Photo: A. Christen

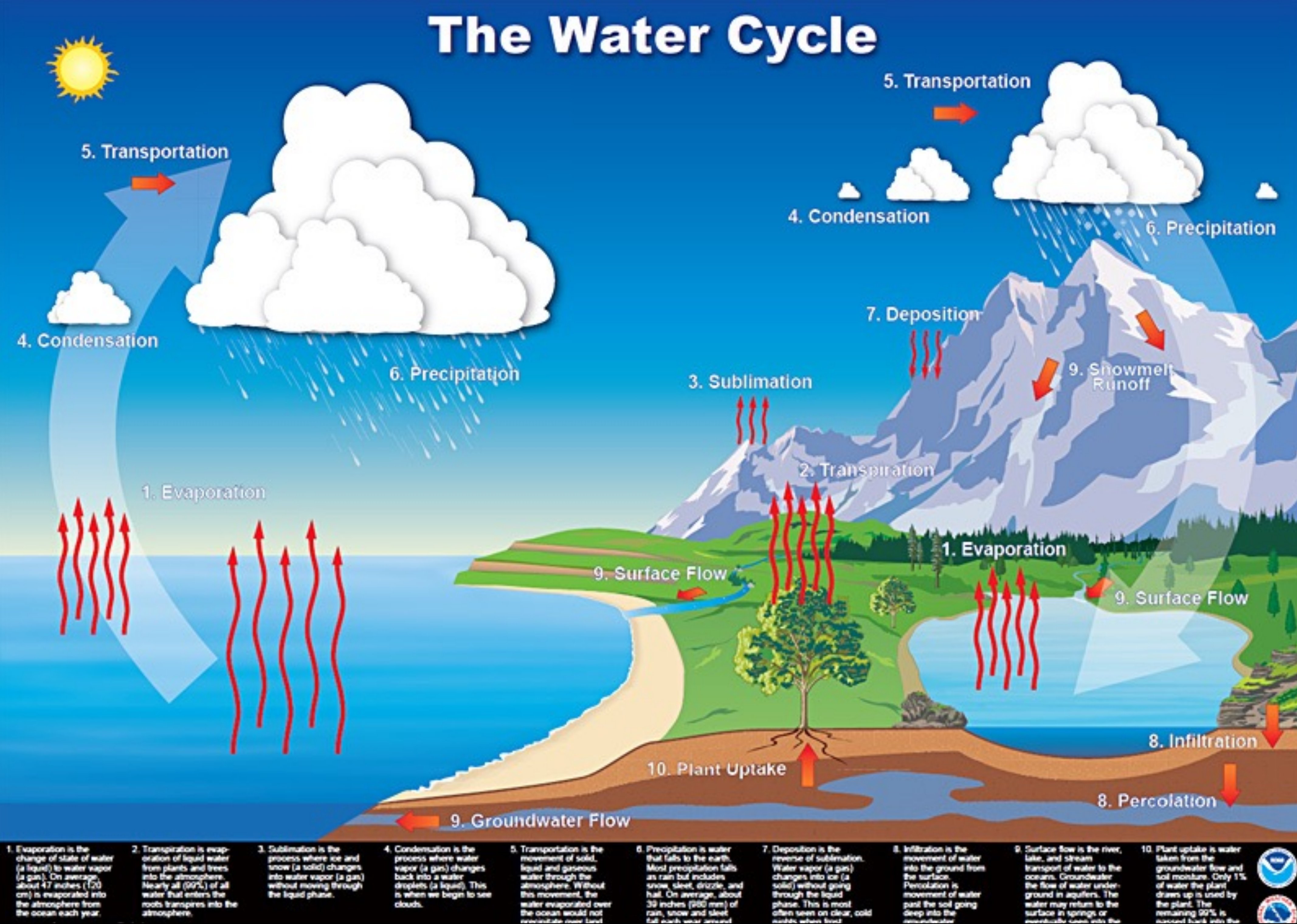
# 29 The water cycle at land-atmosphere interfaces

# Learning objectives

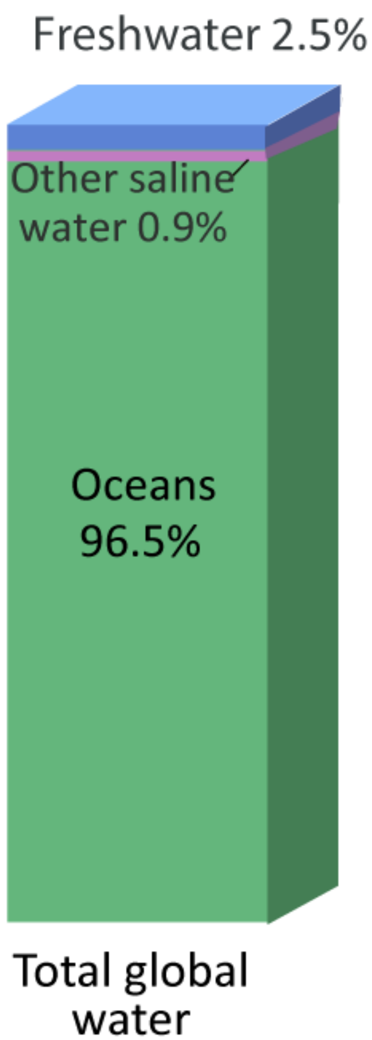
- Describe the water balance at a surface-atmosphere interface.
- Explain how the surface water balance is linked to the energy balance.
- Know what are water inputs, outputs and stores within vegetation canopies.

Photo: A. Christen

Measuring throughfall of precipitation in a forest using guttering and a rain gauge

