Introduction to the multilayer soil diffusion scheme and the routing scheme in ORCHIDEE

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ORCHIDEE training course
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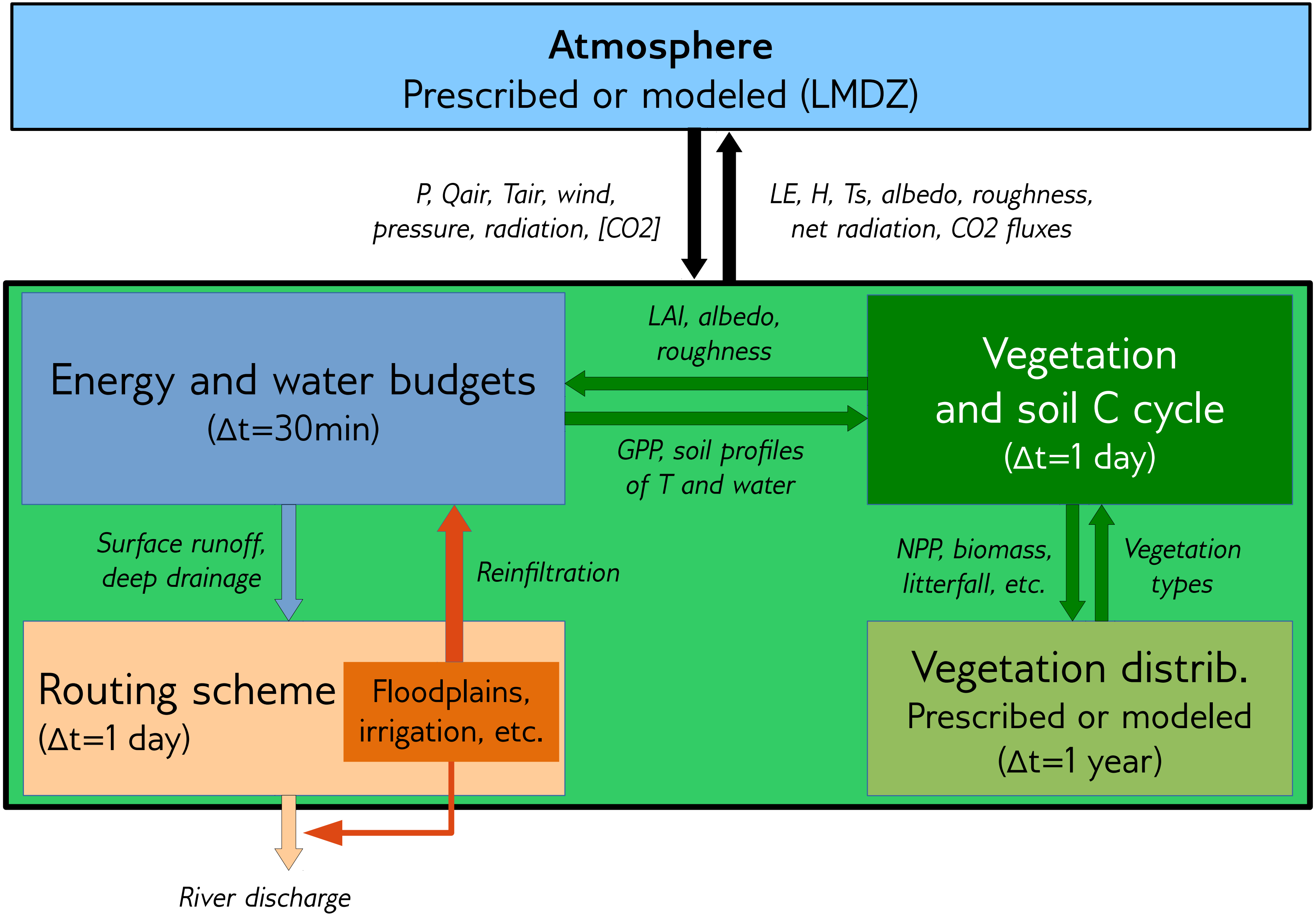
ORCHIDEE



Atmosphere
Prescribed or modeled (LMDZ)

P, Qair, Tair, wind, pressure, radiation, [CO2]

LE, H, Ts, albedo, roughness, net radiation, CO2 fluxes

Energy and water budgets
(Δt=30min)

LAI, albedo, roughness

GPP, soil profiles of T and water

Vegetation and soil C cycle
(Δt=1 day)

Surface runoff, deep drainage

Reinfiltration

NPP, biomass, litterfall, etc.

Vegetation types

Routing scheme
(Δt=1 day)

Floodplains, irrigation, etc.

Vegetation distrib.
Prescribed or modeled
(Δt=1 year)

River discharge

1

The multilayer soil diffusion scheme

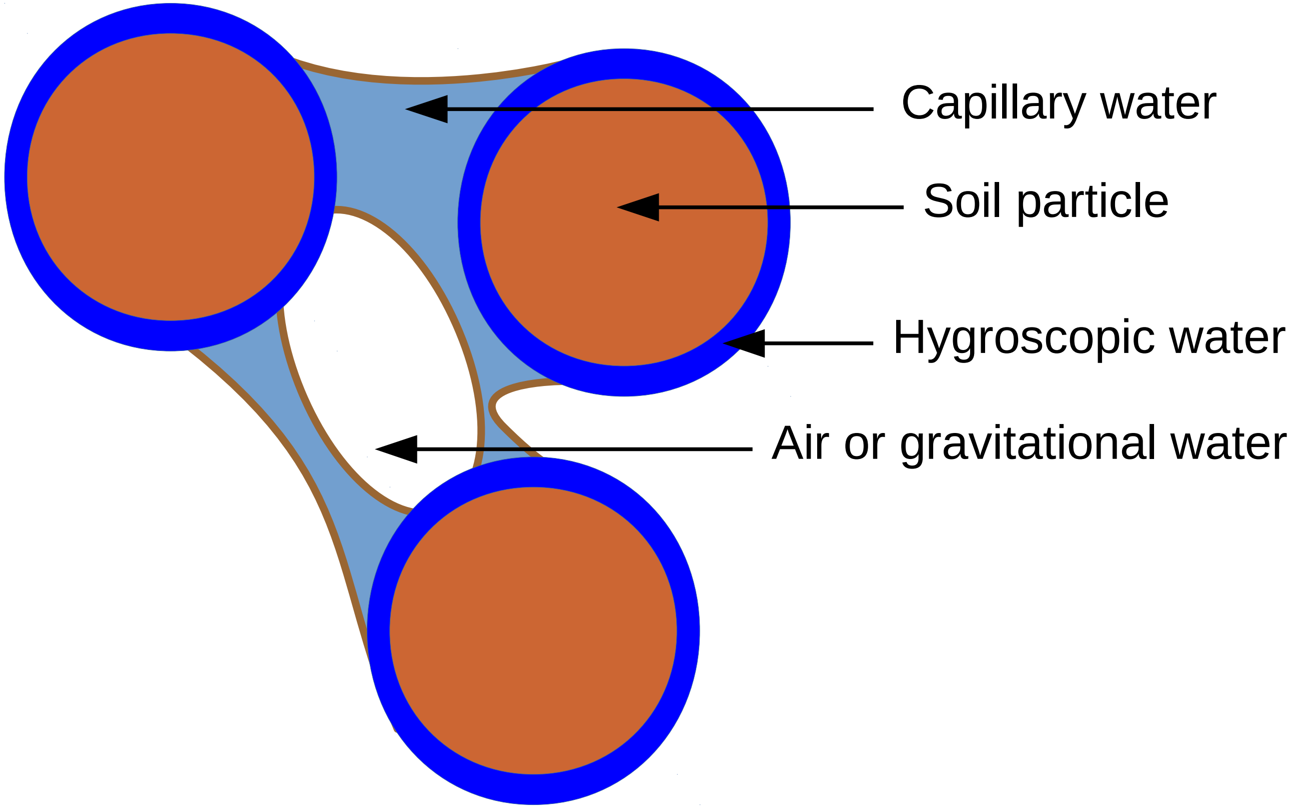
1.1

The multilayer soil diffusion scheme

Fundamental notions of soil water movement

The soil

- Porous medium. Matrix of individual solid granular particles (grains)
- Between each grains: interconnected pore (or void) 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)



Capillary water

Soil particle

Hygroscopic water

Air or gravitational 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.

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

V_w, volume of liquid water

V_s, volume of soil

The porosity of the soil

- It refers to the volume of soil voids that can be filled by water and/or air
  - constant over the time periods
  - decreases with depth (compaction)
  - varies depending on particle size and aggregation
    - large number of small particles in a volume of soil ⇒ large number of soil pores ⇒ high porosity
    - fewer large particles can occupy the same volume of soil ⇒ fewer pores ⇒ less porosity
- Theorical range of θ: $0 < \theta < \phi$. When the soil moisture content reaches the porosity ⇒ the soil is saturated

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

V_a, volume of air

V_w, volume of liquid water

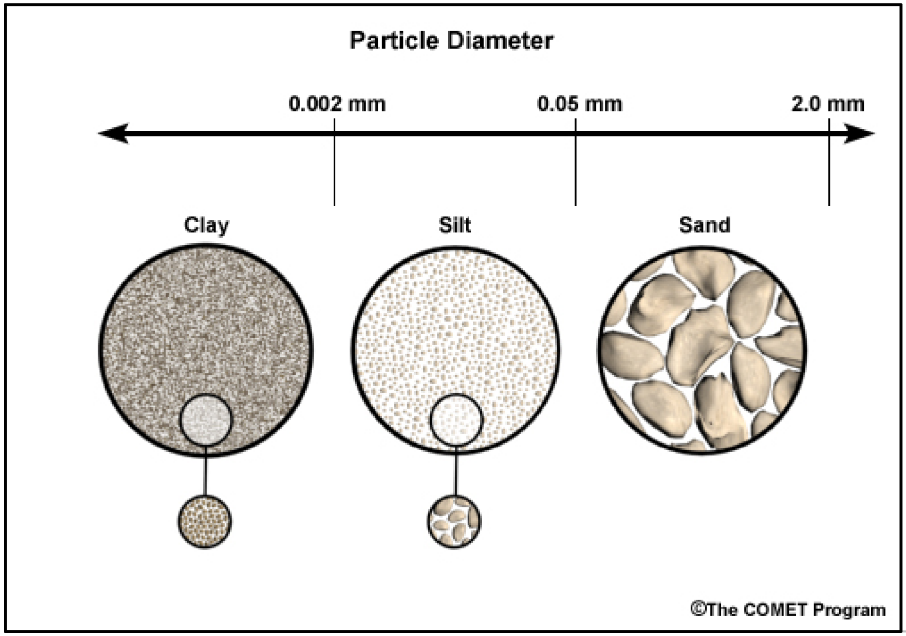
V_s, volume of soil

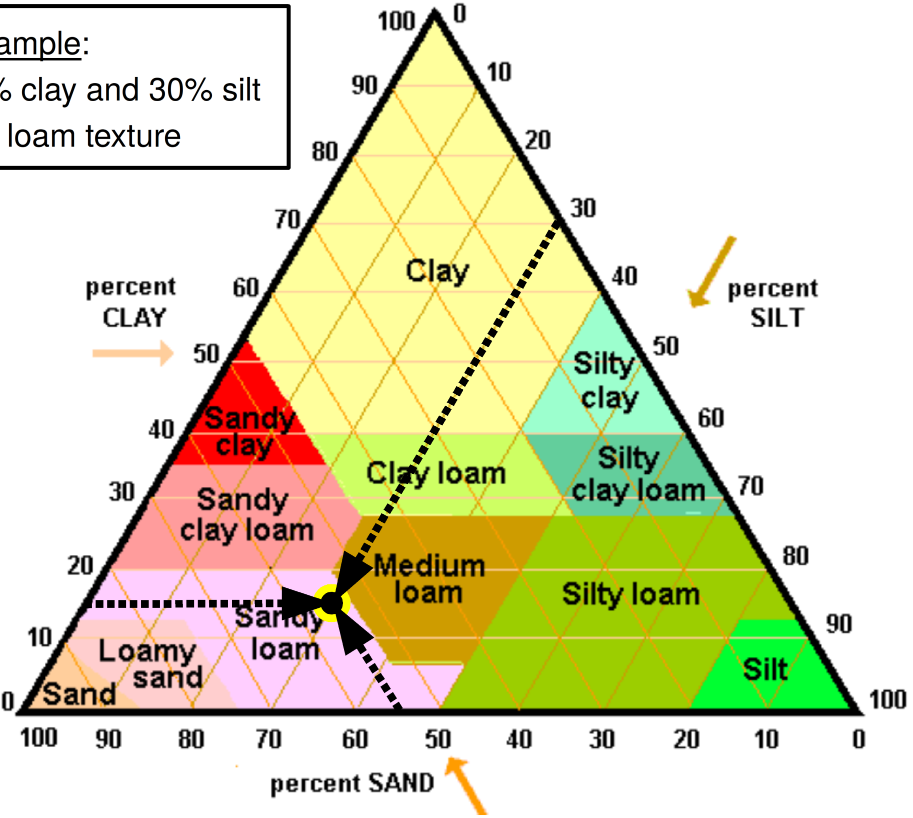
The texture of the soil

- Most soils have a mixture of grain sizes
- The particle size distribution is characterized by the soil texture: the relative contents of particles of clay (fine), silt (medium) and sand (coarse)

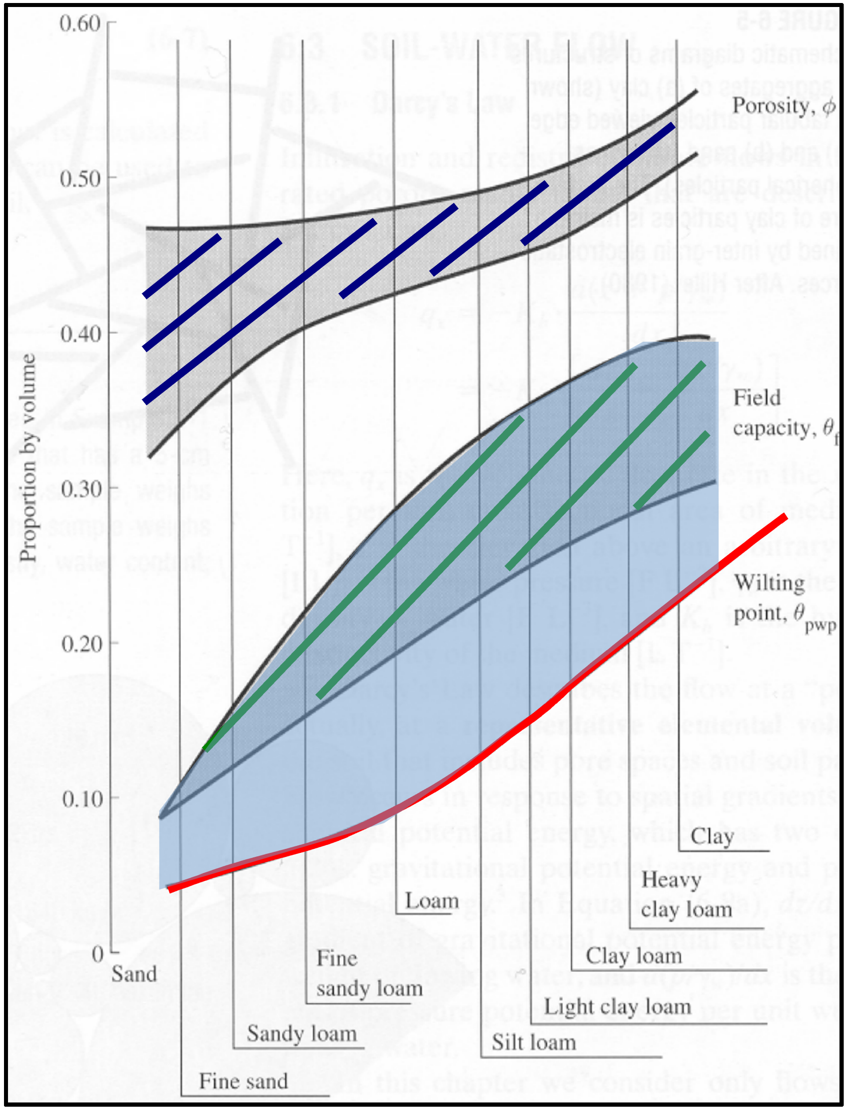
Granulometric composition visualized in texture triangle (here USDA triangle including 12 textures):

