Introduction to the 2 soil hydrology schemes of ORCHIDEE : processes, parameters, options,…

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Outline

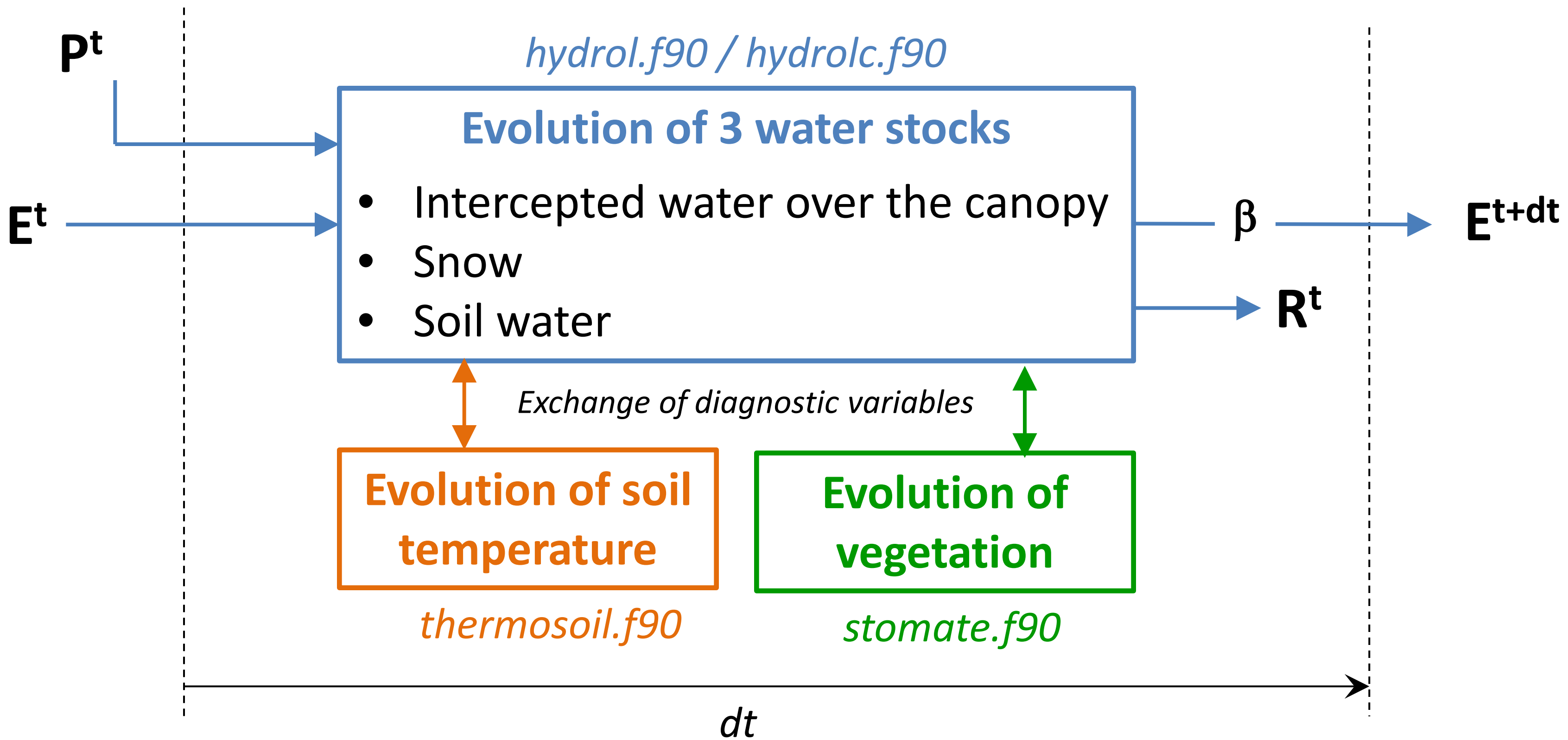
1. **Introduction**
   - Water budget and soil hydrology
   - Interactions with the vegetation
2. **The 2-layer « Choisnel » scheme**
3. **The multi-layer « CWRR » scheme**

More details in the embedded doc for « Choisnel », and on the Wiki for « CWRR »:

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

Water budget and soil hydrology

dS/dt = P – E – R

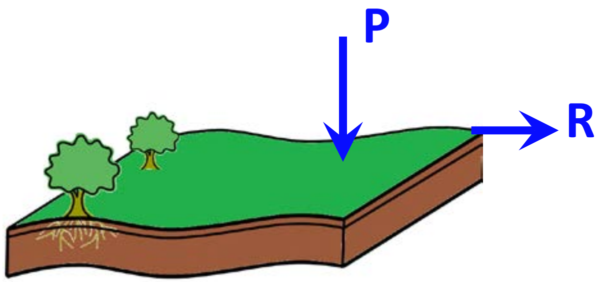


Today, we will focus on soil water and the related water fluxes (soil hydrology)
No interception, no snow, no soil water freezing

Two versions of soil hydrology

Two-layer = Choisnel = ORC2

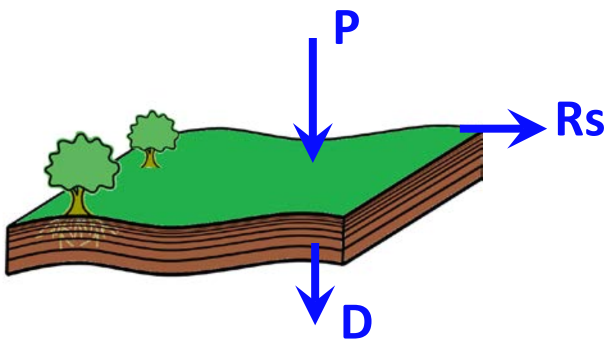
Ducoudré et al., 1993; Ducharne et al., 1998; de Rosnay et al. 1998



- **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

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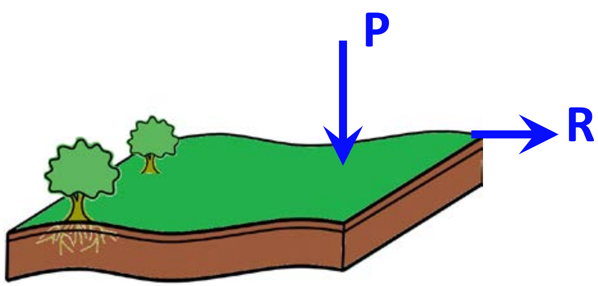

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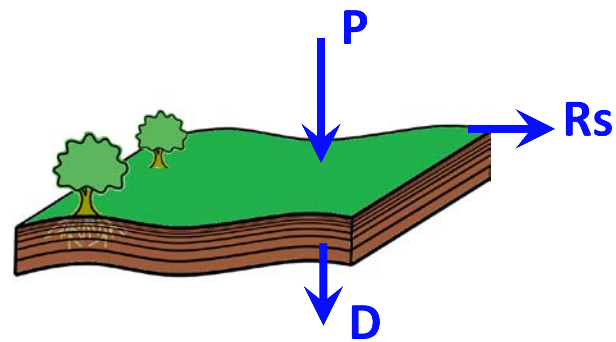

