Soil hydrology

Agnès Ducharne
UMR METIS, UPMC
agnes.ducharne@upmc.fr

Outline

1. **Introduction**
   - Water budget and soil hydrology
   - Interactions with the vegetation
2. **The multi-layer « CWRR » scheme**
   - Processes, parameters, options
3. **Forcing conditions**
   - Vegetation/LC and soil texture

More details on the Wiki

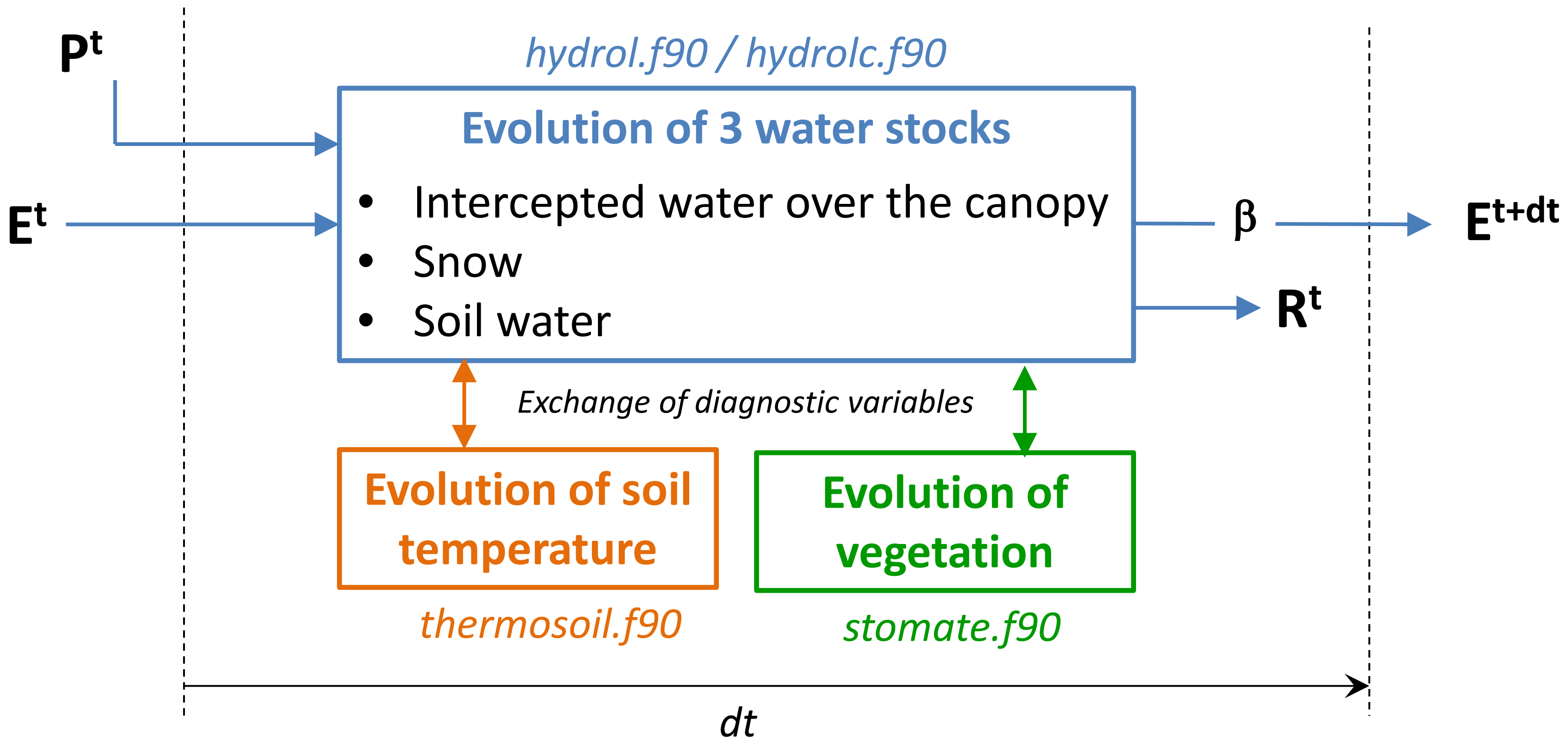
http://forge.ipsl.jussieu.fr/orchidee/attachment/wiki/Documentation/eqs_hydrol.pdf

Reference papers: de Rosnay et al., 2000; de Rosnay et al., 2002; d'Orgeval et al., 2008; Campoy et al., 2013

PhD theses : de Rosnay, 1999; d'Orgeval, 2006; Campoy, 2013

Water budget and soil hydrology

$$dS/dt = P - E - R$$

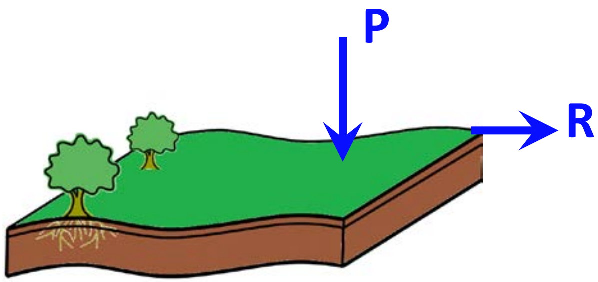


We will focus on soil water and the related water fluxes (soil hydrology)
No interception, no snow, no soil water freezing

Two versions of soil hydrology

Two-layer = Choisnel = ORC2

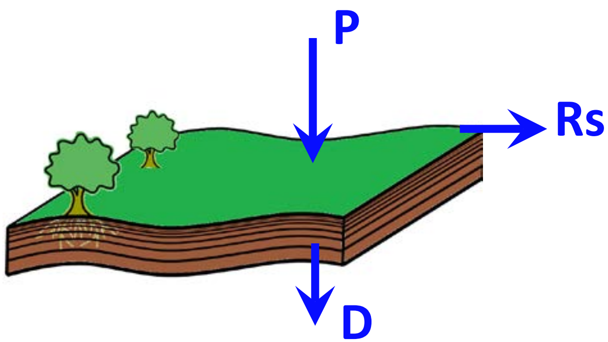
Ducoudré et al., 1993; Ducharne et al., 1998; de Rosnay et al. 1998



- **Conceptual description of soil moisture storage**
- **4-m soil and 2-layers**
- Top layer can vanish
- Constant available water holding capacity (between FC and WP)
- Runoff when saturation
- No drainage from the soil
  We just diagnose a drainage as 95% of runoff for the routing scheme

Multi-layer = CWRR = ORC11

de Rosnay et al., 2002; d'Orgeval et al., 2008; Campoy et al., 2013

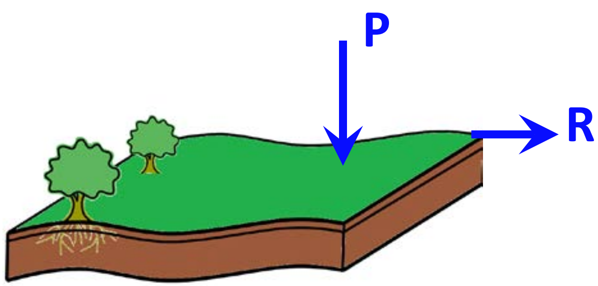


- **Physically-based description of soil water fluxes using Richards equation**
- **2-m soil and 11-layers**
- Formulation of Fokker-Planck
- Hydraulic properties based on van Genuchten-Mualem formulation
- Related parameter based on texture (fine, medium, coarse)
- Surface runoff = P – Esol – Infiltration
- Free drainage at the bottom