Example:
55% sand, 15% clay and 30% silt
⇒ Sandy loam texture



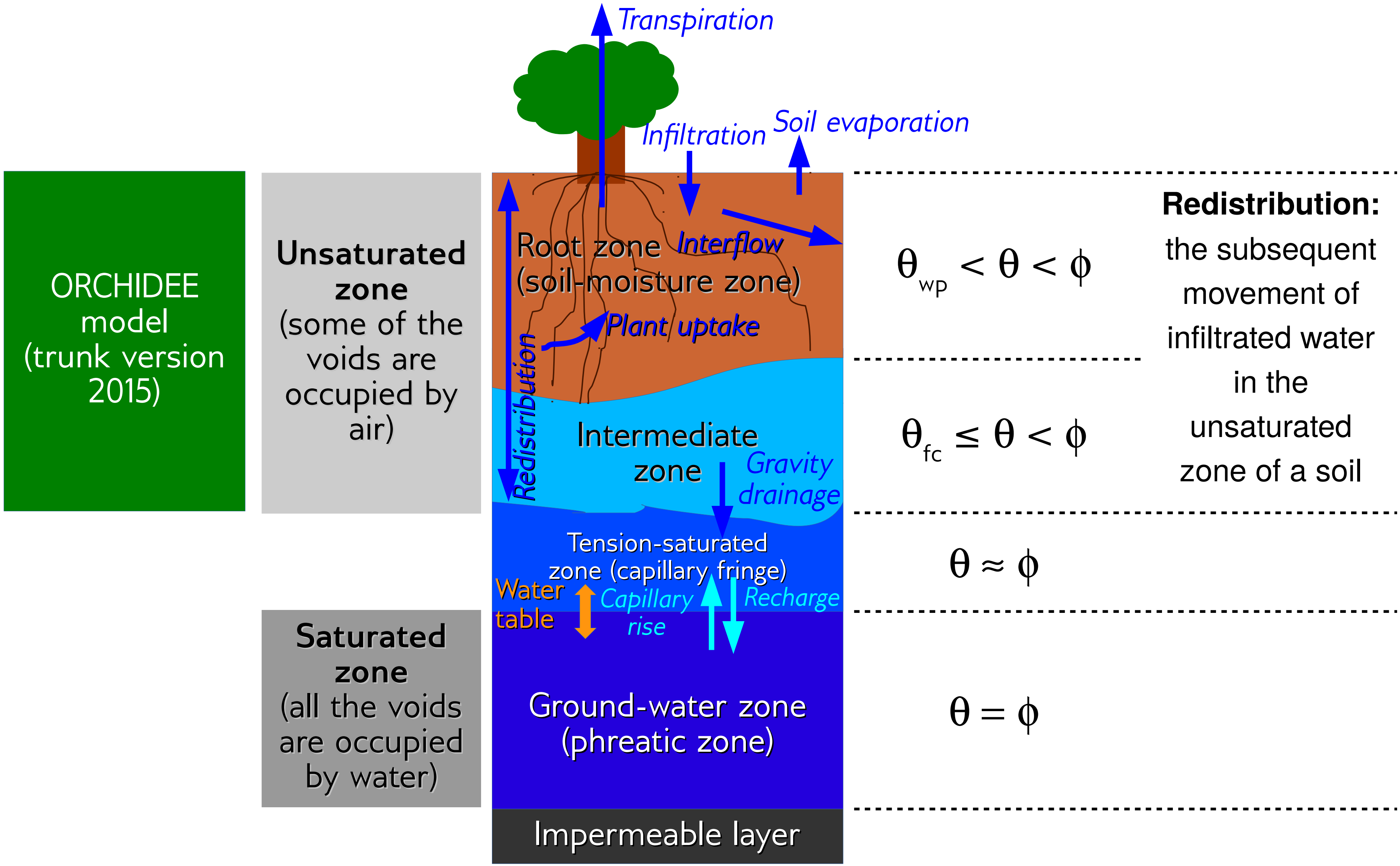


The soil moisture characteristics



- **Saturation, θ_s = Φ**: all soil pores are filled with water (no air left in the soil)
- **Field capacity, θ_{fc}**: maximum amount of water that a soil can hold after gravitational drainage. The large soil pores are filled with both air and water while the smaller pores are still full of water.
- **Wilting point, θ_{wp}**: water content at which the roots can no longer extract water from the soil. Soil water stage where the plant dies.
- **Plant available water content, θ_a**: water available for plant use. $\theta_a = \theta_{fc} - \theta_{wp}$
- **Residual, θ_r:** water content where no liquid flow occurs any more. Water moves only by vapor flow.
- These conditions are constant for a given soil but vary widely from one type of soil to another

Hydrological horizons and water movement



ORCHIDEE model (trunk version 2015)

Unsaturated zone
(some of the voids are occupied by air)

Saturated zone
(all the voids are occupied by water)

Transpiration

Infiltration

Soil evaporation

Root zone (soil-moisture zone)

Interflow

Plant uptake

Redistribution

Intermediate zone

Gravity drainage

Tension-saturated zone (capillary fringe)

Water table

Capillary rise

Recharge

Ground-water zone (phreatic zone)

Impermeable layer

$\theta_{wp} < \theta < \phi$

$\theta_{fc} \leq \theta < \phi$

$\theta \approx \phi$

$\theta = \phi$

Redistribution:
the subsequent movement of infiltrated water in the unsaturated zone of a soil

Darcy's law for unsaturated flows

Describes the flow rate across a unit cross section of soil that includes pores spaces and soil particules (Darcy, 1856)

Gradient of gravitational potential energy

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

Gradient of pressure potential energy

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

Hydraulic conductivity
of the soil (m/s)
⇔
ability of the soil to
"conduct" water

z, elevation (m)
p, water pressure (N/m^2)
γ_w, weight density of water (N/m^3)

Darcy's law for vertical unsaturated flows

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

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

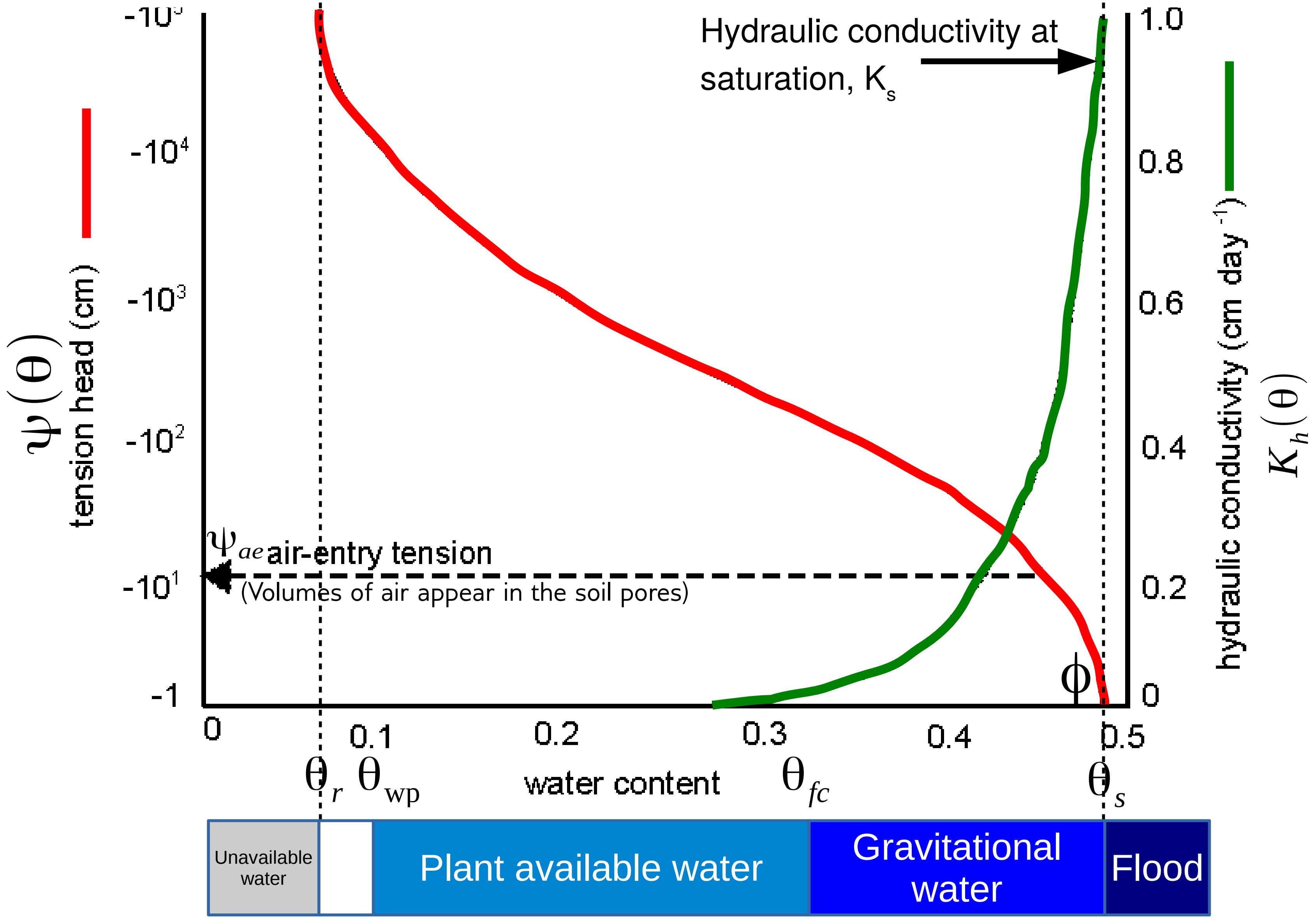
Pressure head, ψ (in m)
(γ_w is constant)

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

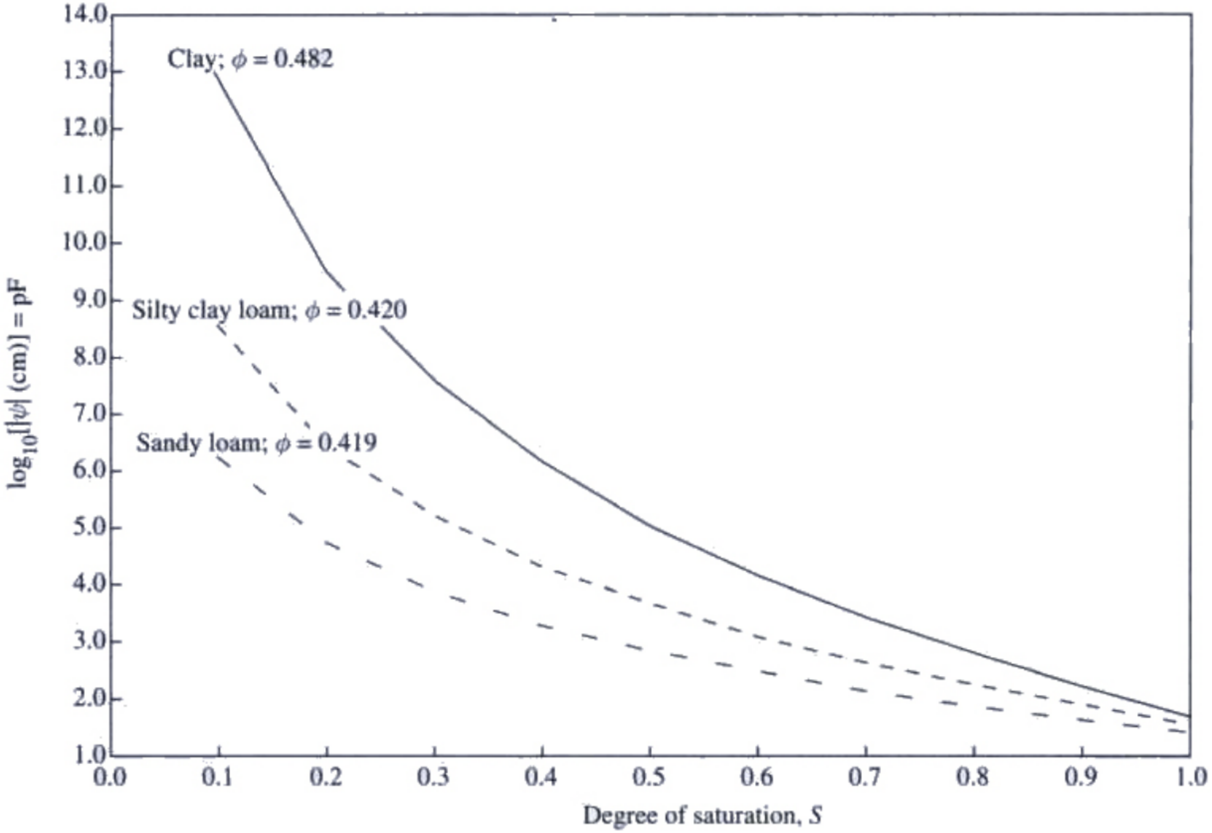
$$\boxed{q_z = -K_h(\theta) \cdot \left[1 + \frac{d\,\psi(\theta)}{dz} \right]}$$

In unsaturated soils, $p < 0$ and thus $\psi < 0$. In this case, ψ is also called tension head, matric potential or matric suction. It is the work required to remove water against surface tension and particle surface forces.

