From a conceptual soil hydrology scheme towards a multilayer soil diffusion scheme in the LSM ORCHIDEE

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Outlines

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- ORCHIDEE – Generalities
- Soil hydrology schemes
  - The conceptual model
  - The physically-based model

    Fundamental notions of soil water movement

    Modeling in ORCHIDEE

ORCHIDEE - Generalities

ORCHIDEE

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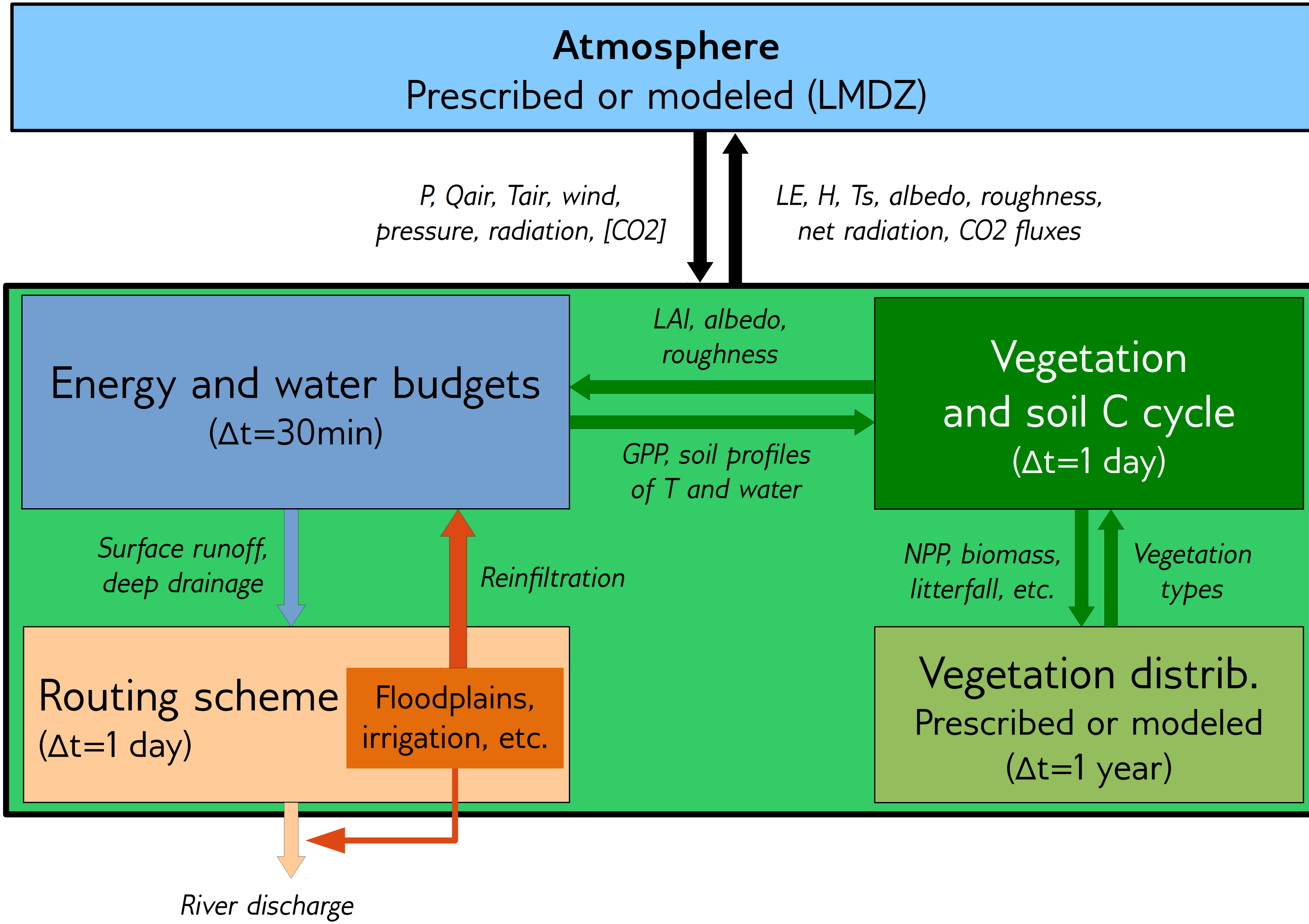
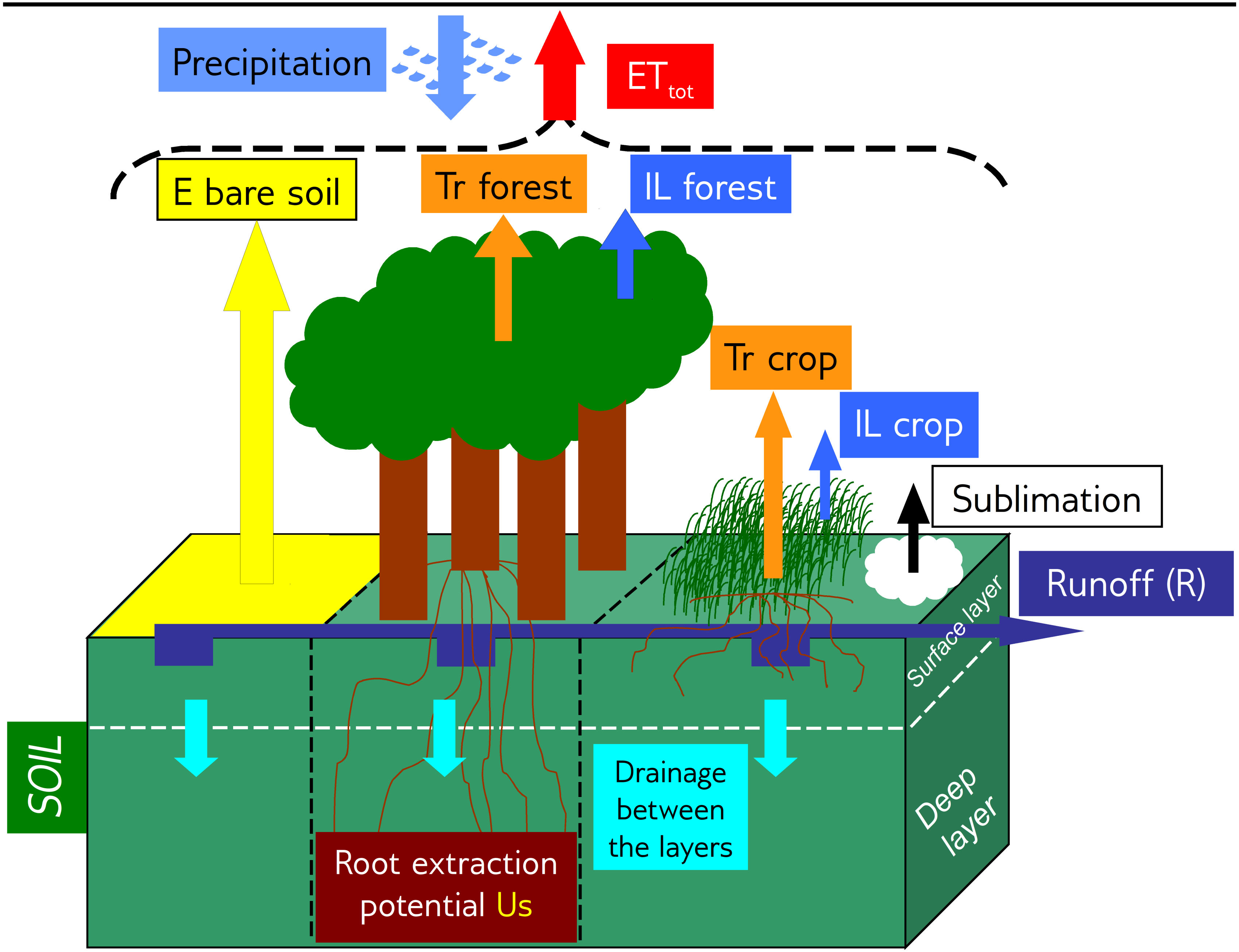