Two versions of soil hydrology

Two-layer = Choisnel = ORC2

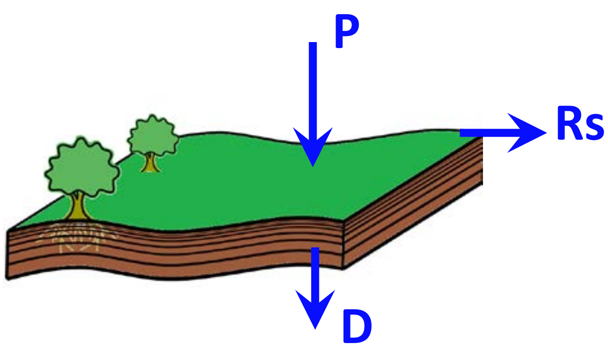
Ducoudré et al., 1993; Ducharne et al., 1998; de Rosnay et al. 1998



- **Conceptual description of soil moisture storage**
- **2-m soil and 2-layers**
- Top layer can vanish
- Constant availabl
  capacity (betwe
- Runoff when sa
- No drainage fro
  We just diagnos
  of runoff for the routing scheme

Multi-layer = CWRR = ORC11

de Rosnay et al., 2002; d'Orgeval et al., 2008; Campoy et al., 2013



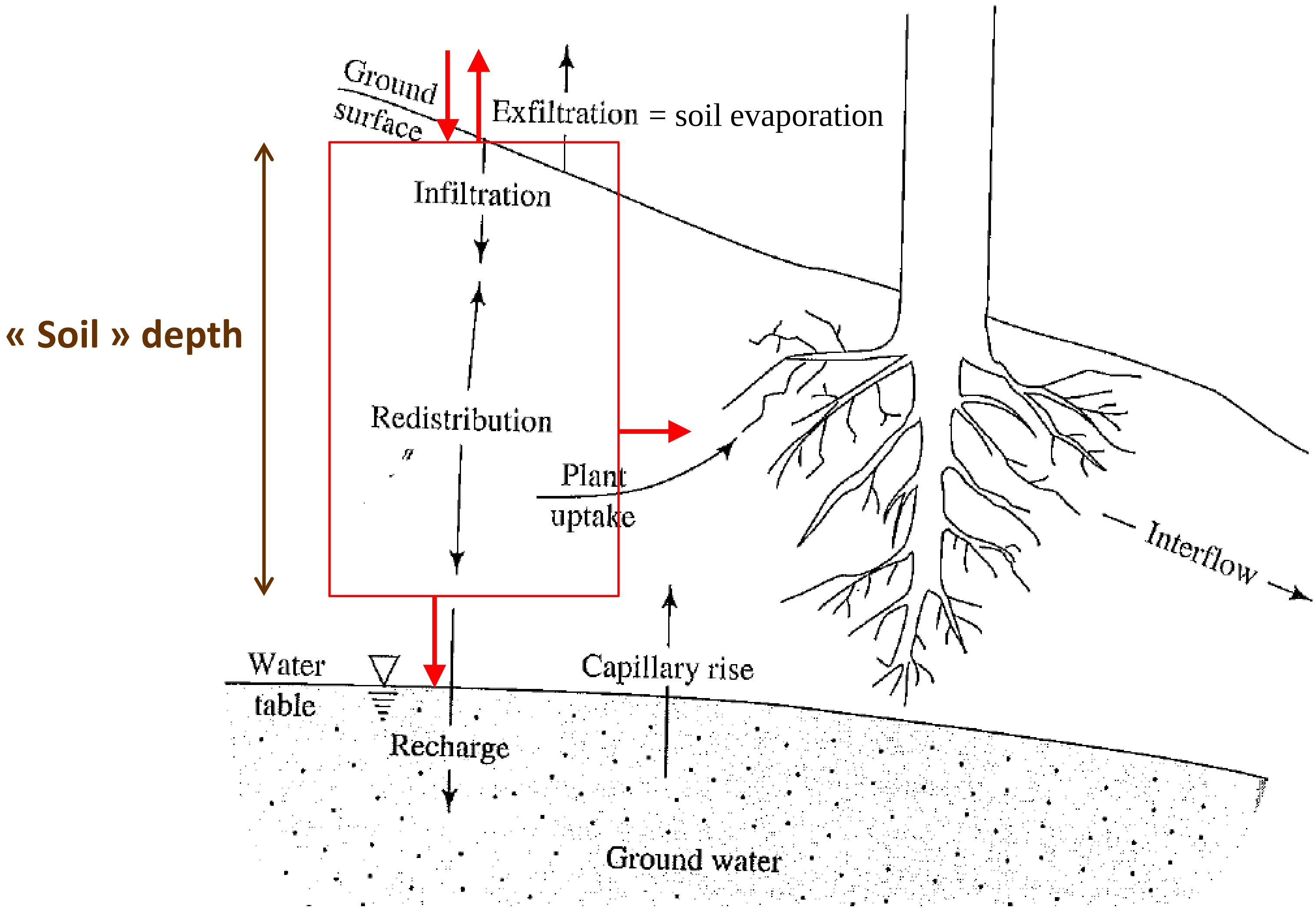
- **Physically-based description of soil water fluxes using Richards equation**
- **2-m soil and 11-layers**
- Formulation of Fokker-Planck
- s based on van
  formulation
  based on texture
  se)
  Esol – Infiltration
- Free drainage at the bottom

In run.def

HYDROL_CWRR = n / **y**

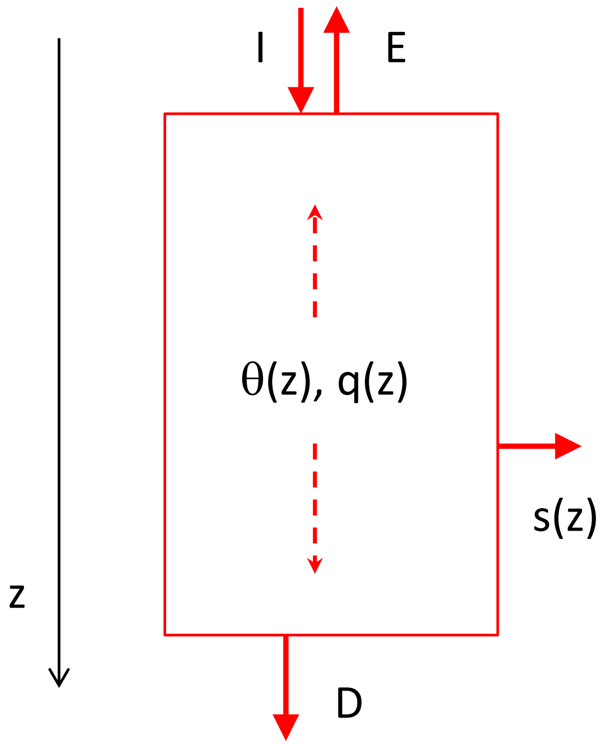
→ either hydrolc.f90 or hydrol.f90

What is modeled ?



How is modeled ?