Relation between ψ, K_h and θ

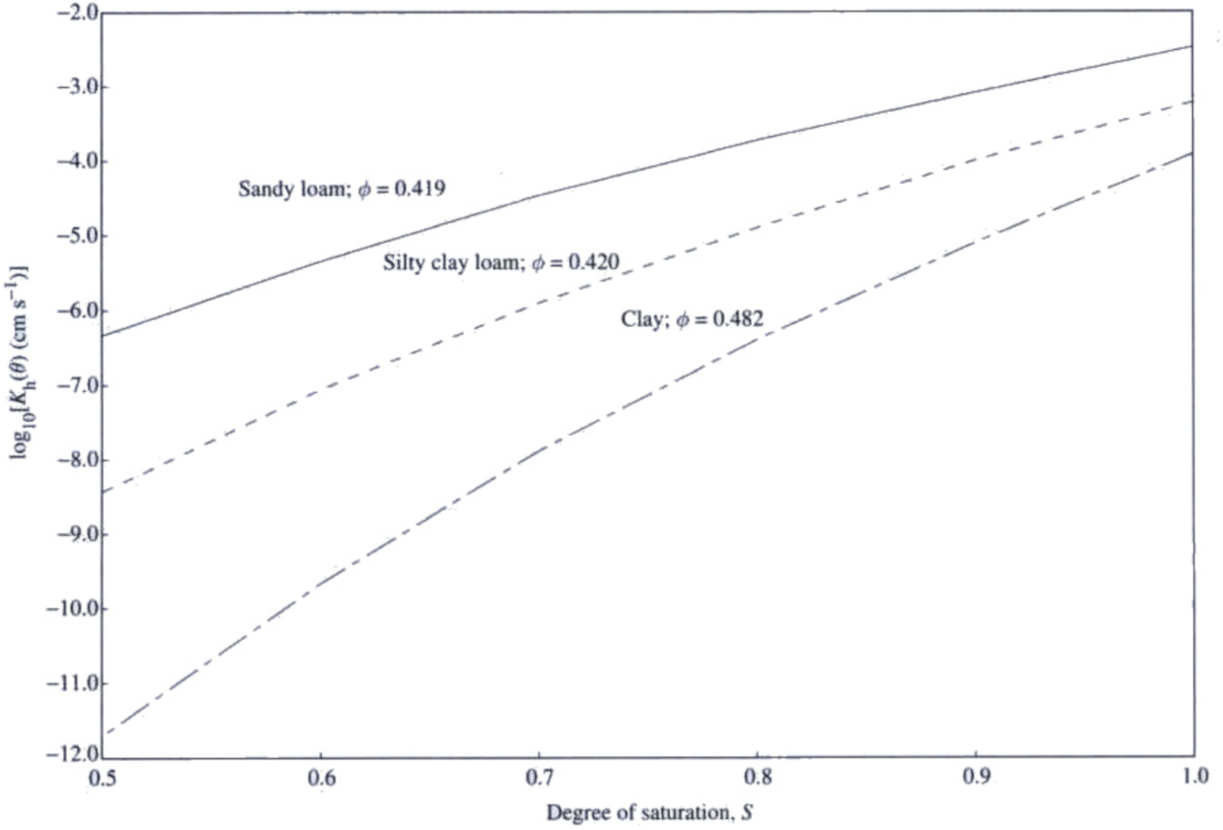


Relation between ψ, θ and soil texture



- 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

Relation between K_h, θ and soil texture



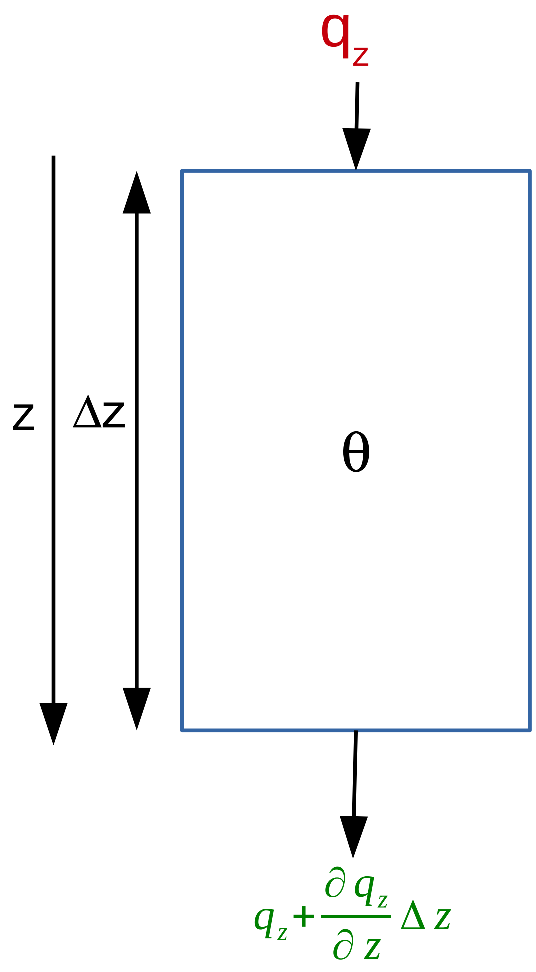
- For a given degree of saturation, K_h increases by several orders of magnitude from fine-grained soils to coarse-grained soils (water path is less sinuous <=> less resistance to flow)

Water transport in unsaturated soils

- The Richards equation (Richards, 1931) is widely used as a basis for numerical modeling soil water flow:
  - by dividing the soil profile into very thin layers
  - by specifying appropriate boundary conditions
  - by applying the equation to each layer sequentially over small increments of time

The Richards equation

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



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 for unsaturated flow (z<0 because the “point” is below the surface):

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

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

The Richards equation

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

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

Fokker-Plank equation uses θ as a state variable, instead of Φ as in the Richards equation

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

The flow due to the pressure gradient can be expressed as the product of the hydraulic diffusivity and the water-content gradient

⇒ **Hydraulic diffusivity (m²/s)**:

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

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

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

$$\boxed{\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial z} \underbrace{K_h(\theta)}_{\text{Conductivity}} + \frac{\partial}{\partial z}\left[\underbrace{D_h(\theta)}_{\text{Diffusivity}} . \underbrace{\frac{\partial\theta}{\partial z}}_{\text{Water-content gradient}} \right]}$$

1.2

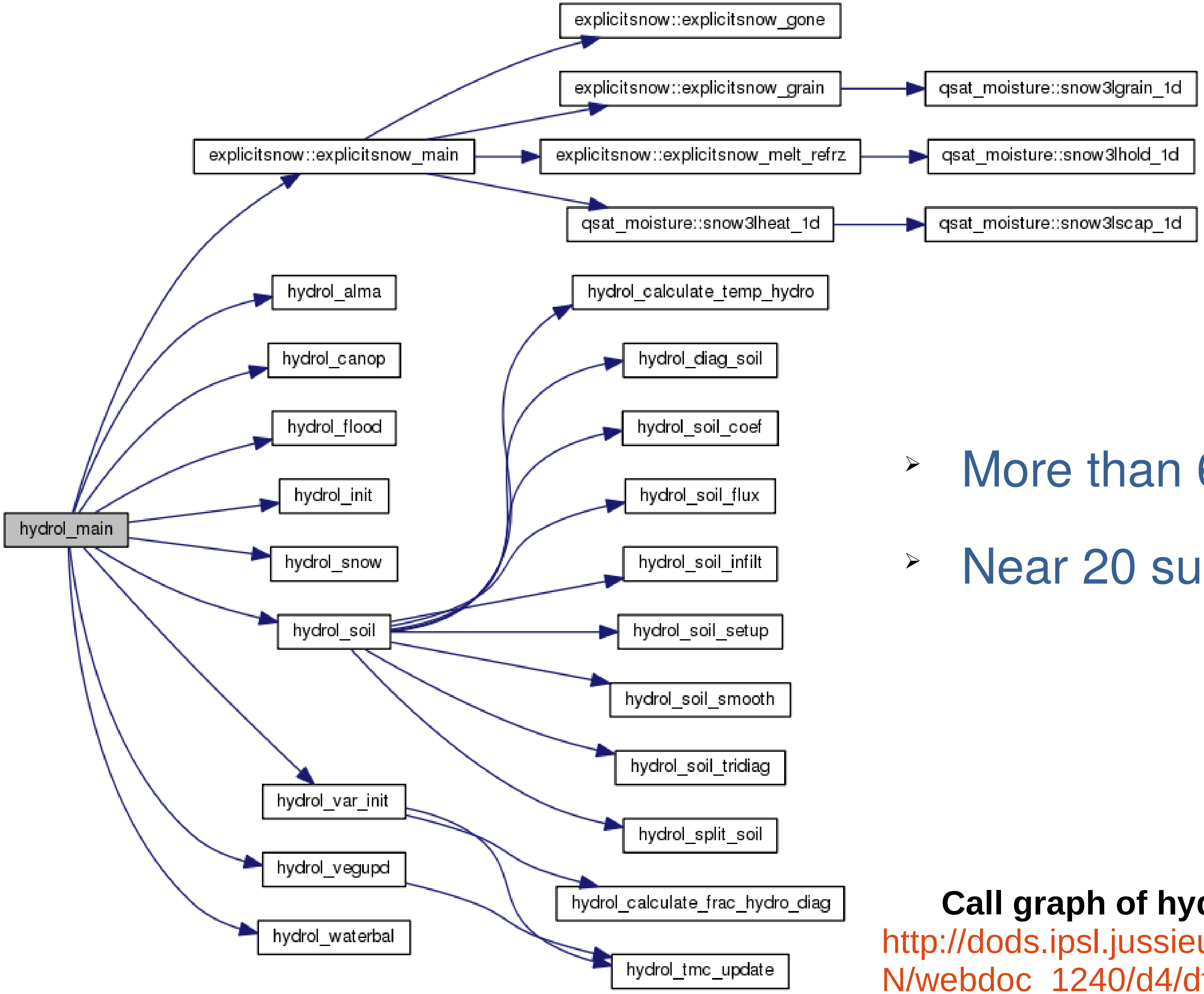
The multilayer soil diffusion scheme

Modeling in ORCHIDEE

Generalities

- Physically-based description of unsaturated soil water flow
- Relies on a 1D Fokker-Planck equation
- The lateral fluxes between adjacent grid-cells are neglected
- We assume that all the variables are horizontally homogeneous
- By default in ORCHIDEE, the multilayer soil diffusion scheme is not activated (2-layer scheme activated by default).
  To activate it: NEWHYDROL = y in sechiba.card

hydrol.f90



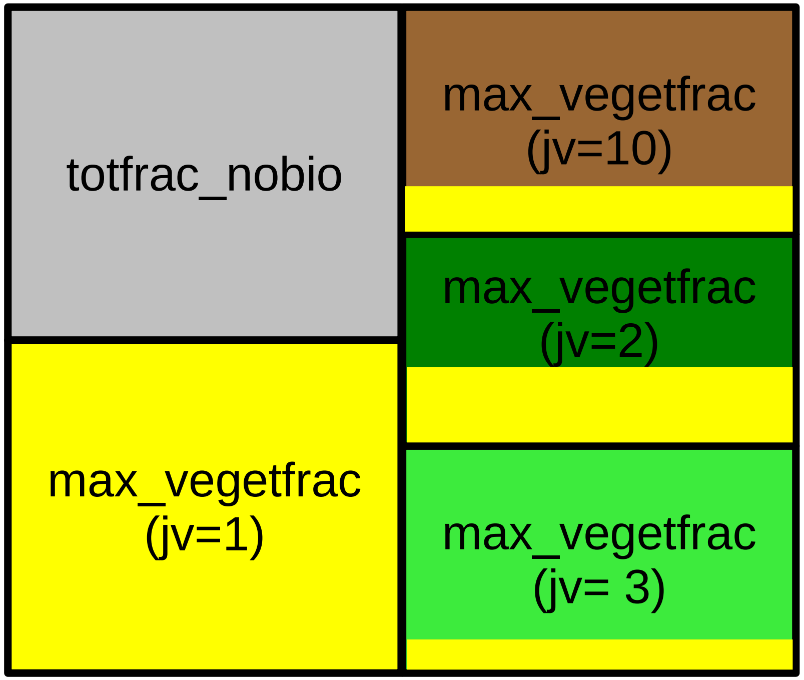
- More than 6500 lines of code
- Near 20 subroutines

Call graph of hydrol_main (rev2400)

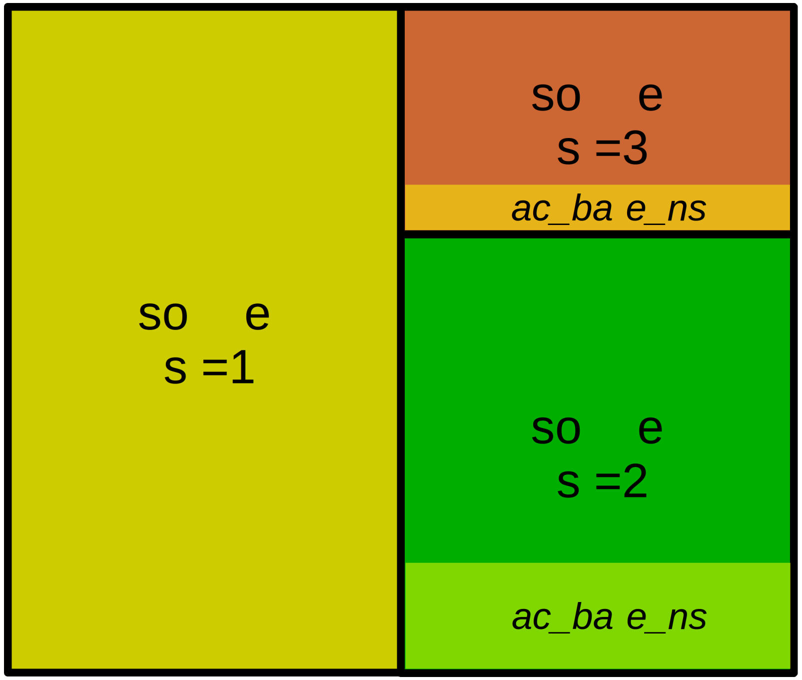
http://dods.ipsl.jussieu.fr/orchidee/DOXYGEN/webdoc_1240/d4/dfe/namespacehydrol.html

A below ground tiling for soil water-vegetation interactions

Example of a PFT distribution within a mesh



Correspondence of the soil water columns

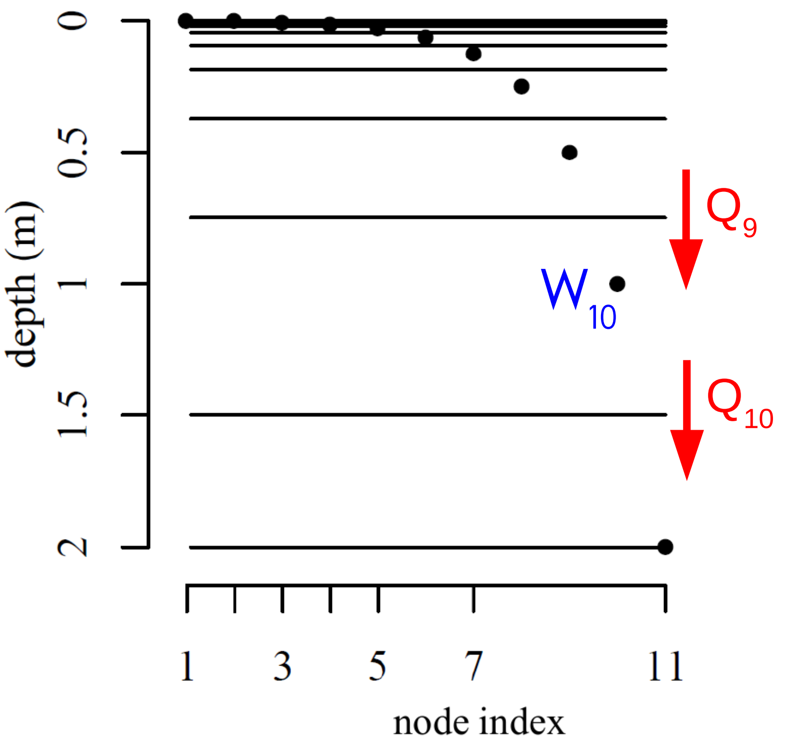


frac_bare_ns (ji, jst): Evaporating bare soil fraction per soiltile

- totfrac_nobio and jv = 1 (cities, lakes, ice...) ⇒ jst = 1
- jv = 2 to 9 (forest) ⇒ jst = 2
- jv = 10 to 13 (crops and grasses) ⇒ jst = 3

