Soil hydrology

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Outline

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

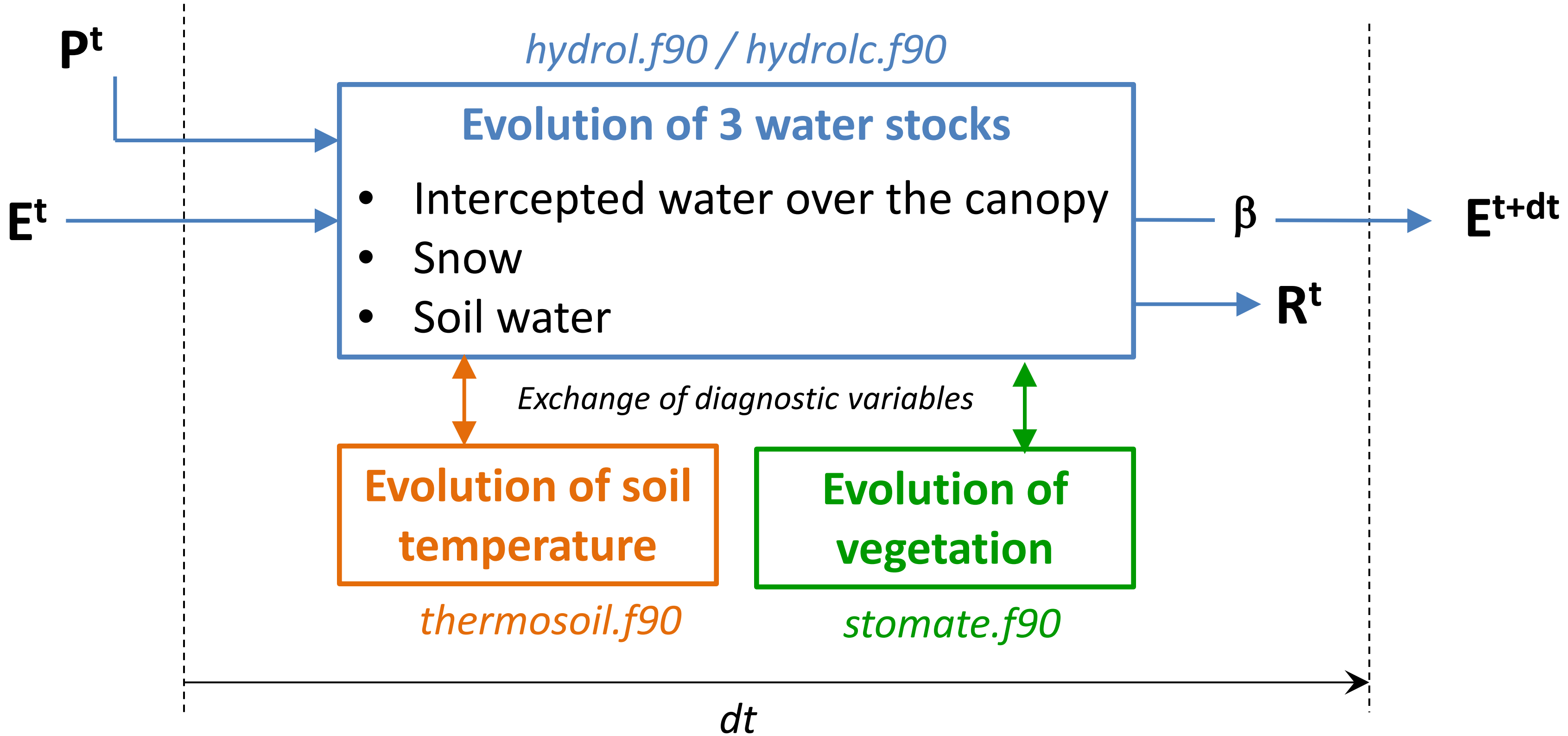
More details on the Wiki

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

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

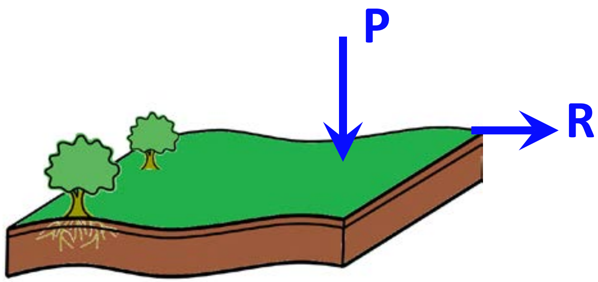


We will focus on soil water and the related water fluxes (soil hydrology)
No interception, no snow, no soil water freezing today

Two versions of soil hydrology

Two-layer = Choisnel = ORC2

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

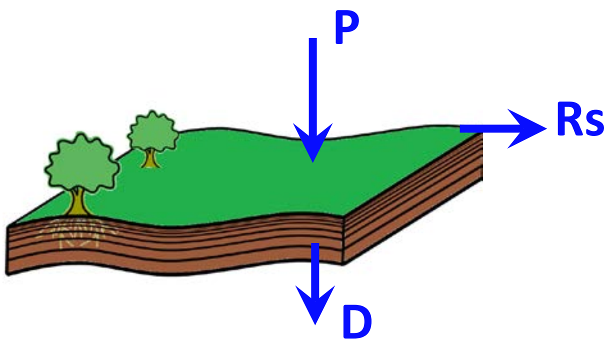


- **Conceptual description of soil moisture storage**
- **4-m soil and 2-layers**
- Top layer can vanish
- Constant available water holding capacity (between FC and WP)
- Runoff when saturation
- No drainage from the soil

  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
- Surface runoff = P – Esol – Infiltration
- Free drainage at the bottom

Two versions of soil hydrology

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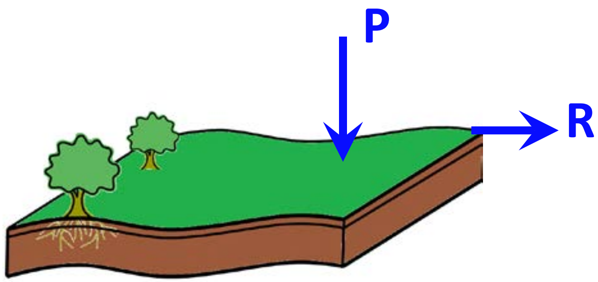

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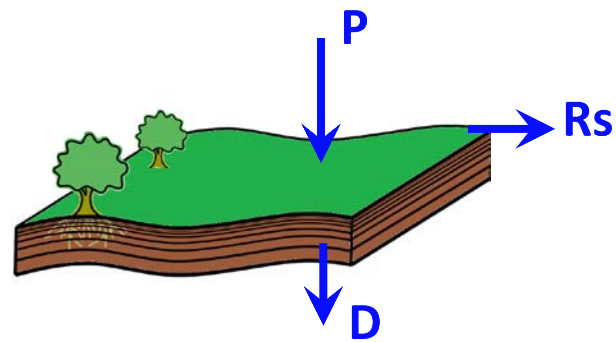