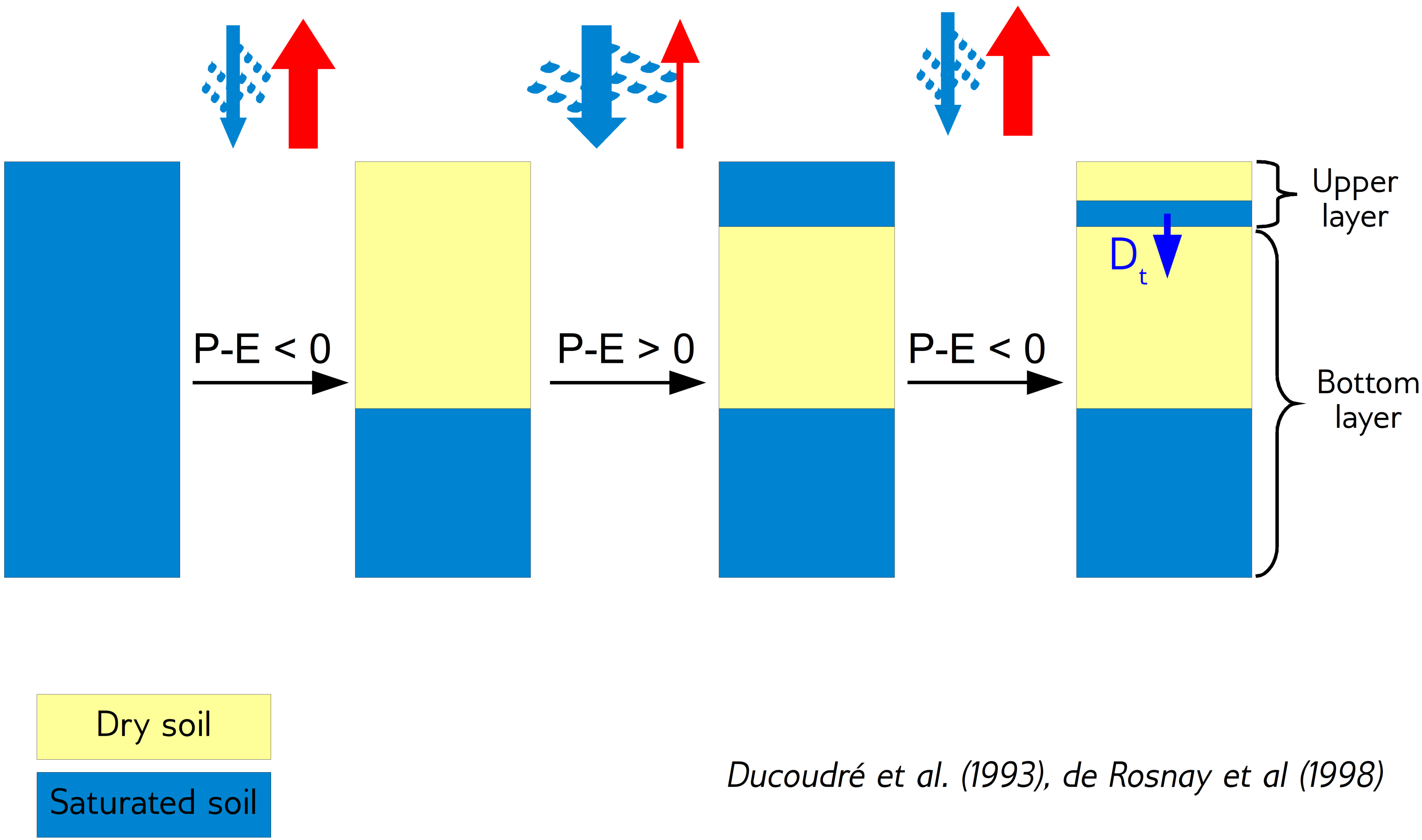
The hydrological modeling



Soil hydrology schemes

1 – The conceptual model

Main principles



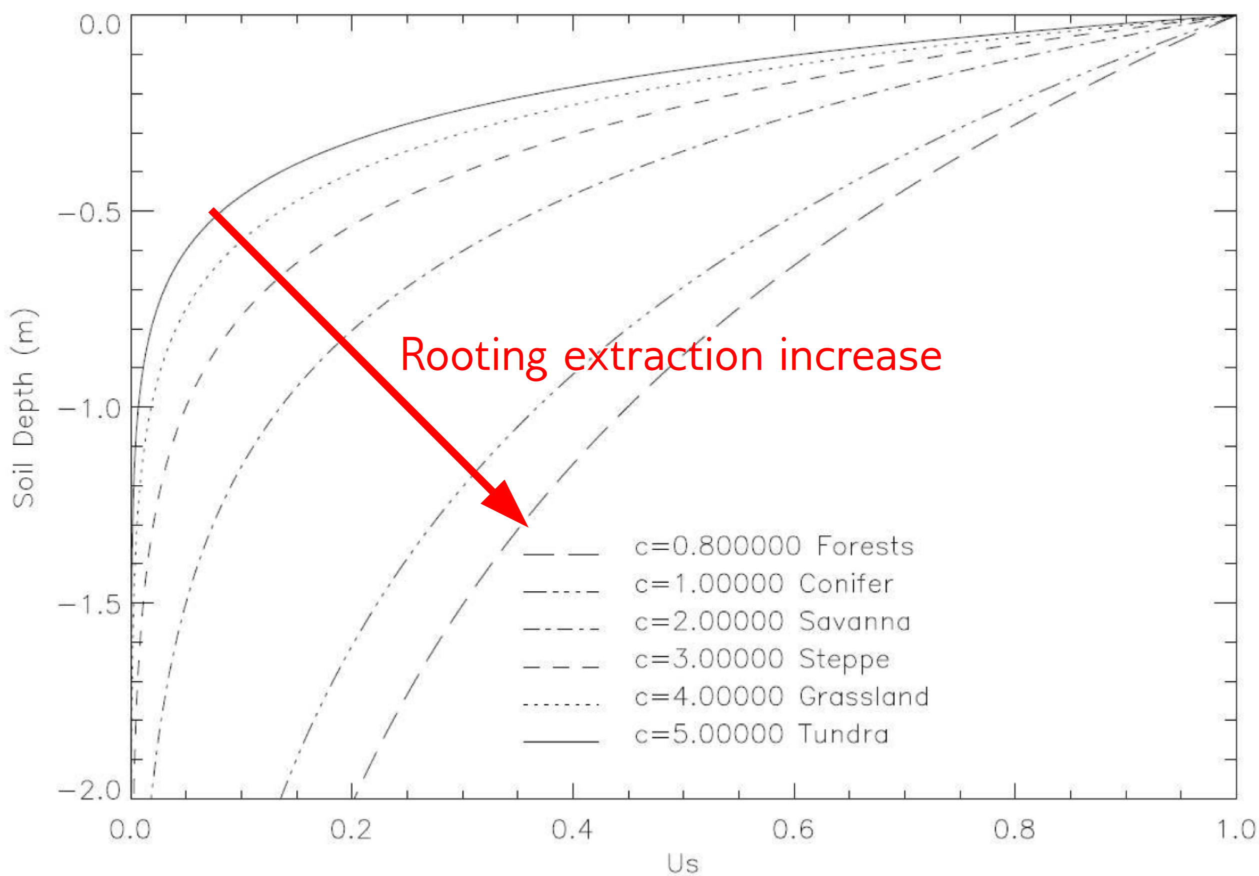
Ducoudré et al. (1993), de Rosnay et al (1998)

- Runoff only occurs when the soil is saturated
- No drainage from the soil

Water stress function, Us

- It conveys the water stress onto transpiration
- It depends on dry soil depth

$$Us = \exp\left(-c_v . h_{totdry}\right)$$



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+/-

⊕

- Simple, limited number of parameters
- Easy to use
- Widely tested by many users now

⊖

- No physical representation of the water movement in the soil
- The comparison with measurements is difficult
- No distinction between surface runoff and drainage => problem for streamflow simulation

Soil hydrology schemes

2 – The physically-based model

Soil hydrology schemes

2 – The physically-based model

2-1. fundamental notions of soil water movement

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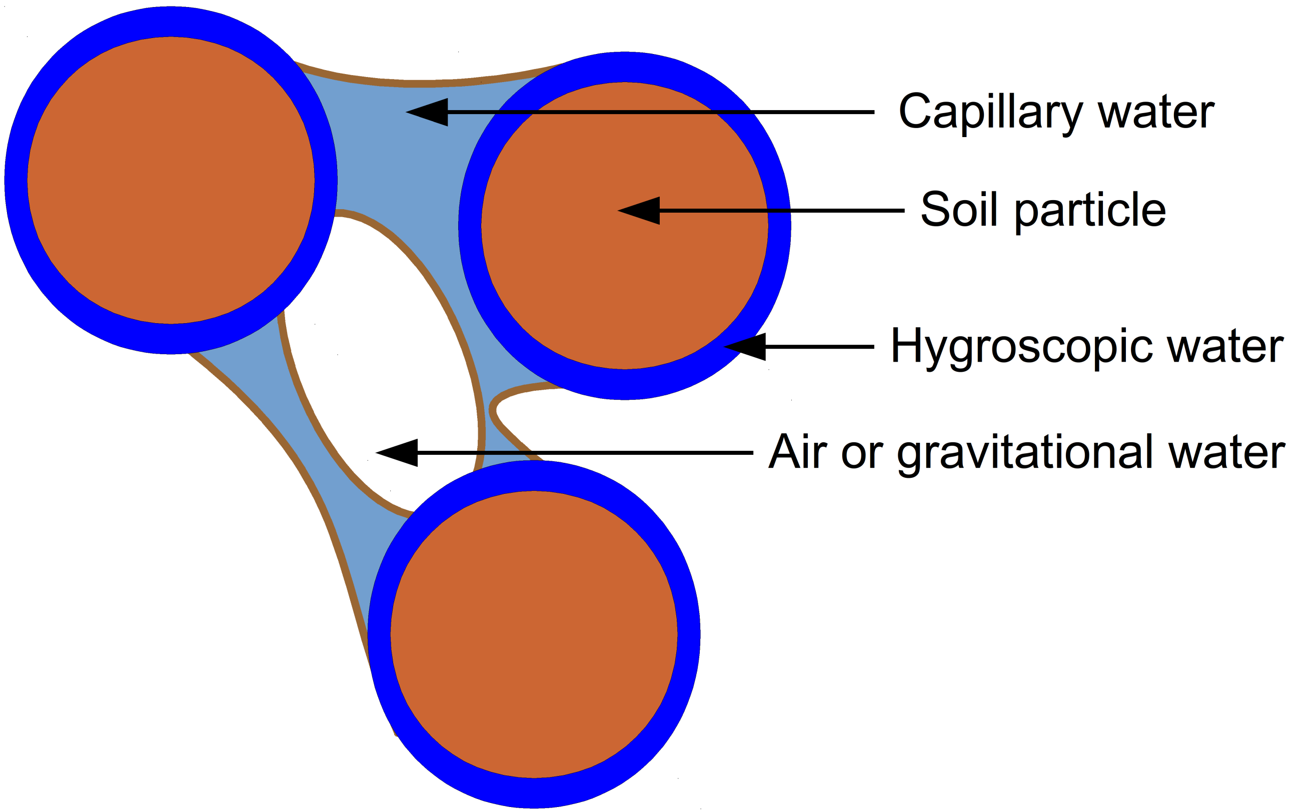
The soil