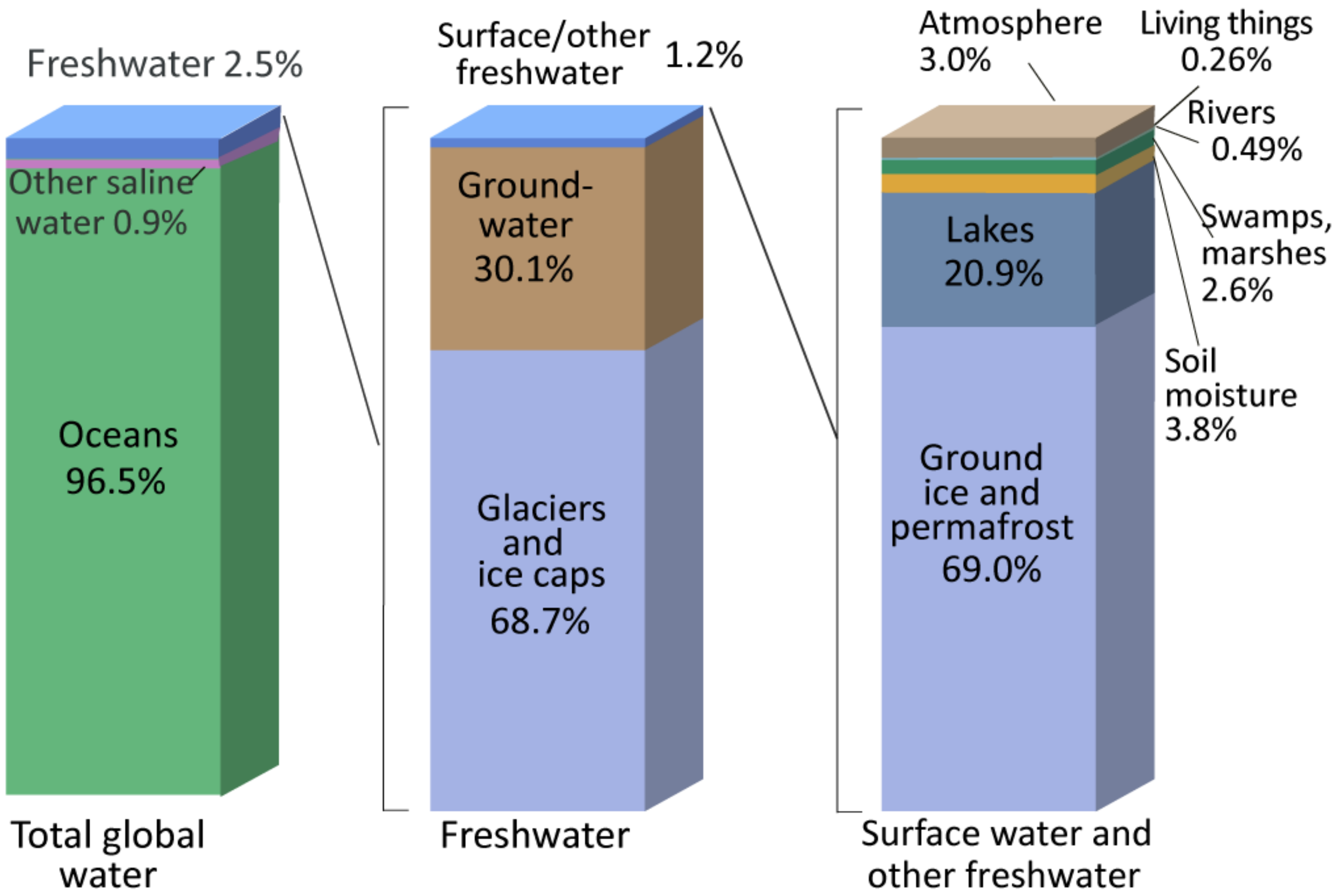

The Water Cycle
5. Transportation
4. Condensation
6. Precipitation
1. Evaporation
5. Transportation
4. Condensation
6. Precipitation
7. Deposition
3. Sublimation
9. Snowmelt Runoff
2. Transpiration
1. Evaporation
9. Surface Flow
9. Surface Flow
8. Infiltration
10. Plant Uptake
8. Percolation
9. Groundwater Flow
1. Evaporation is the change of state of water (a liquid) to water vapor (a gas). On average, about 47 inches (120 cm) is evaporated into the atmosphere from the ocean each year.
2. Transpiration is evaporation of liquid water from plants and trees into the atmosphere. Nearly all (99%) of all water that enters the roots transpires into the atmosphere.
3. Sublimation is the process where ice and snow (a solid) changes into water vapor (a gas) without moving through the liquid phase.
4. Condensation is the process where water vapor (a gas) changes back into a water droplets (a liquid). This is when we begin to see clouds.
5. Transportation is the movement of solid, liquid and gaseous water through the atmosphere. Without this movement, the water evaporated over the ocean would not
6. Precipitation is water that falls to the earth. Most precipitation falls as rain but includes snow, sleet, drizzle, and hail. On average, about 39 inches (980 mm) of rain, snow and sleet
7. Deposition is the reverse of sublimation. Water vapor (a gas) changes into ice (a solid) without going through the liquid phase. This is most often seen on clear, cold
8. Infiltration is the movement of water into the ground from the surface. Percolation is movement of water past the soil going deep into the
9. Surface flow is the river, lake, and stream transport of water to the oceans. Groundwater the flow of water underground in aquifers. The water may return to the surface in springs or
10. Plant uptake is water taken from the groundwater flow and soil moisture. Only 1% of water the plant draws up is used by the plant. The remaining 99% is

# Where is Earth's Water?




Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

# Where is Earth's Water?

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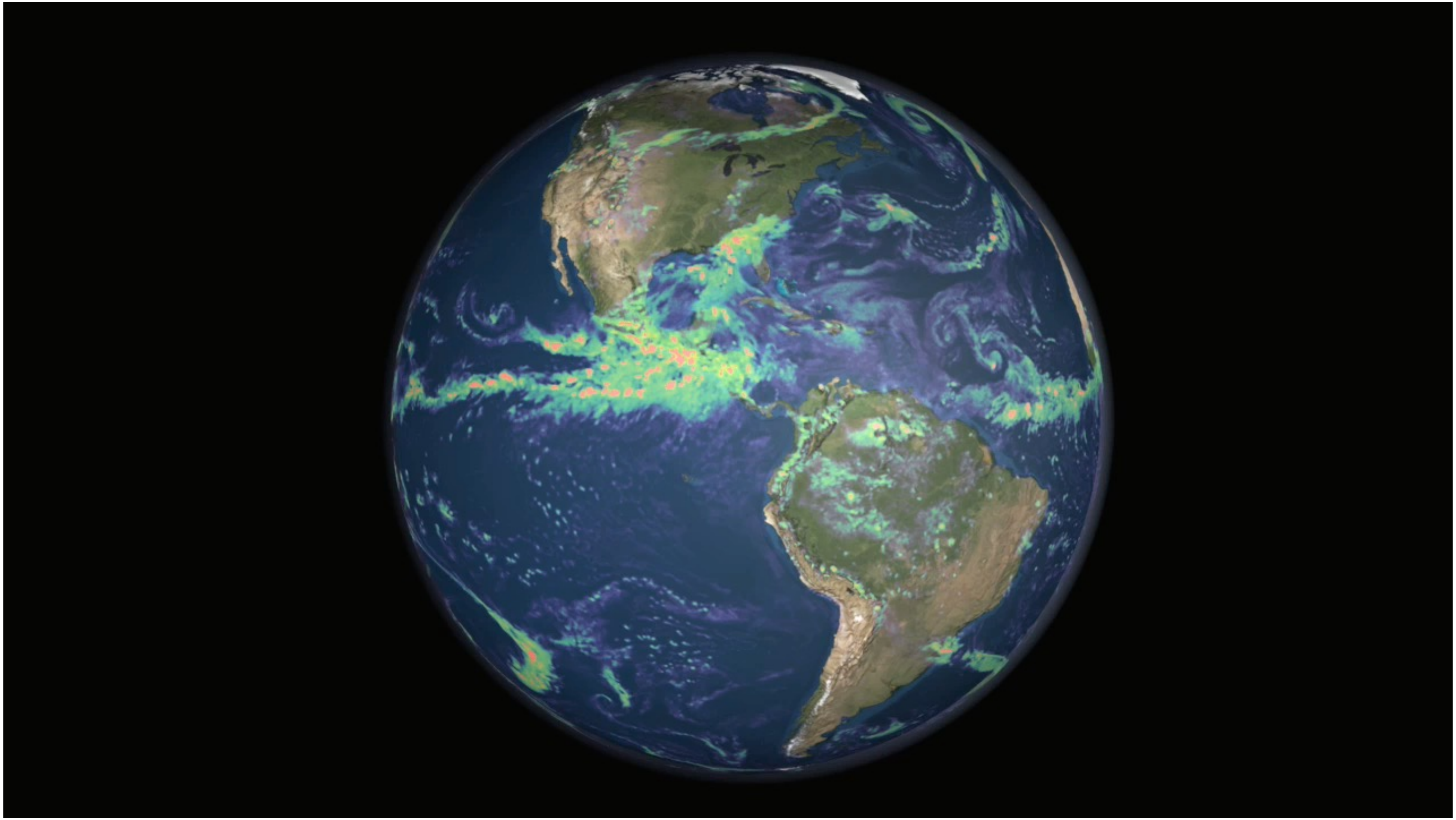
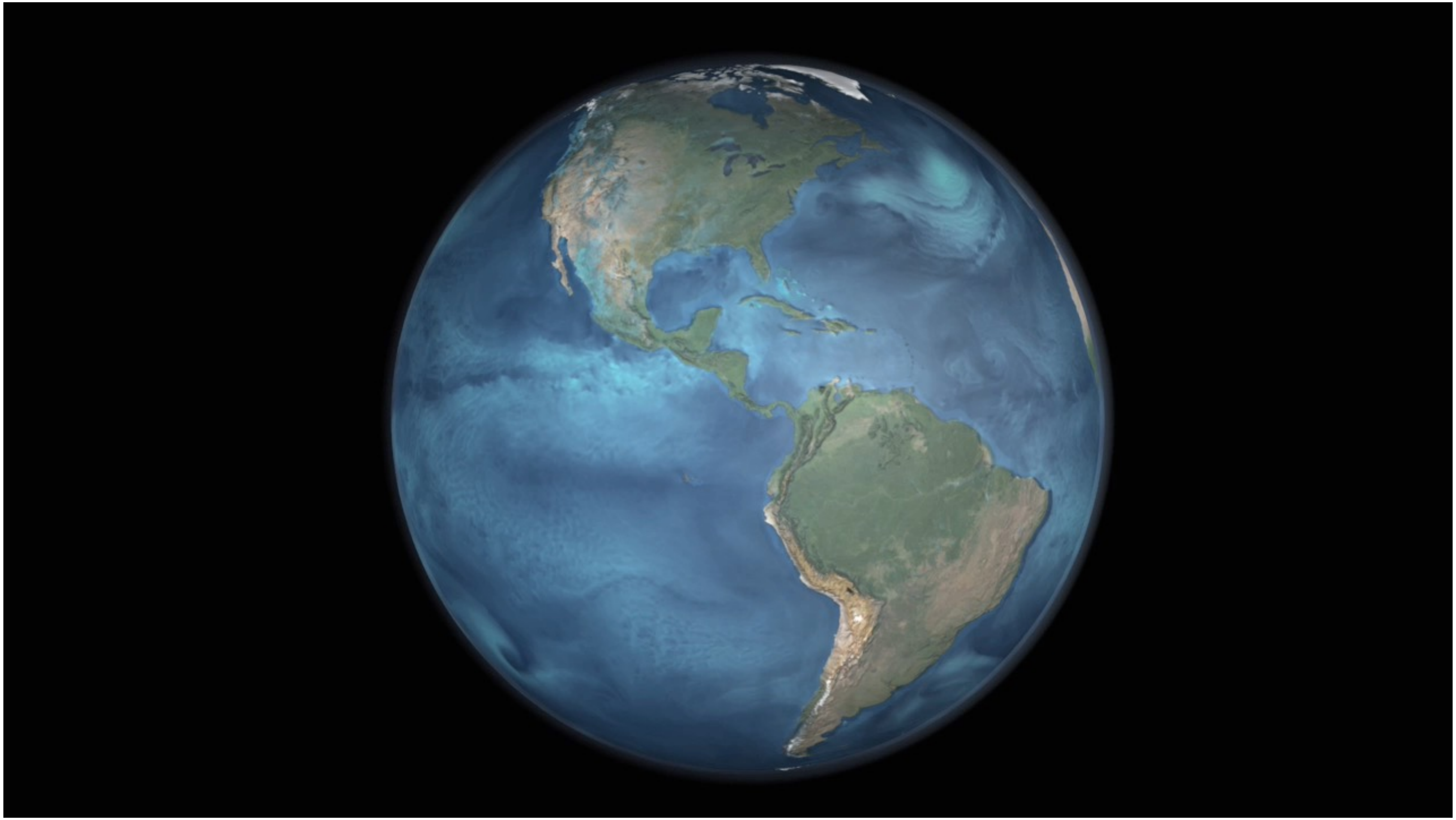
# Precipitation