3 independent soil water budgets per grid-cell

Vertical discretization of the soil and integration



- The soil column is discretized using 11 nodes (geometric increase of internode distance) over 2 meters. There are thin layers on the top soil where θ is likely to exhibit sharp vertical gradients.
- The mass conservation equation is integrated between the nodes and over the time step dt (water budget of each layer i):

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

- Water fluxes Q_i at the interface between layers i are deduced from the Fokker-Planck equation (finite difference integration)

The drivers of the water transport in the soil

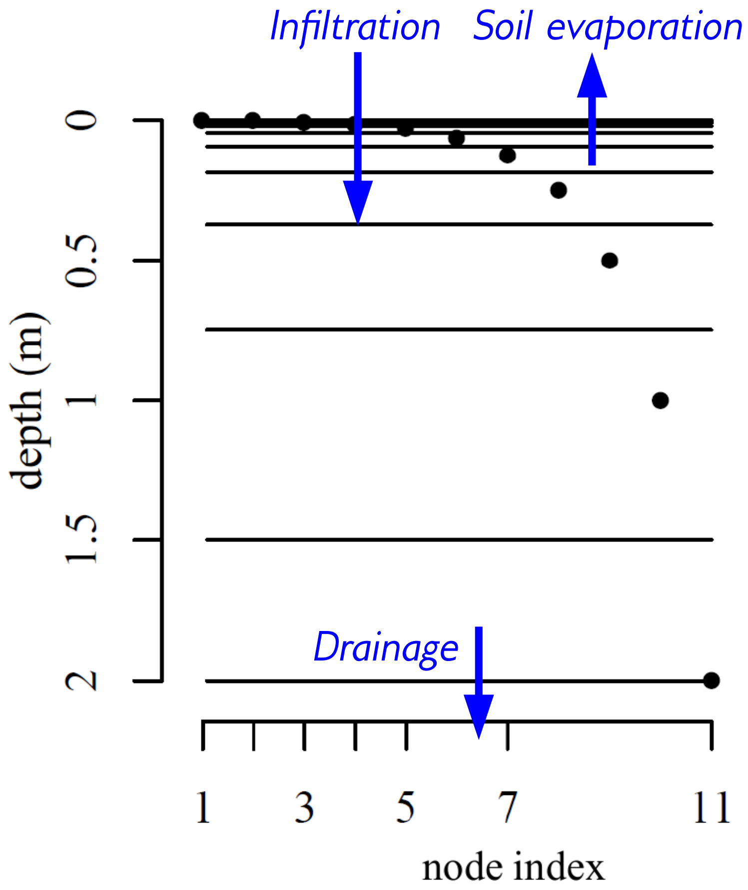
The evolution of θ_i is driven by:

① Top and bottom boundary conditions

② Soil properties

③ Transpiration sink

1 Boundary conditions



- Top boundary condition:

  Q_0 = Infiltration – Soil evaporation

- Bottom boundary condition:

  $Q_{11} = F.K(\theta_{11})$ = Drainage

  $\underbrace{F=1}_{\textit{free\_drain\_coef = 1}}$ (gravitational drainage) or F=0 (impermeable bottom)

for each jst by default in hydrol.f90

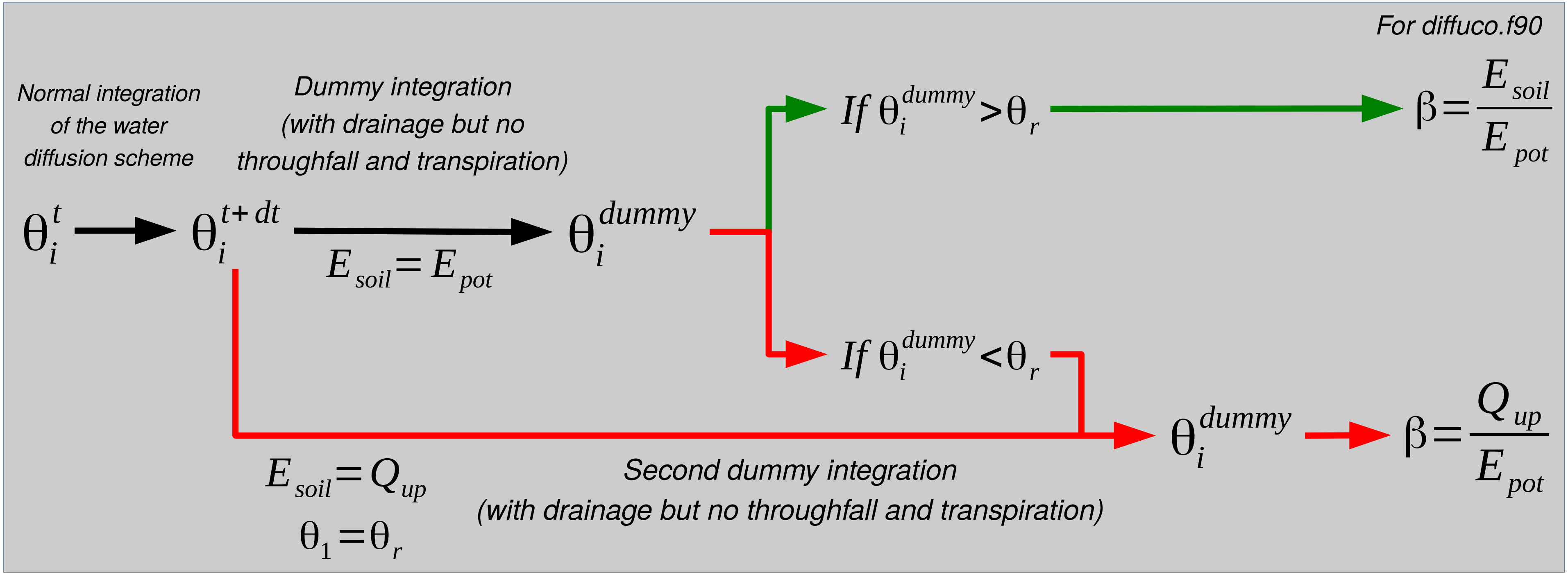
1

Boundary conditions

Soil evaporation

$$\boxed{E_{soil}=min(E_{pot},Q_{up})}$$

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



For diffuco.f90

Normal integration of the water diffusion scheme

Dummy integration (with drainage but no throughfall and transpiration)

$\theta_i^t \rightarrow \theta_i^{t+dt} \xrightarrow[E_{soil}=E_{pot}]{} \theta_i^{dummy}$

$If\ \theta_i^{dummy}>\theta_r \rightarrow \beta=\frac{E_{soil}}{E_{pot}}$

$If\ \theta_i^{dummy}<\theta_r$

$\theta_i^{dummy} \rightarrow \beta=\frac{Q_{up}}{E_{pot}}$

$E_{soil}=Q_{up}$

$\theta_1=\theta_r$

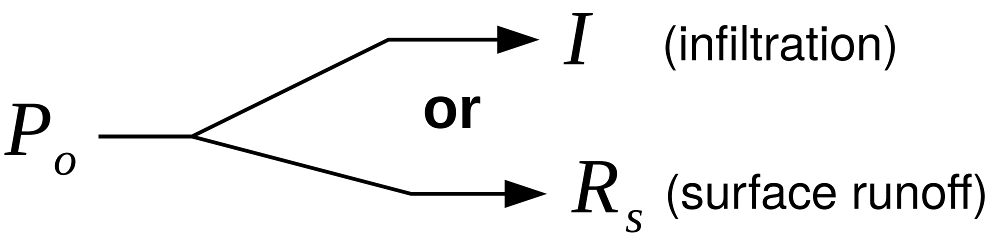
Second dummy integration (with drainage but no throughfall and transpiration)

If $E_{soil} < P_0$ (throughfall, $\overbrace{\text{returnflow, floodplain reinfiltration and irrigation)}}^{\textit{from routing.f90}}$ ⇒ infiltration starts. Else: soil moisture decreases in the layer.

1

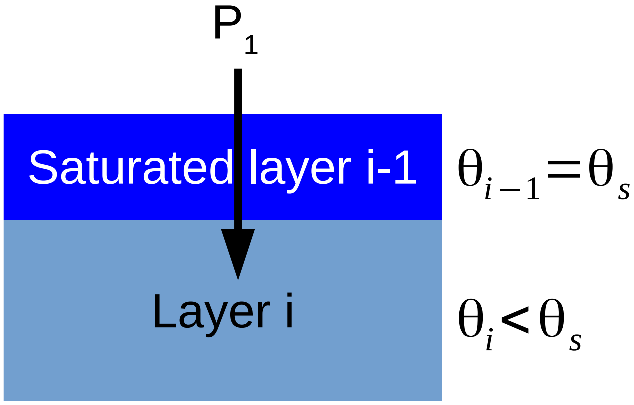
Boundary conditions

Infiltration



- In the first layer (1mm) => direct infiltration (I_1)
- If P_0 > 1mm/dt => wetting front propagation with time splitting procedure

  $P_1 = P_0 - 1\text{mm/dt}$



Exponential distribution of "potential" infiltration

$$I_i = I_i^{pot}\left[1 - \exp\left(\frac{-P_1}{I_i^{pot}}\right)\right]$$

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

<u>Time required to saturate the layer i</u>:

$$t_i = h_i \frac{(\theta_s - \theta_i)}{I_i} \longrightarrow \theta_i \text{ updated}$$

$if \sum (t_i < dt) \longrightarrow$ next layer i+1

1

Boundary conditions

Reinfiltration and resulting runoff

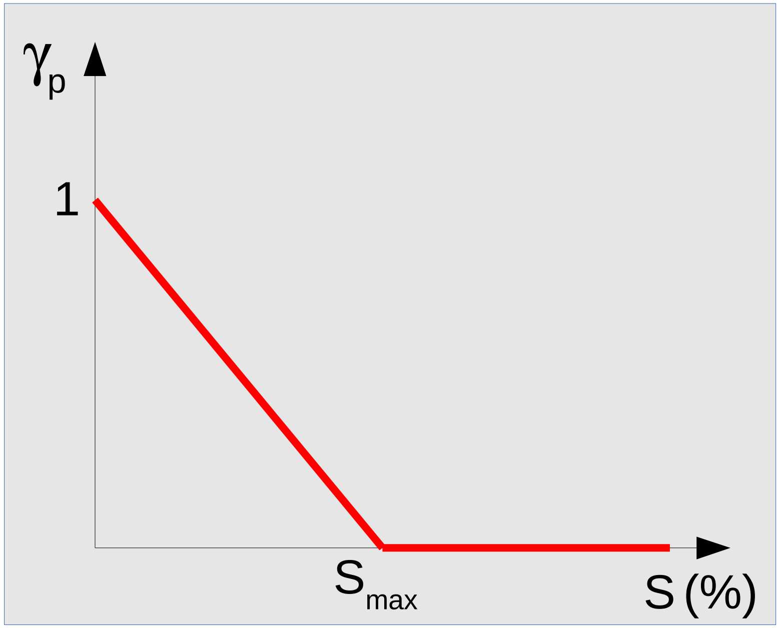
- Rs may reinfiltrate if the slope of the land surface $S < S_{max}$
- Computation of a reinfiltrated fraction:

“slopemap”
in slowproc.f90

“slopecoef”
in slowproc.f90

$$\boxed{\gamma_p = MIN\left(\frac{S}{S_{max}}, 1\right)}$$

“slope_noreinf” = 0.5 %
in slowproc.f90



- Rs is updated: $$\boxed{R_s = \underbrace{(1-\gamma_p)}_{\text{“reinf\_slope” in slowproc.f90}} R_s^{pot}}$$ with: $R_s^{pot} = P_0 - \sum I_i$

2

Soil properties

Soil texture classes

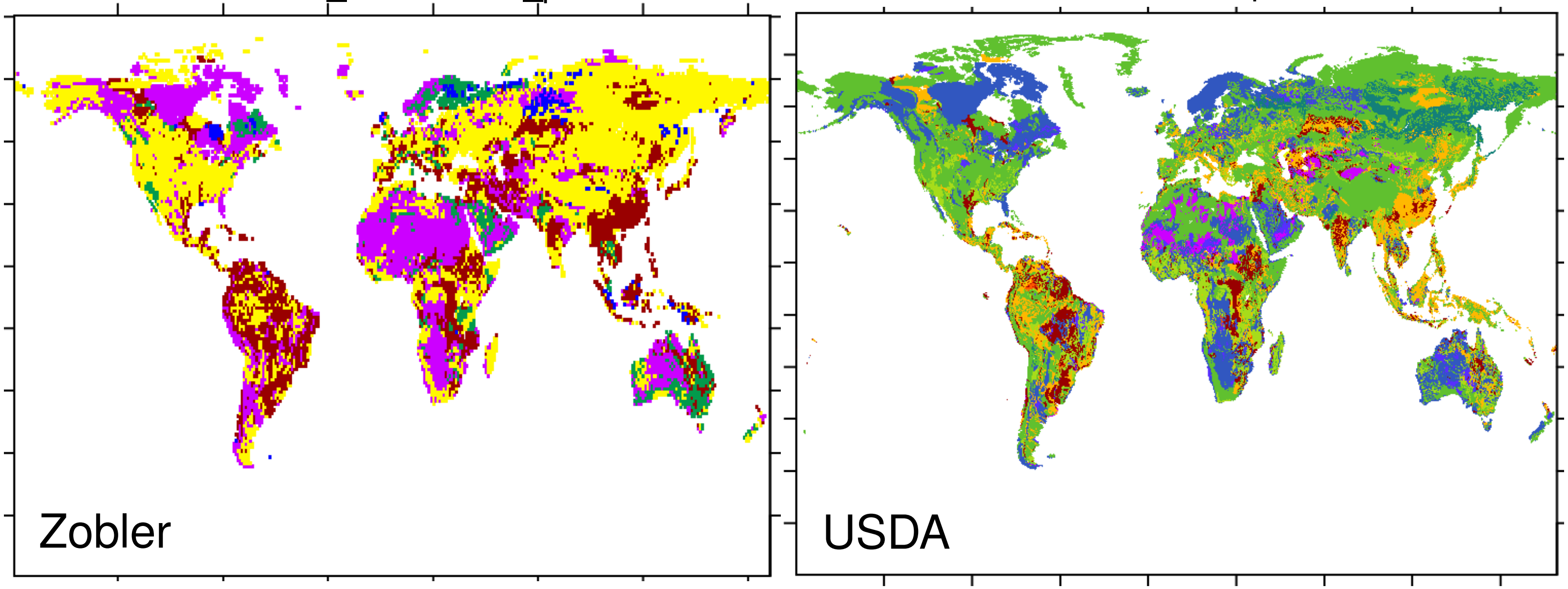
In slowproc.f90:

- **textfrac_table** ⇒ correspondence between textural classes and their granulometric composition
- **soilclass** ⇒ areal fractions of each textural class in each grid-cell read from a soil texture map:
  - Zobler map (Zobler (1986), 1° resolution, 5 texture classes). By default in the model.
    The 5 soil textures are reduced to only 3 (called Coarse, Medium and Fine) in the code
  - USDA map (Reynolds et al. (2000), (1/12)° resolution, 12 texture classes)
- **njsc (kjpindex)** ⇒ dominant textural class in each grid-cell. At the end, there is <u>only ONE soil texture class per grid-cell</u>.