- Porous medium. Matrix of individual solid granular particles (grains)
- Between each grains: interconnected pore spaces that contain varying fractions of water and air
- Water is attracted to soil particles
- Soil dries => water is held more tightly to grains => capillary water disappears => only a thin film of water held very tightly to grains (hygroscopic water)



The soil moisture content

- The **volumetric soil water content (or soil moisture content)** measures the volume occupied by water
- Vary in both time and space.

$$\theta = \frac{V_w}{V_s}$$

V_w, volume of liquid water
V_s, volume of soil

The porosity of the soil

- Proportion of pore spaces in a volume of soil
  - constant over the time periods
  - decreases with depth (compaction)
- $0 < \theta < \phi$

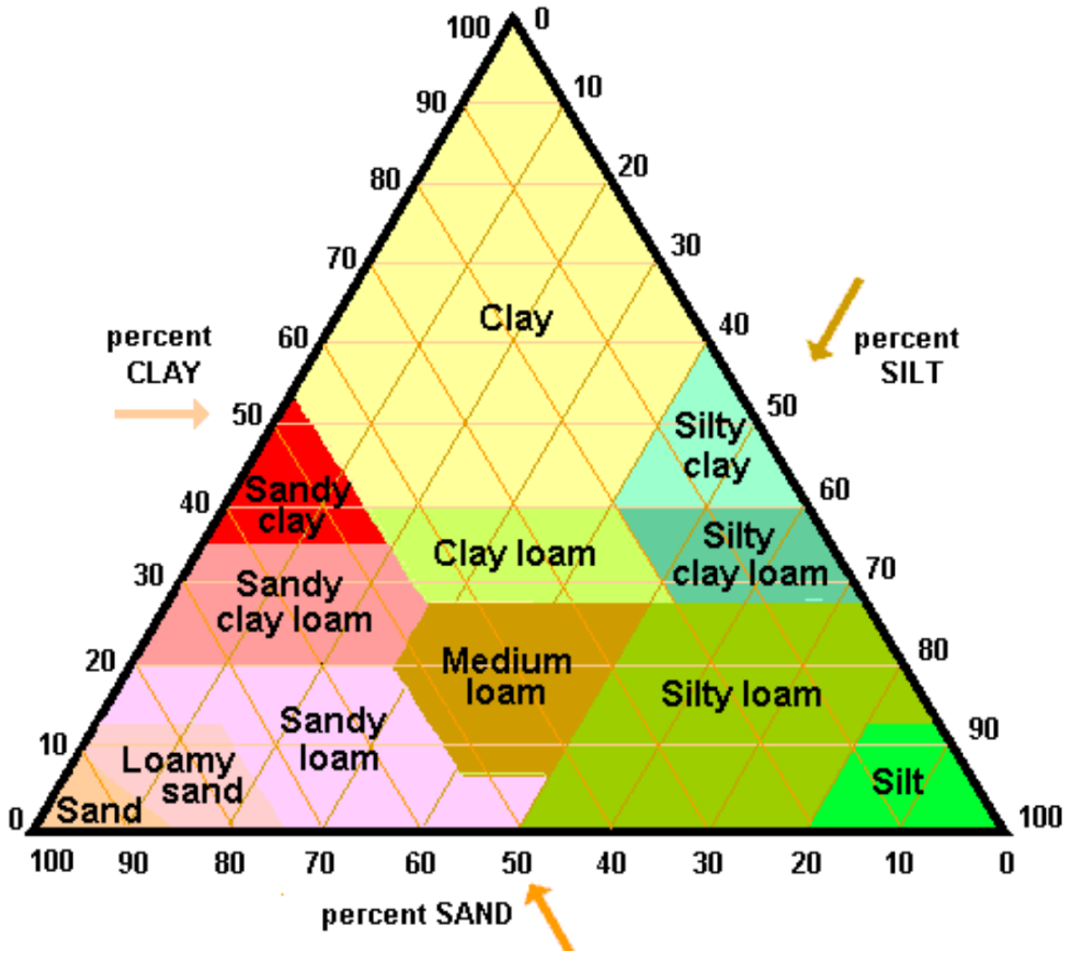
  when the soil moisture content reaches the porosity => the soil is saturated

$$\phi = \frac{(V_a) + (V_w)}{V_s}$$

Va, volume of air
Vw, volume of liquid water
Vs, volume of soil

The texture of the soil

- Most soils have a mixture of grain sizes
- The particle size distribution is characterized by **the soil texture**
  - determined by the proportions by weight of clay, silt and sand



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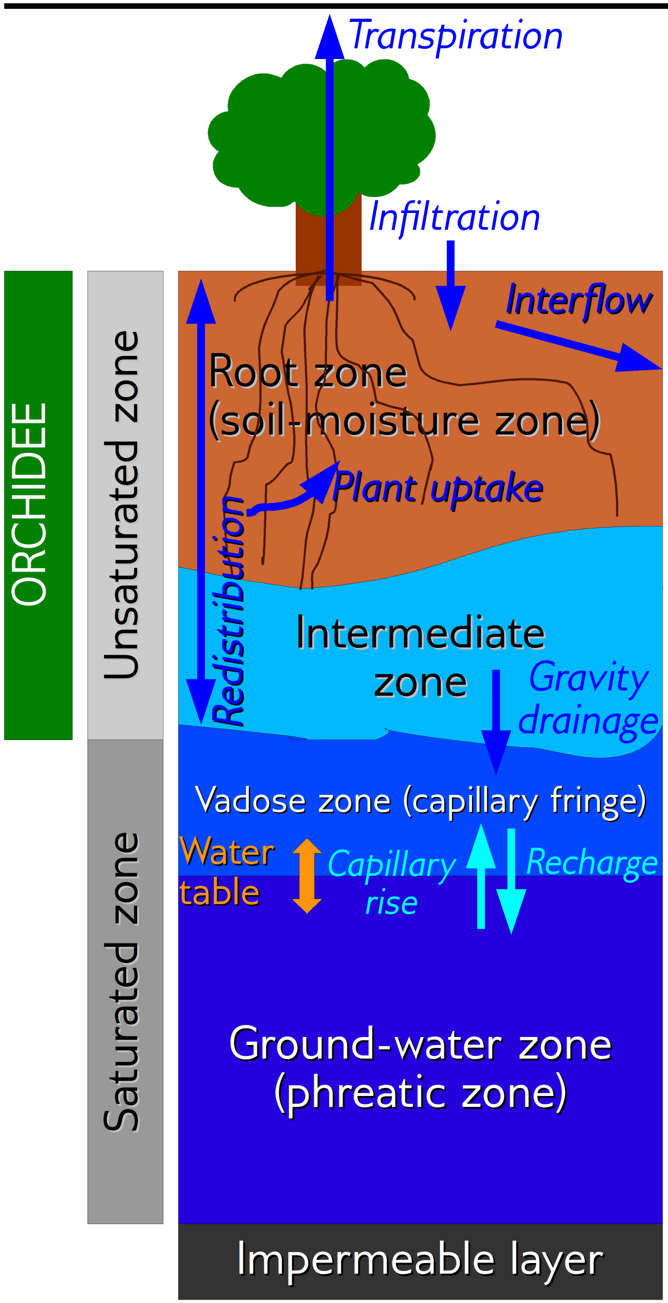
Hydrological horizons and water movement



- **Redistribution**: the subsequent movement of infiltrated water in the unsaturated zone of a soil => evaporation or capillary rise or recharge or interflow
- $\theta wp < \theta < \phi$

- May extend over many ten meters
- May be absent in other soil regimes

- Tension-saturated zone
- The soil is saturated due to capillary rise

The water flow in the soil

- Controlled by the size and shape of pores, which is in turn controlled by the size and packing of soil particles.
- Unsaturated flow: when some of the voids are occupied by air
- Saturated flow: when all the voids are occupied by water

Darcy's law for unsaturated flows

- Describes the flow rate across a unit cross section of soil

$$q_x = -K_h \cdot \left[\frac{dz}{dx} + \frac{d(p/\gamma_w)}{dx} \right]$$

Gradient of gravitational potential energy ($\frac{dz}{dx}$)

Gradient of pressure potential energy ($\frac{d(p/\gamma_w)}{dx}$)

q_x: Volumetric flow rate in the x direction (m/s)

K_h: **Hydraulic conductivity** of the soil (m/s) <=> ability of the soil to "conduct" water

p, water pressure

γ_w, weight density of water

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Darcy's law for unsaturated flows

- We focus on the vertical component of flow (z direction)

$$q_z = -K_h . \left[1 + \frac{d\left(p/\gamma_w\right)}{dz} \right]$$

Pressure head, ψ (γ_w is constant)