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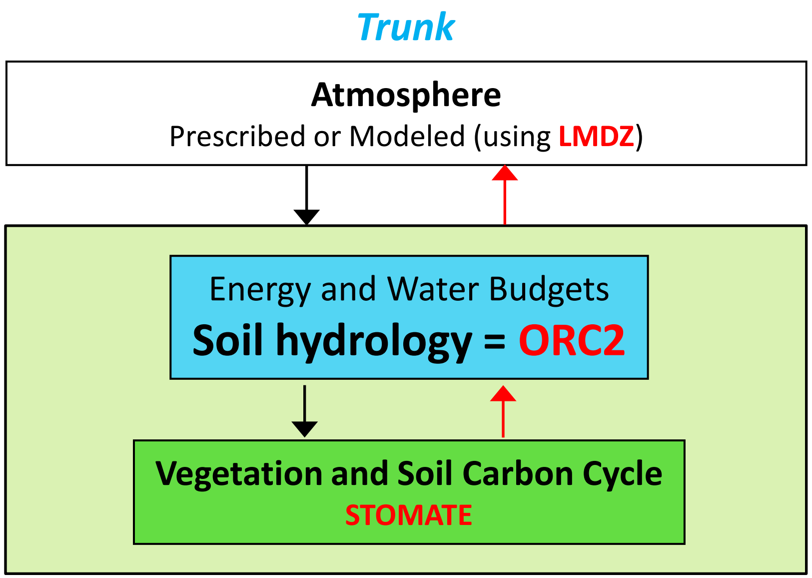
- **2-m soil and 11-layers**
- Formulation of Fokker-Planck
- …s based on van … formulation … based on texture …se)
- … Esol – Infiltration
- Free drainage at the bottom

In run.def

HYDROL_CWRR = n / y

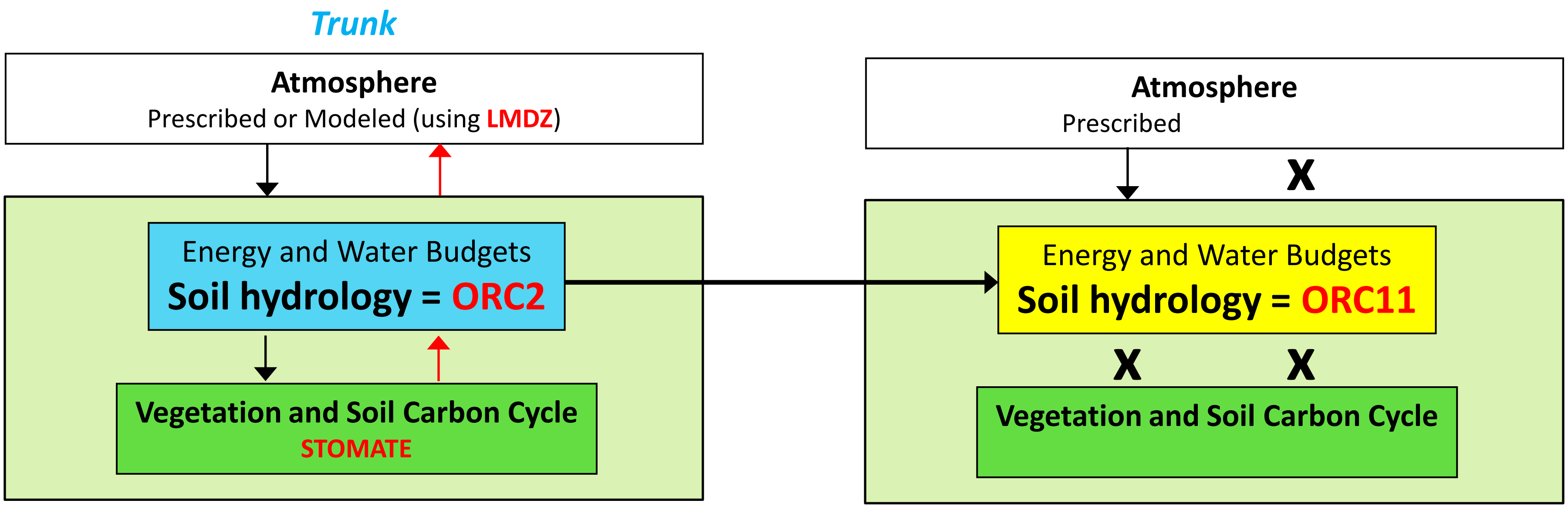
→ either hydrolc.f90 or hydrol.f90

The « merge »



CMIP3
CMIP5
Guimberteau, 2010

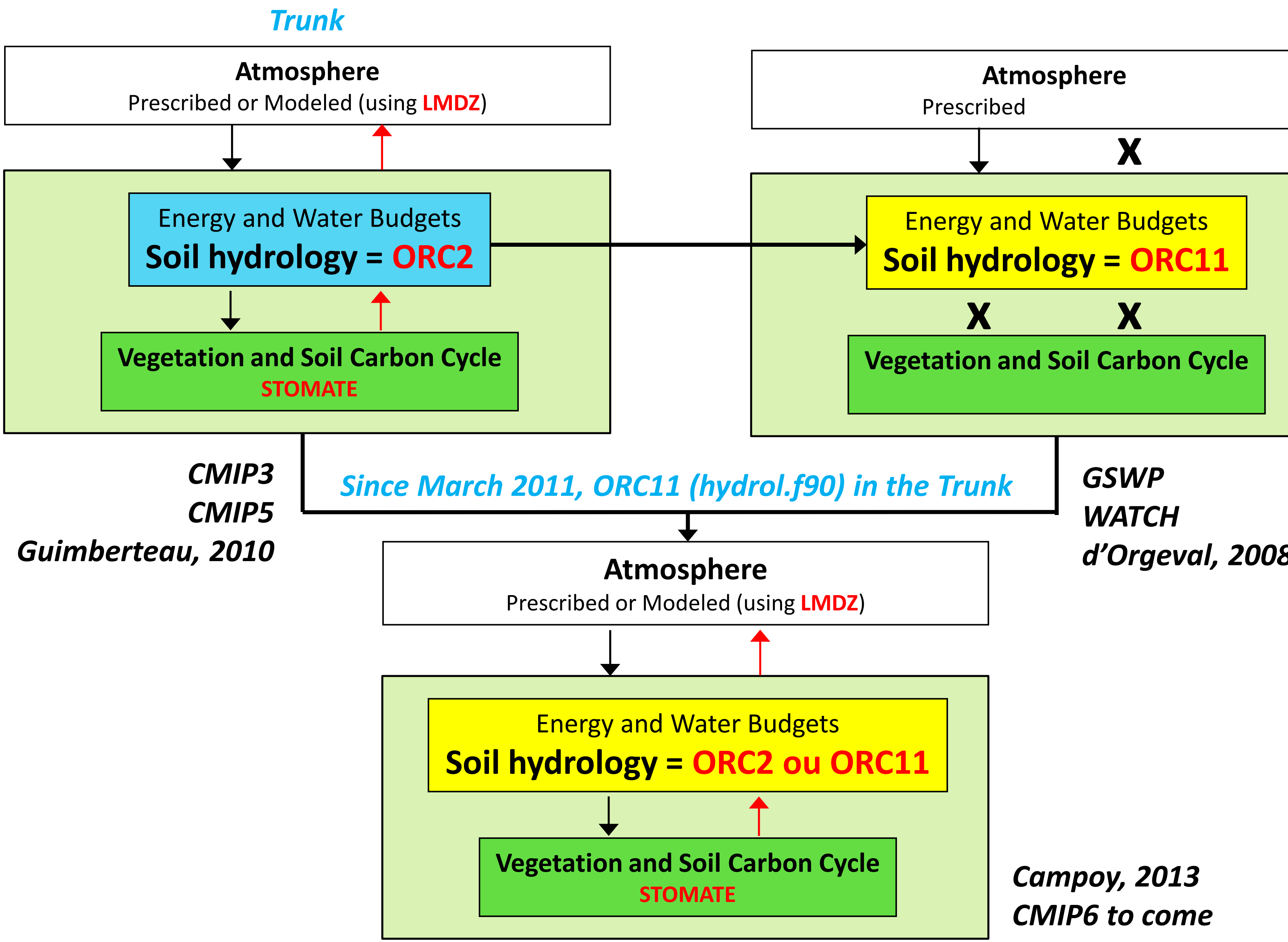
The « merge »