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



θ : volumetric water content in $m^3.m^{-3}$
q : flux density in $m.\,s^{-1}$
h : hydraulic head in m
K : hydraulic conductivity in $m.s^{-1}$
s : transpiration sink in $m^3.m^{-3}.s^{-1}$

2. Continuity :

$$\frac{\partial \theta}{\partial t} + \frac{\partial q}{\partial z} = -s$$

3. Motion = diffusion equation because of low velocities in porous medium

$$q(z) = -K(z)\frac{\partial h}{\partial z}$$

Richards equation

4. Hydraulic head h quantifies the gravity and pressure potentials

$$h = -z + \psi$$

ψ is the matric potential (in m, <0)

5. K and ψ depend on θ (unsaturated soils)

$$q(z) = -K(\theta)\left[\frac{\partial \psi}{\partial z} - 1\right]$$

$$\boxed{q(z) = -D(\theta)\frac{\partial \theta}{\partial z} + K(\theta)}$$

+2 → Fokker-Planck eq.

$$D(\theta) = K(\theta)\frac{\partial \psi}{\partial \theta}$$

D is the diffusivity (in $m^2.s^{-1}$)

The hydrodynamic parameters

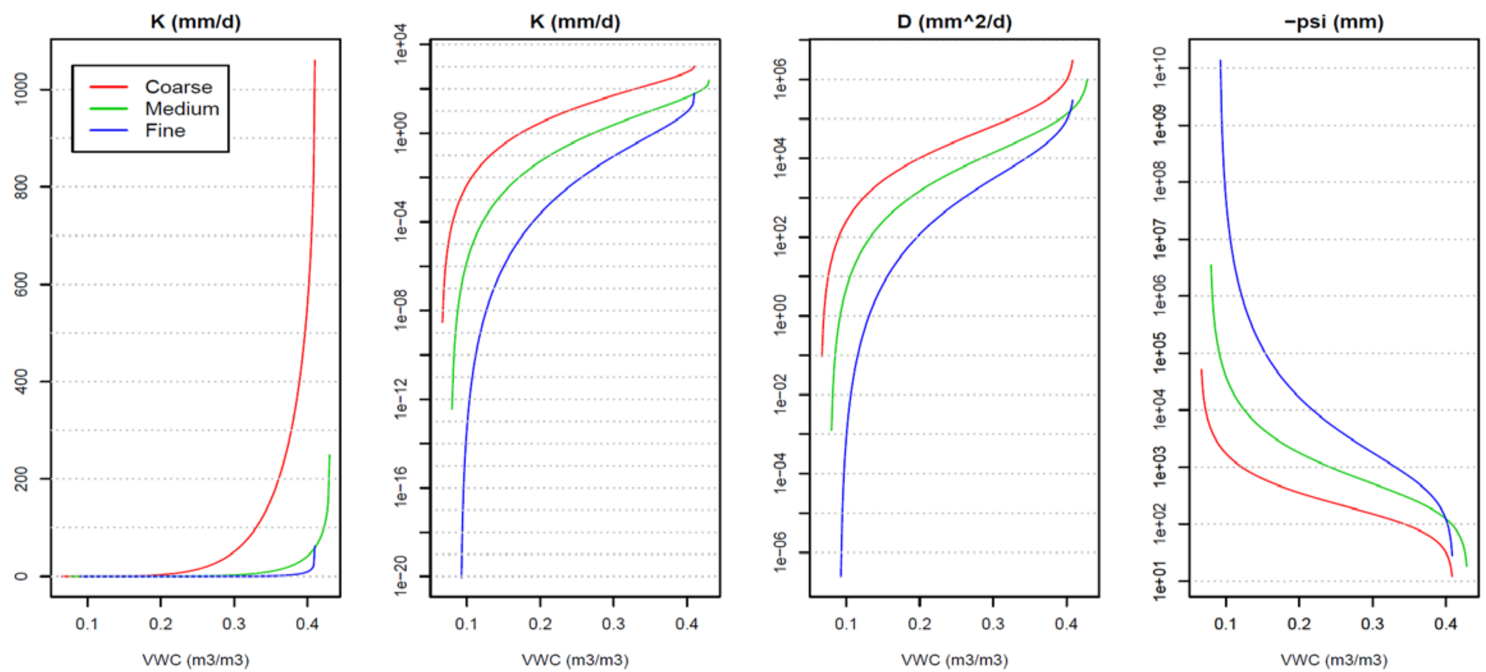
- K and D depend on saturated properties (measured on saturated soils) and on θ
- Their dependance on θ is very non linear
- In ORCHIDEE, this is decribed by the so-called Van Genuchten-Mualem relationships:

$$K(\theta) = K_s \sqrt{\theta_f} \left(1 - \left(1 - \theta_f^{1/m}\right)^m\right)^2 \qquad \theta_f = (\theta - \theta_r)/(\theta_s - \theta_r)$$

$$\psi(\theta) = -\frac{1}{\alpha}\left(\theta_f^{-1/m} - 1\right)^{1/n} \qquad m = 1 - 1/n$$

$$D(\theta) = \frac{(1-m)K(\theta)}{\alpha m} \frac{1}{\theta - \theta_r} \theta_f^{-1/m} . \left(\theta_f^{-1/m} - 1\right)^{-m}$$

Parameters:
θ_s θ_r K_s m
$\alpha = -1/\psi_{ae}$



Modifications of Ks with depth

Ks decreases exponentially with depth

- This follows observational reports (starting from Beven & Kirkby, 1979)
- In ORCHIDEE, the exponential decay starts at 30 cm

$$K_s(z) = K_s^{\mathrm{ref}}.\min(\exp(-f(z - z_{\mathrm{lim}}), 1)$$

Parameters:
K_s^{ref} f z_{lim}

Ks also increases towards the surface because of bioturbation (roots)

$$K_j(z) = \max\left(1, \left(\frac{K_s^{\mathrm{max}}}{K_s^{\mathrm{ref}}}\right)^{\frac{1-c_j z}{2}}\right)$$

$$K_s^*(z) = K_s(z)\prod_{j=2}^{13} K_j(z)^{f_v^j} = K_s(z)\, F_{K\mathrm{root}}$$

Parameters:
K_s^{ref} K_s^{max} c_j^z
(+ f_v^j = veget)

Impact on the other Van Genuchten parameters

- K_s^{ref}, α and m depend on soil texture
- To keep the consistency between them when Ks varies with depth, the other two are also changed (cf. d'Orgeval, 2006).

Parameters:
n0, nk_rel, a0, ak_rel

Modifications of Ks with depth

Ks decreases exponentially with depth

- This follows observational reports (starting from Beven & Kirkb... ...79)
- In ORCHIDEE, the exponential decay starts at 30 cm

$$K_s(z) = K_s^{\mathrm{ref}}.\min(\exp(-f(\ldots$$

Ks also increases toward...

All this is done in hydrol_var_init

Details can be found in :

http://forge.ipsl.jussieu.fr/orchidee/attachment/wiki/Documentation/eqs_hydrol.pdf

$$\ldots_s(z) \prod_{j=2} K_j(z)^{f_v^j} = K_s(z)\, F_{K\mathrm{root}}$$

Parameters:
K_s^{ref} K_s^{max} c_j^z
(+ f_v^j = veget)

Impact on the other Van Genuchten parameters

- Ksref, α and m depend on soil texture
- To keep the consistency between them when Ks varies with depth, the other two are also changed (cf. d'Orgeval, 2006).