- **Physically-based description of soil water fluxes using Richards equation**
- **2-m soil and 11-layers**
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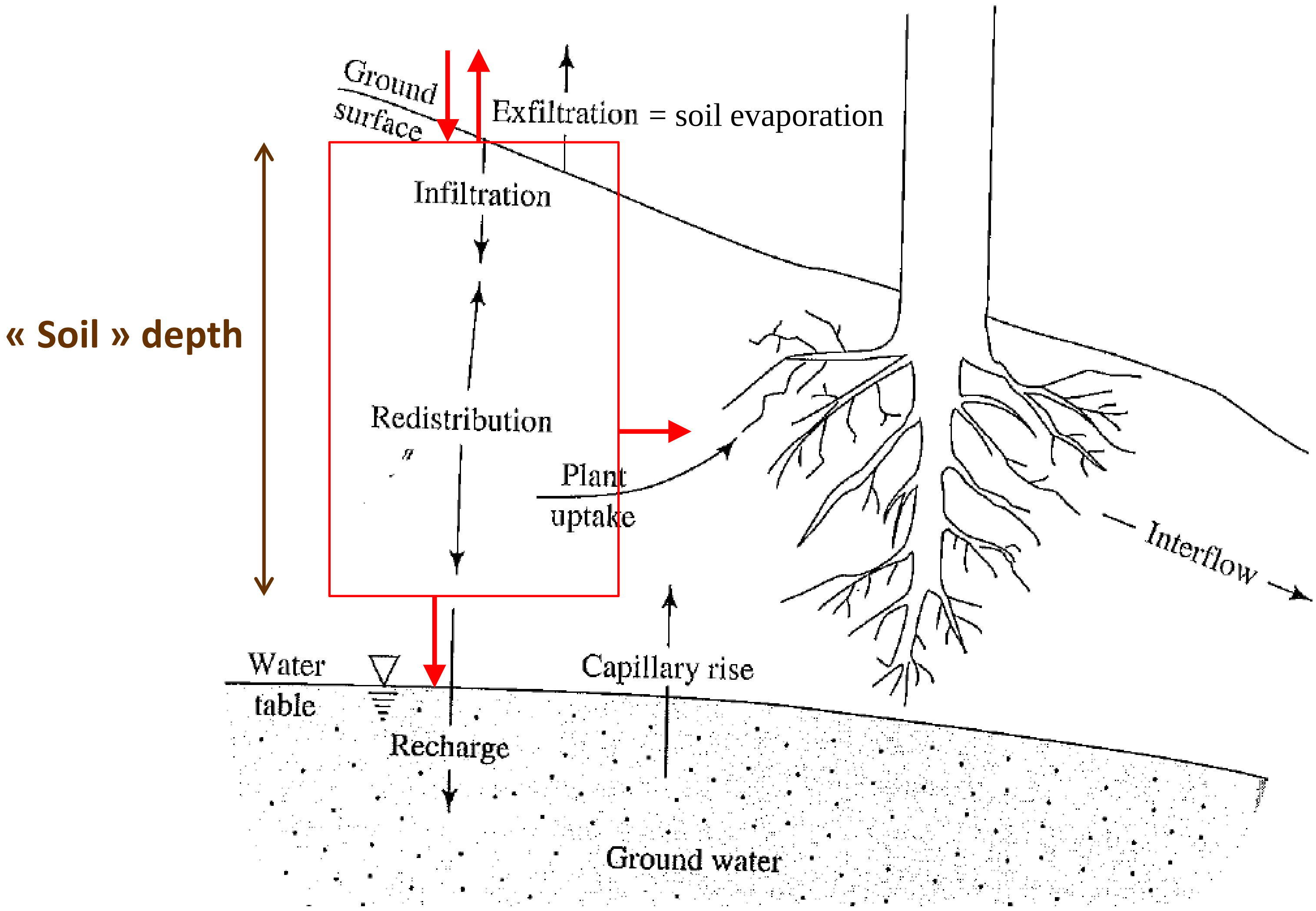
formulation
based on texture
Esol – Infiltration
bottom

In run.def

HYDROL_CWRR = n / **y**

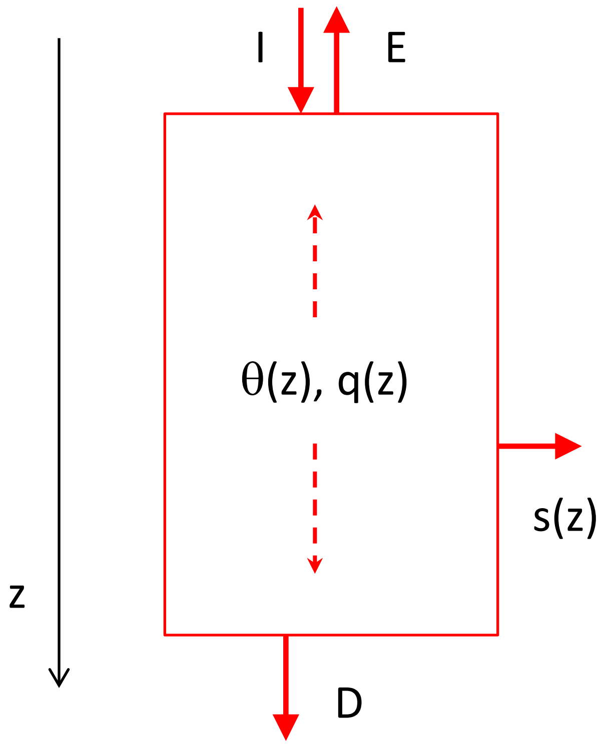
→ either hydrolc.f90 or hydrol.f90

What is modeled ?



How is it modeled ?