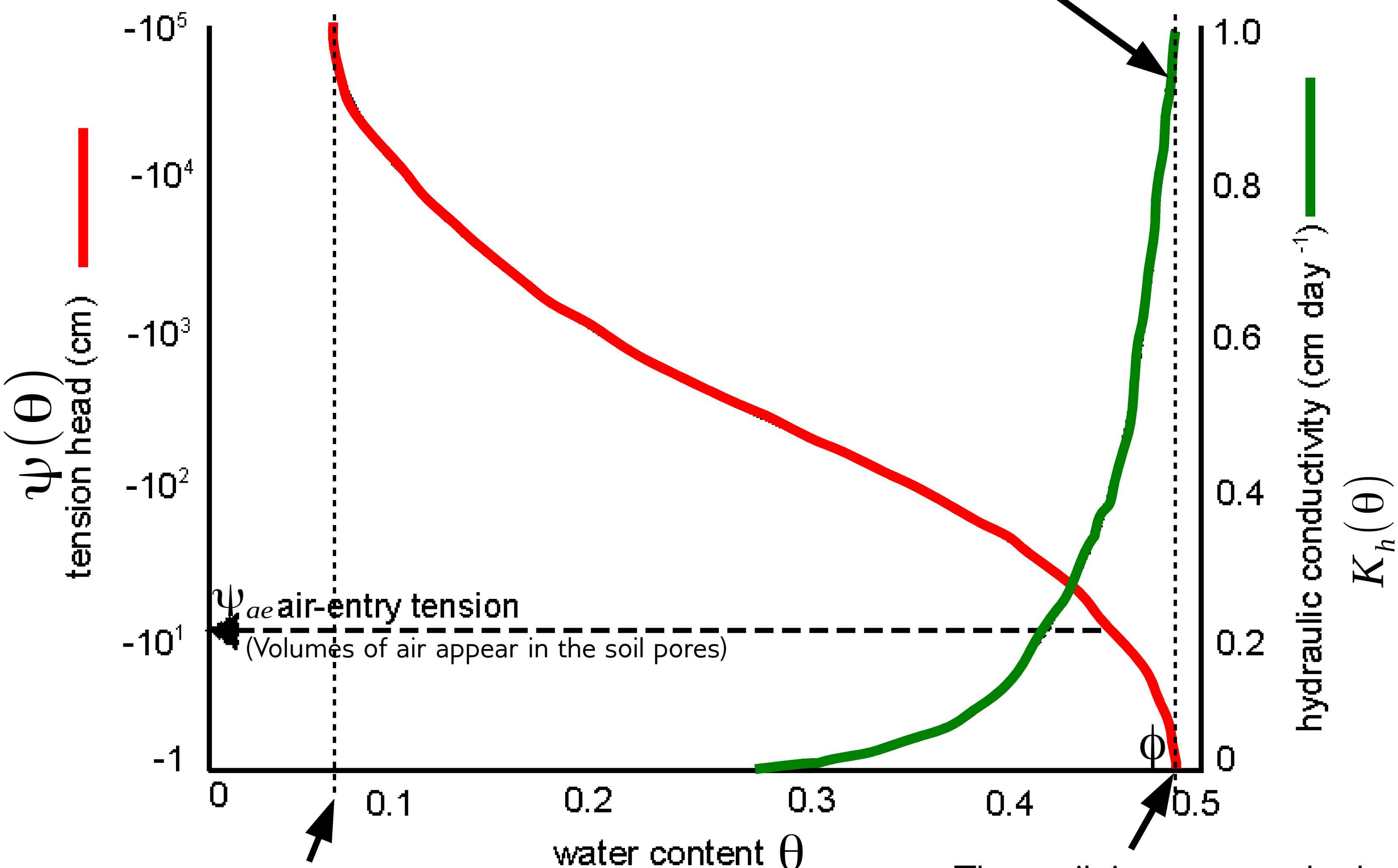
- In unsaturated flows, both ψ and K_h are functions of θ, so:

$$q_z = -K_h(\theta) . \left[1 + \frac{d\,\psi(\theta)}{dz} \right]$$

- In unsaturated soils, $\psi < 0$. Negative pressure head is also called tension head, matric potential or matric suction

Relation between ψ and θ

K_h increases with increasing soil moisture to is maximum value at saturation (**hydraulic conductivity at saturation**)



Residual water content, θr

The soil is saturated, the pressure is atmospheric

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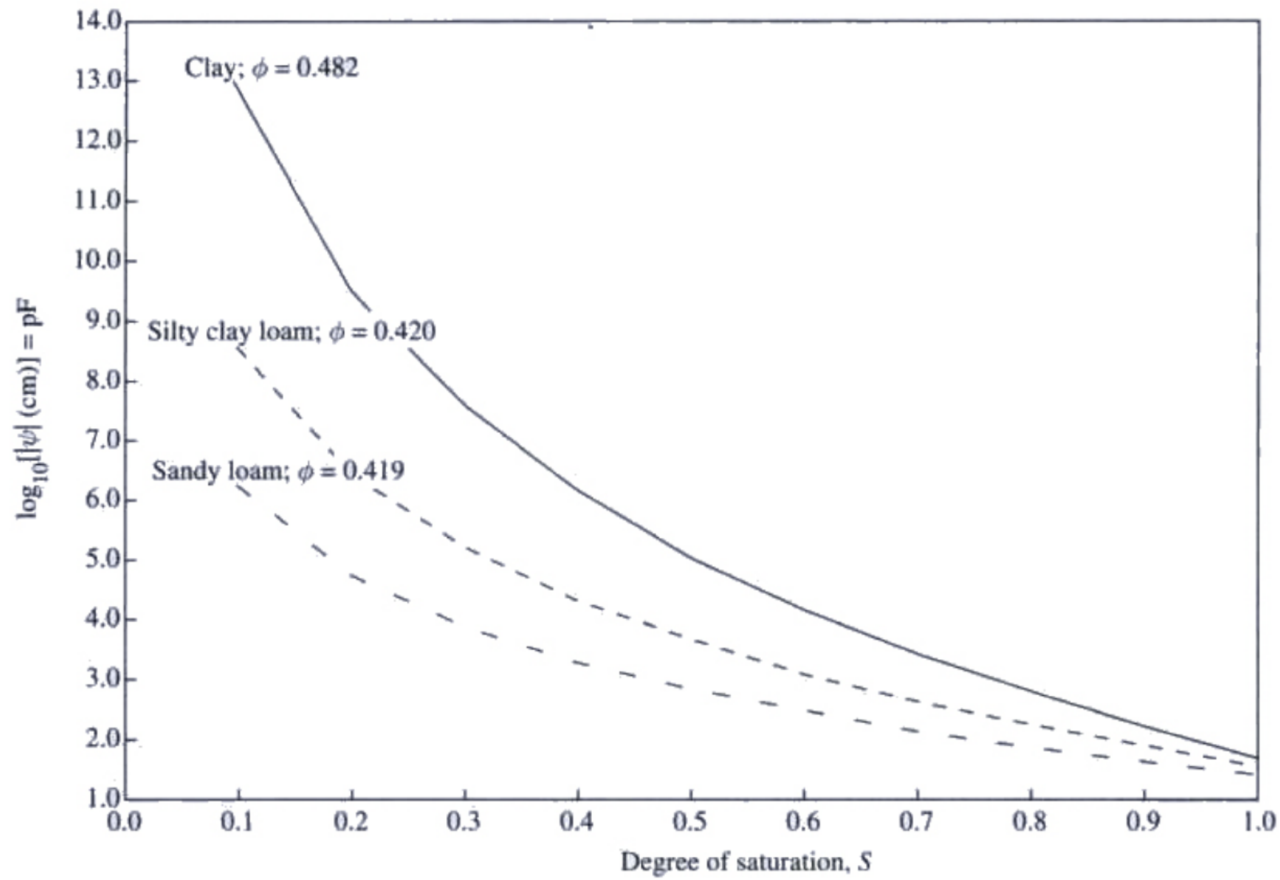
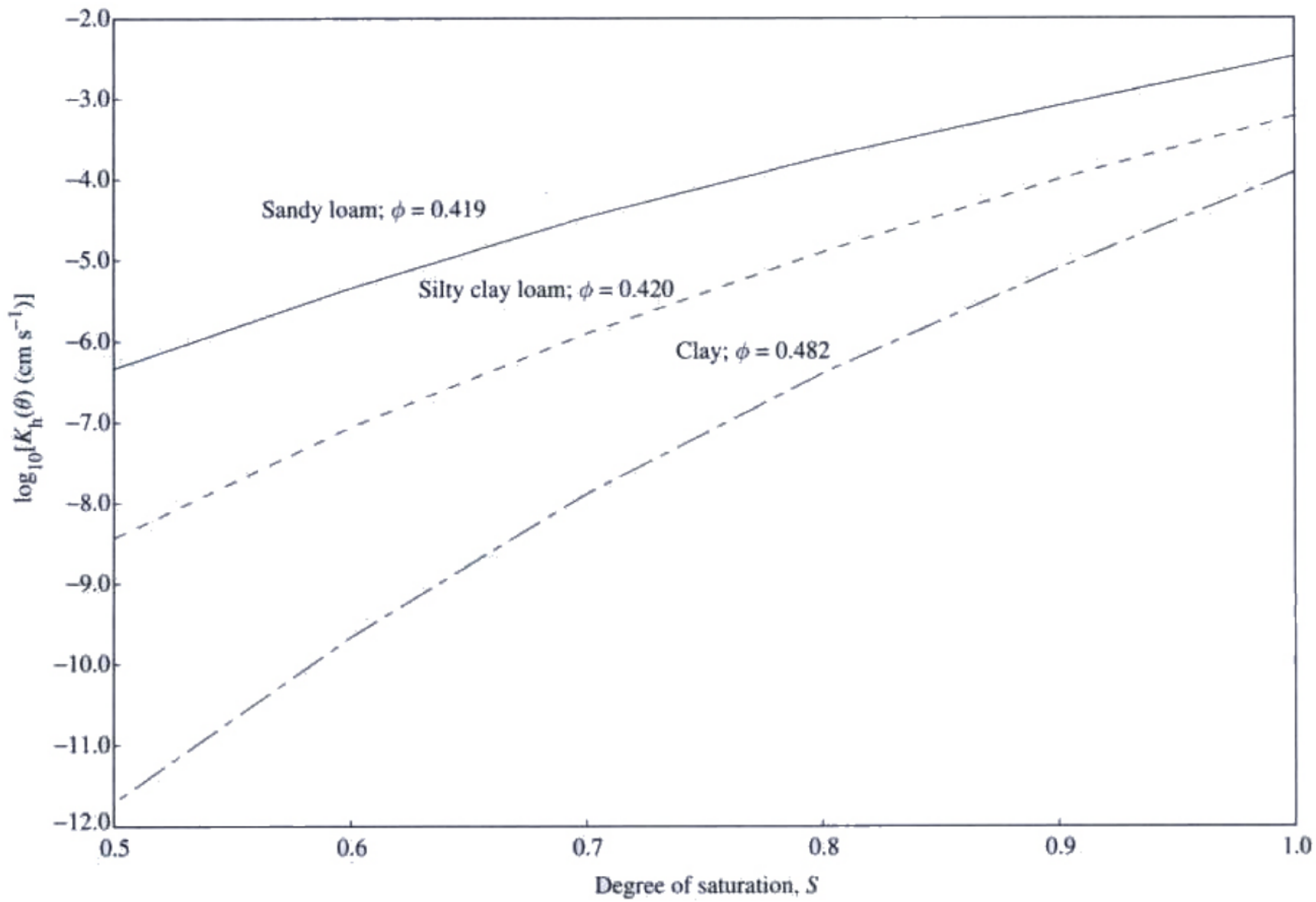
Relation between ψ and soil types