Source: https://svs.gsfc.nasa.gov/vis/a000000/a003600/a003648/

# Evapotranspiration



Source: https://svs.gsfc.nasa.gov/vis/a000000/a003600/a003648/

# Mass balance of water - catchments

In hydrology, we use mass conservation for water within catchments

Input:

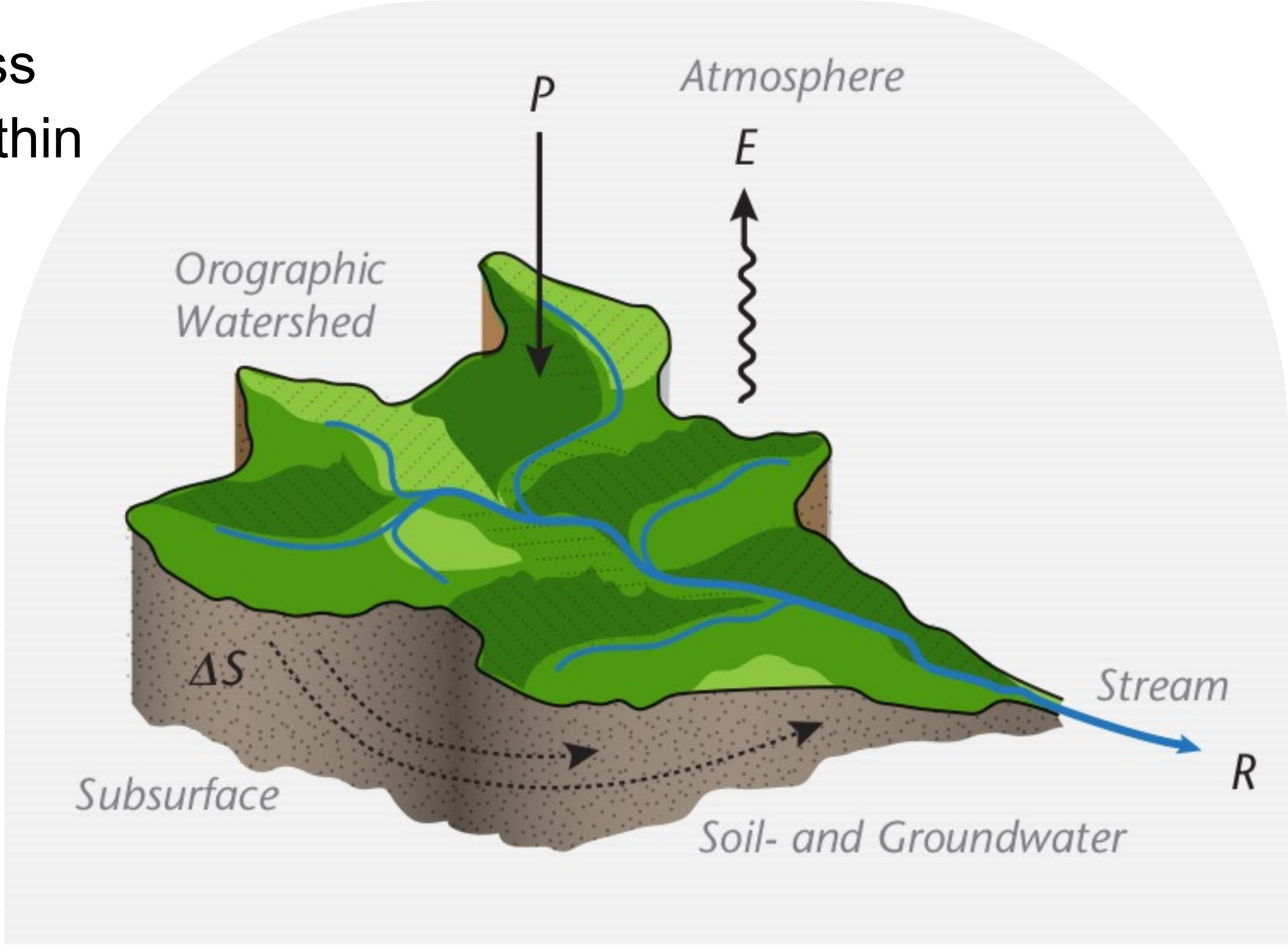
- Precipitation P

Output:

- Evapotranspiration E
- Run off R

Internal mass change:

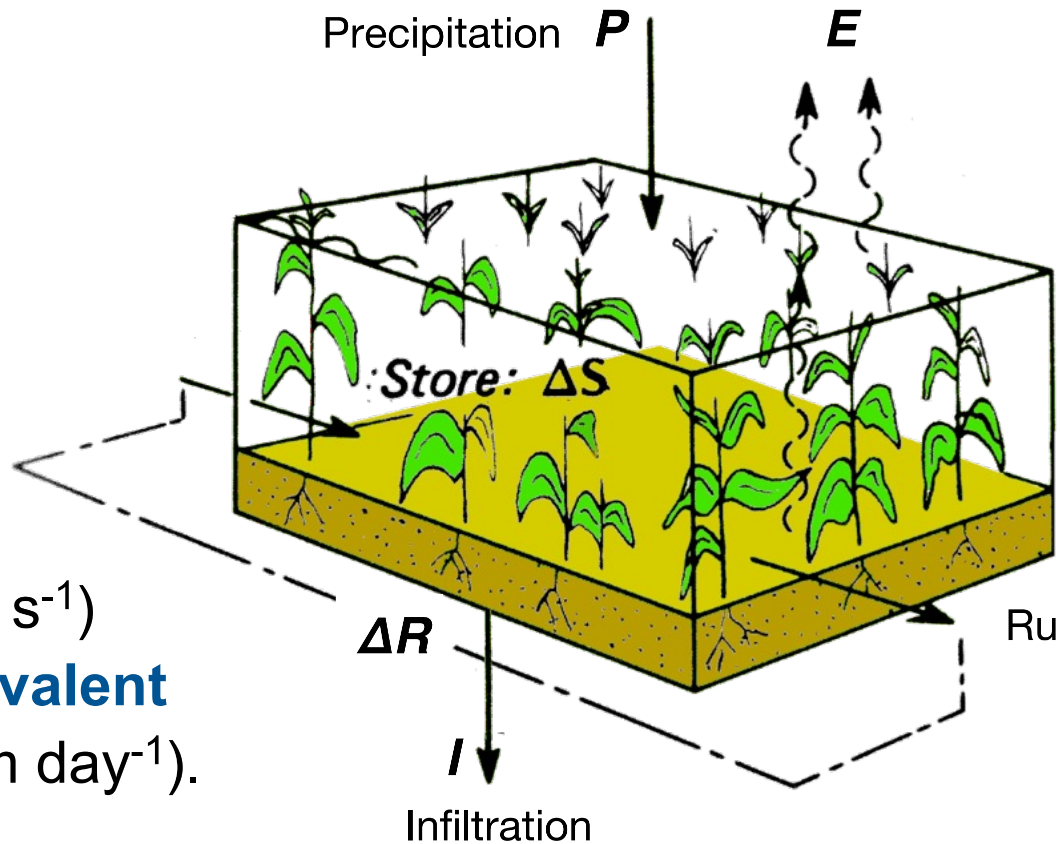
- Storage change $\Delta S$



# What is the equation for the water balance of a land-atmosphere interface?

The mass balance for a shallow land-atmosphere interface is:

All components can be considered as mass flux densities (~volume of water per unit ground area in $m^3\ m^{-2}\ s^{-1}$) which is the same as the **equivalent depth of water** ($mm\ h^{-1}$ or $mm\ day^{-1}$).