CMIP3
CMIP5
Guimberteau, 2010

GSWP
WATCH
d'Orgeval, 2008

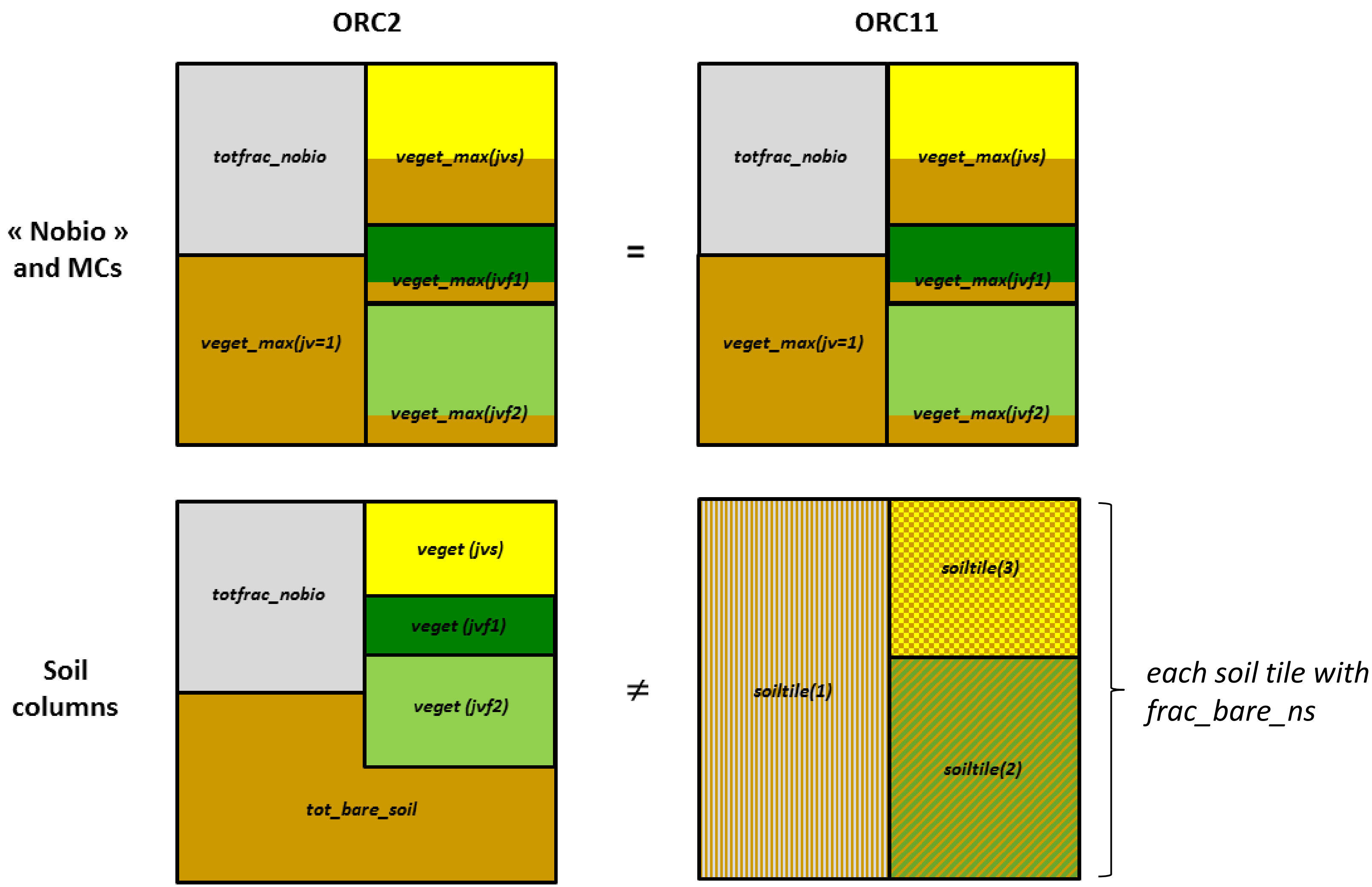
The « merge »


Trunk
Atmosphere
Prescribed or Modeled (using LMDZ)
Energy and Water Budgets
Soil hydrology = ORC2
Vegetation and Soil Carbon Cycle
STOMATE
Atmosphere
Prescribed
X
Energy and Water Budgets
Soil hydrology = ORC11
X
X
Vegetation and Soil Carbon Cycle
CMIP3
CMIP5
Guimberteau, 2010
Since March 2011, ORC11 (hydrol.f90) in the Trunk
GSWP
WATCH
d'Orgeval, 2008
Atmosphere
Prescribed or Modeled (using LMDZ)
Energy and Water Budgets
Soil hydrology = ORC2 ou ORC11
Vegetation and Soil Carbon Cycle
STOMATE
Campoy, 2013
CMIP6 to come

Interactions with the vegetation

1. Horizontally, PFTs define soil tiles (below ground tiling)

This tiling, and the treatment of the bare soil fraction, are different in ORC2/ORC11



Interactions with the vegetation

2. Vertically, ORCHIDEE defines a root density profile

In each PFT j: $\mathbf{R_j(z) = exp\ (-c_j\ z)}$

Water stress function on ET

ORC2

Us acts on Tr and Esol

ORC11

in each soil layer i,
us(i) acts on Tr only
(sink term)

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

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

```
REAL(r_std), PARAMETER, DIMENSION(nvmc) :: humcste_mtc  = &
 & (/ 5.0,   0.4,   0.4,   1.0,   0.8,   0.8,   1.0, &
 &    1.0,   0.8,   4.0,   1.0,   4.0,   1.0 /)
!! Values for dpu_max = 4.0
```

```
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
```