- ψ depends on soil types
- For a given degree of saturation, ψ is much higher in fine-grained soils than in coarser-grained soils
- The value of tension for a given water content also depends on the history of wetting and drying

Hydraulic conductivity for different soils



- K_h depends on soil types
- For a given degree of saturation, K_h increases by several orders of magnitude from fine-grained soils to coarse-grained soils (water path is less sinuous <=> less resistance to flow)

Soil water

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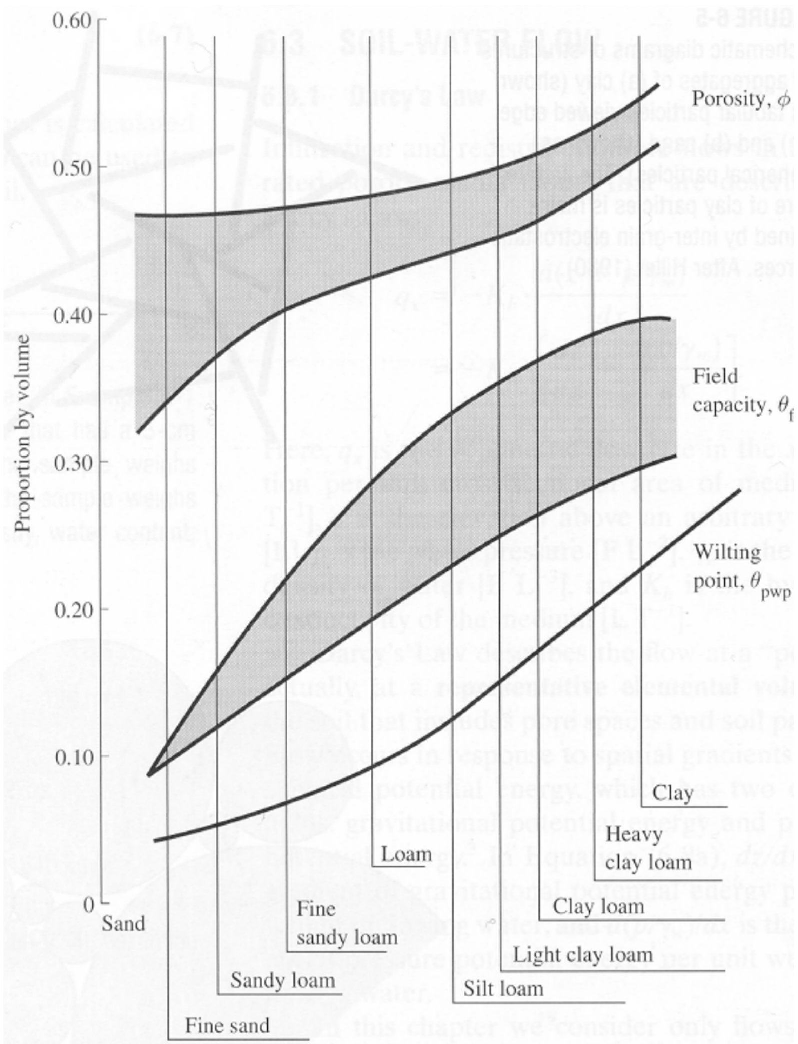

- **Field capacity, θfc**: maximum amount of water that a soil can hold after gravitational drainage
- **Wilting point, θwp:** water content at which plants can no longer extract water from the soil
- **Plant available water content, θa:** water available for plant use
- They vary depending on the soil

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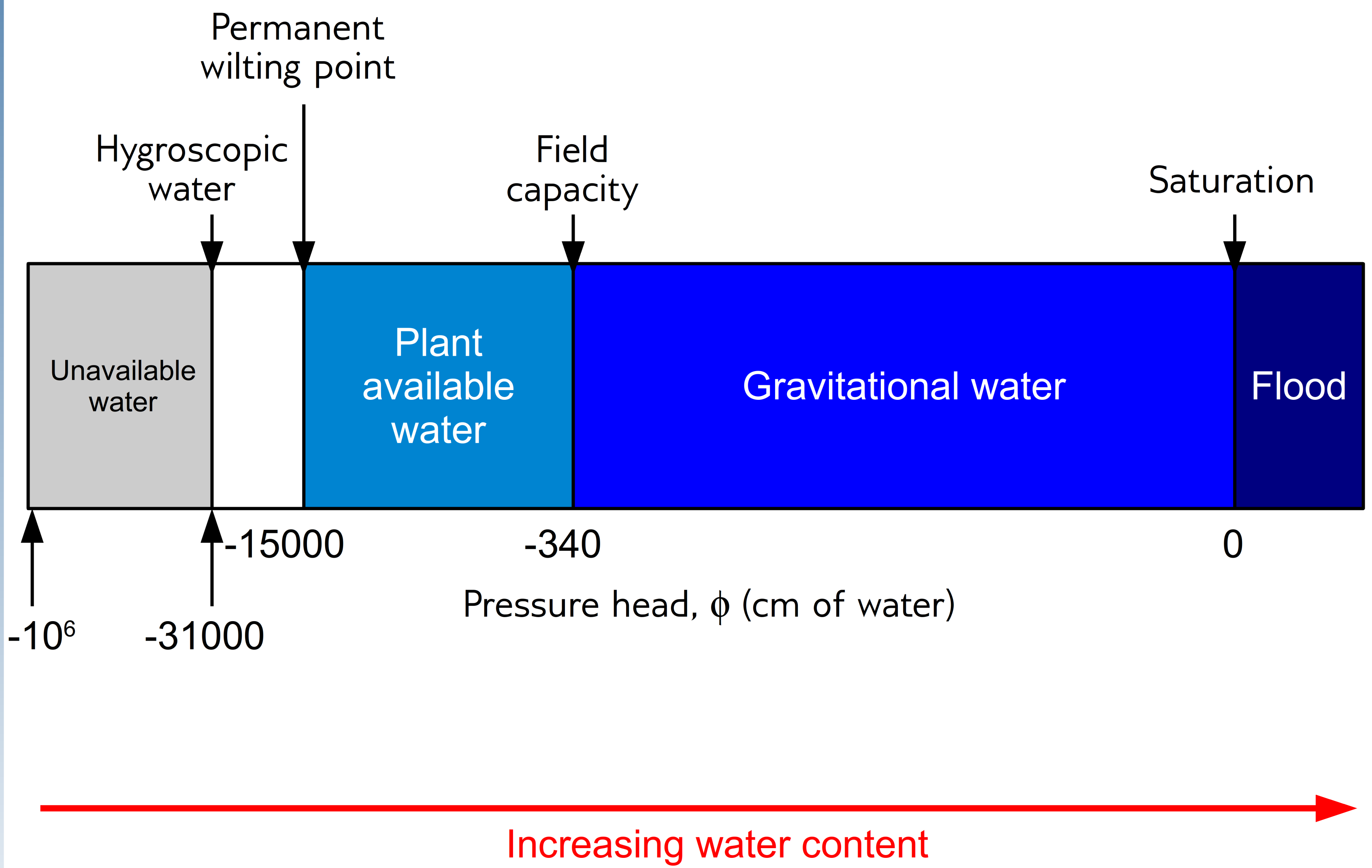
Soil water status as a function of pressure