In run.def:

SOILTYPE_CLASSIF = zobler
SOILCLASS_FILE = soils_param.nc

SOILTYPE_CLASSIF = usda
SOILCLASS_FILE = soils_param_usda.nc



2

Soil properties

The hydrodynamic parameters

- In ORCHIDEE, the hydraulic parameters required for the diffusion equation are given by the Mualem (1976) - Van Genuchten (1980) model.
- K_h and D_h depend on saturated properties (measured on saturated soils) and on θ:

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

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

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

- 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

2

Soil properties

The hydrodynamic parameters

- Values of the parameters given by Carsel and Parrish (1988):

	For "USDA case" in ORCHIDEE					For "Zobler case" in ORCHIDEE				
	K_s $mm \cdot j^{-1}$	n	α m^{-1}	$theta_r$ $m^3.m^{-3}$	$theta_s$ $m^3.m^{-3}$	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	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	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	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					

- In ORCHIDEE, K_s is modified with depth (and thus α and m):
  - K_s decreases exponentially with depth below the top 30cm (increasing soil compaction)
  - K_s increases towards the surface (root channel macropores enhance downward movement of water)

3

Transpiration sink

- Coupling between the soil water distribution and the rooting demand at a given soil depth
- In each soil layer i, the water stress function us_i acts on the transpiration

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

with: $\mathbf{S_i}=\frac{us_i}{U_s}T_r=\frac{us_i}{\sum us_i}T_r$

3

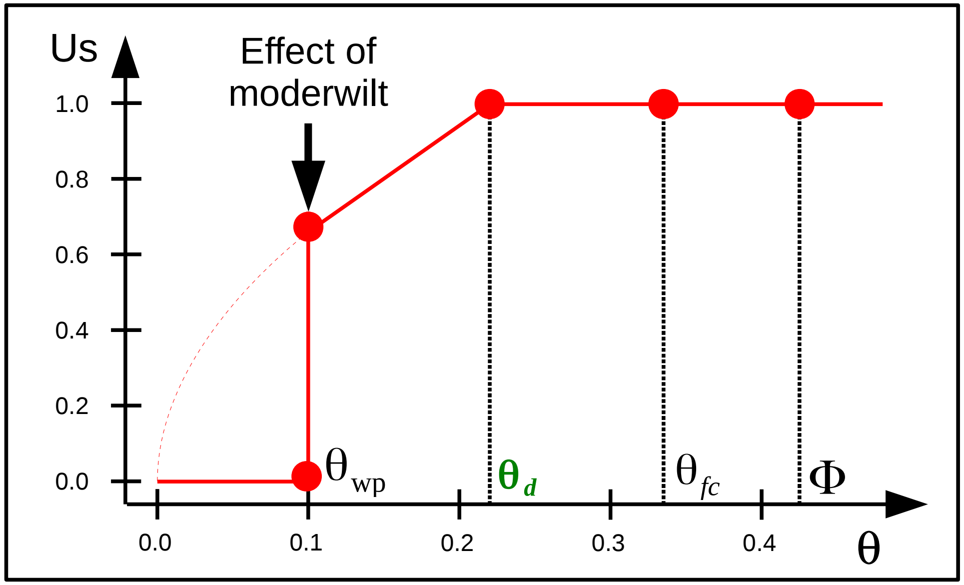
Transpiration sink

Water stress

$$us_1 = 1$$

$$us_i = \mathrm{moderwilt}(i).n_{root}(i).\min\left(\sqrt{\frac{W_i}{(z_i - z_{i-1}).\theta_d}}, 1\right)$$

$$n_{root} = \frac{\int_{h_i} R_v(z)\,dz}{\int_{h_{tot}} R_v(z)\,dz}$$



$$\mathrm{moderwilt} = 1 \quad \text{if}\ \theta_i > \theta_{wp}\ \text{else}\ 0$$

$$\theta_d = 0.5\,\Phi$$

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

θ_d is called “pcent_fao” or “pcent_usda” in the code (defined in constantes_soil_var.f90)

In constantes_soil_var.f90	**θ_{wp}**	**θ_{fc}**
Name	mcw_usda or mcw_fao	mcf_usda or mcf_fao
Default values	0.10 m^3/m^3 for all the textures	0.32 m^3/m^3 for all the textures

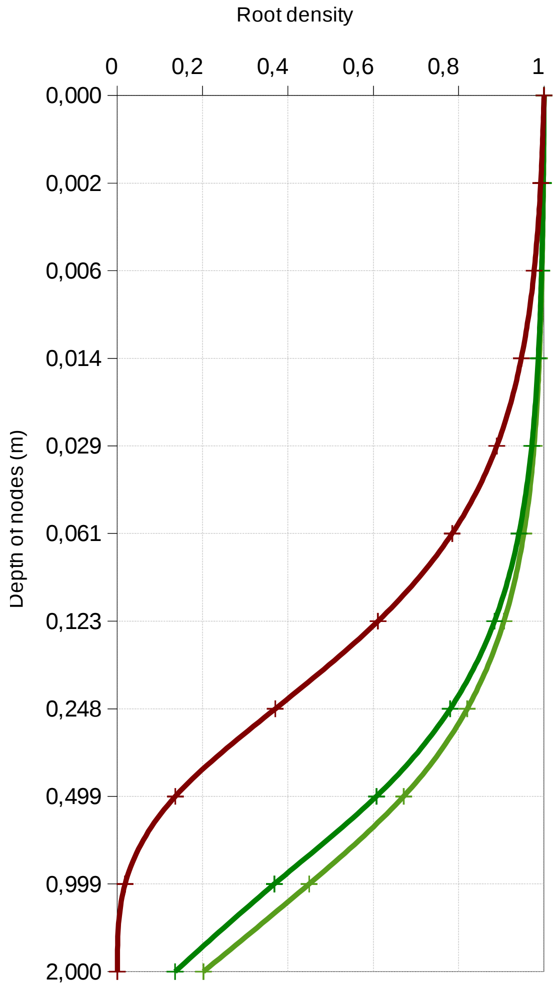
Transpiration sink

Root density profile

For each PFT v, a root density profile: $$\boxed{R_v(z) = \exp(-\boxed{c_v} z_i)}$$

Called “humcste_cwrr” in the code
(defined in constantes_mtc.f90)

Depth of
the node i



Forests: c_v = 0.8 or 1.0

Crops and grasses: c_v = 4.0

The values of c_v depends on the total soil depth.

In the code, values for 2 meters.

1.2.1

The multilayer soil diffusion scheme

References

Where you can find informations about the multilayer soil diffusion scheme of ORCHIDEE

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2

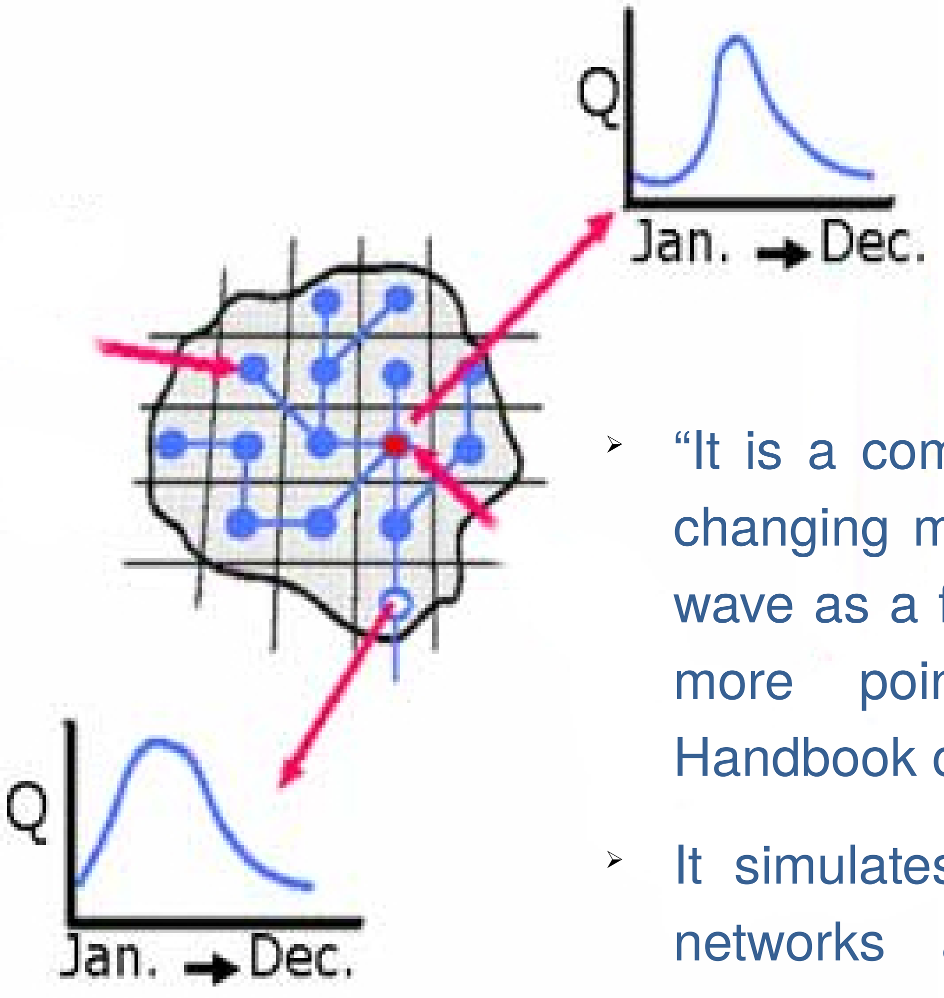
The routing scheme

2.1

The routing scheme

Generalities

What is a flow routing?

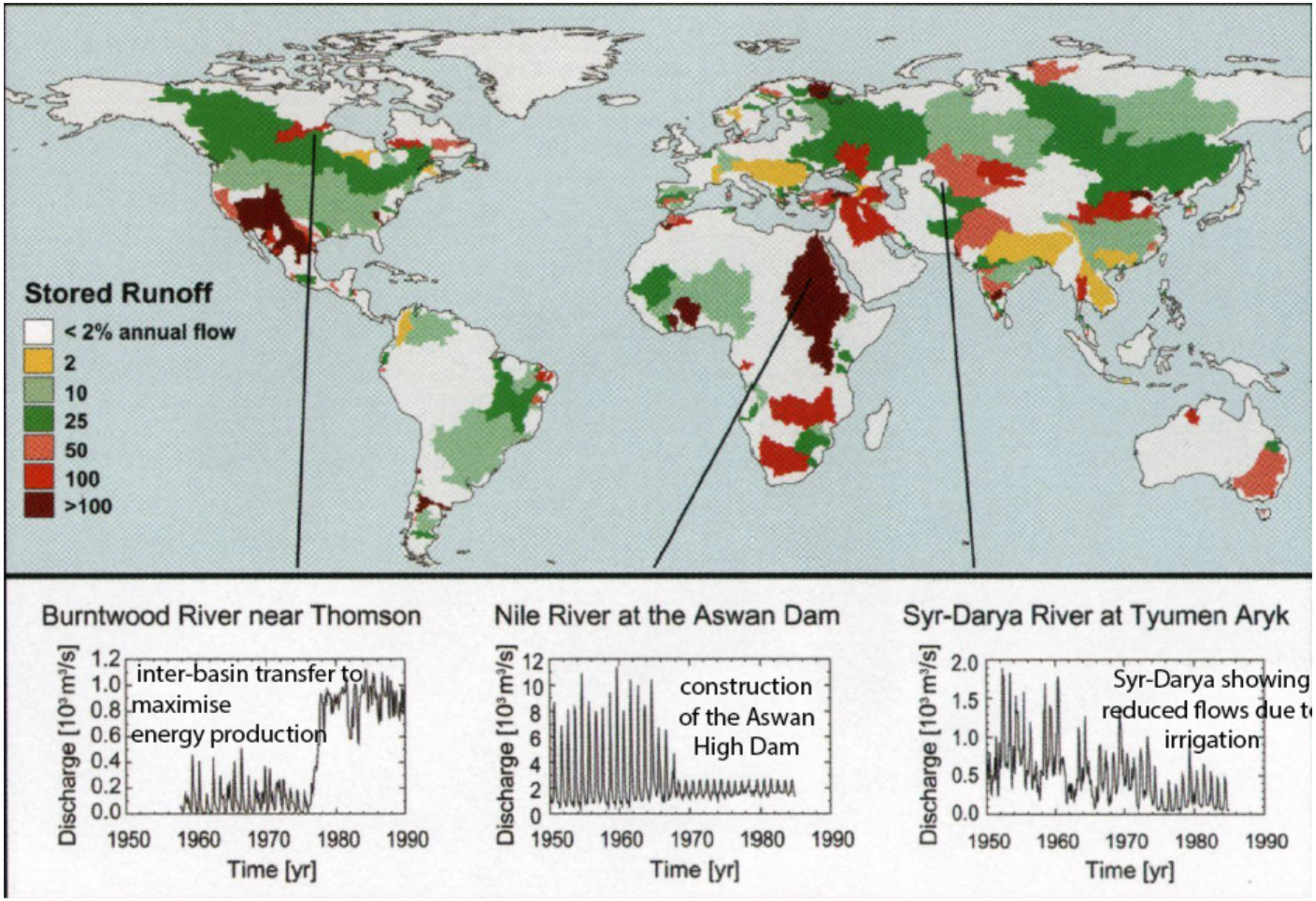


- “It is a computational procedure for predicting the changing magnitude, speed, and shape of a flood wave as a function of time (hydrographs) at one or more points along a watercourse” (Fread, Handbook of hydrology, 1992)
- It simulates the transport of runoff through river networks across continents (streamflow, river discharge) into the oceans

Why do we need it in GCMs ?

- Crucial for hydrological cycle closure (when coupled to the ocean model)
- It provides freshwater to the ocean (affects ocean salinity and thermohaline circulation)
- It gives independent measure of the performance of the hydrological cycle of the GCM: comparison of simulated streamflow with river gauge data
    - if both streamflow and precipitation given with reasonable accuracy => check of evaporation accuracy
- It enables studies of climate change impacts on water resources and the hydrology of the basins
- ...