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More details in the embedded doc for « Choisnel », and on the Wiki for « CWRR »:

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

Reference papers: Ducoudré et al., 1993; Ducharne et al., 1998; de Rosnay et al. 1998
PhD theses : Ducoudré, 1992; Ducharne, 1997; de Rosnay, 1999

Main principles of the Choisnel scheme

1. There can be either 1 or 2 soil layers in ORC2, depending on hydrological history

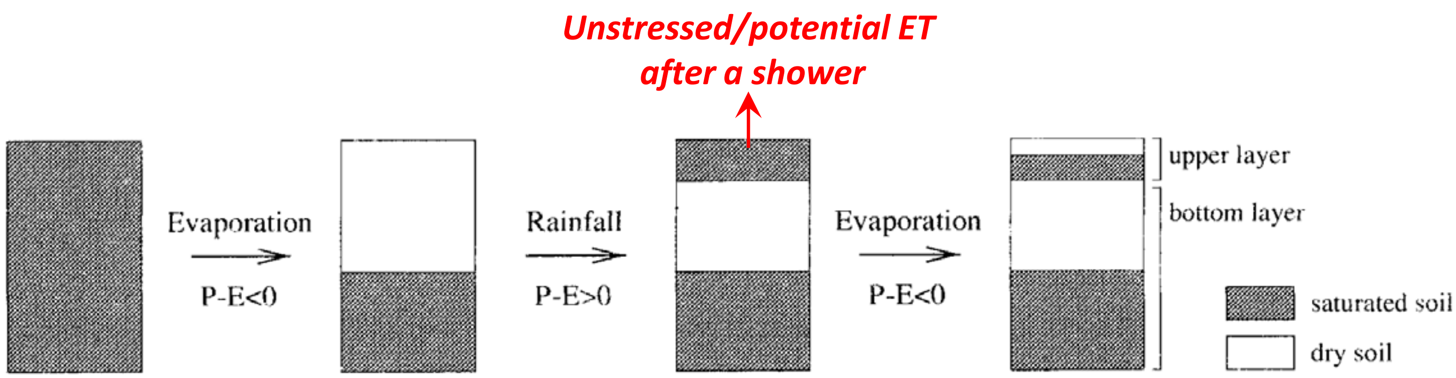


FIG. 1. Schematic diagram of the evolution of the two soil layers in SECHIBA.

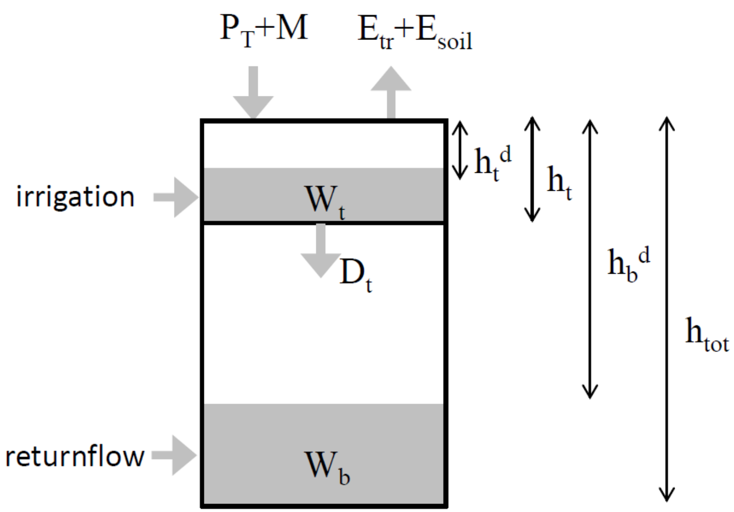
If the top layer dries out => 1 layer

The soil can also be totally dry => 1 layer

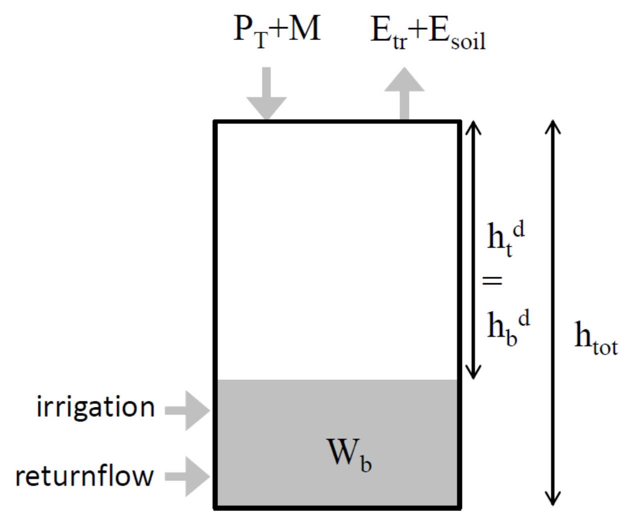
If the soil becomes saturated again => 1 layer

Prognostic and diagnostic variables

2 soil layers



1 soil layer



Symbol	Name in ORC	Units	Symbol	Name in ORC	Units
h_{tot}	dpu_cste	m	W_t	gqsb	$kg.m^2$
h_t^d	dss	m	W_b	bqsb	$kg.m^2$
h_t	dsg	m	D_t	gdrainage	$kg.m^2.s^{-1}$
h_b^d	dsp	m			

The link between depth and moisture involves an *available* water-holding capacity (in kg/m^3)
(i.e. restricted to the storage volume between wilting point and field capacity)

```
REAL(r_std), PARAMETER, DIMENSION(nvmc) :: wmax_veg_mtc  = &
 & (/ 150.0,   150.0,   150.0,   150.0,   150.0,   150.0, 150.0,   150.0,   150.0,   150.0,   150.0,   150.0,   150.0  /)
```

The water stress factor Us

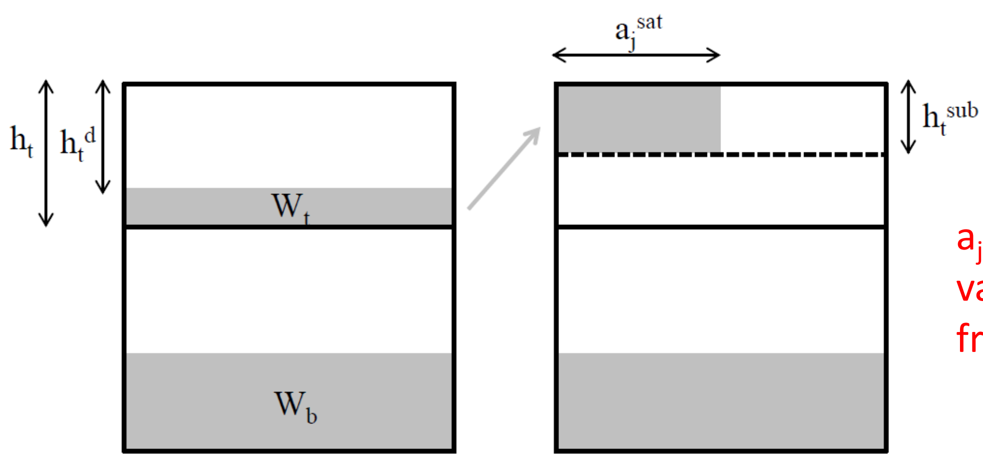
Us conveys the water stress onto transpiration and (bare) soil evaporation