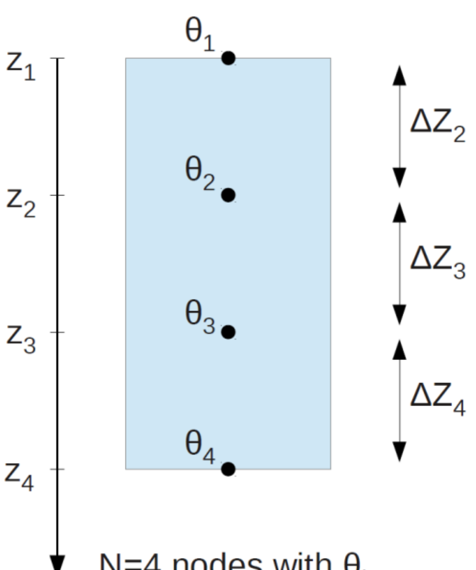
Parameters:
n0, nk_rel, a0, ak_rel

Finite difference integration (1)

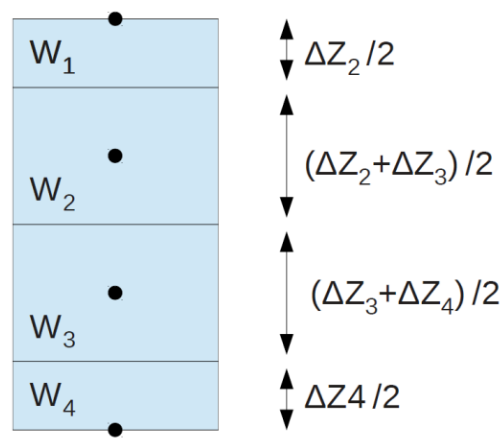
- The differential equations of continuity and motion are solved using finite differences

$$\frac{\partial \theta}{\partial t} + \frac{\partial q}{\partial z} = -s \qquad q(z) = - \; D(\theta)\frac{\partial \theta}{\partial z} + K(\theta)$$

- The soil column is discretized using N **nodes,** where we calculate θi
- The middle between 2 consecutive nodes defines the interface between 2 soil **layers**, except for the top and bottom layers
- The total water content Wi of a layer is obtained vertical integration of θ(z) in the layer, assuming a linear variation of θ(z) between 2 consecutive nodes



N=4 nodes with θ_i
3 internode heights



N=4 layers with W_i
5 interfaces

$$W_i = [\,\Delta Z_i\,(3\,\theta_i + \theta_{i-1}) + \Delta Z_{i+1}\,(3\,\theta_i + \theta_{i+1})\,]/8$$

$$W_1 = [\,\Delta Z_2\,(3\,\theta_1 + \theta_2)\,]/8$$

$$W_N = [\,\Delta Z_N\,(3\,\theta_N + \theta_{N-1})\,]/8$$

$$h_i = [\,\Delta Z_i + \Delta Z_{i+1}\,]/2$$

$$h_1 = \Delta Z_2/2$$

$$h_N = \Delta Z_N/2$$

In hydrol, zi, ΔZi, hi and Wi in mm

Finite difference integration (2)

- The continuity and motion equations become:

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

Si = transpiration sink

$$\frac{Q_i}{A} = -\frac{D(\theta_{i-1})+D(\theta_i)}{2}\,\frac{\theta_i-\theta_{i-1}}{\Delta Z_i} + \frac{K(\theta_{i-1})+K(\theta_i)}{2}$$

A: grid-cell area

- They can be solved using a tridiagonal matrix which updates θi (**prognostic variable**)
- To this end, K(θi) and D(θi) must be linearized at first order in θ

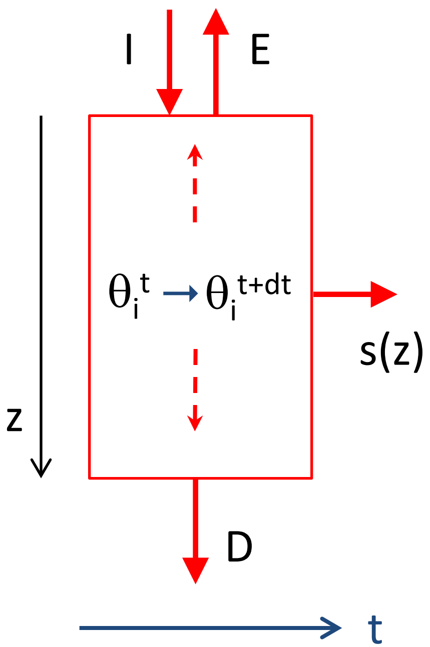
→ piecewise functions over 50 interval in [θr, θs]

$$\begin{aligned} K_k &= a_k\theta_k + b_k \\ D_k &= d_k \end{aligned}$$

- Care is taken that θ remains in [θr, θs] ← *hydrol_smooth_...*

- **In this framework, the evolution of θi is driven by**
  - soil properties (K, D, θr, θs, soil depth and Zi)
  - transpiration sink
  - top and bottom boundary conditions:

Q_0 = I - E and **Q_N = D**



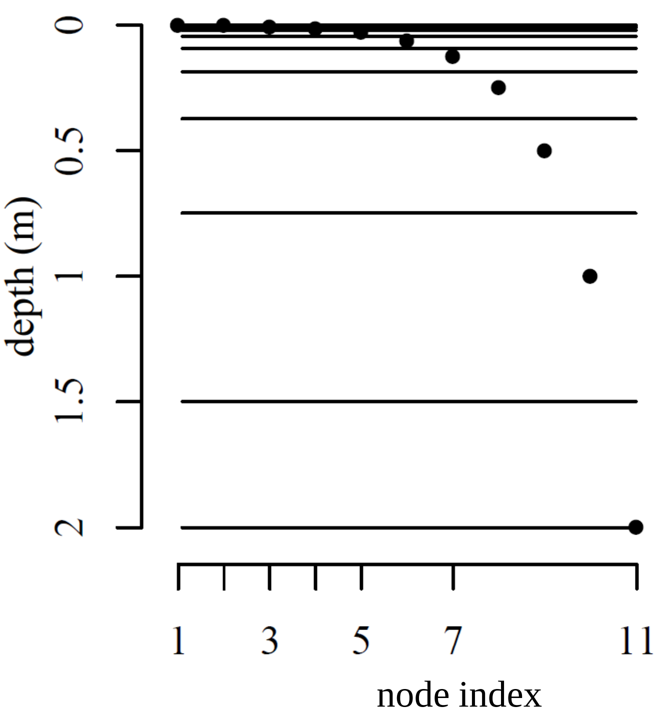
Vertical discretization (1)

- The *effective* vertical discretization must permit an accurate calculation of θi and the related water fluxes qi
- We need thin layers where θ is likely to exhibit sharp vertical gradients
  (to better approximate the local derivative)
- Vertical discretization and boundary conditions must be decided together !

By default, in hydrol, we use :

- 11 nodes (layers) with geometric increase of internode distance
- consistent with free/gravitational drainage at the bottom
- consistent with exponential decrease of root density for transpiration

(cf. de Rosnay et al., 2000)



i	≈ hi (mm)
1	1
2	3
3	6
4	12
5	23,5
6	47
7	94
8	188
9	375
10	751
11	500

Vertical discretization (2)

- The *effective* vertical discretization must permit an accurate calculation of θi and the related water fluxes qi
- We need thin layers where θ is likely to exhibit sharp vertical gradients (to better approximate the local derivative)
- Vertical discretization and boundary conditions must be decided together !

- **Alternative discretizations can be defined by externalized parameters (but use with caution)**

DEPTH_MAX_H	2.0 or 4.0 depending on hydrol_cwrr	m	Maximum depth of soil moisture	Maximum depth of soil for soil moisture (CWRR).
DEPTH_MAX_T	10.0	m	Maximum depth of the soil thermodynamics	Maximum depth of soil for temperature.
DEPTH_TOPTHICK	9.77517107e-04	m	Thickness of upper most Layer	Thickness of top hydrology layer for soil moisture (CWRR).
DEPTH_CSTTHICK	DEPTH_MAX_H	m	Depth at which constant layer thickness start	Depth at which constant layer thickness start (smaller than zmaxh/2)
DEPTH_GEOM	DEPTH_MAX_H	m	Depth at which we resume geometrical increases for temperature	Depth at which the thickness increases again for temperature.