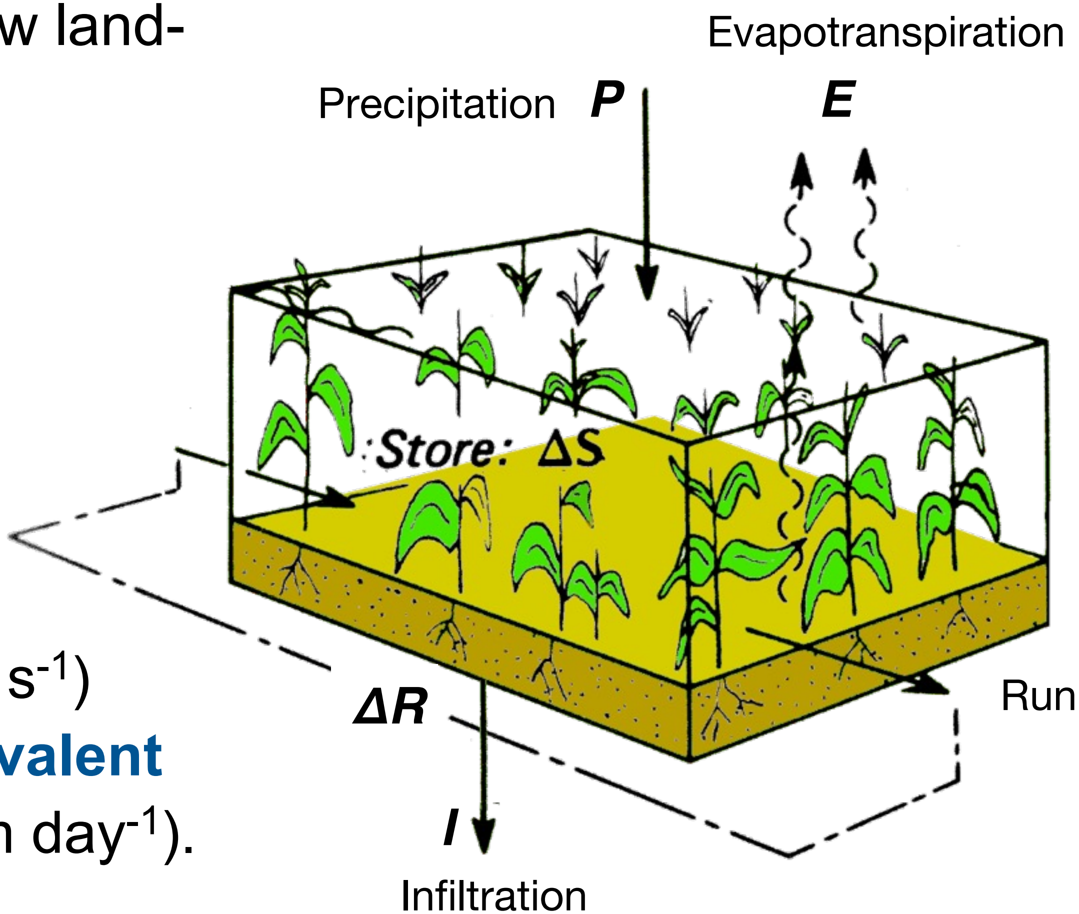

Oke, 1987

# The water balance of a land-atmosphere interface

The mass balance for a shallow land-atmosphere interface is:

$$P = E + I + \Delta R + \Delta S$$

All components can be considered as mass flux densities (~volume of water per unit ground area in $m^3\ m^{-2}\ s^{-1}$) which is the same as the **equivalent depth of water** ($mm\ h^{-1}$ or $mm\ day^{-1}$).

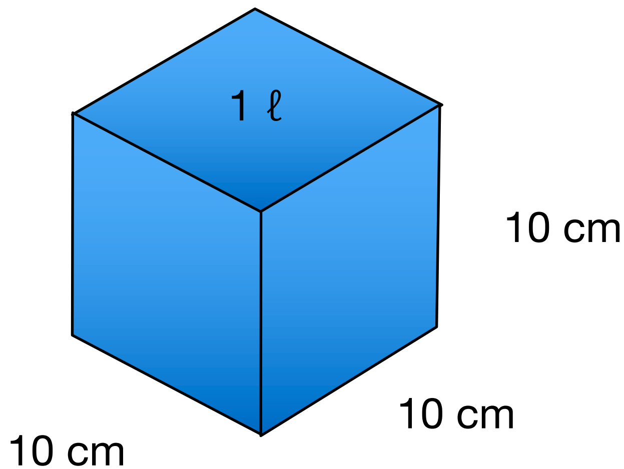



Oke, 1987

# Mass flux vs. height equivalent

1 kg of Water ≈ 1 $\ell$ of water

1 $\ell$ of water is a cube of 10 x 10 x 10 cm:

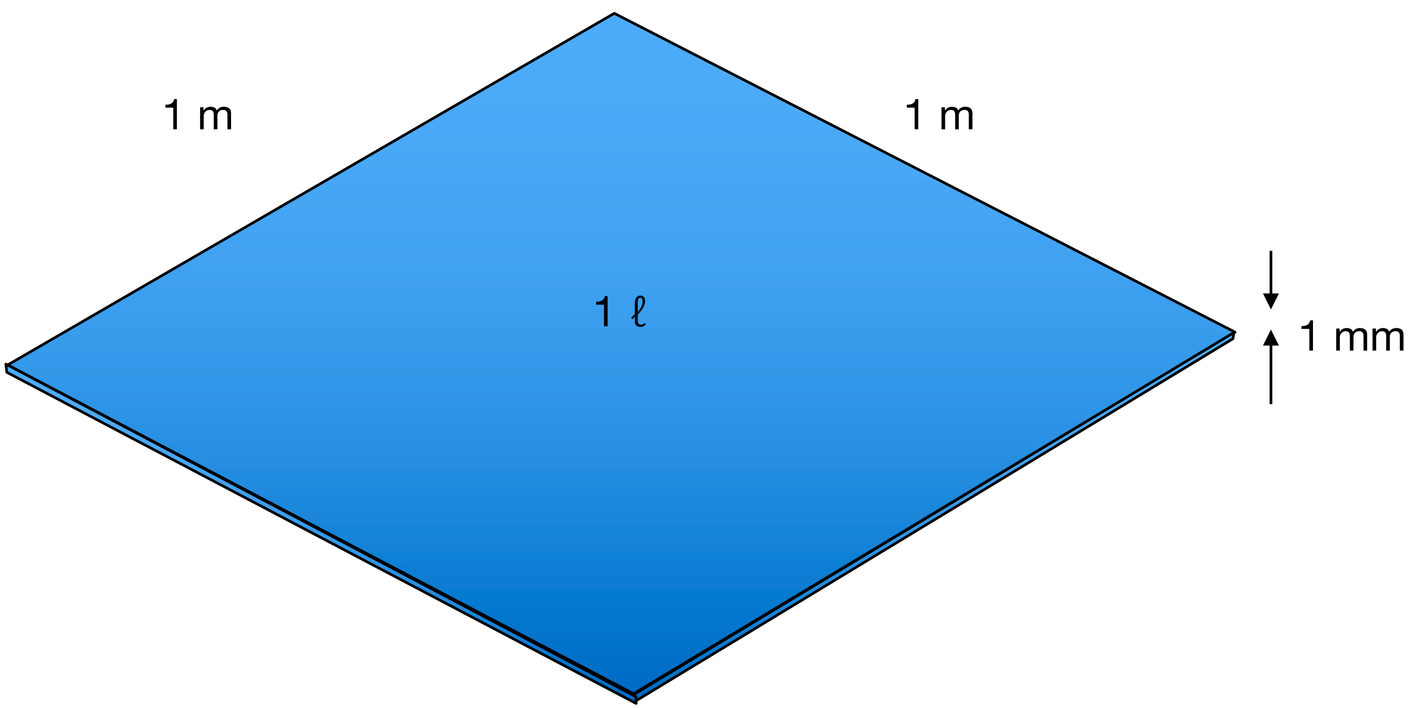



Oke, 1987

# Mass flux vs. height equivalent

1 ℓ of water is the same volume as 100 x 100 x 0.1 cm = 1000 $cm^2$

So if we spread out 1 ℓ over an area of 1 $m^2$ we have a depth of 1 mm



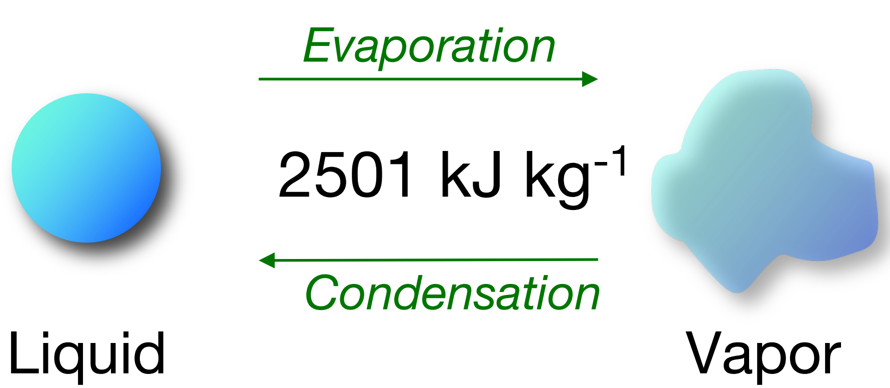

Oke, 1987

# Evapotranspiration

Latent heat flux $Q_E$ (in W $m^{-2}$) and evapotranspiration $E$ (in mm $s^{-1}$) are linked by the latent heat of vaporization:

$$Q_E = L_v \, E$$

$J\ m^{-2}\ s^{-1}$ | $J\ kg^{-1}$ | $kg\ m^{-2}\ s^{-1} \approx mm\ s^{-1}$



# Energy balance and water balance

*Energy balance* *Water mass balance* *Carbon mass balance*

Precipitation

=

| Net all-wave radiation | = | Sensible heat flux density | + | Latent heat flux density (evapotranspiration) | + | Soil heat flux density | + | Net $CO_2$ flux |
|---|---|---|---|---|---|---|---|---|

+

Runoff

+

Infiltration

+

Water storage

*Linked via stomatal control*

Net $CO_2$ flux = Photosynthesis - Respiration

## Class activity

Define the terms of the surface water balance below and write the surface water balance.

| Symbol | Term |
|---|---|
| P | |
| E | |
| I | |
| ΔR | |
| ΔS | |

# Test your knowledge – Canvas activity

Define the terms of the surface water balance below and write the surface water balance.