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

It depends on dry soil height

If 1 layer: $U_s = \exp(-c_j \, h_t^d)$

If 2 layers: $U_s = a_j^{\mathrm{sat}} \exp(-c_j \, h_t^d) + (1 - a_j^{\mathrm{sat}}) \exp(-c_j \, h_b^d)$



a_j^{sat} serves to smooth the variation of Us when going from 2 to 1 soil layer

a_subgrd = $a_j^{sat} = \min[1, Wt/(h_t^{sub} \, \theta^{max})]$

Soil resistance to bare soil evaporation

r_{sol} is the main control of water stress onto bare soil evaporation

$$E_{sol} = \rho U_s \frac{q_{sat}(T_s) - q_{air}}{r_a + r_{sol}}$$

It depends on the dry soil height of PFT 1

$$r_{\rm soil} = r^{\rm m}_{\rm soil}\left(h_{\rm dry} + \frac{1}{100(h_{\rm tot} - h_{\rm dry})^2}\right)$$

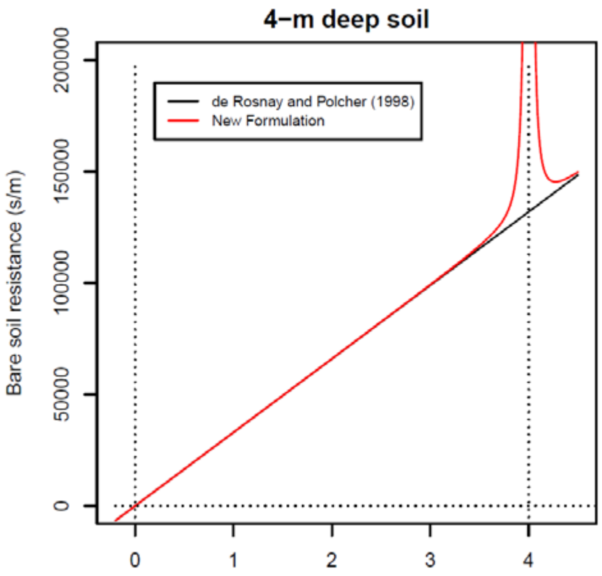
$$h_{\rm dry} = a_1^{\rm sat} h^d_{t_1} + (1 - a_1^{\rm sat}) h^d_{b_1}$$

r^{m}_{soil} corresponds to rsol_cste in the code

It is externalized but you should keep the default value

```
REAL(r_std), SAVE :: rsol_cste = 33.E3
```

1 cm of dry soil exerts r_{soil} = 330 s/m



Internal water redistribution

Vertically, ORC2 accounts for internal drainage between the 2 soil layers

$$D_t = D_t^{\min} \frac{W_t}{W_t^{\max}}, \text{ if } W_t < W_t^{\lim}$$

Slower drainage if low top soil moisture

$$D_t = D_t^{\min} \frac{W_t}{W_t^{\max}} + (D_t^{\max} - D_t^{\min}) \left(\frac{W_t - W_t^{\lim}}{W_t^{\max} - W_t^{\lim}} \right)^{\alpha_t}, \text{ if } W_i \geq W_i^{lim}$$

There are two kinds of horizontal diffusion between the PFTs

After each timestep, the PFTs are forced to share the same bottom moisture

$$W_{b_j} = \frac{\sum_j a_j W_{b_j}}{\sum_j a_j}$$

Optionally (and not by default), the top soil moisture variables (W_t and h_t^d) can be relaxed to their grid-cell weighted average, with a relation time of 1d

$$\Delta X_j = -\frac{\Delta t}{\tau_h}(X_j - \overline{X})$$

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   (CWRR = Center for Water Resources Research, Dublin)

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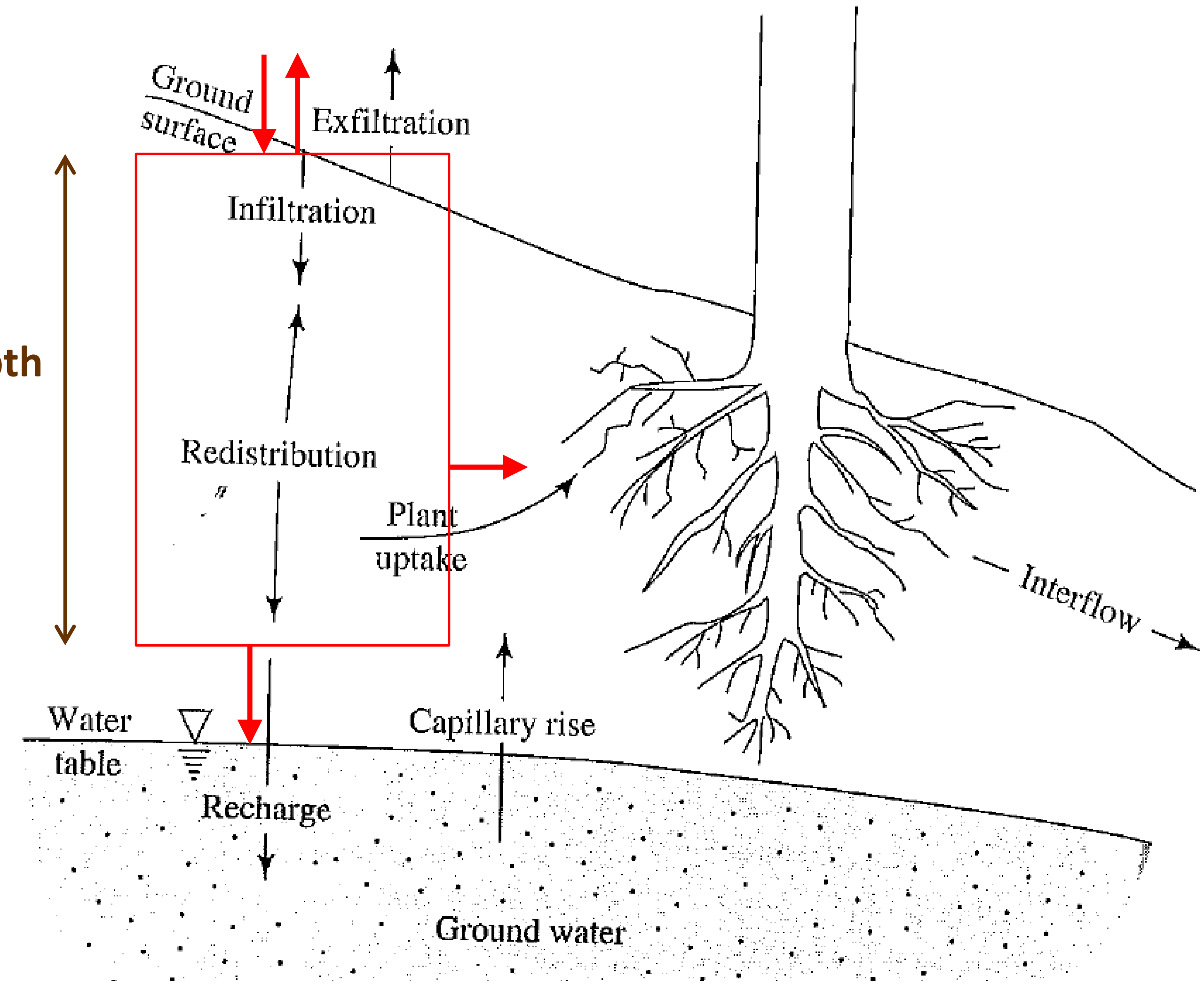
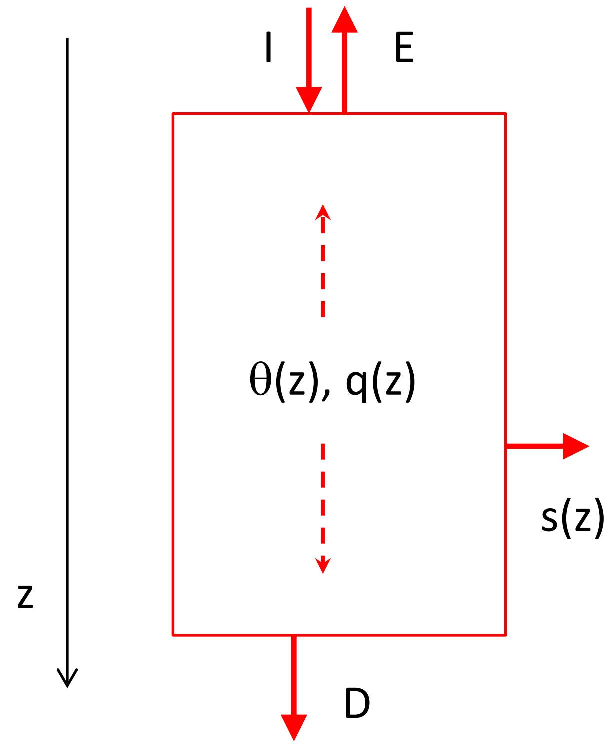
What is modeled ?