Drainage

- **By default :** $\boxed{Q_N = K(\theta_N)}$
- Based on the initial motion equation, this corresponds to :
  - gravity is the only contribution to energy potential/hydraulic head

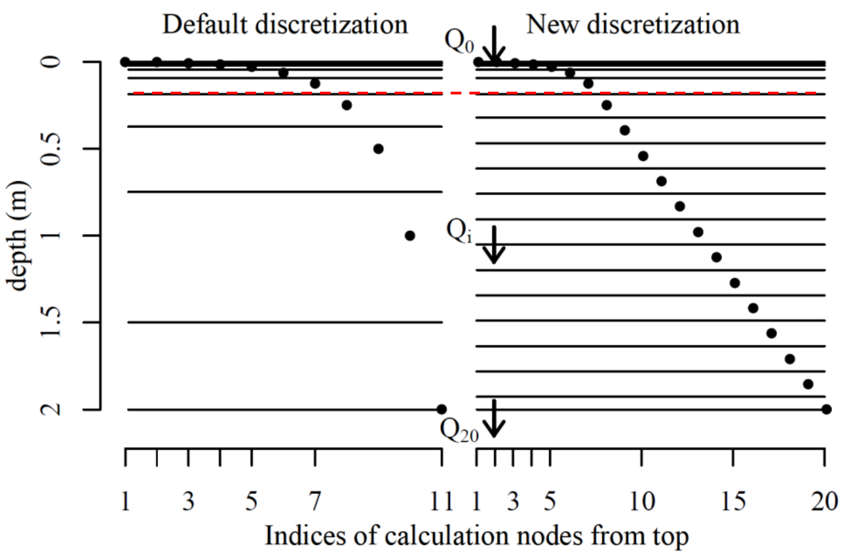
$$q(z) = -K(z)\frac{\partial h}{\partial z} \qquad h = z + \psi$$

  - θ does not show any vertical variations below the modeled soil

$$q(z) = -D(\theta)\frac{\partial \theta}{\partial z} + K(\theta)$$

- The code is also <u>numerically apt</u> to use reduced drainage : $Q_N = F.K(\theta_N)$ F in [0,1]
- With F=1, you get an impermeable bottom, like in the Choisnel scheme

- F is externalized by **free_drain_coef (1,1,1)**
- Reduced drainage enhances θ gradients in the bottom soil,
- The default 11-layer discretization is not adapted anymore
- You can use the flexible discretization



Infiltration (and surface runoff)

- At the soil surface, throughfall can either infiltrate or run off (surface runoff)
- The routing scheme can also produce water to infiltrate (return flow, irrigation, etc.)

P_0

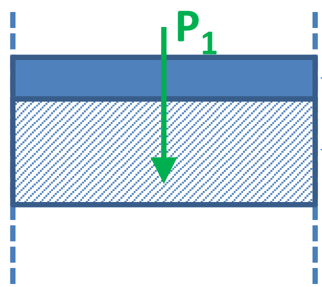
- The modeling of infiltration relies on gravitational fluxes: $q(z) = K(\theta)$

Soil absorption is neglected

1. Direct infiltration to the top soil layer (1-mm deep)
2. If **P_0 is sufficient,** infiltration to the lowest layers of **P_1** = what's left of P_0 after filling the top layer: **wetting front propagation with time splitting procedure and sub-grid-variability**

saturated layer i-1

propagation to layer i



$\theta_{i-1} = \theta_s$; $K_s(i-1)$

$\theta_i < \theta_s$; $K(\theta_i)$

Loop on i

$I_i^{pot} = K_{i/i-1} = [K_s(i-1) + K(\theta_i)]/2.$

$I_i = I_i^{pot}\,[1 - \exp(-P_1 / I_i^{pot})]$

$t_i = h_i\,(\theta_s - \theta_i) / I_i$

θ_i updated

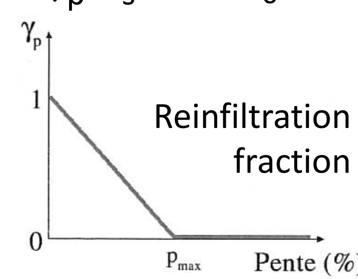
Exponential distribution of I_i^{pot} with runoff production where $P_1 > K = I_i^{pot}$

Until P_1 fully processed or $\Sigma t_i = dt$

$R_s^{pot} = P_0 - \Sigma\, I_i$

$R_s = (1-\gamma_p)\, R_s^{pot}$

$\gamma_p\, R_s^{pot} \rightarrow P_0^{t+dt}$



Reinfiltration fraction

In the code :

reinf_slope = γ_p

Soil evaporation

- **Soil evaporation follows a supply/demand approach:**

$$\boxed{E_{soil} = \min(E^*_{pot}, Q_{up})} \qquad E_{pot} = \rho\,\frac{q_{sat}(T_s) - q_{air}}{r_a} \qquad E^*_{pot} = \rho\,\frac{q_{sat}(T_w) - q_{air}}{r_a}$$

- **E_{soil} is estimated from soil moisture at the previous time step, with dummy integrations of the water diffusion** (with D, but assuming no throughfall and no Tr/Si)
  1. After redistribution at (t-dt), we solve dummy water diffusion assuming $E_{soil} = E^*_{pot}$
  2. If this keeps θ in $[\theta r, \theta s]$, we accept that soil moisture can sustain $E_{soil} = E^*_{pot}$
  3. Else, we replace the previous step by dummy water diffusion assuming $\theta_1 = \theta r$
  4. The resulting θi allow to reconstruct Qi, thus $Q_{up} = - Q_0 \leq E^*_{pot}$
  5. evap_bare_lim /frac_bare = Q_{up}/E_{pot} or $Q_{up}/2E_{pot}$, depending if $\sum_1^4 W_i$ > or < $\sum_1^4 W_w$

tmc_litter

- **At the current timestep in diffuco:**

β_4 = evap_bare_lim /frac_bare

β = vegtot($\beta_2 + \beta_3$) + frac_bare β_4

$E_{soil} = \beta_4 E_{pot}$

$E = \beta E_{pot}$

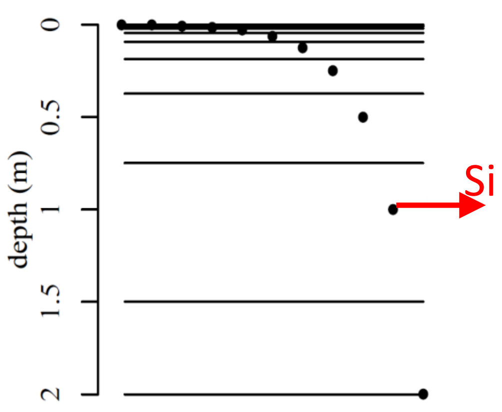
- **At the current timestep in hydrol:**
  - If $P_0 > E_{soil}$, the infiltration phase works only on $P_0 - E_{soil} > 0$
  - If $E_{soil} > P_0$, hydrol does not perform infiltration and soil moisture decreases

    $\theta_1 = \theta_1 - E_{soil}/h_1$

    If this brings θ under θr, the moisture deficit is propagated downward (eventually to negative drainage)

Effective water diffusion

The transpiration sink (1)



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

$$T_r = \rho \left(1 - \frac{I}{I_{max}}\right) U_s \frac{q_{sat}(T_s) - q_{air}}{r_a + r_c + r_{st}}$$

$$\left.\begin{aligned} T_r &= \Sigma S_i \\ U_s &= \Sigma us_i \end{aligned}\right\} \quad S_i = T_r\, us_i / U_s$$