| Symbol | Term |
| --- | --- |
| P | Precipitation |
| E | Evapotranspiration |
| I | Infiltration |
| ΔR | Net runoff |
| ΔS | Change in storage |

$$P = E + I + \Delta R + \Delta S$$

# Water balance as a climate index

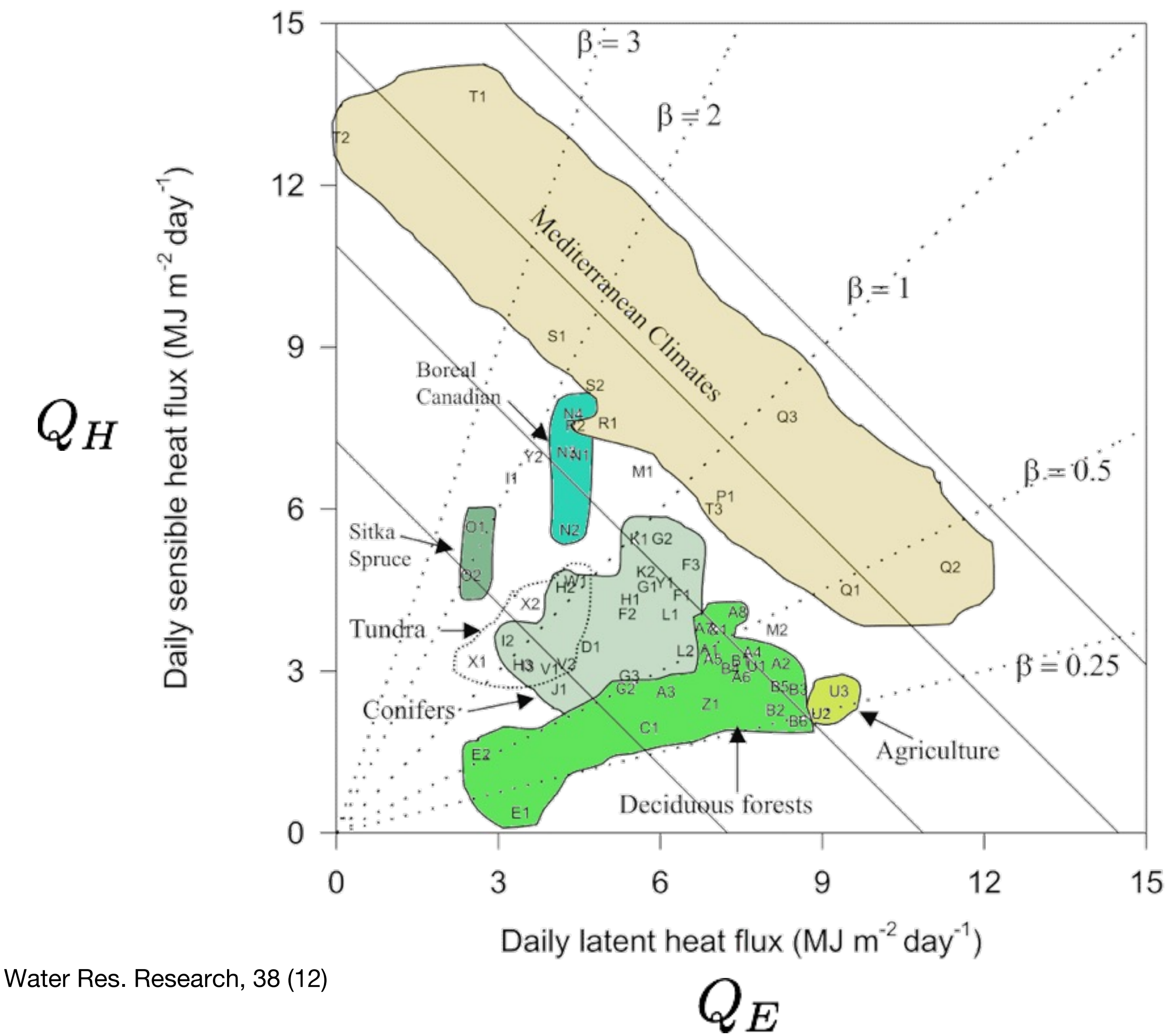
The Russian climatologist, Mikhail Budyko has used both the run-off ratio (*R*/*P*) and evaporation ratio (*E*/*P*) as climatic indices.

For similar annual precipitation and similar Q*, the annual **Bowen ratio** ($\beta = Q_H / Q_E$) increases as *R*/*P* increases and *E*/*P* decreases.

| Ecosystem | R/P | E/P |
|---|---|---|
| Tundra | > 0.7 | < 0.3 |
| Forest | 0.3 – 0.7 | 0.3 – 0.7 |
| Steppe | 0.1 – 0.3 | 0.7 – 0.9 |
| Semi-desert | 0.03 – 0.1 | 0.9 – 0.97 |
| Desert | < 0.03 | > 0.97 |

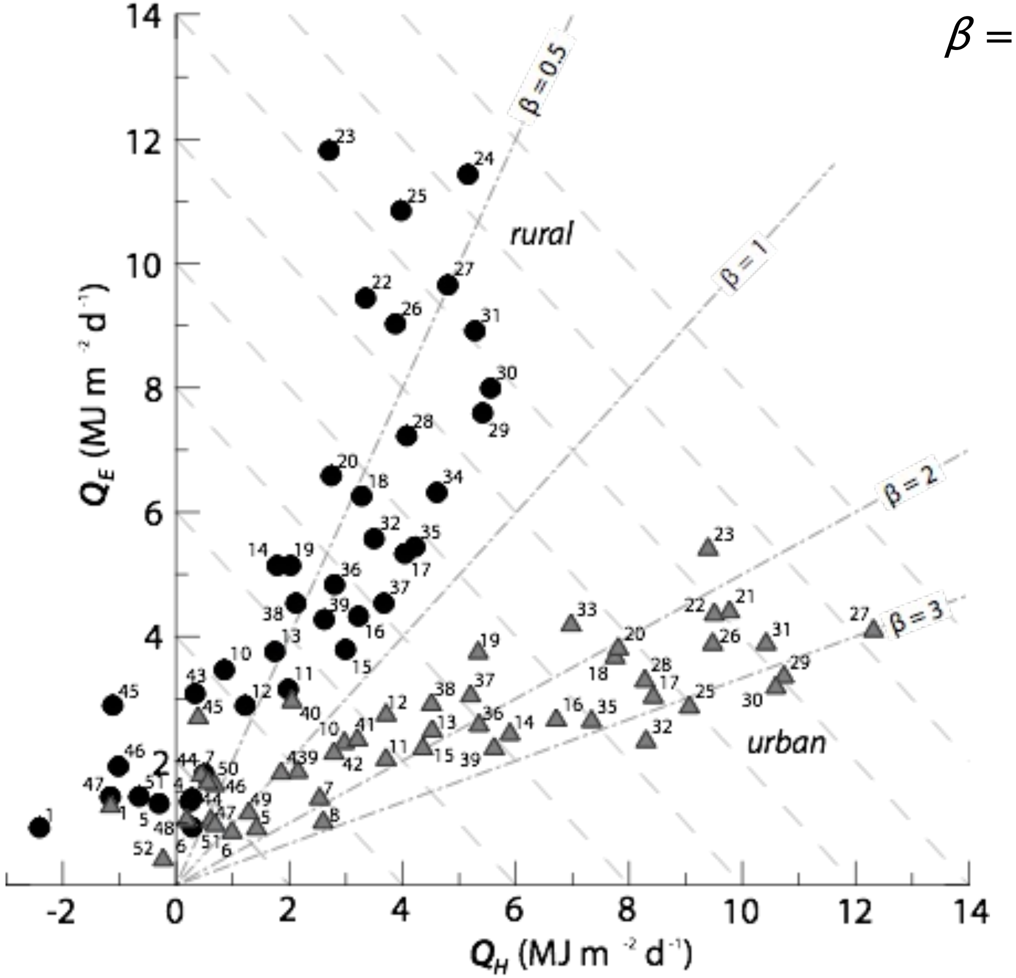
# Bowen ratio and climate

$\beta = Q_H / Q_E$




Wilson et al.. (2002). Water Res. Research, 38 (12)