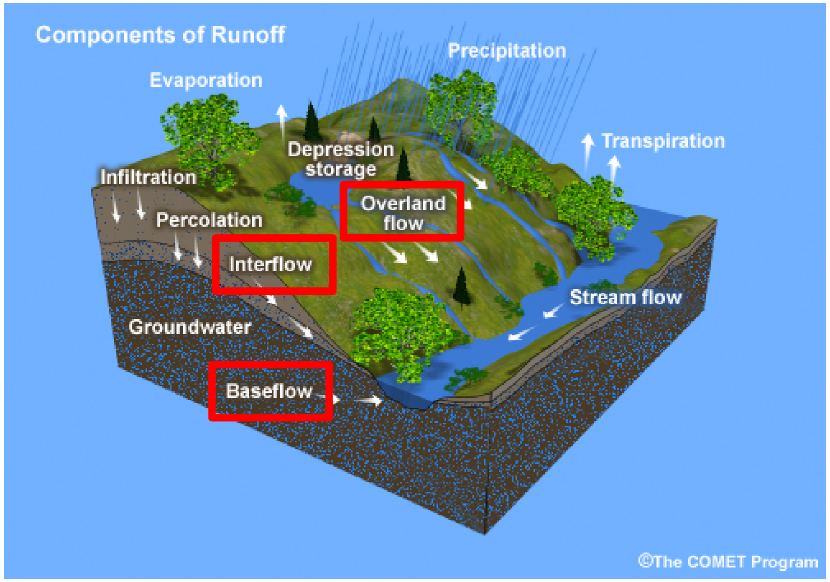
Human activities on river discharge

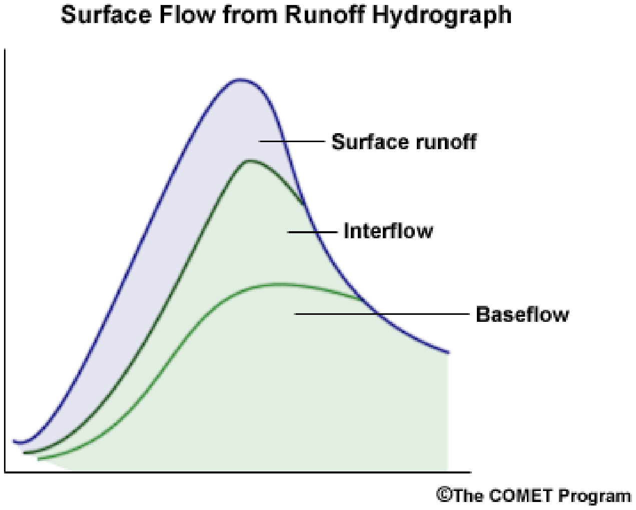


Flow distortion caused by water engineering in three heavily-regulated rivers

Vorosmarty et al., 2004

Lateral waterflow components

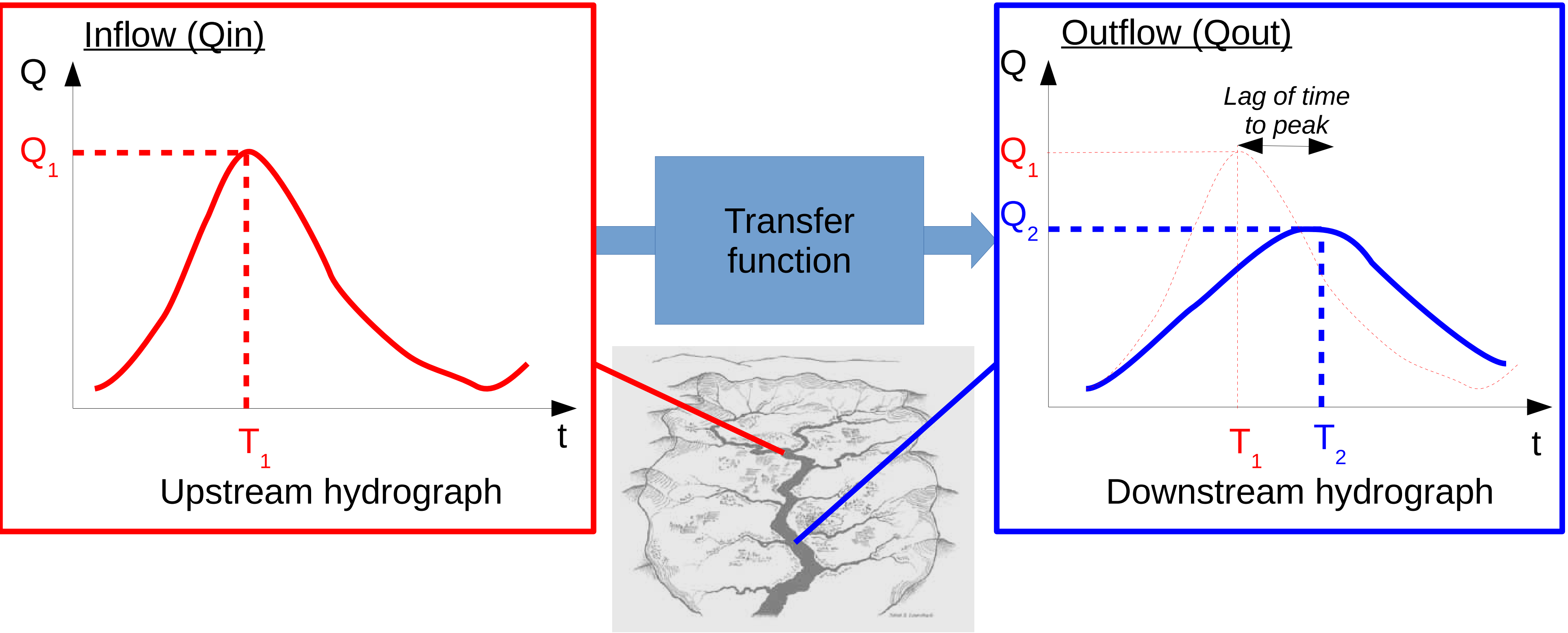




Lateral waterflow components

- **Overland flow (surface runoff)**: flow of water that does not infiltrate and travels relatively quickly towards the stream channel
- **Interflow (subsurface runoff)**: portion of infiltrated throughfall that moves laterally through the upper soil layers until it reaches the stream channel
- **Baseflow (groundwater runoff)**: portion of infiltrated throughfall that reaches water tables by deep drainage and then discharges into streams

Hydrographs



Inflow (Qin)

Upstream hydrograph

Transfer function

Outflow (Qout)

Lag of time to peak

Downstream hydrograph

- As flood wave travels downstream, it undergoes:
  - outflow peak attenuation ($Q_2<Q_1$)
  - outflow timing delay ($T_2>T_1$)

2.2

The routing scheme

Modeling in ORCHIDEE

2.2.1

The routing scheme

Modeling in ORCHIDEE: overview

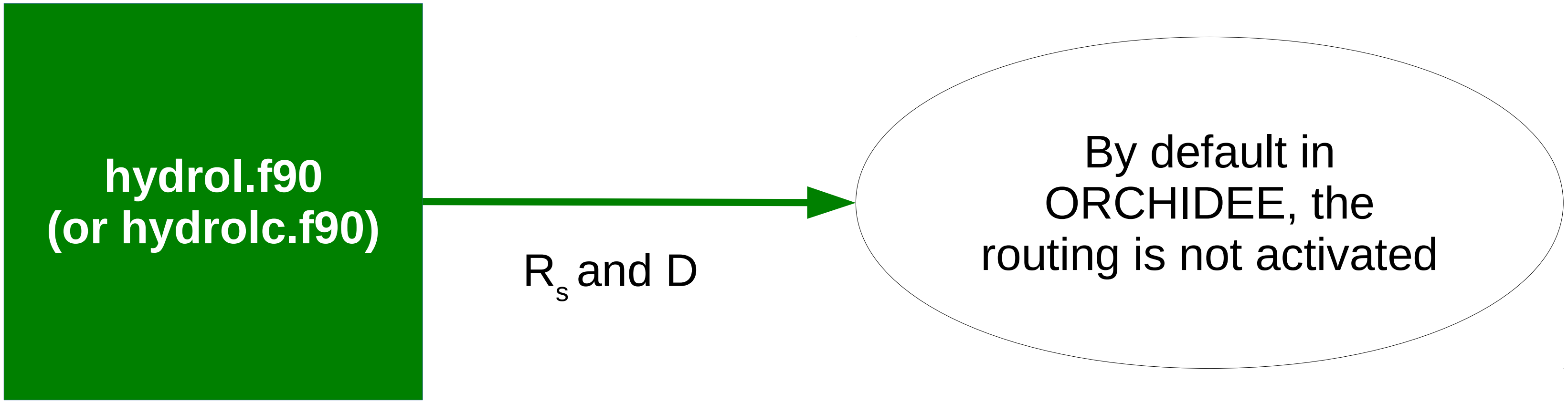
Basic functioning

- Based on existing routing schemes:
    - Ledoux (Phd Thesis, 1980)
    - Miller et al. (J. Climate, 1994)
    - Hagemann and Dümenil (Clim. Dyn., 1998)
    - Ducharne et al. (J. Hydrol., 2003)
- routing.f90 introduced by Jan Polcher (HDR, 2003) in SECHIBA

Basic functioning

- “Cell-to-cell” or “cell-based” methodology
  - simulation of the transport of runoff generated within the modeling units (e.g. grid cells), through river networks across continents into the oceans
  - a watershed can be represented as a single grid cell, a cascade of n equal grid cells, or a network of n equal grid cells (based on Singh (Hydrologic systems, 1989))
    - division of a watershed into a set of interconnected grid cells
    - each of the grid cell is approximated as a cascade of n linear reservoirs
- Computation of hydrographs at any grid cell and not only at the outlet

From precipitation to river discharge in ORCHIDEE

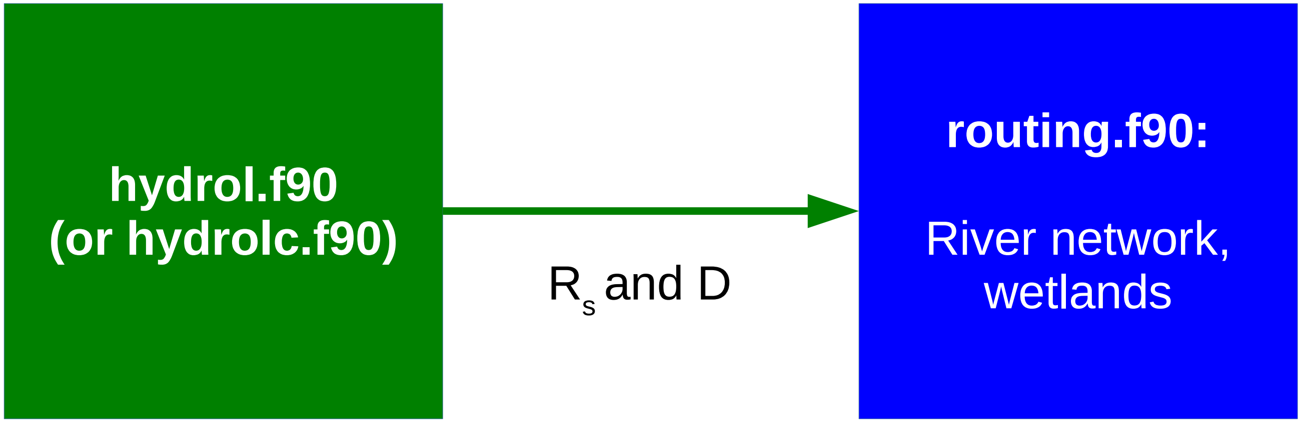


hydrol.f90
(or hydrolc.f90)

R_s and D

By default in ORCHIDEE, the routing is not activated

From precipitation to river discharge in ORCHIDEE



hydrol.f90
(or hydrolc.f90)

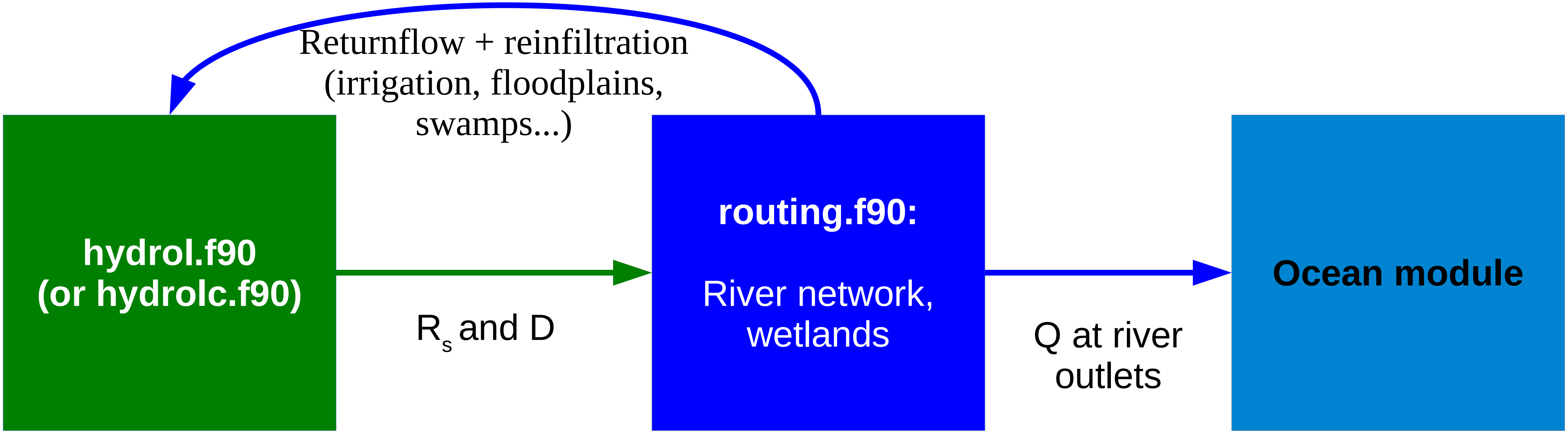
R_s and D

routing.f90:

River network,
wetlands

To activate it:
put **ROUTING=y** in sechiba.card

From precipitation to river discharge in ORCHIDEE



Returnflow + reinfiltration
(irrigation, floodplains,
swamps...)

hydrol.f90
(or hydrolc.f90)

R_s and D

routing.f90:

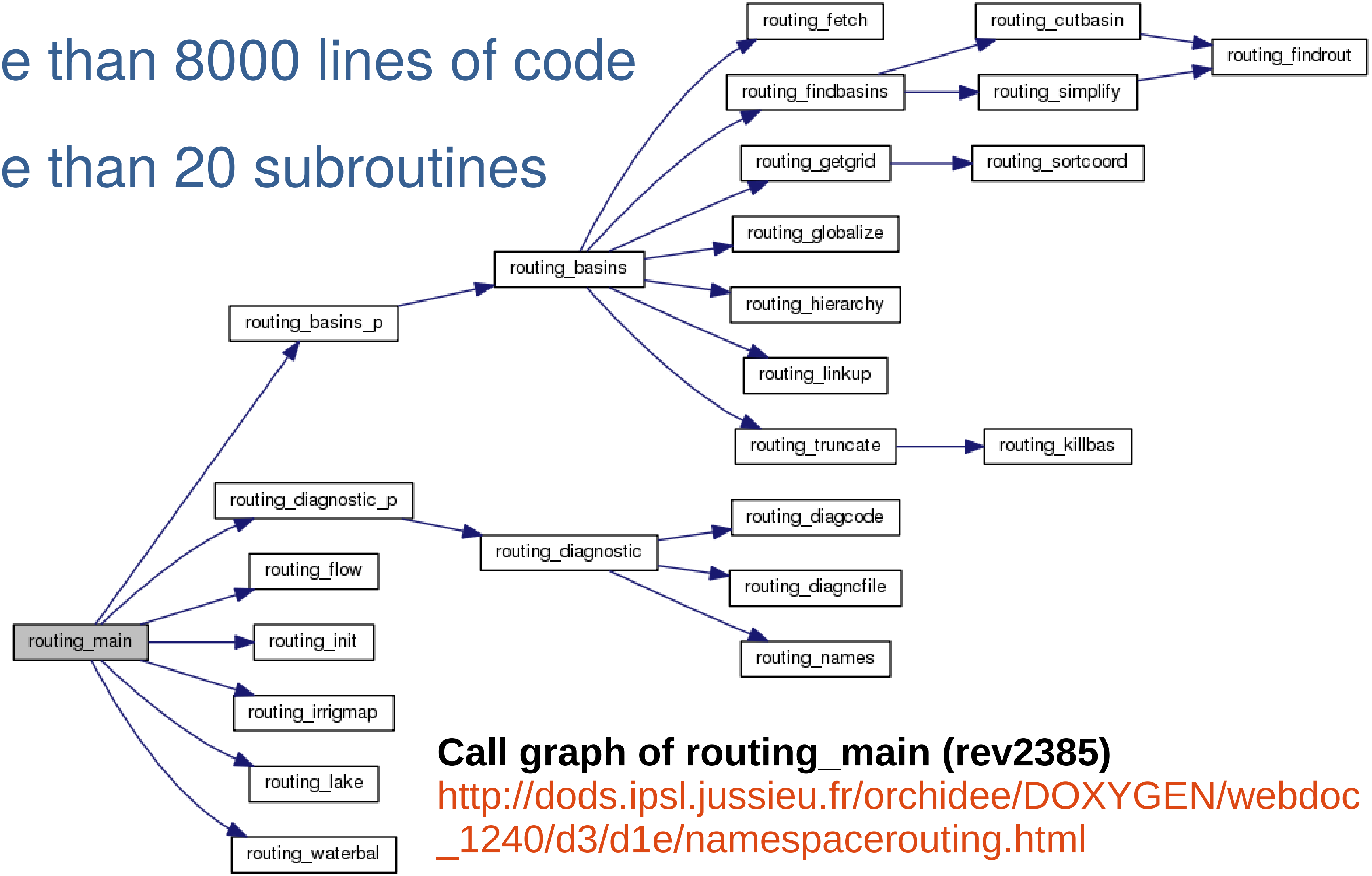
River network,
wetlands

Q at river
outlets

Ocean module

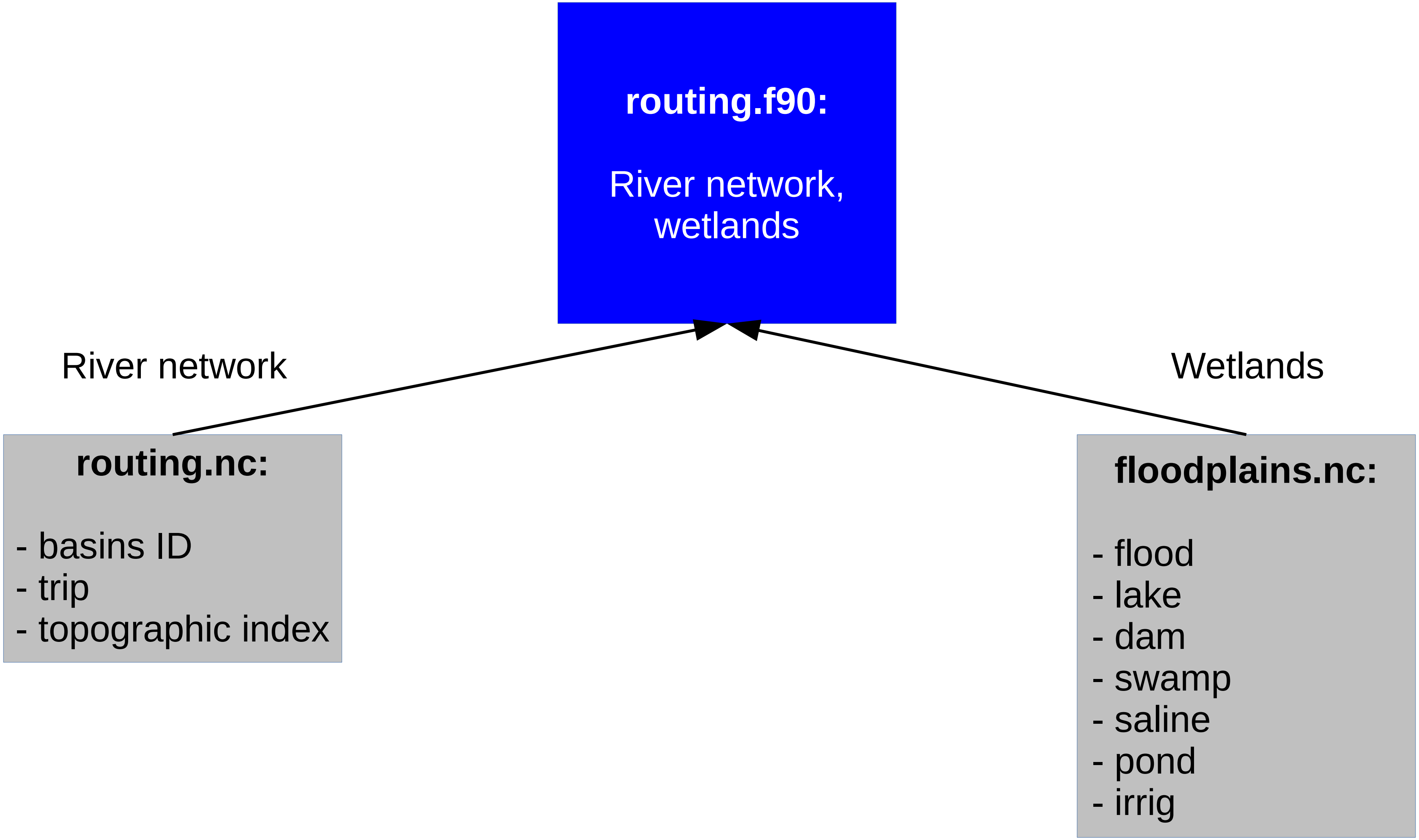
routing.f90

- More than 8000 lines of code
- More than 20 subroutines



Call graph of routing_main (rev2385)
http://dods.ipsl.jussieu.fr/orchidee/DOXYGEN/webdoc_1240/d3/d1e/namespacerouting.html

Maps read by routing.f90



routing.f90:

River network,
wetlands

River network

Wetlands

routing.nc:

- basins ID
- trip
- topographic index

floodplains.nc:

- flood
- lake
- dam
- swamp
- saline
- pond
- irrig

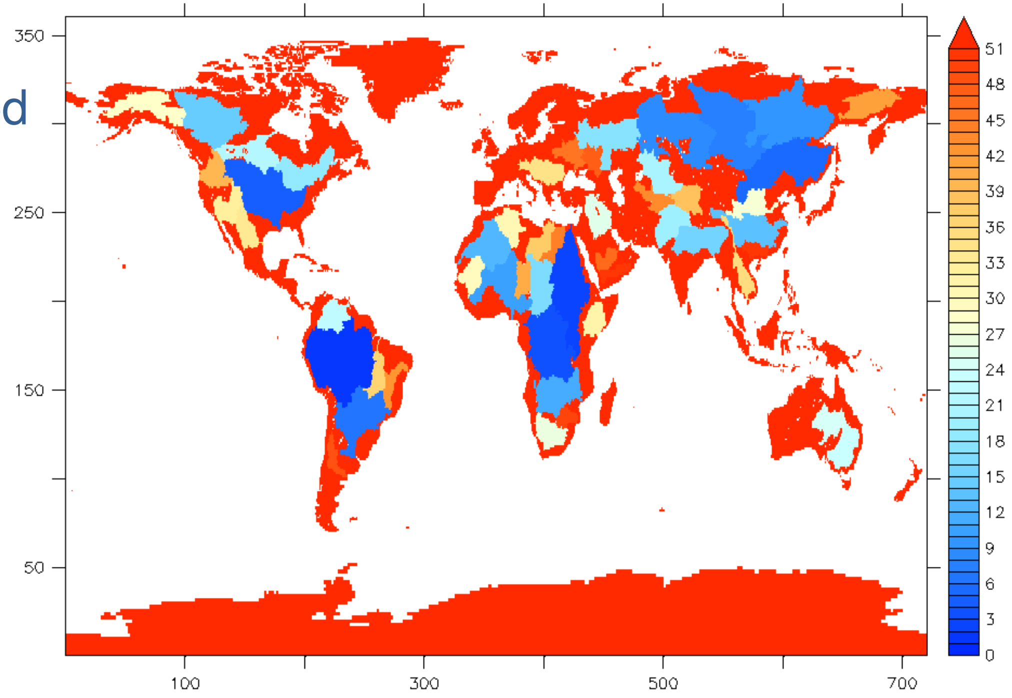
2.2.2

The routing scheme

Modeling in ORCHIDEE: river network

Basin map

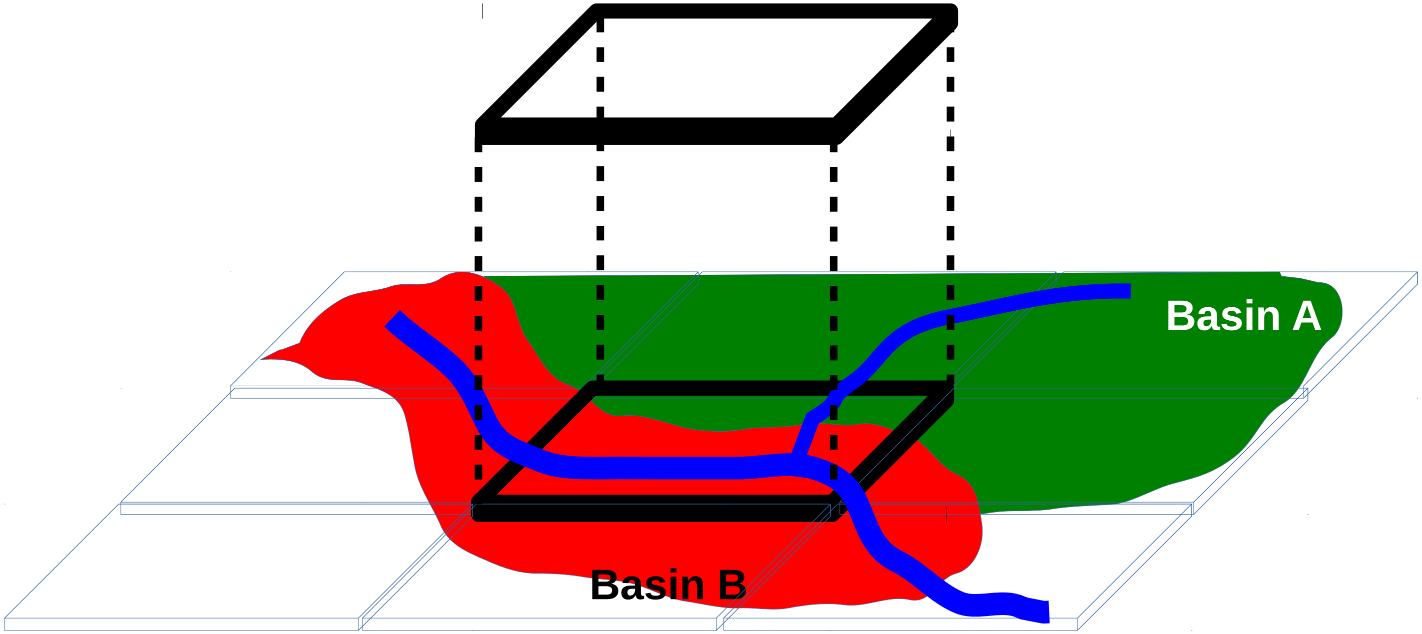
- Basin map: 6930 basins available at 0.5°x0.5° spatial resolution
  - 6152: continental non-glacierized land area (Vörösmarty et al., 2000) available at 0.5°x0.5° spatial resolution
    - sizes ranges from ~ 390 km² to ~ 5.8.10⁶ km² (Amazon basin)
  - 778: continental glacierized land area (Greenland and the poles) from TRIP (Total Runoff Integrating Pathways) (Oki et al., 1999; Oki and Sud, 1998) available at 1.0°x1.0° spatial resolution
- By default in the code, the 50 largest basins of the running area are selected in the code (num_largest parameter)
- Attribution of a unique ID by the map



IDs of the 50 largest basins

Basin map

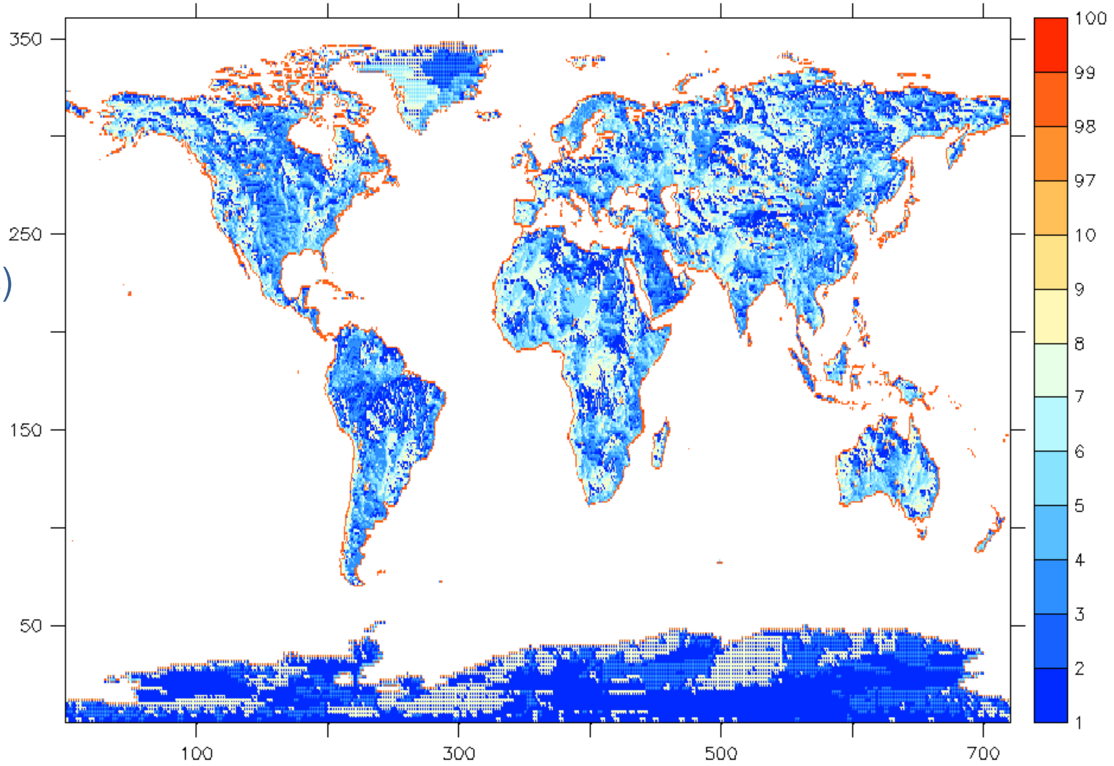
- The spatial resolution of the atmospheric grid cell is coarser (>0.5°) than that of the routing → more than one basins can be included in the grid-cell
- Truncation: by default in the code, no more than 7 basins can be included in a grid cell (nbasmax parameter)