The dependance of Tr on θi/Wi is conveyed by us(i)

$$u_s(1) = 0$$

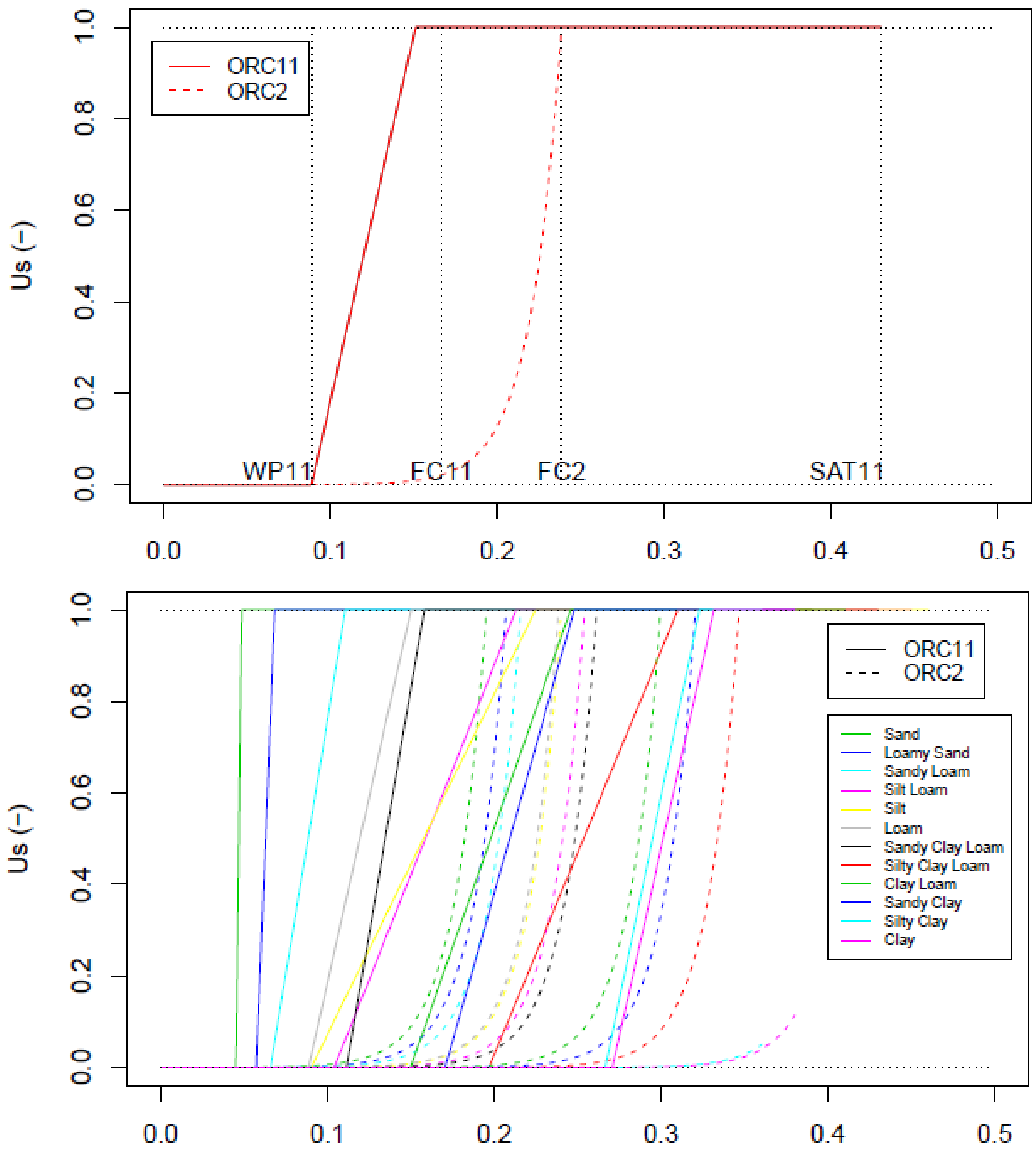
$$u_s(i) = \texttt{moderwilt}(i)\, n_{\mathrm{root}}(i) \min(1, (W_i - W_w)/(W_{\%} - W_w))$$

- W_w = wilting point
- W_f = field capacity
- AWC = W_f-W_w
- $W_{\%}$: moisture at which us becomes 1 (no stress)
  $W_{\%} = W_w + 0.8$ AWC

- moderwilt(i) = 1 but if $W_i < W_w$
- n_{root} : mean root density in layer i
  $n_{root} = \int_{hi} R(z)dz \,/\, \int_{htot} R(z)dz$
  $R(z) = \exp(-c_j\, z)$

In constantes_soil.f90:
$W_{\%}$ = pcent = (/ 0.8, 0.8, 0.8 /)

The transpiration sink (2)



New features

New diagnostics:

- **TWBR = Total water budget residu** (in kg/m²/s) to check water conservation
- **wtd = water table depth** (m), defined in each soiltile as the depth of deepest saturated node overlaid by an unsaturated node.

  It is sought starting at the soil bottom, such that a part of the soil that is saturated but underlaid with unsaturated nodes is not considered as a water table. If the bottom node is not saturated, the water table depth is set to undef

To come:

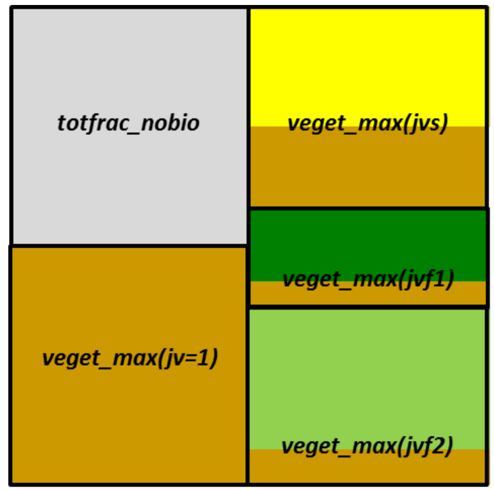
- Possibility to reduce the bare soil evaporation with a **soil resistance**

Interactions with the vegetation/LC

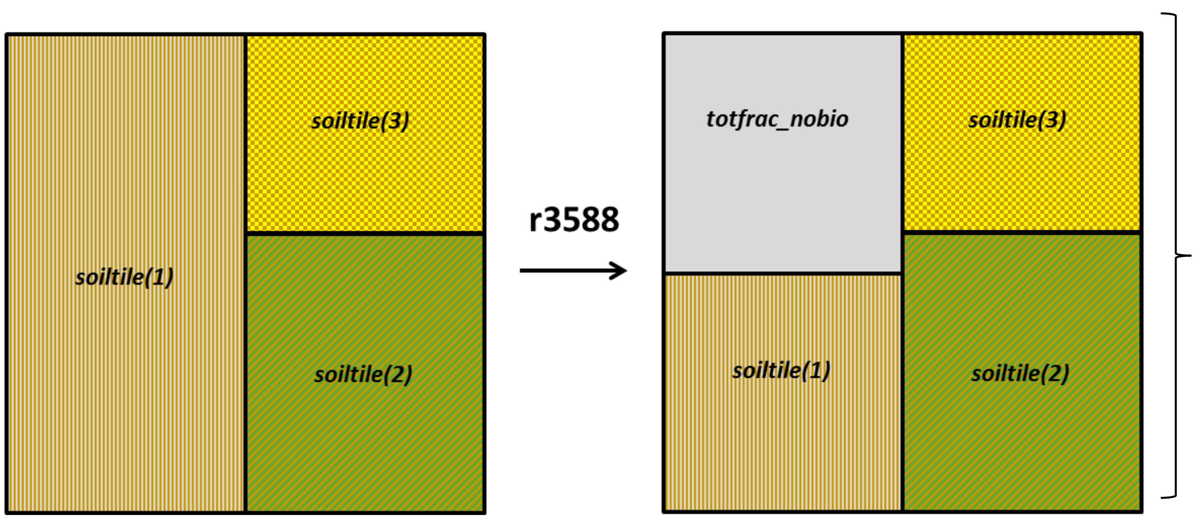
1. Horizontally, PFTs define soil tiles with independent water budget