# Flux partitioning in the Lower Fraser Valley

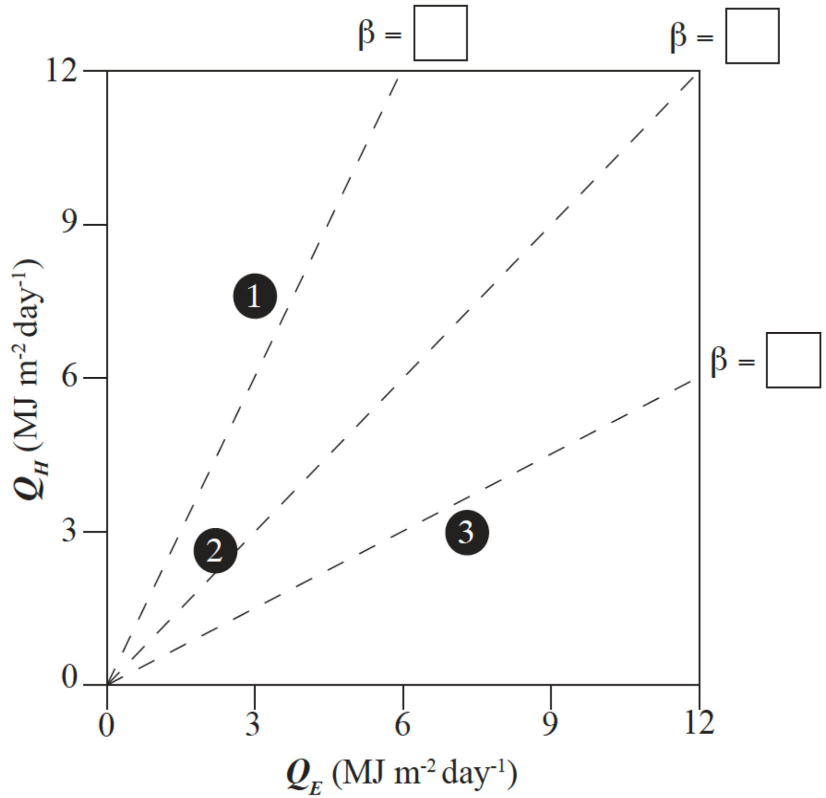



$\beta = Q_H / Q_E$

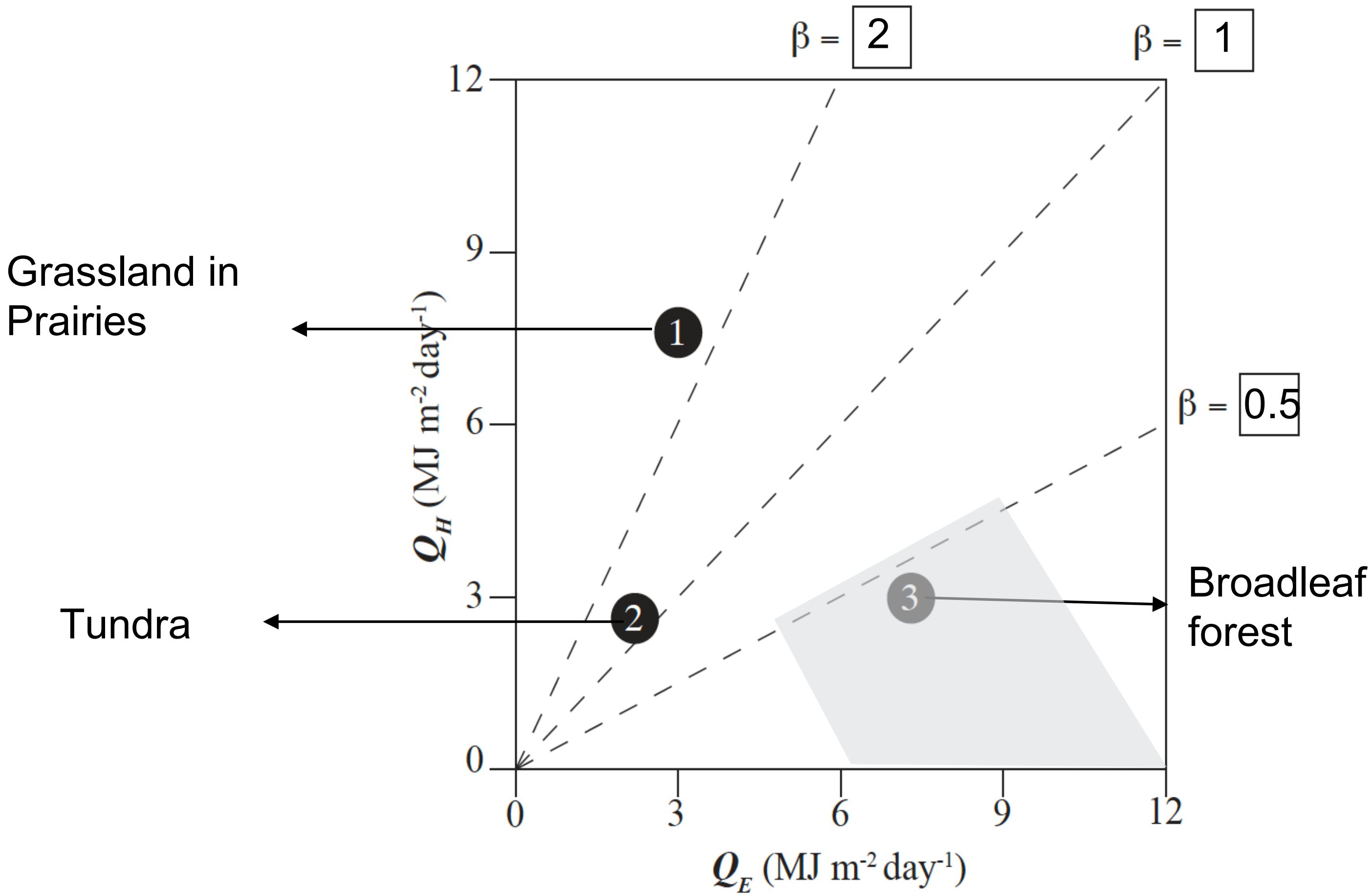
# Test your knowledge – Think & share

The following graph shows daily totals of $Q_H$ and $Q_E$ for the summer season of a tundra ecosystem in Canada's North, an Atlantic Canadian broadleaf forest, and an unmanaged grassland in the Canadian Prairies.

- Attribute points 1, 2, and 3 to the corresponding land-surface
- Fill in the three missing boxes for the Bowen Ratio β
- Where would an irrigated crop in the Fraser Valley be likely to fall on this graph?



# Answers



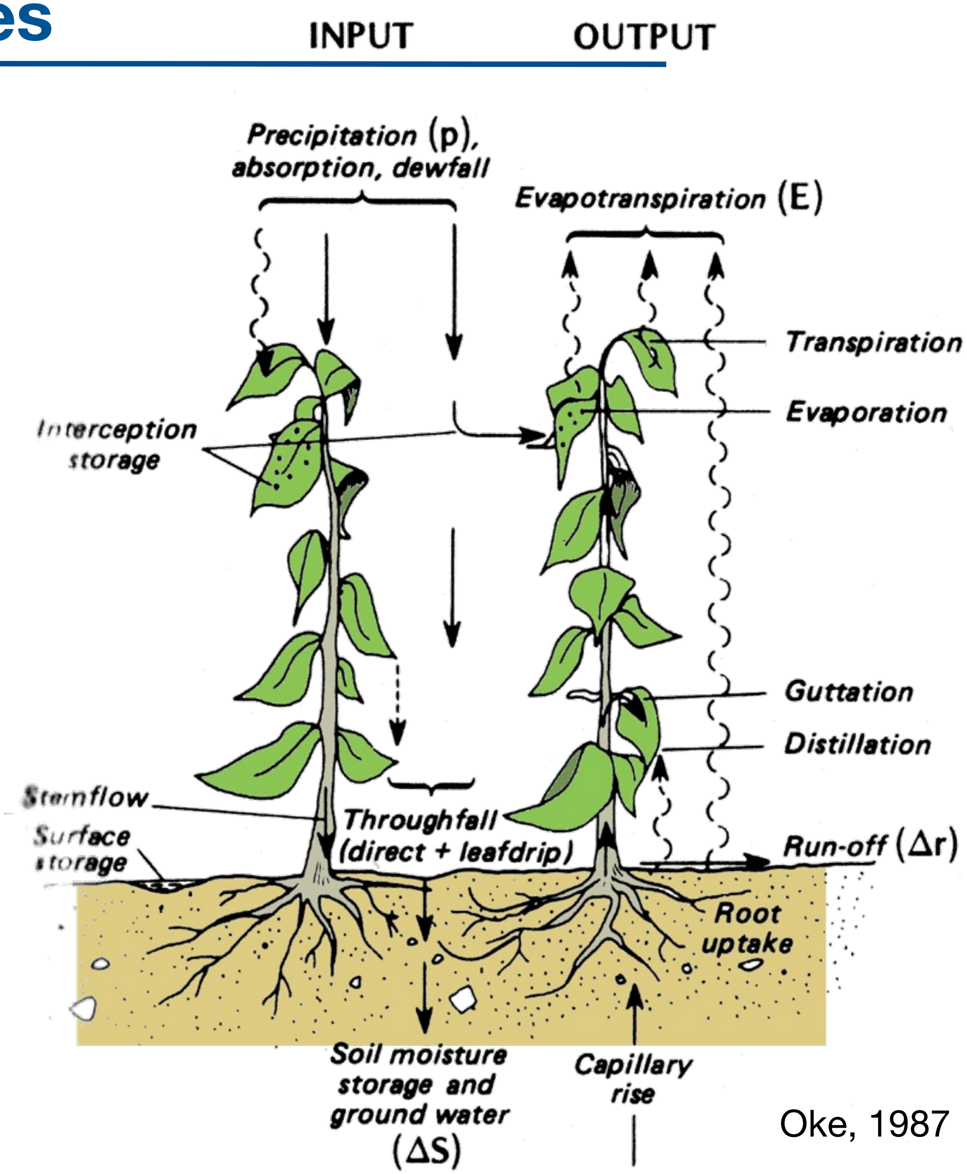
β = 2
β = 1
β = 0.5
Grassland in Prairies
Tundra
Broadleaf forest
1
2
3
12
9
6
3
0
0
3
6
9
12
$Q_H$ (MJ m$^{-2}$ day$^{-1}$)
$Q_E$ (MJ m$^{-2}$ day$^{-1}$)