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



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)

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

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

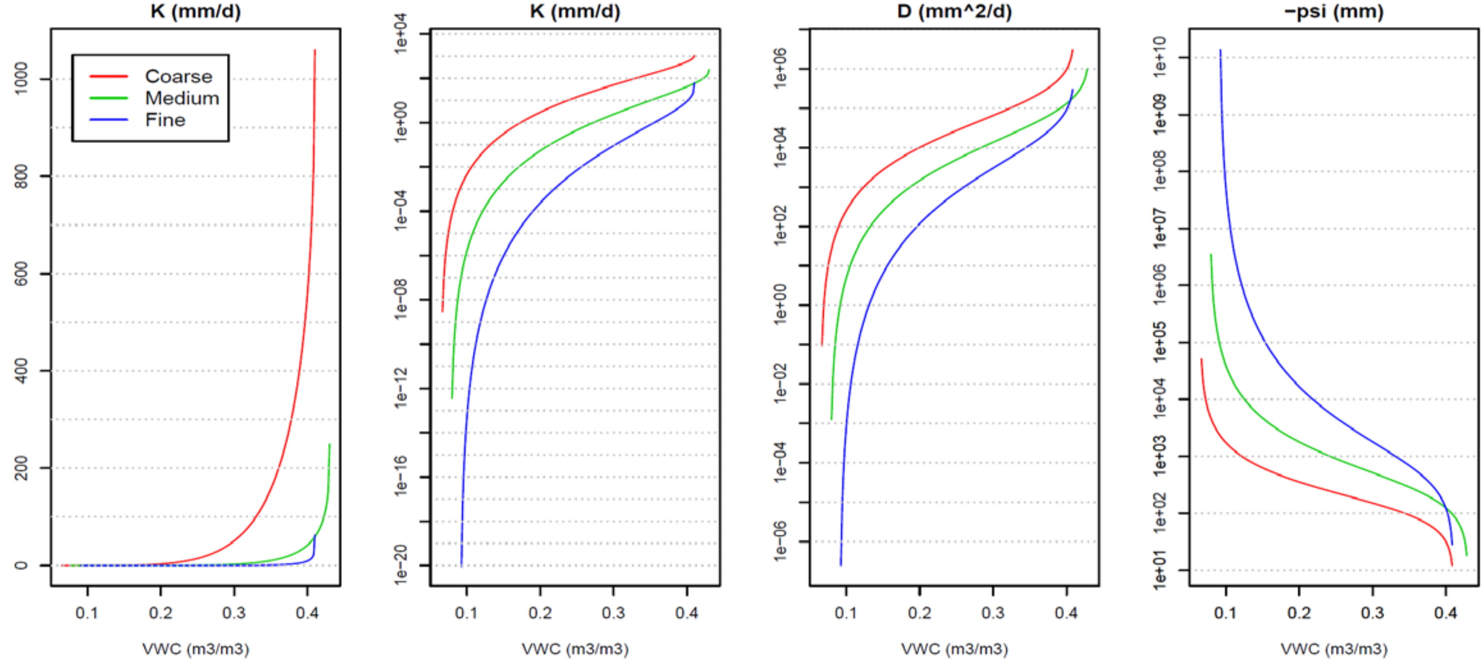
$$D(\theta) = K(\theta)\frac{\partial \psi}{\partial \theta}$$

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

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

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 n
$\alpha = -1/\psi_{ae}$

Modifications of Ks with depth

Ks(z) in mm/d

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

Orange: grass PFT,
cj = humcste = 4

Yellow: forest PFT,
cj = humcste = 0.8

(2) Ks decreases exponentially with depth below 30 cm

(1) K_s^{ref} = 1060 mm/d
[Sandy Loam/Zobler class 1]

Modifications of Ks with depth

(a) Ks decreases exponentially with depth

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

$$F_K(z) = \min(\max(\exp(-f(z - z_{\text{lim}}), 1/F_K^{\max}), 1)$$

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

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

$$F_{K\text{root}}(z, c) = \prod_{j \in c} \max\left(1, \left(\frac{K_s^{\max}}{K_s^{\text{ref}}}\right)^{f^j(1-c_j z)/4}\right)$$

Parameters: K_s^{ref} K_s^{max} c_j (= humcste) f^j (= veget_max)

(c) Combined effect

$$K_s^*(z, c) = K_s^{\text{ref}} F_K(z) F_{K\text{root}}(z, c)$$

K_s^{ref} depends on soil texture

Modifications of Ks with depth

(a) Ks decreases exponentially with depth

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$$F_K(z) = \min(\max(\exp(-f(z - z \ldots$$

Parameters: K…

(b) Ks also incr… …turbation (roots)

$$\ldots \max\left(1, \left(\frac{K_s^{\max}}{K_s^{\mathrm{ref}}}\right)^{f^j(1-c_j z)/4}\right)$$

…ters: K_s^{ref} K_s^{max} c_j^z (+ f^j = veget_max)

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

(c) Combined effect

$$K_s^*(z,c) = K_s^{\mathrm{ref}} F_K(z)\, F_{K\mathrm{root}}(z,c)$$

K_s^{ref} depends on soil texture

Finite difference integration

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

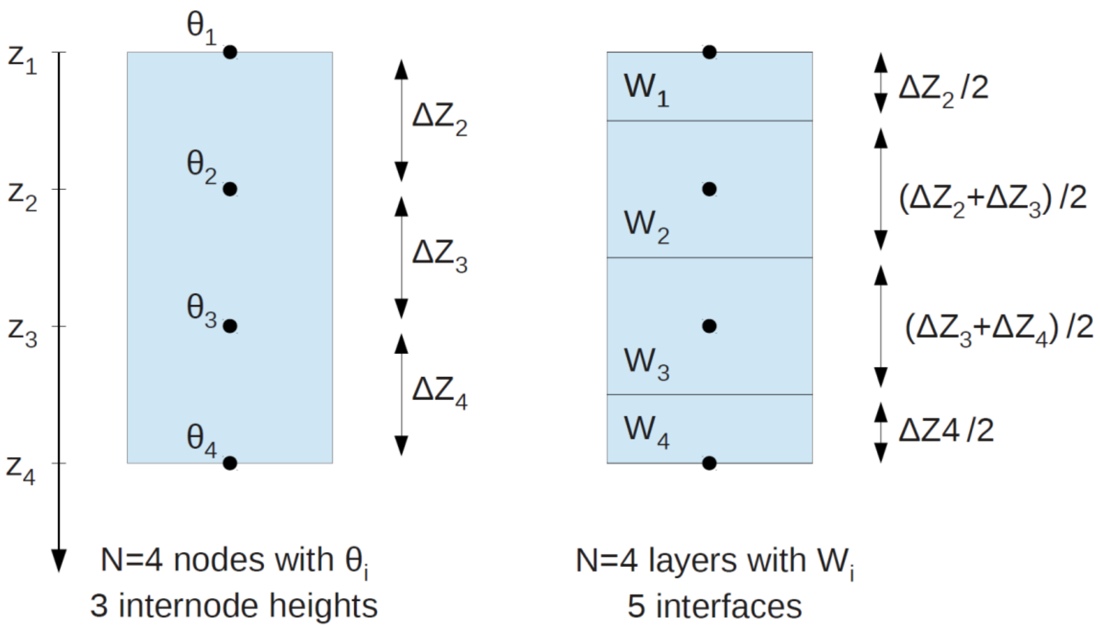
$$\frac{W_i(t+dt)-W_i(t)}{dt} = Q_{i-1}(t+dt) - Q_i(t+dt) - S_i$$