(below ground tiling)

« Nobio » and PFTs



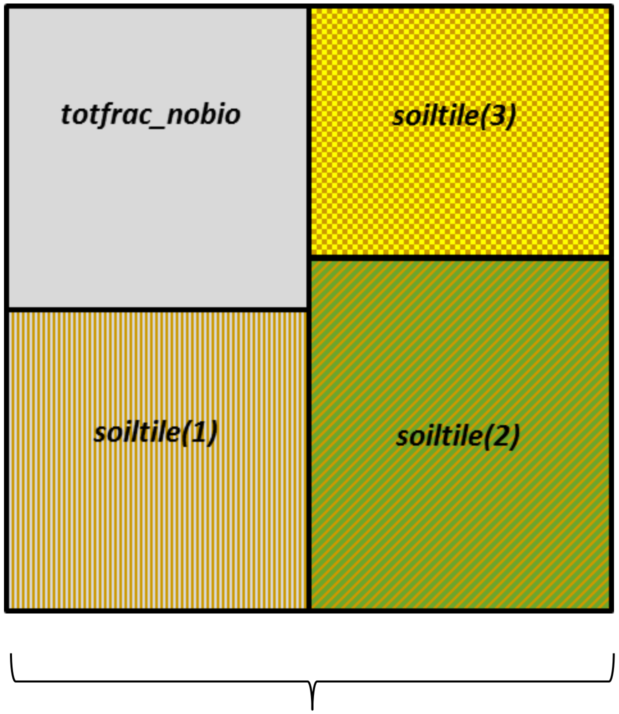
Soil columns



each soil tile with frac_bare_ns

Interactions with the vegetation/LC

1. Horizontally, PFTs define soil tiles with independent water budget (below ground tiling)



each soil tile with frac_bare_ns = veget_max [1 - exp(- LAI)]

But one single energy budget !

$$\mathbf{E} = \beta_{tot} E_{pot}$$

$$E_{pot} = \frac{\rho}{r_a}(q_{sat}(T_s) - q_{air})$$

$$\beta_{tot} = \beta_1 + (1 - \beta_1)(\Sigma\beta_2 + \Sigma\beta_3 + \beta_4)$$

$$E_{subli} = \beta_1 E_{pot}$$

$$E_{transp} = \Sigma\beta_2 E_{pot}$$

$$E_{inter} = \Sigma\beta_3 E_{pot}$$

$$E_{soil} = \beta_4 E_{pot}$$

For each evapotive flux, the β conveys information on:

- the fraction of the grid-cell that evaporates
- the intensity of the flux (1/r)

Interactions with the vegetation/LC

2. Vertically, ORCHIDEE defines a root density profile

In each PFT j **$R_j(z) = \exp(-c_j\, z)$**

In each soil layer i $n_{root}(i)$ is the mean root density
with $\Sigma_i n_{root}(i) = 1$

↓

It controls the water stress on transpiration in each soil layer i

$$u_s(1) = 0$$
$$u_s(i) = \texttt{moderwilt}(i)\, n_{\mathrm{root}}(i)\, \min(1, (W_i - W_w)/(W_{\%} - W_w))$$

In the code, c_j is called humcste and defined in constantes_mtc.f90

It can be « externalized », with default values depending on soil hydrology/depth

```
REAL(r_std), PARAMETER, DIMENSION(nvmc) :: humcste_cwrr  = &
 & (/ 5.0,   0.8,   0.8,   1.0,   0.8,   0.8,   1.0, &
 &    1.0,   0.8,   4.0,   4.0,   4.0,   4.0 /)
!! Values for dpu_max = 2.0
```

The role of soil texture

- **In hydrol, the main soil properties are:** θ_s θ_r K_s^{ref} m $\alpha=1/\psi_{ae}$
- clay_fraction is a parameter for Stomate

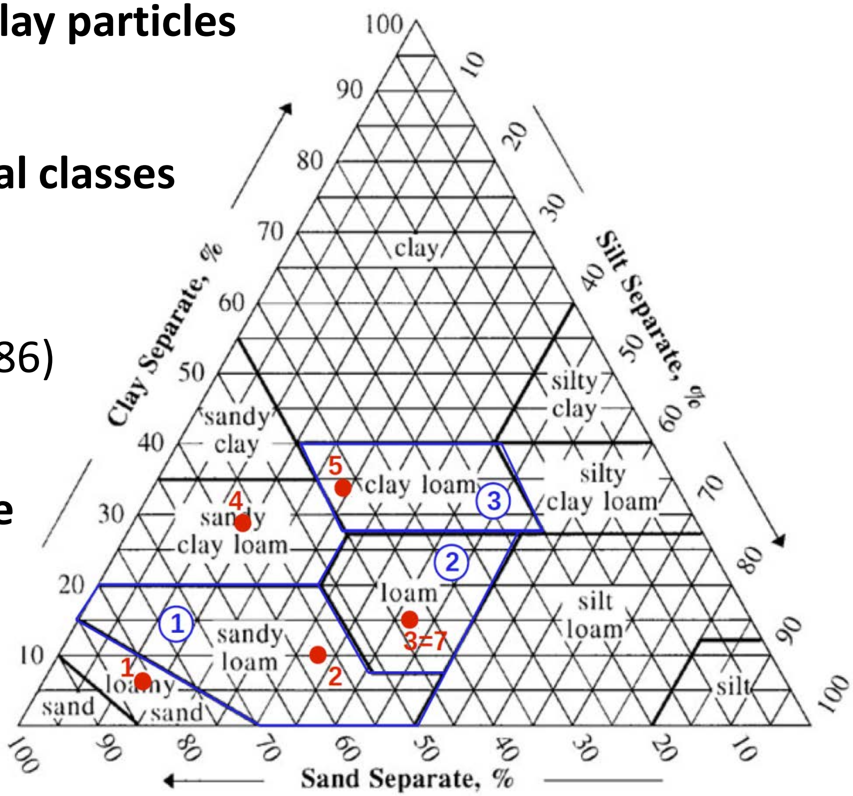
- Wilting point and Field capacity also depend on Texture
- They are defined based on soil texture

(in the real world, they can depend on other factors, as soil structure, OMC, etc.)

- **Soil texture is defined by the % of sand, silt, clay particles in a soil sample** (granulometric composition)

- **Soil texture can be summarized by soil textural classes**
- By default, ORCHIDEE reads texture from the 1/12° USDA map of Reynolds et al. (2000)
- Alternative soil map : 1°x1° map of Zobler (1986) with 3 classes

- **In each grid-cell, we use the dominant texture**



In red, the interpretation of the Zobler texture classes in ORCHIDEE.
In blue, the definition of the default three main textures in ORCHIDEE

The role of soil texture

- **In hydrol, the main soil properties are:** θ_s θ_r K_s^{ref} m $\alpha=1/\psi_{ae}$ θ_w θ_f

Their default values are defined in constantes_soils,
with the suffix _usda or _fao (Zobler)

- They are defined based on soil texture
(in the real world, they can depend on other factors, as soil structure, OMC, etc.)