# Water balance of plant canopies

Inside a canopy there are significant air, soil and plant flows leading to the **re-distribution** of water and temporary water storage (on leaves, in plants, soils, surface)

The plant structure can cause atmospheric water to condense (**dewfall**, **distillation**)

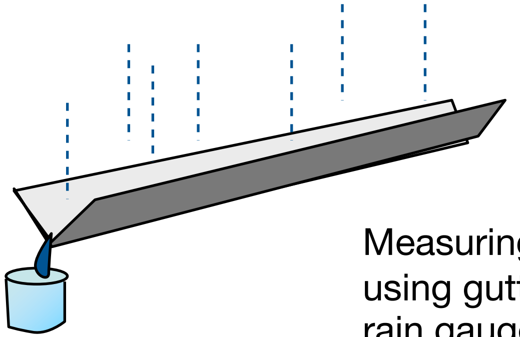
Water vapour is released from plant into atmosphere by **guttation** and **transpiration**




Oke, 1987

# Throughfall

**Throughfall** ($P_T$) is precipitation directly falling through the canopy / crown space or deflected by the tree crowns reaching the ground.



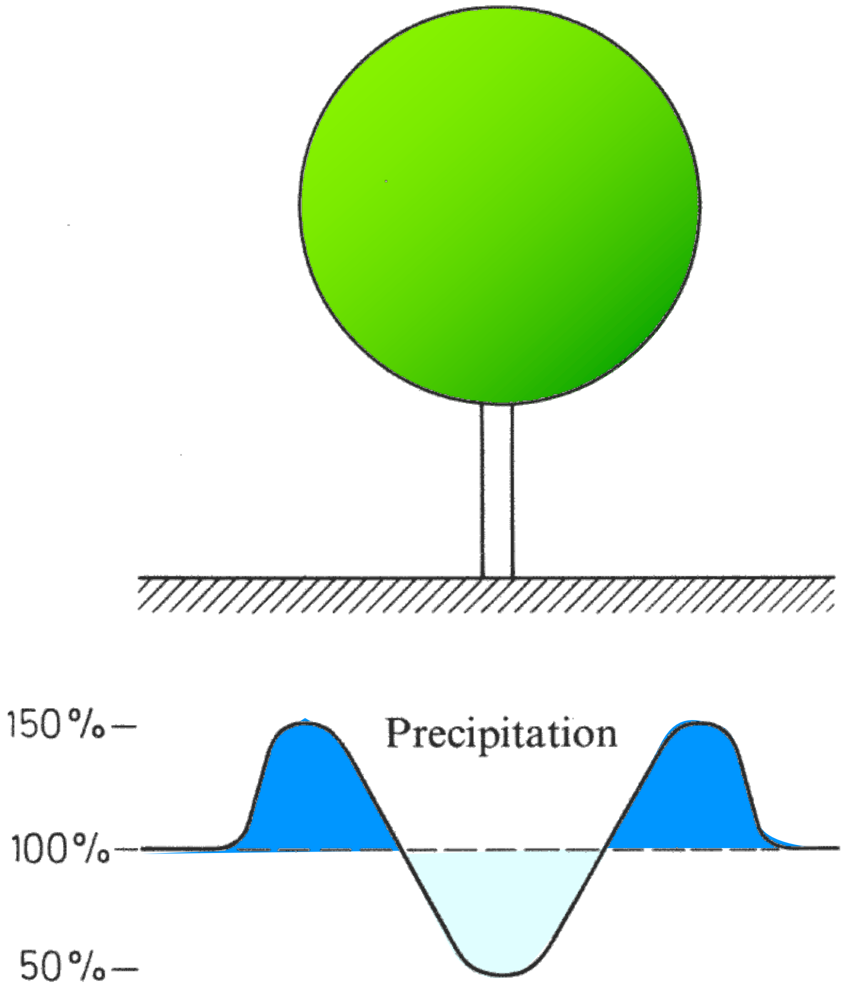
Measuring throughfall using guttering and a rain gauge

Photo: A. Christen

# Throughfall

A special case of throughfall is **canopy drip**.

In particular coniferous trees prefer to direct water to the edge of the tree, due to their characteristic shape. In the case of canopy drip, soil moisture is increased in a ring around a tree.




J. Seemann, et al. (1979): "Agrometeorology", Springer.

# Stem flow


**Stem flow** (*Ps*) is the process where water is drained along leaves, branches, and finally directed to the tree's stem.

Stem flow results is an increased water availability (higher soil moisture) in the soil close to the stem.

Measurement of stem flow
*Photo: A. Christen*

# Interception


**Interception** ($P_I$) is water form a precipitation event that **remains on the surface of the tree** (leaves, branches) and does not immediately reach the ground. Intercepted water evaporates (or drips later down to the ground).

We can write for the microscale partitioning of precipitation in a vegetation canopy:

$$P = P_T + P_S + P_I$$

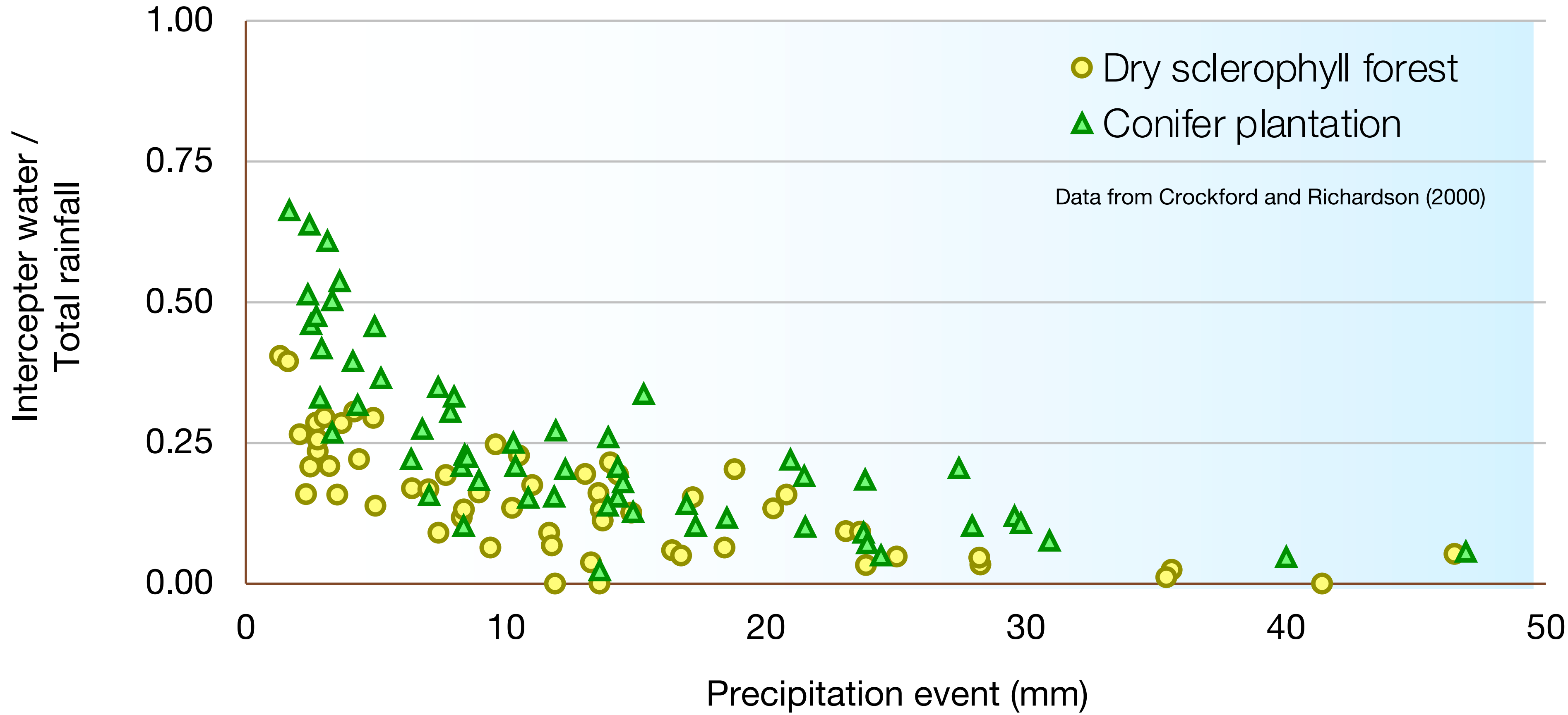
# Annual fractions of interception, stemflow and throughfall

| Forest type | Interception $P_I/P$ | Stemflow $P_S/P$ | Throughfall $P_T/P$ |
|---|---|---|---|
| Tropical rainforest | 13% | 2% | 85% |
| Sclerophyll forests | 17% | 2% | 81% |
| Dry scrubland | 17% | 11% | 72% |
| Deciduous forests | 19% | 7% | 74% |
| Coniferous forests | 20% | 3% | 77% |