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

Si = transpiration sink

A: grid-cell area

- The soil column is discretized using N **nodes,** where we calculate **θi**
- Each node is contained in one **layer**, with a total water content **Wi**
- The fluxes **Qi** are calculated at the **interface** between two layers



Wi is obtained by vertical integration of θ(z) in layer i, assuming a linear variation of θ(z) between 2 nodes

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

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

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

To sum up water diffusion

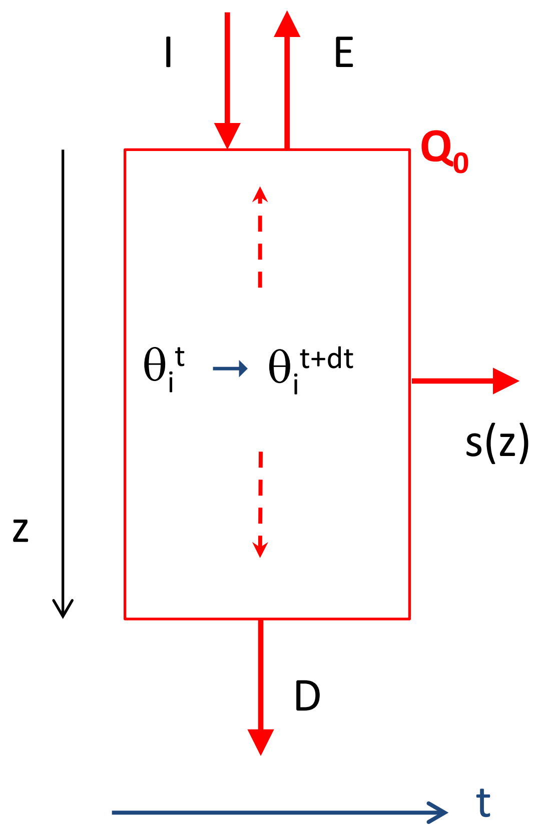
- **The prognostic variables are θi at the nodes**
- They are updated **simultaneously** by solving a tridiagonal matrix
- **Their evolution is driven by**
  - the soil properties K(z) and D(z)
  - the vertical discretization (soil depth and node position Zi)
  - the transpiration sink s_i
  - the top and bottom boundary conditions:

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

I: infiltration

E_g : soil evaporation

D: drainage



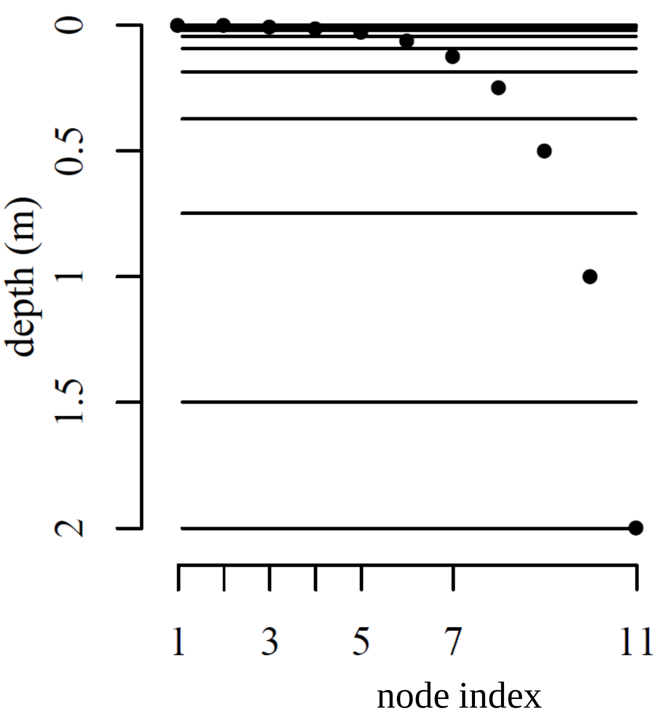
Vertical discretization

- The 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 :

- 2-m soil
- 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

- The 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.

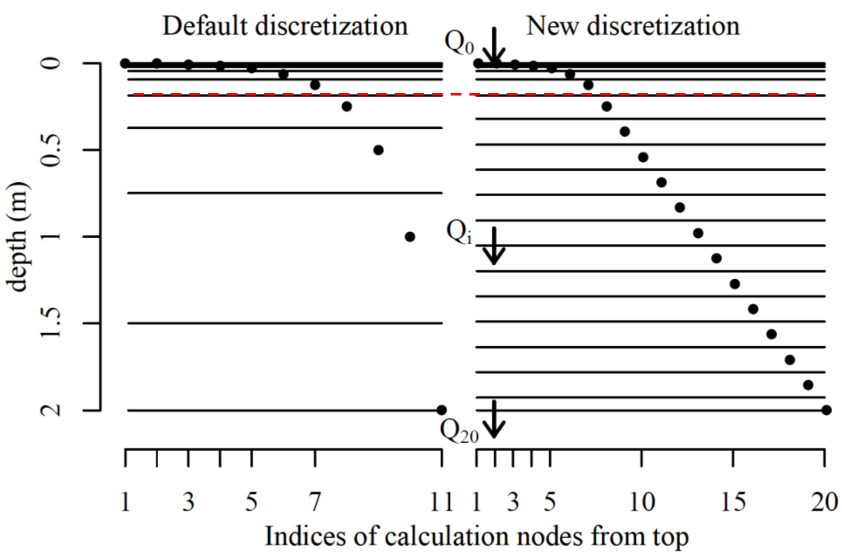
Drainage

- **By default :** $Q_N = K(\theta_N)$
- Based on the motion equation, this corresponds to a situation where 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

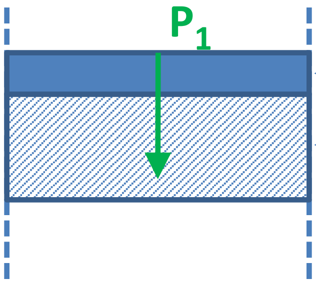
- The modeling of infiltration relies on gravitational fluxes: $q(z) = K(\theta)$
- With **wetting front propagation based on time splitting procedure and sub-grid-variability**

Soil absorption is neglected

1. Direct infiltration of P_0 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):

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 $P_1 > K = I_i^{pot}$

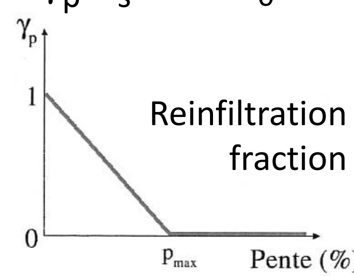
Until P_1 fully processed or $\Sigma t_i = dt$