« Soil » depth



How is 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)

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

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

+2 → Fokker-Planck eq.

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

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 head in m
K : hydraulic conductivity in $m.s^{-1}$
s : transpiration sink in $m^3.m^{-3}.s^{-1}$

The hydrodynamic parameters

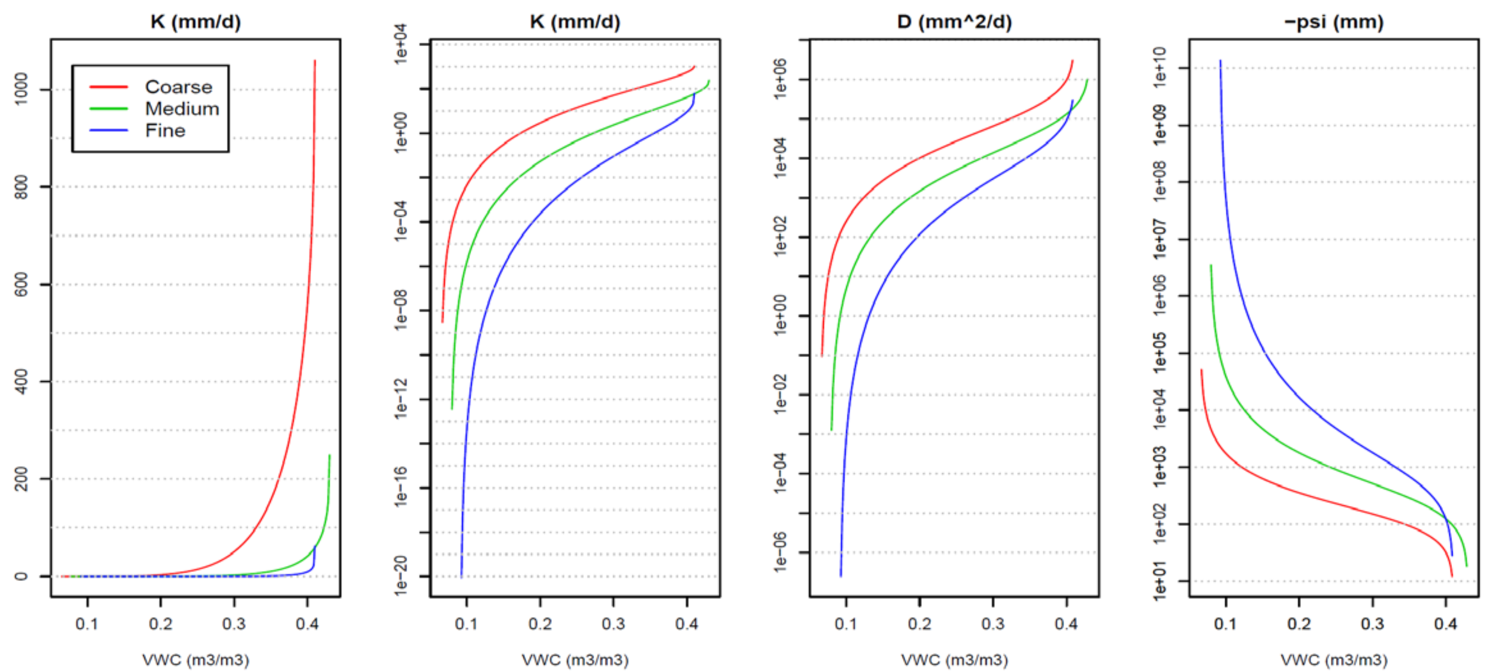
- K and D depend on saturated properties (measured on saturated soils) and on θ
- Their dependance on θ is very non linear
- In ORCHIDEE, this is decribed by the so-called Van Genuchten-Mualem relationships:

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

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

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

Parameters:
θ_s θ_r K_s 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)