Three ways of defining soil texture in run.def

1. Default run.def: SOILTYPE_CLASSIF = usda ; SOILCLASS_FILE = soils_param_usda.nc

2. Default keywords: SOILTYPE_CLASSIF = zobler; SOILCLASS_FILE = soils_param.nc

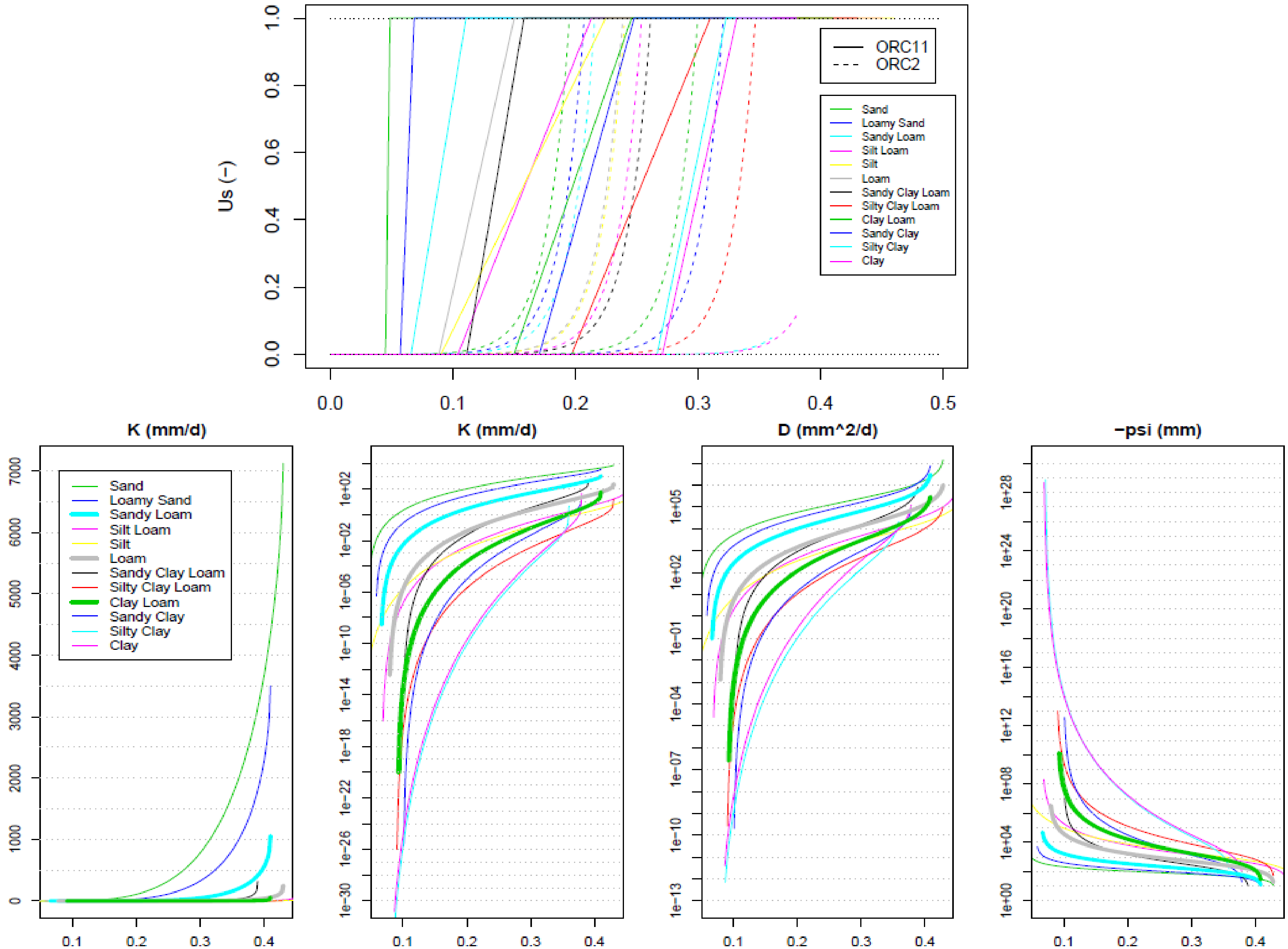
3. IMPVEG=y, IMPSOIL=y, SOIL_FRACTION = (x,y,z, etc.)

→ x,y,z <u>are</u> areal fraction allocated to the soil textural classes defined by your selected map

→ x,y,z <u>are not</u> % sand, silt, clay defining your soil's texture, despite the fact that this option is primarily intended for 0D simulations

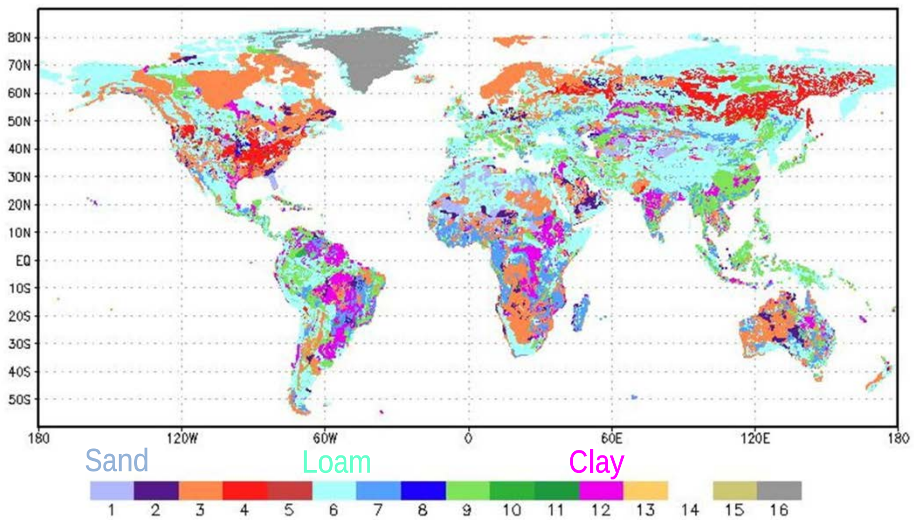
→ to get the soil properties of one texture class, set SOIL_FRACTION = (1,0,0, …0…), and use the externalization to redefine the 1st value of the vectors defining soil properties

The role of soil texture

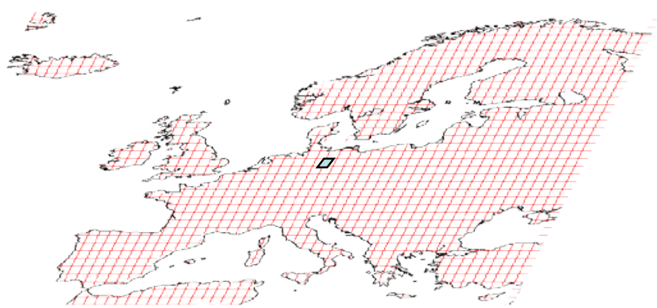


Spatial heterogeneities of soils

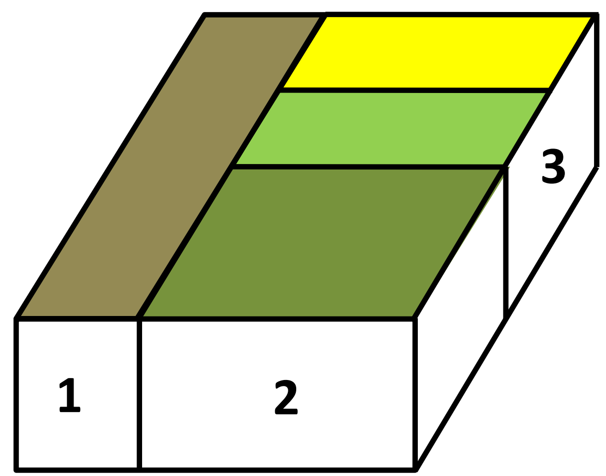
5' USDA texture map (Reynolds et al., 2000)



Dominant texture in each ORCHIDEE grid-cell:
defining the hydraulic properties



Sub-grid scale heterogenity:
3 soil columns based on PFTs
with independent water budget



1: Bare soil PFT
2: All Forest PFTs
3: All grassland and cropland PFTs

Thank you for your attention
Questions ?

ORCHIDEE