Reinfiltration

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

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

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

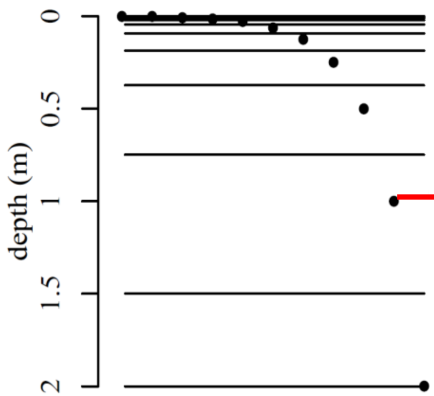


In the code :

γ_p = reinf_slope

p_{max} = 0.5%

The transpiration sink (1)



$S_i = f(us_i)$

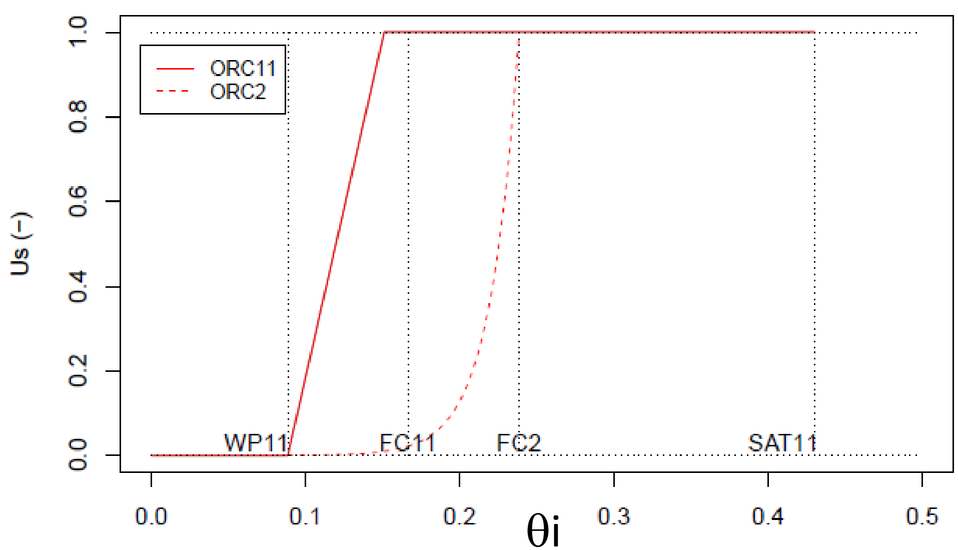
$$\frac{W_i(t+dt) - W_i(t)}{dt} = Q_{i-1}(t+dt) - Q_i(t+dt) - S_i$$

$$T_r = \Sigma S_i$$

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

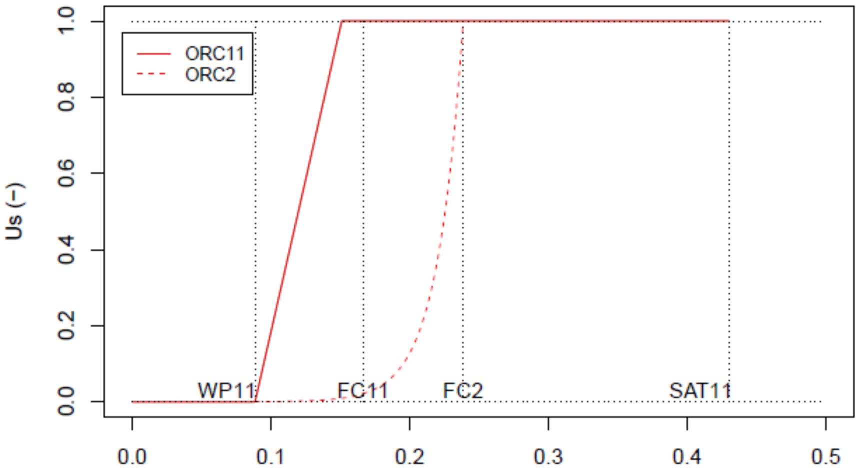
$$U_s = \Sigma us_i \qquad S_i = T_r \, us_i / U_s$$

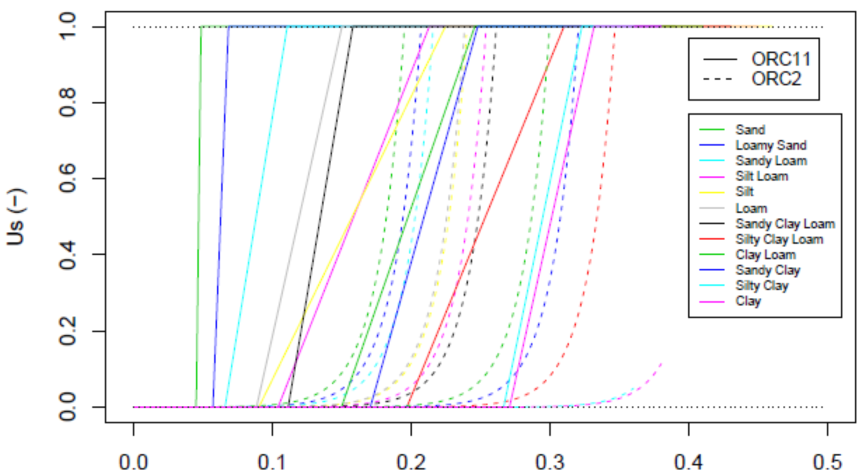
The dependance of Tr on θi/Wi is conveyed by us(i)



In the code :
U_s = humrel

The transpiration sink (2)





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

$$u_1 = 0$$
$$u_i = n_{\text{root}}(i)\max(0, \min(1, (W_i - W_w)/(W_{\%} - W_w)))$$

n_{root} : mean root density in layer i

$n_{root} = \int_{hi} R(z)dz \,/\, \int_{htot} R(z)dz$

$R(z) = \exp(-c_j z)$

W_w = wilting point

W_f = field capacity

$AWC = W_f - W_w$

$W_{\%}$: moisture at which us becomes 1 (no stress)

$W_{\%} = W_w + p_{\%}\, AWC$

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

Soil evaporation (E_g)

1. The soil evaporation that controls the surface boundary flux (Q_0 = I - E_g) is known from the energy budget

2. **The issue in hydrol is to calculate the stress function β_g** to calculate soil evaporation at the next time step

3. **This is done by a supply/demand approach** at the end of the time step, based on the soil moisture that will prevail at the beginning of the next time step