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

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

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 towar…

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

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

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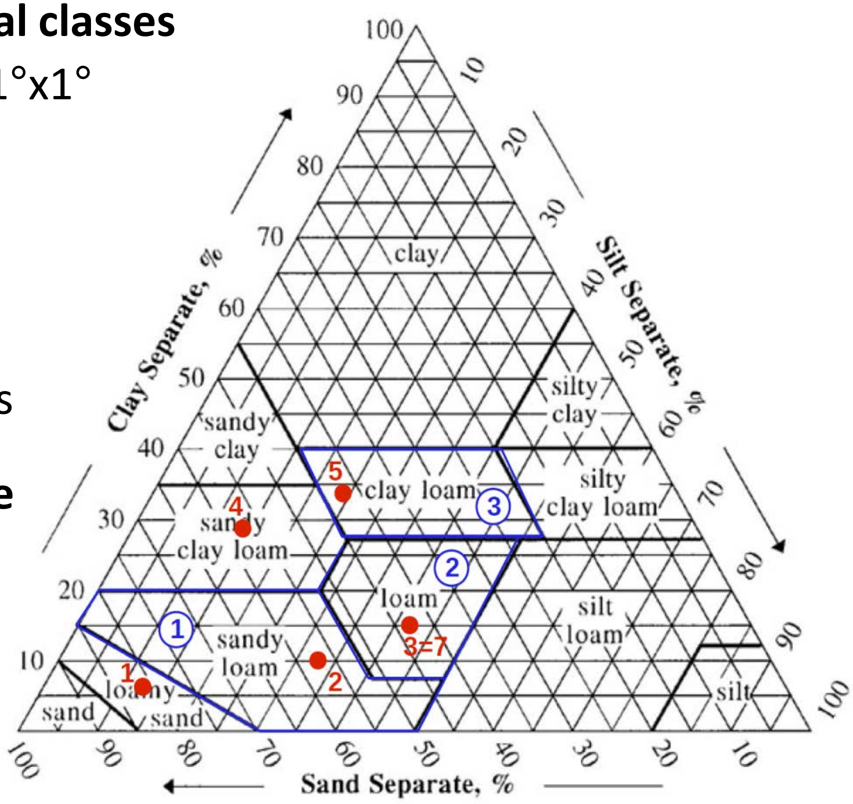
The role of soil texture

- **In hydrol, the main soil properties are:** θ_s θ_r K_s^{ref} m $\alpha=1/\psi_{ae}$
- 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)
  - 6 main textural classes
  - reduced to 3 = Coarse, Medium, Fine
- clay_fraction is a parameter for Stomate
- In progress : 1/12° map of the 12 USDA 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 $\alpha=1/\psi_{ae}$

Their default values for the Zobler case are defined in constantes_soils, with the suffix _fao

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

Two ways of defining soil texture in run.def

1. Default: SOILTYPE_CLASSIF = zobler ; SOILCLASS_FILE = soils_param.nc

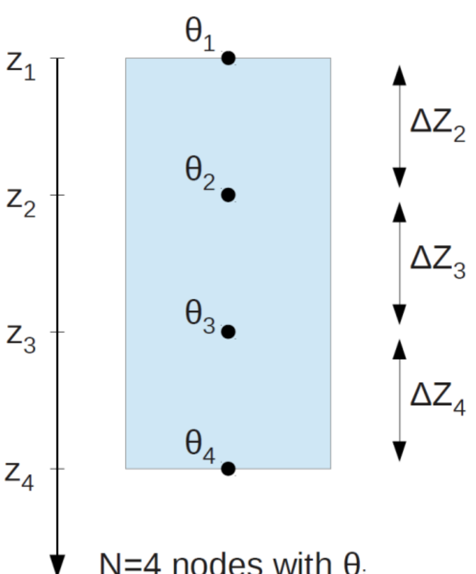
2. IMPVEG=y, IMPSOIL=y, SOIL_FRACTION = (x,y,z)
→ x,y,z are areal fraction allocated to the Coarse, Medium, Fine soil textural classes
→ x,y,z are not % sand, silt, clay defining your soil's texture, despite the fact that this option is primarily intended for 0D simulations
→ to get the soil properties you want, set SOIL_FRACTION = (1,0,0), and use the externalization to redefine the 1st value of the vectors defining soil properties

Finite difference integration (1)

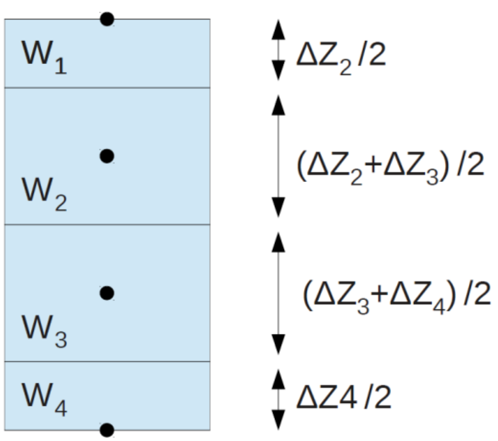
- The differential equations of continuity and motion are solved using finite differences

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

- 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

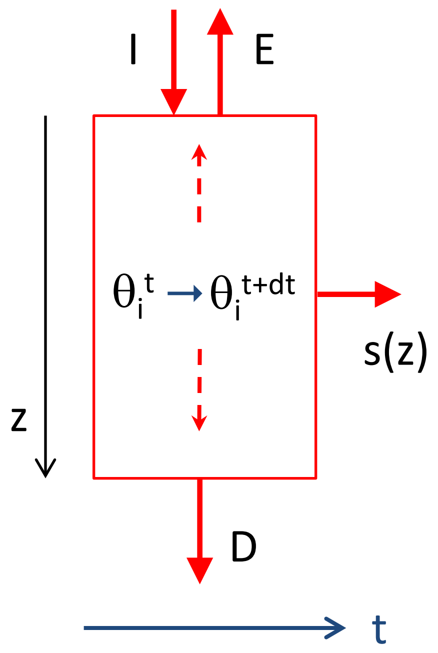
- They can be solved using a tridiagonal matrix which updates θi (**prognostic variable**)
- To this end, K(θi) and D(θi) must be linearized at first order in θ
  → piecewise functions over 50 interval in [θr, θs]

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

- 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**



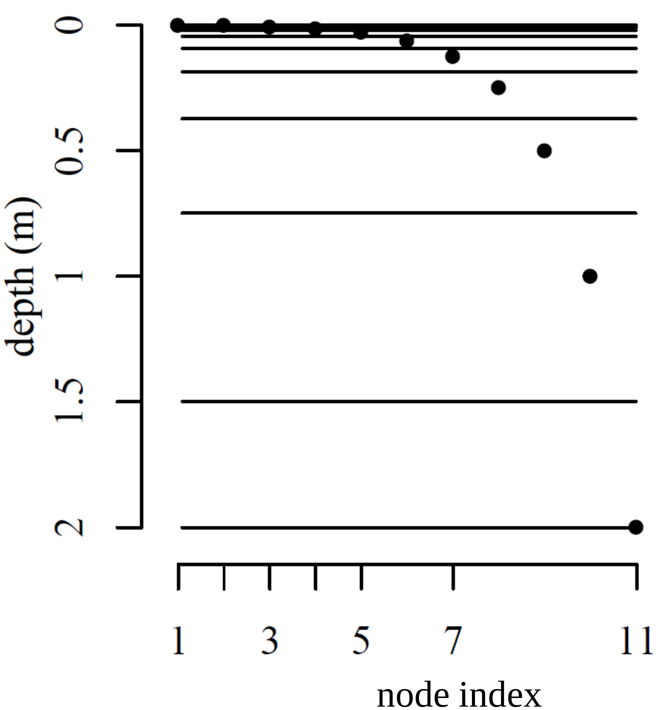
Finite difference integration (3)

- 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 :

