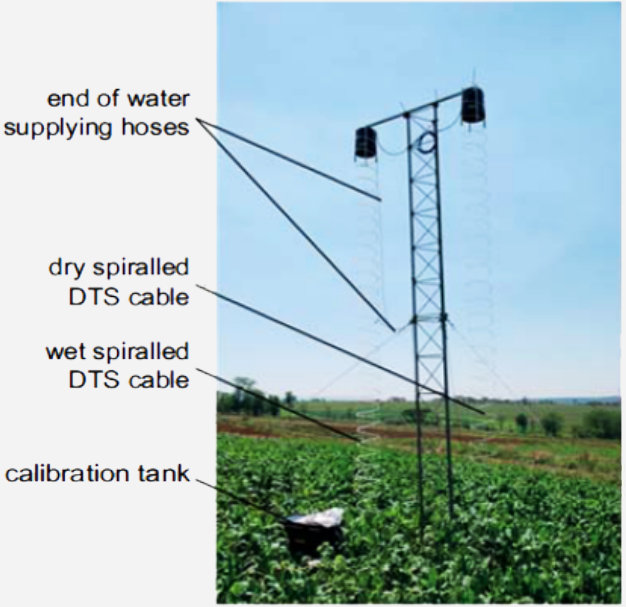

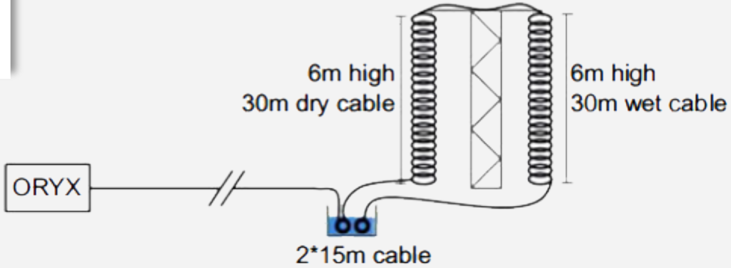

Further reading

Mohamed, Y. A., van den Hurk, B. J. J. M., Savenije, H. H. G., and Bastiaanssen, W. G. M., 2005. Hydroclimatology of the Nile: Results from a regional climate model. *Hydrol. and Earth Syst. Sc.*, 9: 263-27. http://www.hydrol-earth-syst-sci.net/9/263/2005/hess-9-263-2005.html

Wang-Erlandsson, L., R. van der Ent, L. Gordon and H.H.G. Savenije. 2014 Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Simple Terrestrial Evaporation to Atmosphere Model, *Earth Syst. Dynam. Discuss.*, 5, 203-279. http://www.earth-syst-dynam-discuss.net/5/203/2014/esdd-5-203-2014.html

Gerrits, A.M.J., H.H.G. Savenije, L. Hoffmann and L. Pfister, 2007. New technique to measure forest floor interception – an application in a beech forest in Luxembourg, *Hydrol. and Earth Syst. Sc.*, 11, 695–701.http://www.hydrol-earth-syst-sci.net/11/695/2007/hess-11-695-2007.html

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Questions

1. *Why is actual evaporation smaller than potential evaporation?*
2. *Why is average annual evaporation less than average annual precipitation?*
3. *Is evaporation also less than precipitation on a daily basis?*