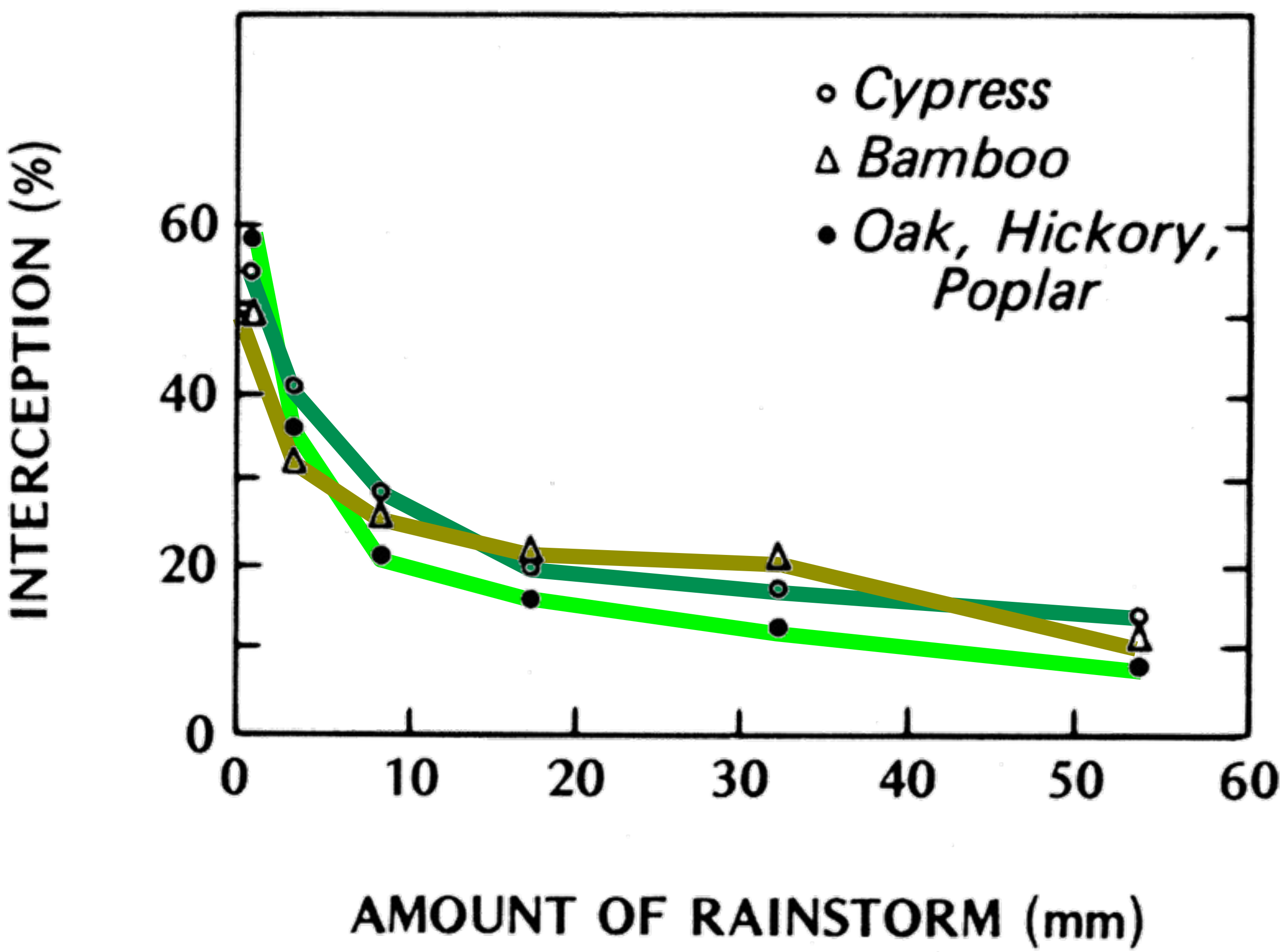
Average values based on 60 studies worldwide.

# Precipitation events - intercepted water

The percentage of intercepted water depends on canopy architecture, and duration, intensity of the precipitation event.



# Interception vs. precipitation event - different trees




Oke, 1987

# Test your knowledge – Canvas activity

How is precipitation partitioned? Write the equation for the microscale partitioning of precipitation in a vegetation canopy.

## Test your knowledge – Canvas activity

How is precipitation partitioned? Write the equation for the microscale partitioning of precipitation in a vegetation canopy.

$$P = P_T + P_S + P_I$$

Photo: A. Christen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# Fog drip

Water dripping to the ground from trees or other objects that have collected the cloud droplets from drifting fog.

Fog drip through needles of Redwood forests of Northern Coastal California is important to prevent an excessive aridity.

Harp collector to measure Fog drip on Maui, Hawaii (Photo: USGS, http://water.usgs.gov/nrp/proj.bib/hawaii/photo_gallery.htm)

# Water harvesting from fog


*Mesh billboards can capture tiny fog droplets in mountainous regions (Image credit: Aqualonis)*

In dry, mountainous areas, or those on the coast that experience a lot of fog, one solution is to use giant nets to 'fish' for water. The latest region to adopt this is in southwest Morocco. There, on the slopes of Mount Boutmezguida, stands a row of net 'billboards' that are harvesting water from the clouds.

# SVAT - Soil-vegetation-atmosphere transfer schemes

In most numerical weather forecasting and climate models, Soil-vegetation-atmosphere transfer (SVAT) schemes are incorporated. SVATs account for the numerous physical and physiological processes in an appropriate complexity.

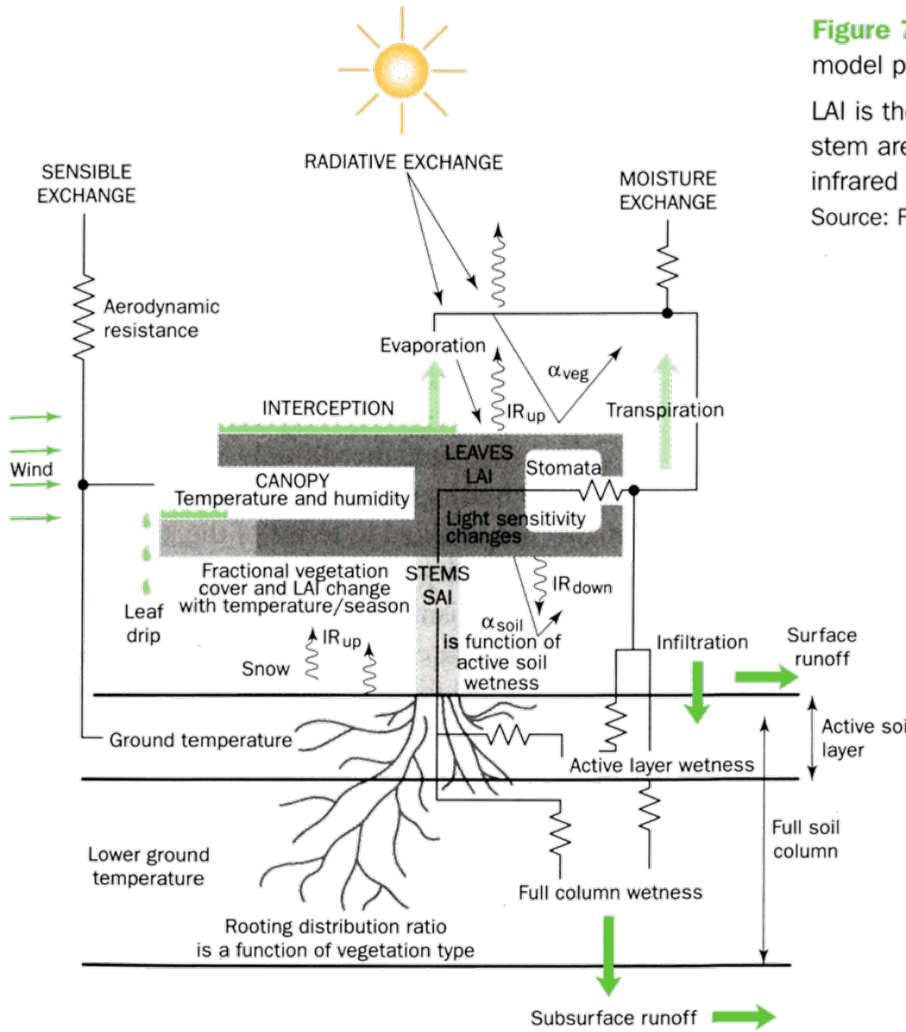


**Figure 7.7** Schematic of SVAT model processes.

LAI is the leaf area index, SAI is stem area index and IR stands for infrared radiation

Source: From Wilson *et al.* (1987)

G. O'Hare, J. Sweeny, R. Wilby (2005): 'Weather, Climate and Climate Change - Human Perspectives'.

## Take home points

- Water at land-atmosphere interfaces can be **balanced** the same way we accounted for energy using a flux per unit area (resulting in mm per time).
- **Water balance and energy balance are linked** through the latent heat flux / Evapotranspiration (by latent heat of vaporization, $Q_E = L_v E$).
- The **three-dimensional structure** of a plant canopy causes vertical differences in the input, storage and re-distribution of water (throughfall, interception, stem flow, fog drip).