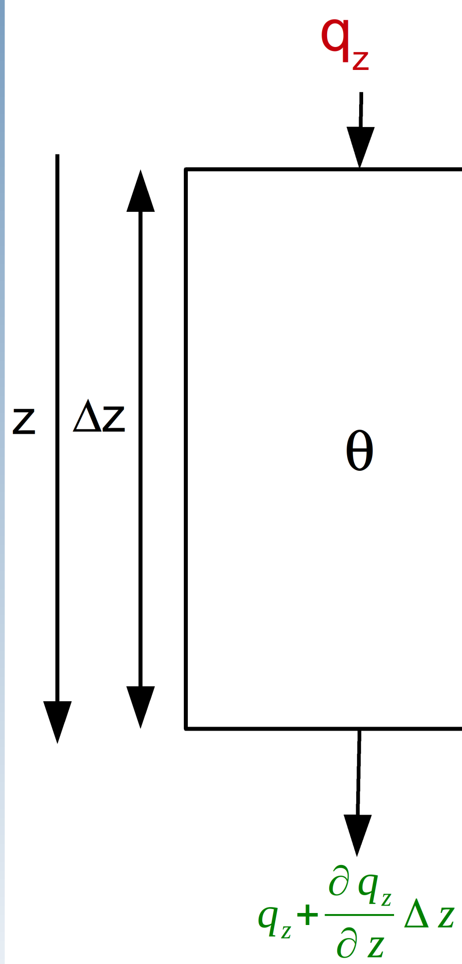


The Richards equation (Richards, 1931)

- It is widely used as a basis for numerical modeling soil water flow:
  - by specifying appropriate boundary conditions
  - by dividing the soil profile into very thin layers
  - by applying the equation to each layer sequentially over small increments of time

The Richards equation (Richards, 1931)

We assume 1D vertical water flow below a flat surface:



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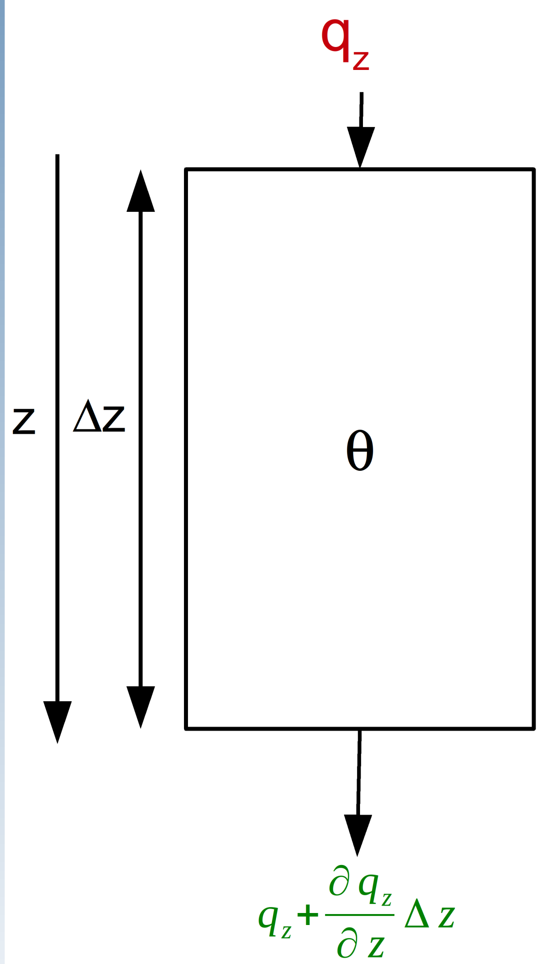

Conservation of the mass:

$$\frac{\partial \theta}{\partial t} \Delta z = q_z - \left(q_z + \frac{\partial}{\partial z} q_z . \Delta z \right)$$

$$\frac{\partial \theta}{\partial t} = - \frac{\partial}{\partial z} q_z$$

Combining Darcy's law
(z<0 because the "point" is below the surface):

$$q_z = - K_h(\theta) . \left[-1 + \frac{\partial}{\partial z} \psi(\theta) \right]$$

$$\frac{\partial \theta}{\partial t} = - \frac{\partial}{\partial z} K_h(\theta) + \frac{\partial}{\partial z} \left[K_h(\theta) . \frac{\partial}{\partial z} \psi(\theta) \right]$$

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The Richards equation (Richards, 1931)

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} K_h(\theta) + \frac{\partial}{\partial z}\left[K_h(\theta) . \frac{\partial}{\partial z} \psi(\theta) \right]$$

The time rate of change in volumetric soil moisture for a given thin layer of soil depends on:

- the vertical rate of change of the hydraulic conductivity
- the vertical rate of change of the product of:
  - the hydraulic conductivity
  - the vertical rate of change of the pressure head

The Fokker-Planck equation

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} K_h(\theta) + \frac{\partial}{\partial z}\left[K_h(\theta) . \frac{\partial}{\partial z} \psi(\theta) \right]$$

Hydraulic diffusivity (m²/s):

$$D_h(\theta) = K_h(\theta) . \frac{\partial}{\partial \theta} \psi(\theta)$$

$$D_h(\theta) . \frac{\partial \theta}{\partial z} = K_h(\theta) . \frac{\partial}{\partial \theta} \psi(\theta) . \frac{\partial \theta}{\partial z}$$

$$D_h(\theta) . \frac{\partial \theta}{\partial z} = K_h(\theta) . \frac{\partial}{\partial z} \psi(\theta)$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} K_h(\theta) + \frac{\partial}{\partial z}\left[D_h(\theta) . \frac{\partial \theta}{\partial z} \right]$$

Conductivity — $K_h(\theta)$

Diffusivity — $D_h(\theta)$

Water-content gradient — $\frac{\partial \theta}{\partial z}$

Soil hydrology schemes

2 – The physically-based model

2-2. Modeling in ORCHIDEE

The hydrodynamic parameters

- K_h and D_h depend on saturated properties of the soils and on θ
- Their dependence on θ are very non linear
- In ORCHIDEE, this is described by the Van Genuchten-Mualem relationships

	K_s $mm \cdot j^{-1}$	n	α m^{-1}	$theta_r$ $m^3.m^{-3}$	$theta_s$ $m^3.m^{-3}$
Sand	7128.0	2.68	14.5	0.045	0.43
Loamy Sand	3501.6	2.28	12.4	0.057	0.41
Sandy Loam	1060.8	1.89	7.5	0.065	0.41
Silt Loam	108.0	1.41	2.0	0.067	0.45
Silt	60.0	1.37	1.6	0.034	0.46
Medium Loam	249.6	1.56	3.6	0.078	0.43
Sandy Clay Loam	314.4	1.48	5.9	0.100	0.39
Silty Clay Loam	16.8	1.23	1.0	0.089	0.43
Clay Loam	62.4	1.31	1.9	0.095	0.41
Sandy Clay	28.8	1.23	2.7	0.100	0.38
Silty Clay	4.8	1.09	0.5	0.070	0.36
Clay	48.0	1.09	0.8	0.068	0.38

Values of Van Genuchten's parameters (Carsel and Parrish, 1988)

The hydrodynamic parameters

$$\psi(\theta)=-\frac{1}{\alpha}\left[\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-\frac{1}{m}}-1\right]^{\frac{1}{n}}$$

$$K_h(\theta)=K_s\sqrt{\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)}\left[1-\left(1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{m}}\right)^m\right]^2$$

$$D_h(\theta)=\frac{(1-m)K_h(\theta)}{\alpha m}\frac{1}{\theta-\theta_r}\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-\frac{1}{m}}\left(\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-\frac{1}{m}}-1\right)^{-m}$$

- θ_s: saturated water content (m^3/m^3)
- θ_r: residual water content (m^3/m^3)
- K_s: hydraulic conductivity at saturation (m/day)

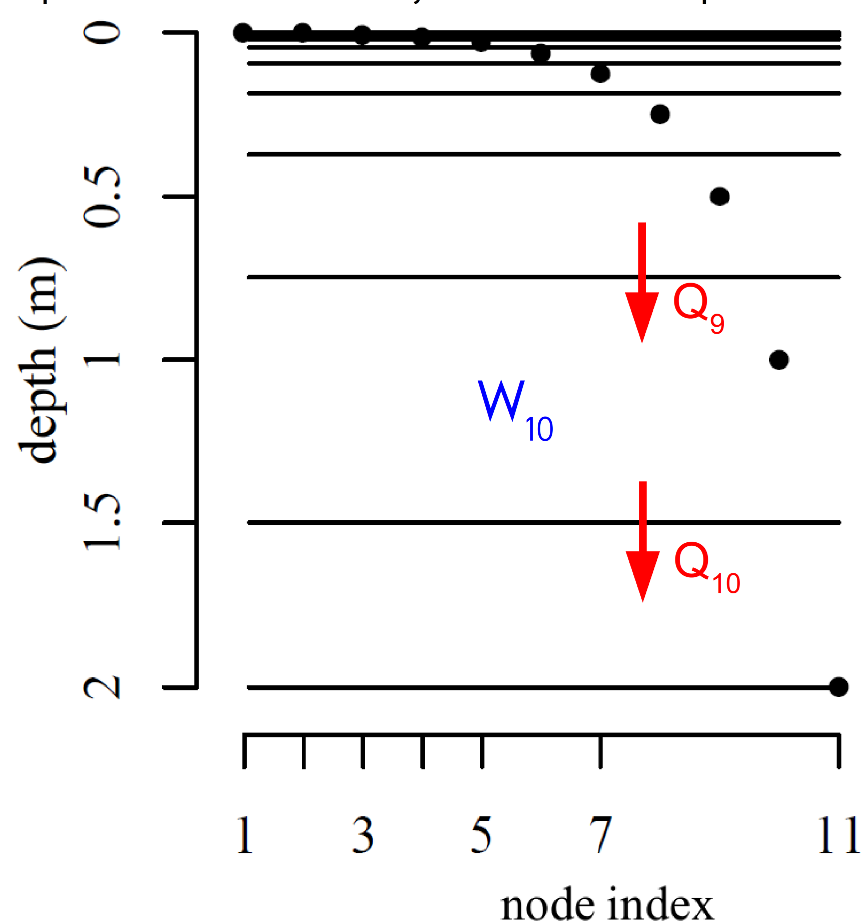
Defined based on soil texture

In each grid-cell, we use the dominant texture from the USDA map

- α: Van Genuchten parameter (m^{-1}), related to the inverse of the air entry suction
- m and n: Van Genuchten parameters related to pore-size distribution. m=1-1/n according to the Mualem model.