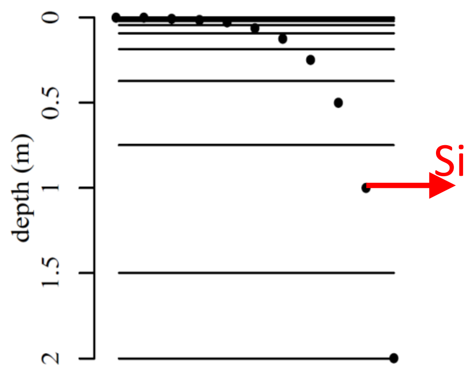
- 11 nodes (layers) with geometric increase of internode distance
- consistent with free/gravitational drainage at the bottom
- consistent with exponential decrease of root density for transpiration

(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

The transpiration sink



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

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

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

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

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

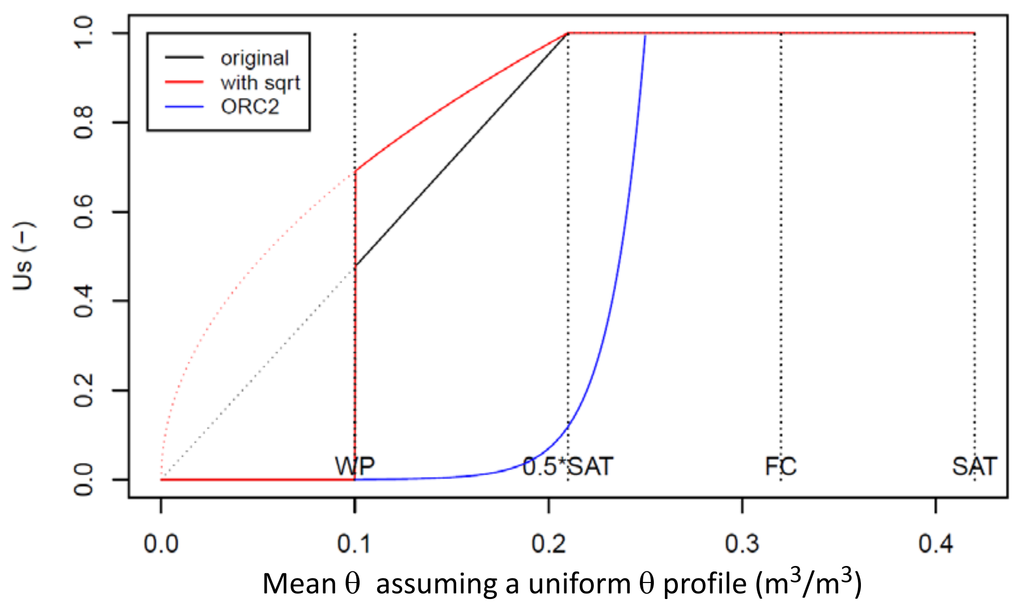
$$u_s(1) = 0$$

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

PARAMETERS

- moderwilt(i) = 1 but if $W_i < W_w$
- n_{root} : mean root density in layer i
  $n_{root} = \int_{hi} R(z)dz \,/ \int_{htot} R(z)dz$
  $R(z) = \exp(-c_j\, z)$
- W_w = wilting point
- $W_{\%}$: fraction of θ_s over which Tr is unstressed

In constantes_mtc.f90:
c_j = humcste (by PFT)
In constantes_soil.f90:
$W_{\%}$ = pcent_fao = (/ 0.5, 0.5, 0.5 /)
θ_w = mcw_fao = (/ 0.1, 0.1, 0.1 /)



Drainage

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

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

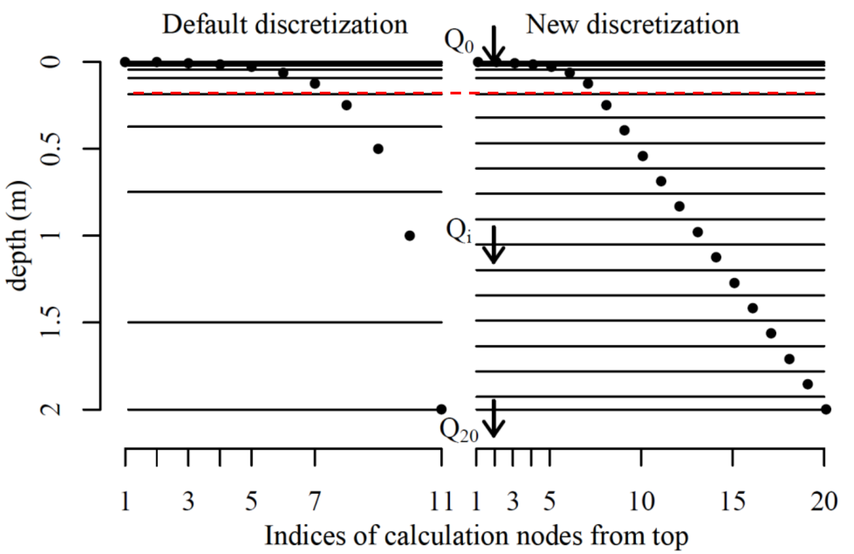
  - θ does not show any vertical variations below the modeled soil

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

- 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

WARNING !

- Reduced drainage enhances θ gradients in the bottom soil,
- The default 11-layer discretization is not adapted anymore
- Campoy (2013) proposed a more flexible discretization, but it has not been included yet in the Trunk
- **So keep free_drain_coef to (1,1,1)**



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

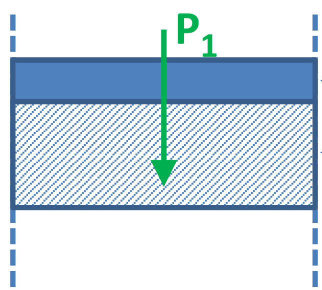
- The modeling of infiltration relies on gravitational fluxes: $q(z) = K(\theta)$

Soil absorption is neglected

1. Direct infiltration to the top soil layer (1-mm deep)
2. If P_0 > 1mm/dt, infiltration of $P_1 = P_0$ - 1mm/dt to the lowest layers : **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

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

$I_i = I_i^{pot} [1 - \exp(-P_1/ I_i^{pot})]$ — Exponential distribution of « potential » infiltration I_i^1

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

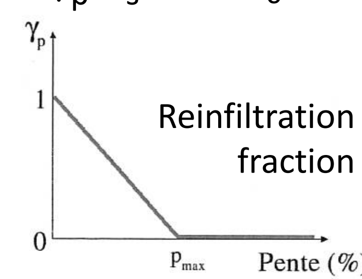
θ_i updated

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

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

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

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



In the code :
reinf_slope = γ_p ??

Soil evaporation

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

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

- **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 [θr, θs], 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

Effective water diffusion

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

  β_4 = evap_bare_lim /frac_bare — $E_{soil} = \beta_4 E_{pot}$

  β = vegtot($\beta_2 + \beta_3$) + frac_bare β_4 — $E = \beta E_{pot}$

- **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)

Thank you for your attention
Questions ?

ORCHIDEE