4. **Supply/demand: E_g can proceed at potential rate unless this dries the soil out**

$$E_g = \min(E^*_{\mathrm{pot}}, Q_{\mathrm{up}})$$

$$E_{\mathrm{pot}} = \frac{\rho}{r_a}\left(q_{\mathrm{sat}}(T_s) - q_{\mathrm{a}}\right) > E^*_{\mathrm{pot}} = \frac{\rho}{r_a}\left(q_{\mathrm{sat}}(T_w) - q_{\mathrm{a}}\right)$$

$$\beta_g = E_g / E_{\mathrm{pot}}$$

In practice, E_g is calculated by 1 or 2 dummy integrations of the water diffusion, assuming no rainfall and no root sink:

(a) We apply E^*_{pot} as a boundary flux at the top, and test if θ_i remains above θ_r
If it does, then $E_g = E^*_{pot}$

(b) Else, we force $\theta_1 = \theta_r$, which drives an upward flux: the surface value Q_0 gives Q_{up}

Soil evaporation (E_g)

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2. **The issue in hydrol is to calculate the stress function β_g** to calculate soil evaporation at the next time step
3. **This is done by a supply/demand approach** at the end of the time step, based on the soil moisture that will prevail at the beginning of the next time step
4. **Supply/demand: E_g can proceed at potential rate unless this dries the soil out**
5. **Since r3975, we can reduce the demand using a soil resistance (Sellers et al., 1992)**

In run.def :
DO_ROIL = y
(default = n)

$$r_{\text{soil}} = \exp(8.206 - 4.255 L/L_s)$$

L is the soil moisture in the 4 top layers
Ls is the equivalent at saturation

$$E_g = \min\left(\frac{q_{sat}(T_W) - q_a}{r_a + r_{soil}}, Q_{up}\right)$$

The minimum is still found via 1 or 2 dummy integrations of the water diffusion, assuming no rainfall and no root sink.

New features

New diagnostics:

- **TWBR = Total water budget residu** (in kg/m²/s) to check water conservation

  TWBR = dS/dt – (P – E – R)
  S includes intercepted water and snow

  Typical values are < 10^{-5} mm/d or less

- **wtd = water table depth** (m), defined in each soiltile as the depth of deepest saturated node overlaid by an unsaturated node.

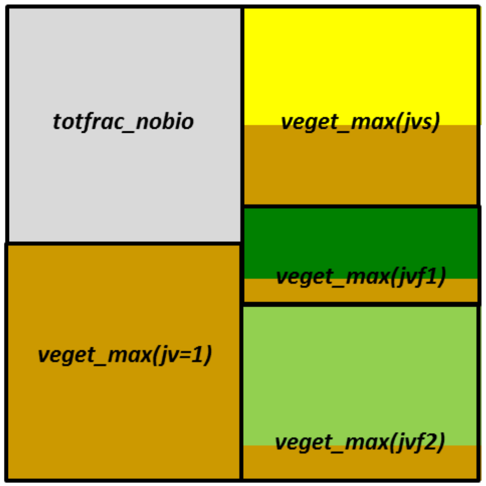
  Sought from the soil bottom: if a part of the soil is saturated but underlaid with unsaturated nodes, it is not considered as a water table.
  If the bottom node is not saturated, the water table depth is set to undef.

Interactions with the vegetation/LC

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

(below ground tiling)

« Nobio » and PFTs



Each PFT with

Effective vegetation fraction

veget = veget_max (1 - exp(- LAI))

Bare soil fraction

*frac_bare = veget_max * exp(- LAI)*

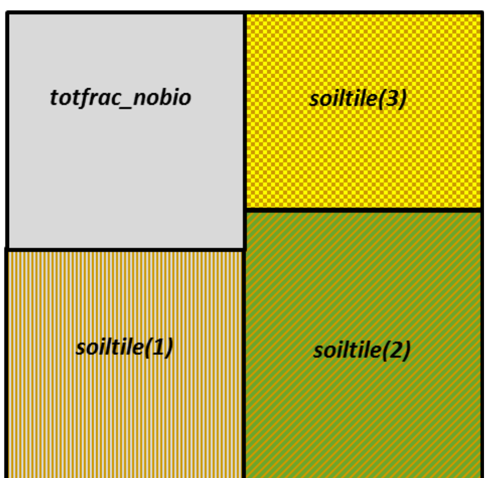
→ **In each PFT j:**

Us and β_3

Grid-cell scale:

$Tr = \underbrace{(\Sigma_j\ veget_j\ \beta_3)}_{SUM(vbeta3)}\ E_{pot}$

Soil columns



Each soil tile with

frac_bare_ns

→ **In each soiltile c:**

β_4 calculation

Independant water budget

Grid-cell scale:

$E_{soil} = \underbrace{(\Sigma_c\ frac\_bare\_ns_c\ \beta_g)}_{vbeta4}\ E_{pot}$

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:

(1) the water stress on transpiration in each soil layer i

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

(2) the increase of Ks towards the surface (F_{Kroot})

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(2) the increase of Ks towards the surface (F_{Kroot})

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

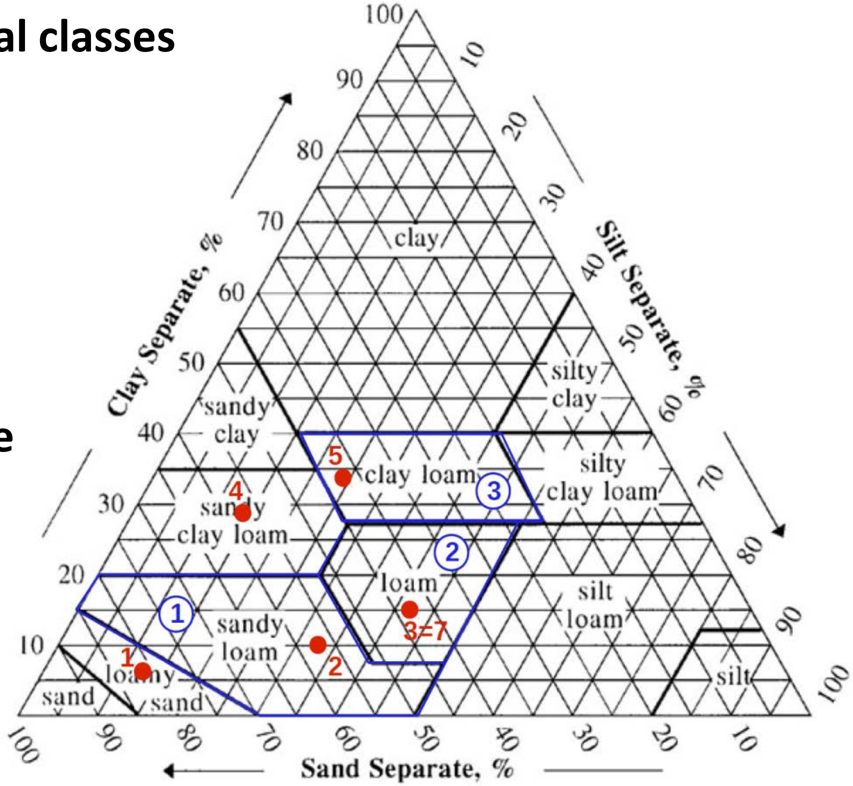
```
REAL(r_std), PARAMETER, DIMENSION(nvmc) :: humcste_cwrr  = &
 & (/ 5.0,   0.8,   0.8,   1.0,   0.8,   0.8,   1.0, &
 &    1.0,   0.8,   4.0,   4.0,   4.0,   4.0 /)
!! Values for dpu_max = 2.0
```