Vertical discretization

- The soil column is discretized using 11 nodes (geometric increase of internode distance)
- Total water content of a layer: vertical integration of θ(z) in the layer (assuming a linear variation between the 2 nodes)
- Permit an accurate calculation of θi and the related water fluxes Qi
- Thin layers on the top soil where θ is likely to exhibit sharp vertical gradients



de Rosnay et al., 2002;
d'Orgeval et al., 2008

Boundary conditions

- The evolution of θi is driven by:
  - soil properties (K_h, D_h, θ_r, θ_s, soil depth and Z_i)
  - transpiration sink: uniform diffuse sink term in each soil layer
- Top and bottom boundary conditions:
  - Q_0 = Infiltration – Evap
  - $Q_{11} = F.K(\theta_{11})$ = Drainage

  F=1 (gravitational drainage) or F=0 (impermeable bottom)

Water stress function, Us

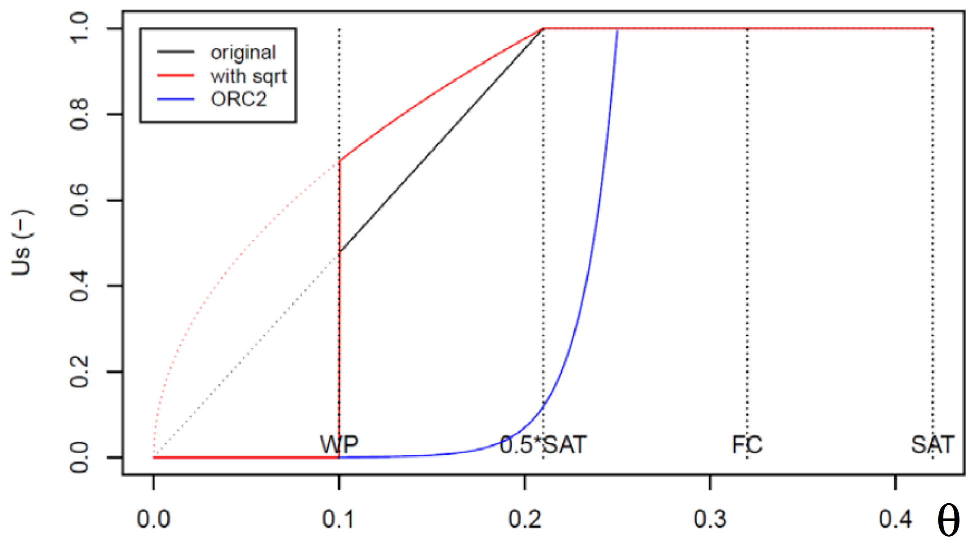
- Coupling between the soil water distribution and the rooting demand at a given soil depth

$$\frac{W_i(t+dt)-W_i(t)}{dt}=Q_{i-1}(t+dt)-Q_i(t+dt)-\mathbf{S_i}$$

$$S_i=\frac{us_i}{U_s}T_r \qquad U_s=\sum us_i$$

Fraction of roots

$$us_i=\frac{W_i}{(z_i-z_{i-1}).\boldsymbol{\theta_d}}.f_{R_i}$$



$$\theta_d=0.5\Phi$$

Critical water content from which water extraction by the roots decreases with the water content of the soil layer

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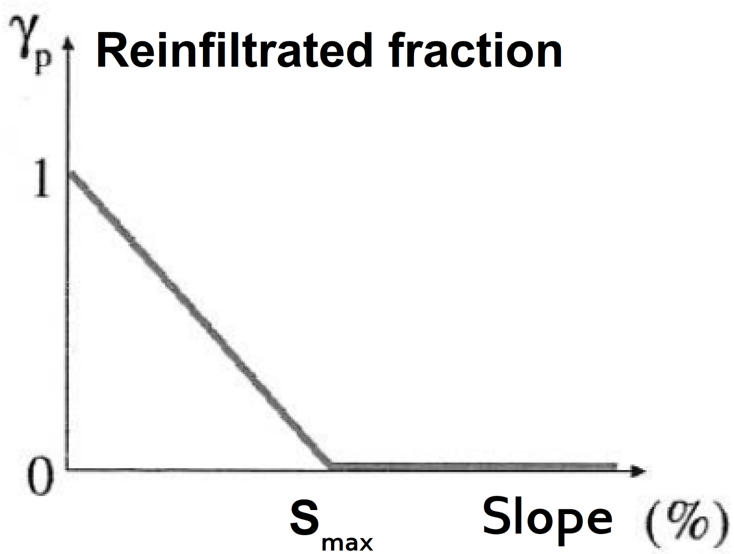
Infiltration and runoff

- At the soil surface: throughfall (P_0) can either infiltrate or run off (Rs)
- In the first layer (1mm) => direct infiltration (I_i)
- If P_0 > 1mm/dt => wetting front propagation with time splitting procedure
- $Rs_{pot} = P_0 - \sum I_i$

But Rs may reinfiltrate if the slope of the land surface s_{max} < 0.5% (slope map)

$Rs = (1-\gamma_p).Rs_{pot}$



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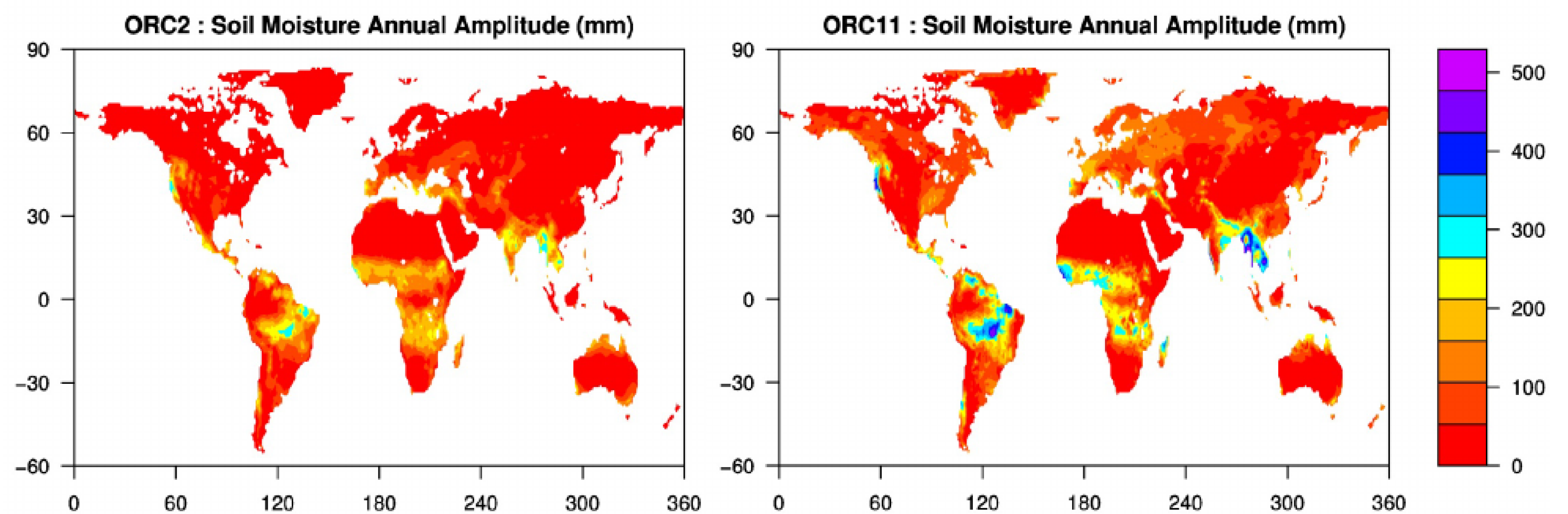
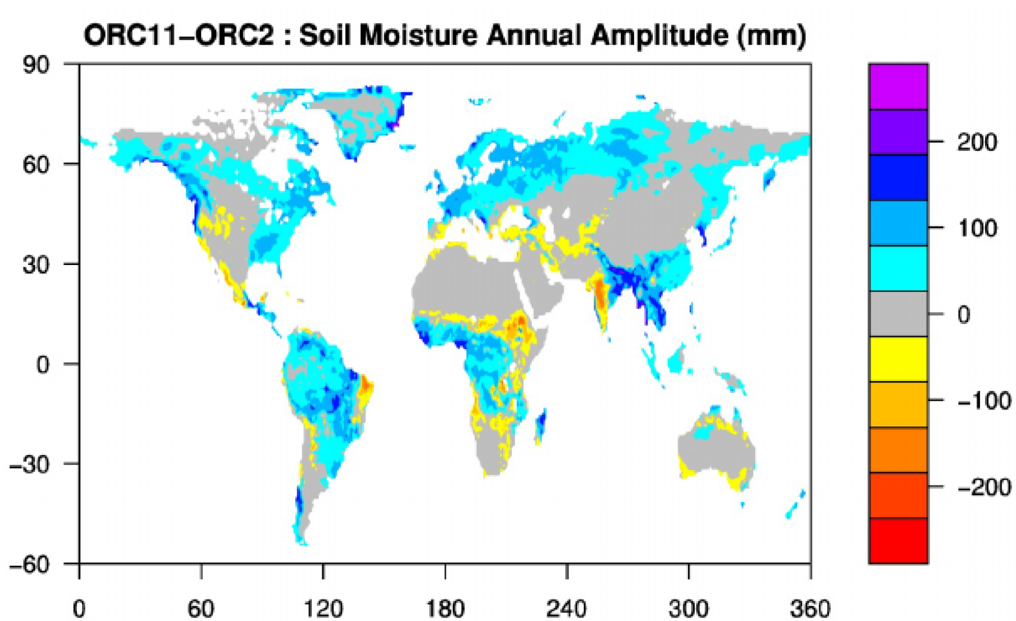
Results comparison





Preliminary results (Ducharne, Guimberteau)

Soil moisture annual amplitude:

- defines the effective water holding capacity
- is maximum in "transition zones"
- with ORC11, it is larger in the rainy regions
- the transitions are more abrupt

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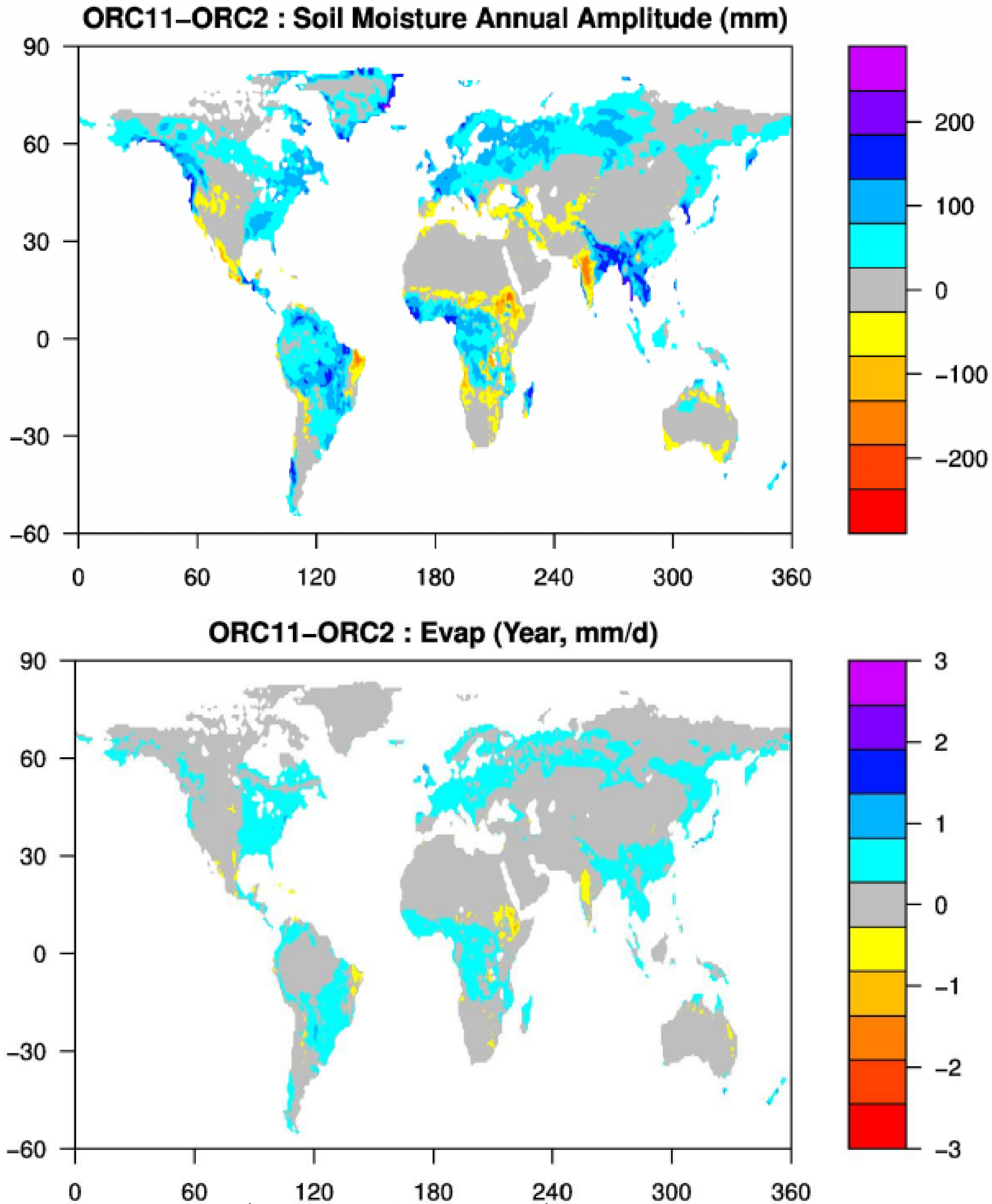

Preliminary results (Ducharne, Guimberteau)

- ET increases where soil moisture annual amplitude increases, except in central Amazonia where ET is not limited by water
- The increase of ET mostly comes from soil evaporation
- Transpiration mostly decreases, especially in transition / arid zones

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Results comparison

- ORC11 has a larger soil evaporation (not limited by a soil resistance but by soil water diffusion to the top soil layer)
- Larger soil evaporation + drainage at the soil bottom => low soil moisture and low transpiration, despite increased water holding capacity
- This suggests ORC11 has a lower soil moisture memory than ORC2

Preliminary results (Ducharne, Guimberteau)

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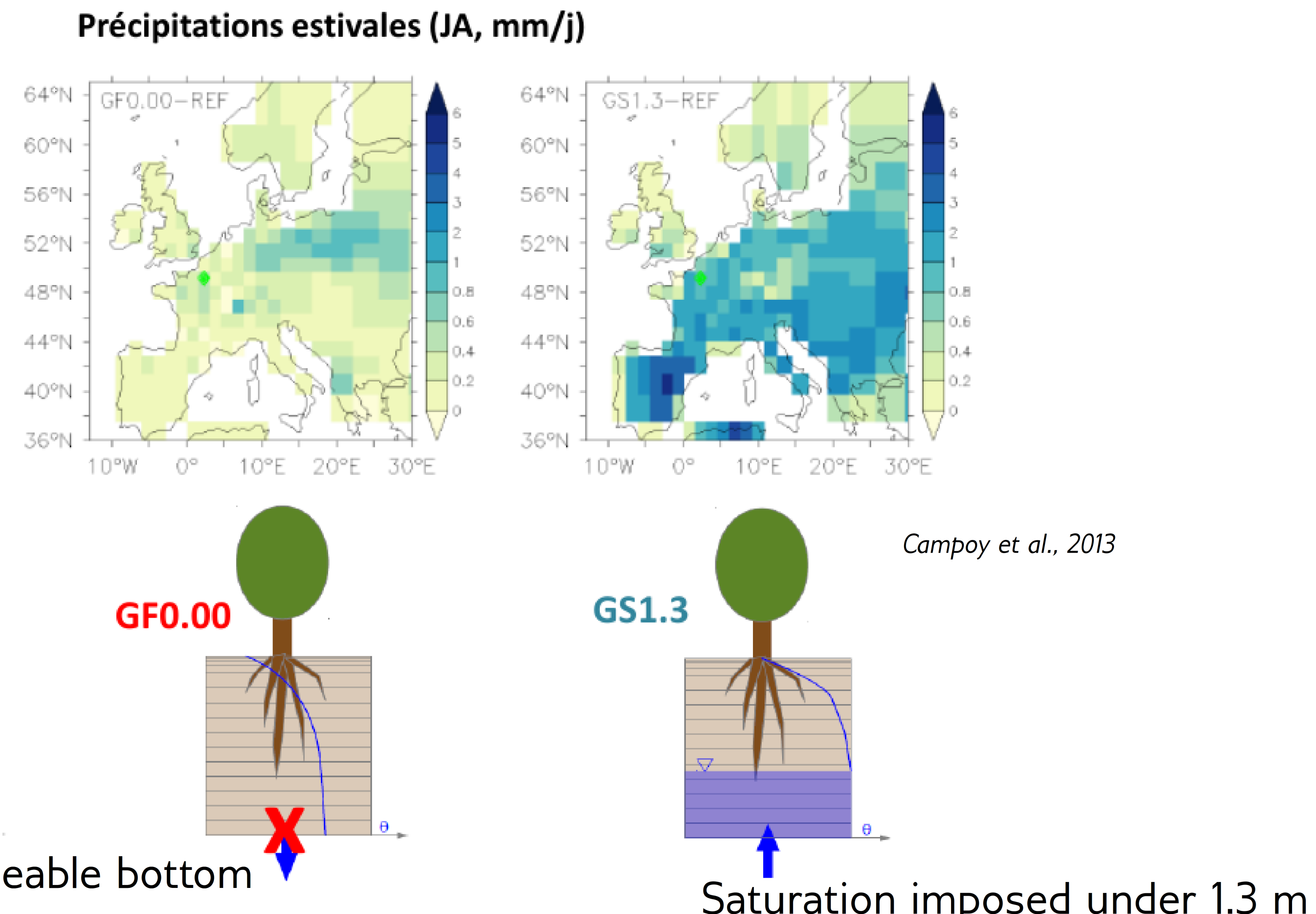
Perspective with the physically-based model

- Link with the saturated zone



Thank you for your attention