The role of soil texture

- **In hydrol, the main soil properties are:** θ_s θ_r K_s^{ref} n $\alpha\ (= -1/\psi_{ae})$ θ_w θ_f
- clay_fraction is a parameter for stomate
- They are defined based on soil texture

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

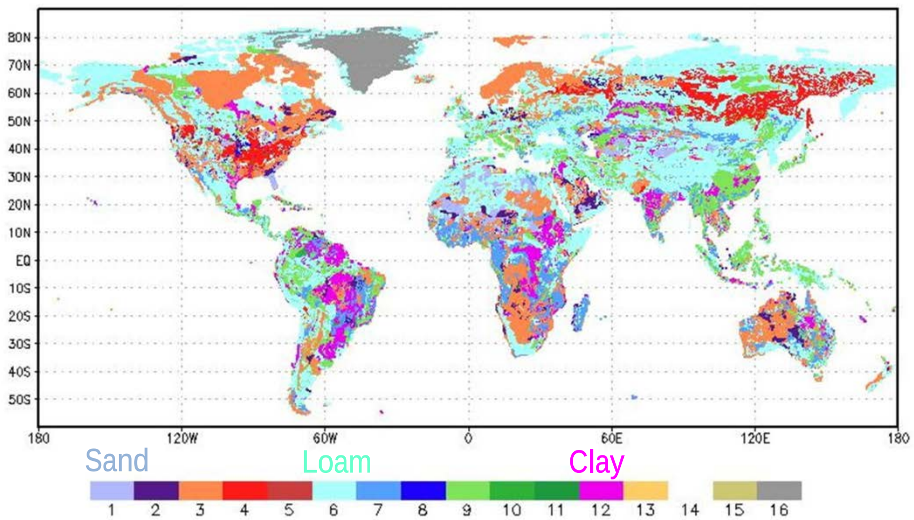
- **Soil texture is defined by the % of sand, silt, clay particles in a soil sample** (granulometric composition)
- **Soil texture can be summarized by soil textural classes**
- By default, ORCHIDEE reads texture from the 1°x1° map of Zobler (1986) **with 3 classes**
- Alternative soil map : 1/12° USDA map of Reynolds et al. (2000)
- **In each grid-cell, we use the dominant texture**



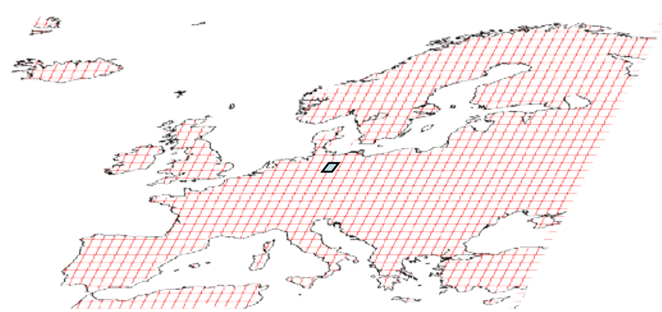
In red, the interpretation of the Zobler texture classes in ORCHIDEE.
In blue, the definition of the default three main textures in ORCHIDEE

The role of soil texture

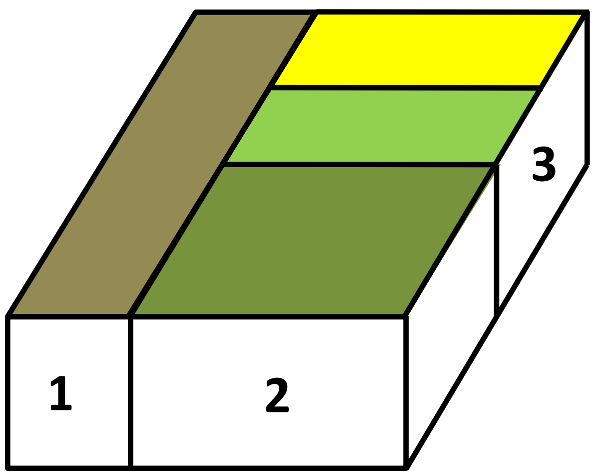
5' USDA texture map (Reynolds et al., 2000)



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
but same texture



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

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

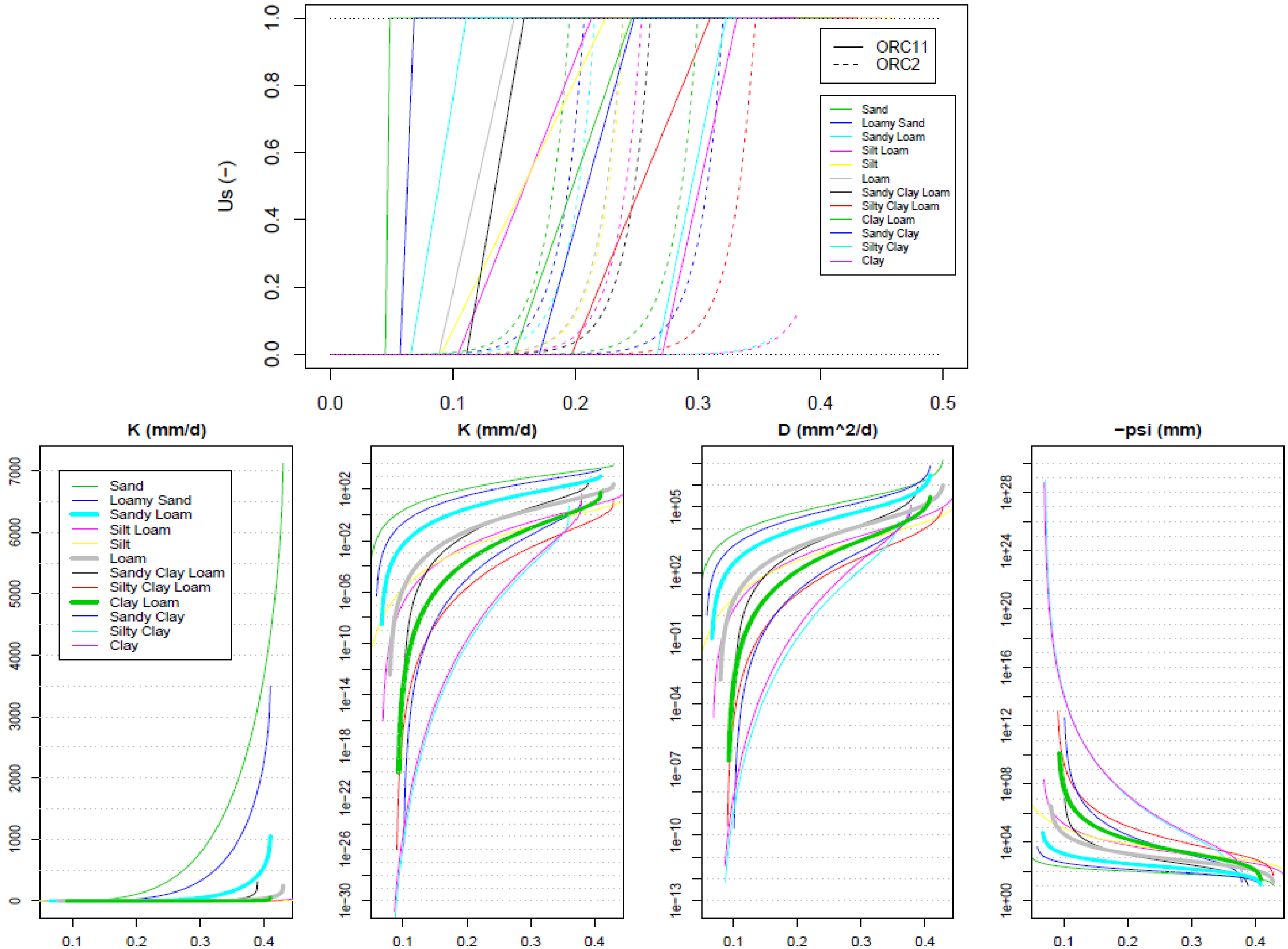
1. **Default keywords: SOILTYPE_CLASSIF = zobler; SOILCLASS_FILE = soils_param.nc**
2. For Reynolds : SOILTYPE_CLASSIF = usda ; SOILCLASS_FILE = soils_param_usda.nc
3. IMPVEG=y, IMPSOIL=y, SOIL_FRACTION = (x,y,z, etc.)

→ 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

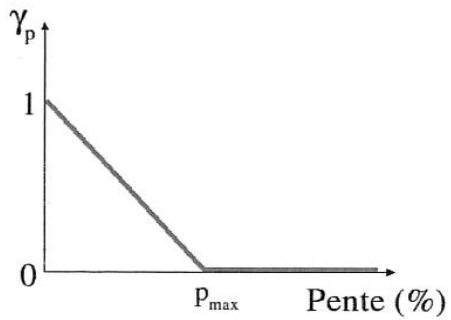


Slope and reinfiltration

Reinfiltration fraction = γ_p

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

Based on slope



In run.def , you can change:

p_{max}: SLOPE_NOREINF = 0.5 (%)

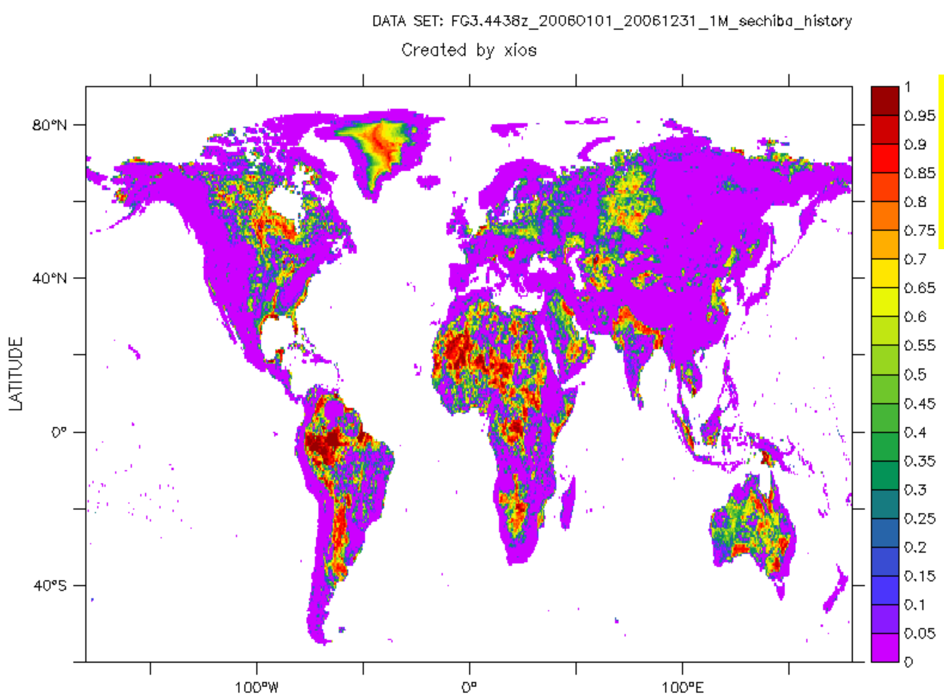
(but 0 may not work to cancel reinfiltration!)

1. Slope is read at the resolution of 0.25°
(cartepente2d_15min.nc)

2. γ_p is calculated at the resolution of 0.25°

$\gamma_p = 1 - \min(1, p/p_{max})$

3. γ_p is averaged at the resolution of ORCHIDEE



Example of reinf_slope from a 0.5° simulation

A lot of reinfil in flat areas

No reinfil if p>0.5%

Soil hydrology in a nutshell

- **During a time step, the soil hydrology scheme :**
  - Updates the soil moisture
  - Calculates the related fluxes (infiltration, surface runoff, drainage)
  - Calculates the water stresses for transpiration and soil evaporation of the next time step
  - Calculates some soil moisture metrics for thermosoil and stomate

- **The equations can be complex, but the parametrization is intended to work without intervention**
  - Default input maps are defined in COMP/sechiba.card
  - Defaults parameters are defined in PARAM/run.def and code
  - Lot of debugging over the past years

- **You can adapt the behavior of the scheme:**
  - Easy : change externalised parameters in PARAM/run.def
  - A bit less easy: use different input maps (you need to comply to the format)
  - More difficult: change the code (welcome to orchidee-dev!)

Soil hydrology in 44 pages

The hydrol module of ORCHIDEE: scientific documentation

[rev 3977] and on, work in progress, towards CMIP6v1

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November 30, 2017

Contents

More details on the Wiki

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

Thank you for your attention
Questions ?

ORCHIDEE