Trip map

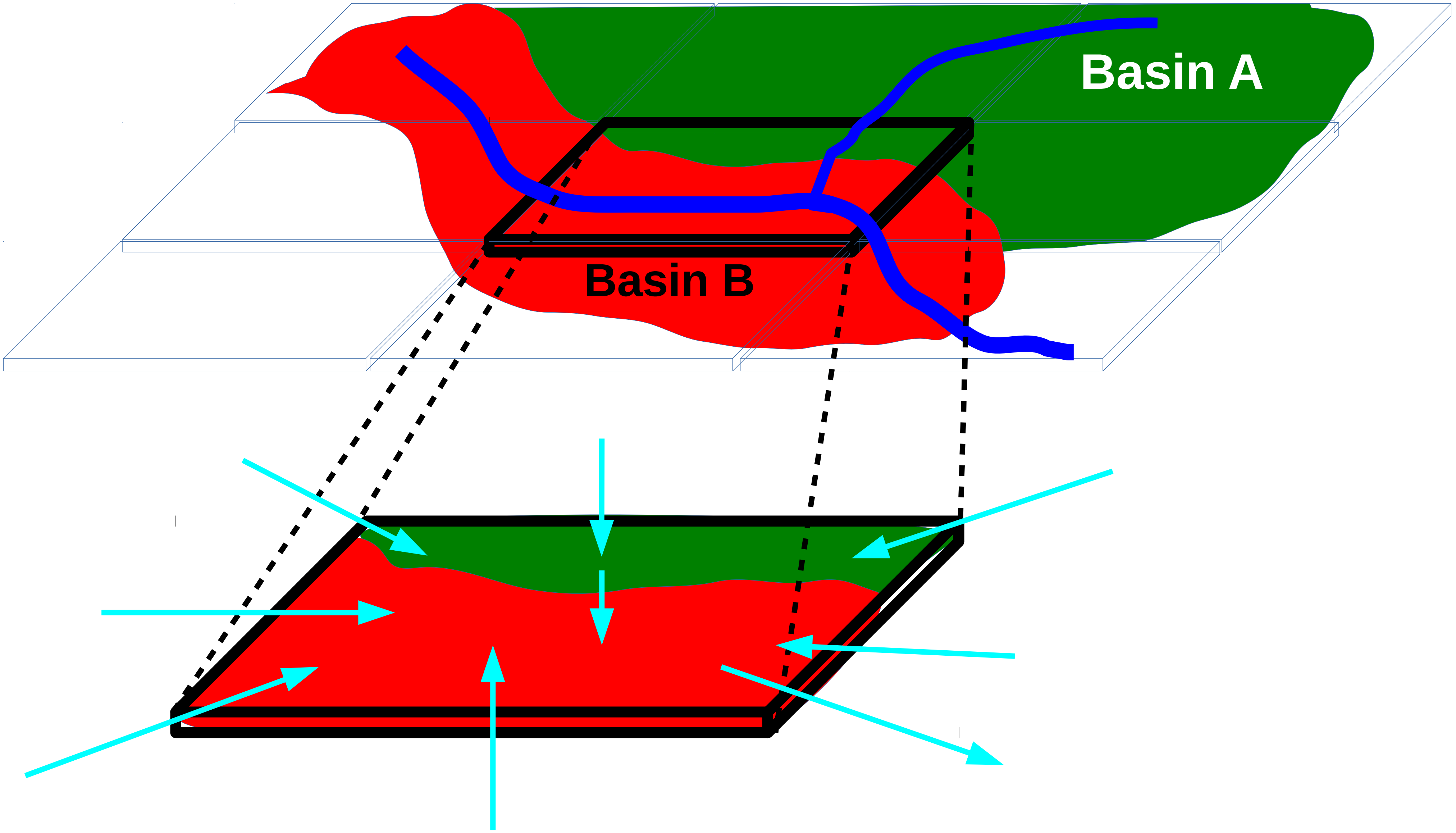
- Map at 0.5°x0.5° spatial resolution from the data of Vörösmarty et al. (2000) and Oki et al. (1999)
- For each grid cell, the map provides single flow direction among the 11 possibilities attributed by numbers in the code:
  - 8 directions (1→8) towards another grid cell
  - 3 other directions:
    - 97 → lake inflow
    - 98 → coastalflow
      (diffusive into the oceans)
    - 99 → riverflow
      (river discharge into the oceans)

8	1	2
7		3
6	5	4



Numbers giving the flow directions between grid cells

The basins (and grid cells) are now connected

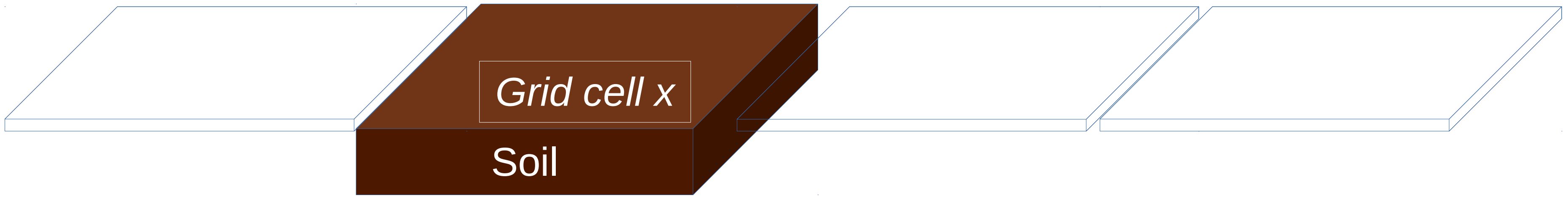


2.2.3

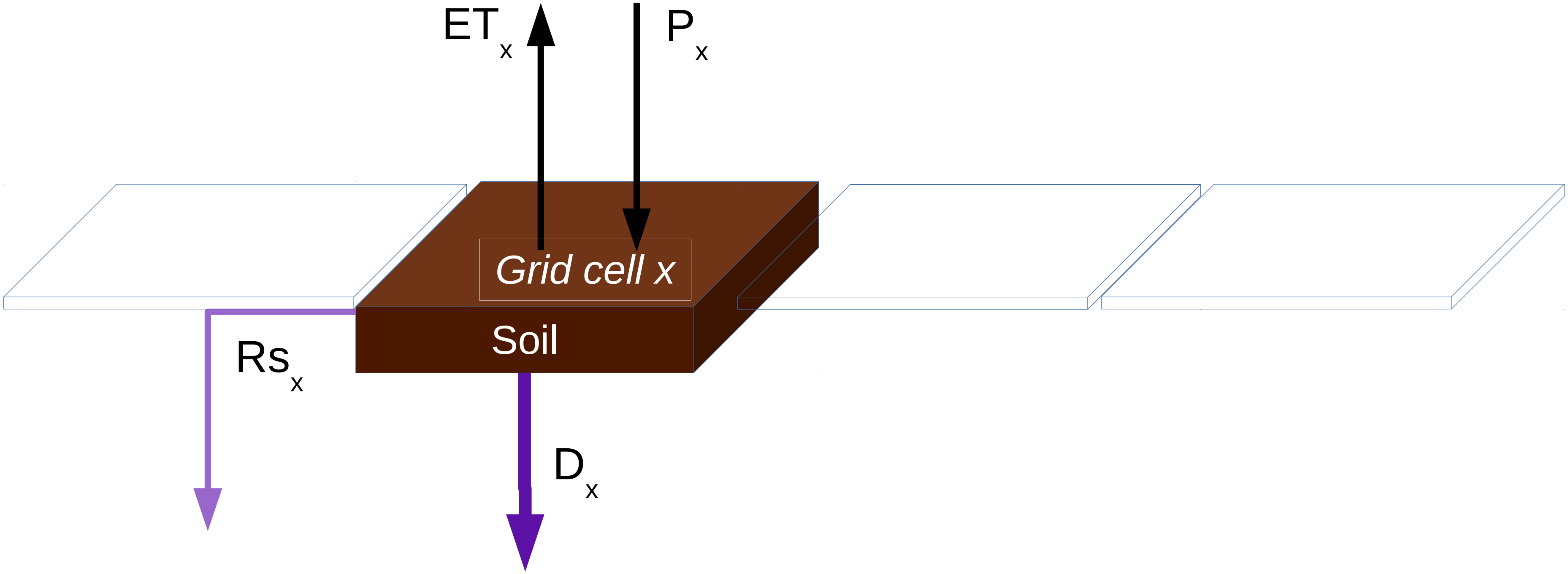
The routing scheme

Modeling in ORCHIDEE:
transfer between reservoirs

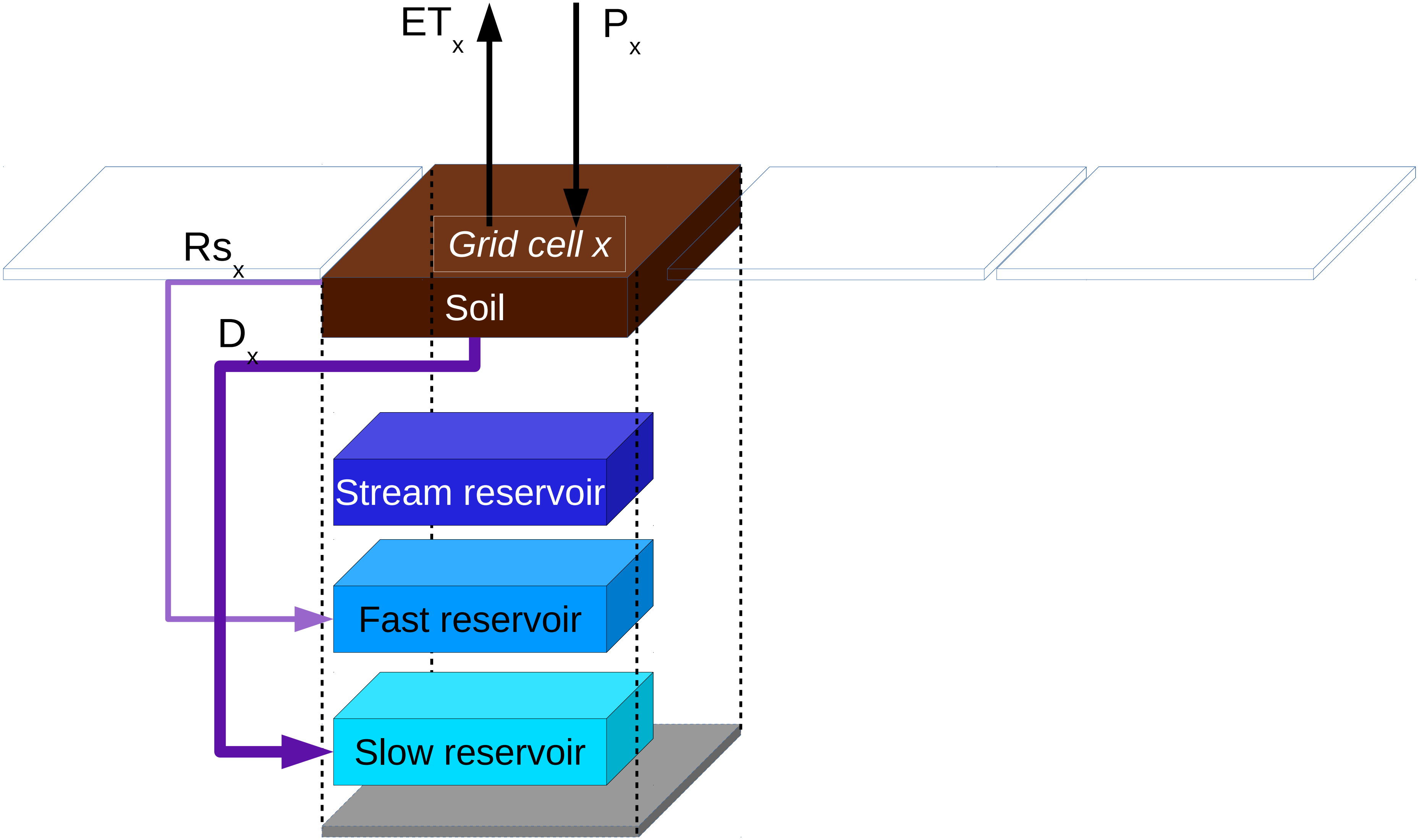
Transfer of runoff into the reservoirs



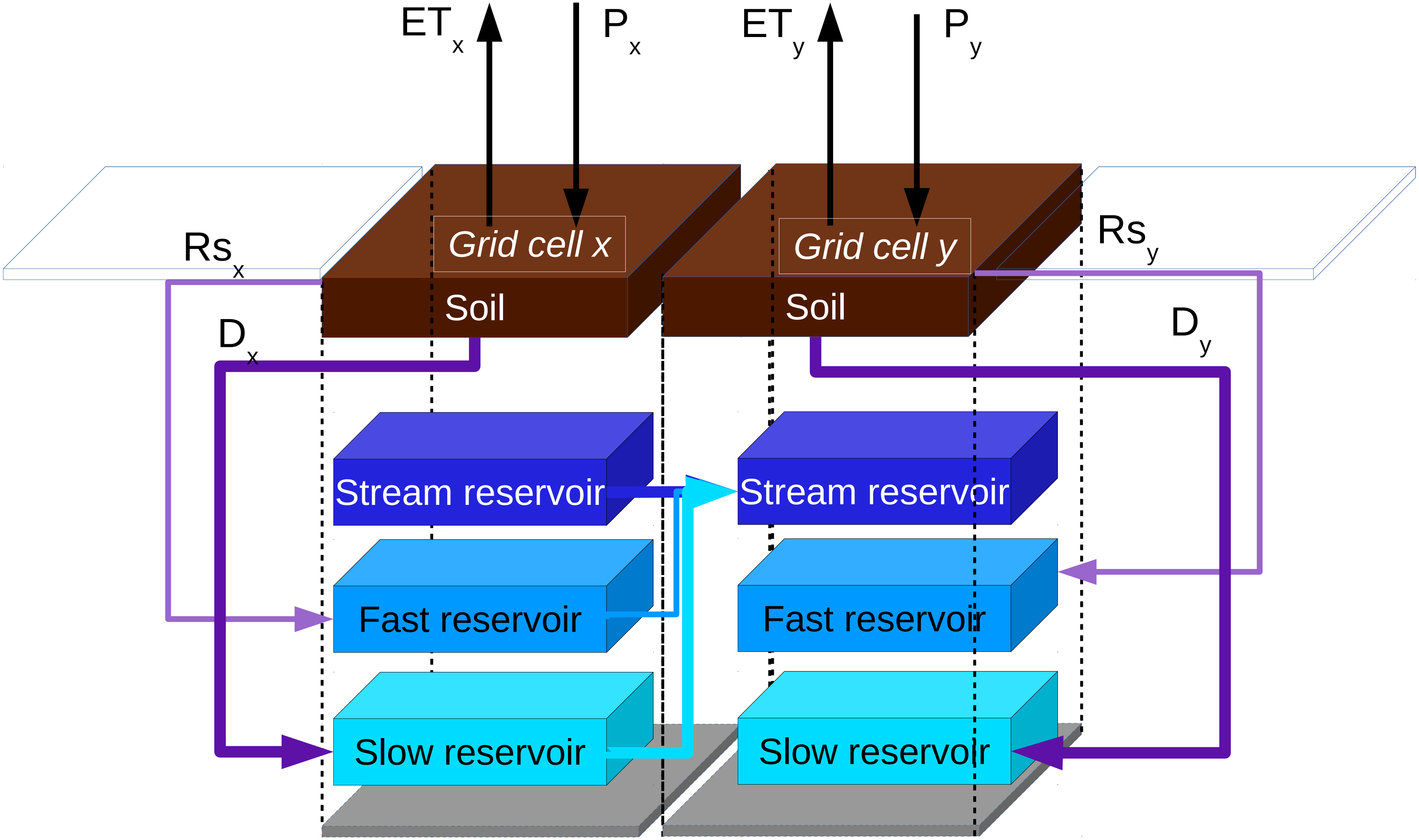
Transfer of runoff into the reservoirs



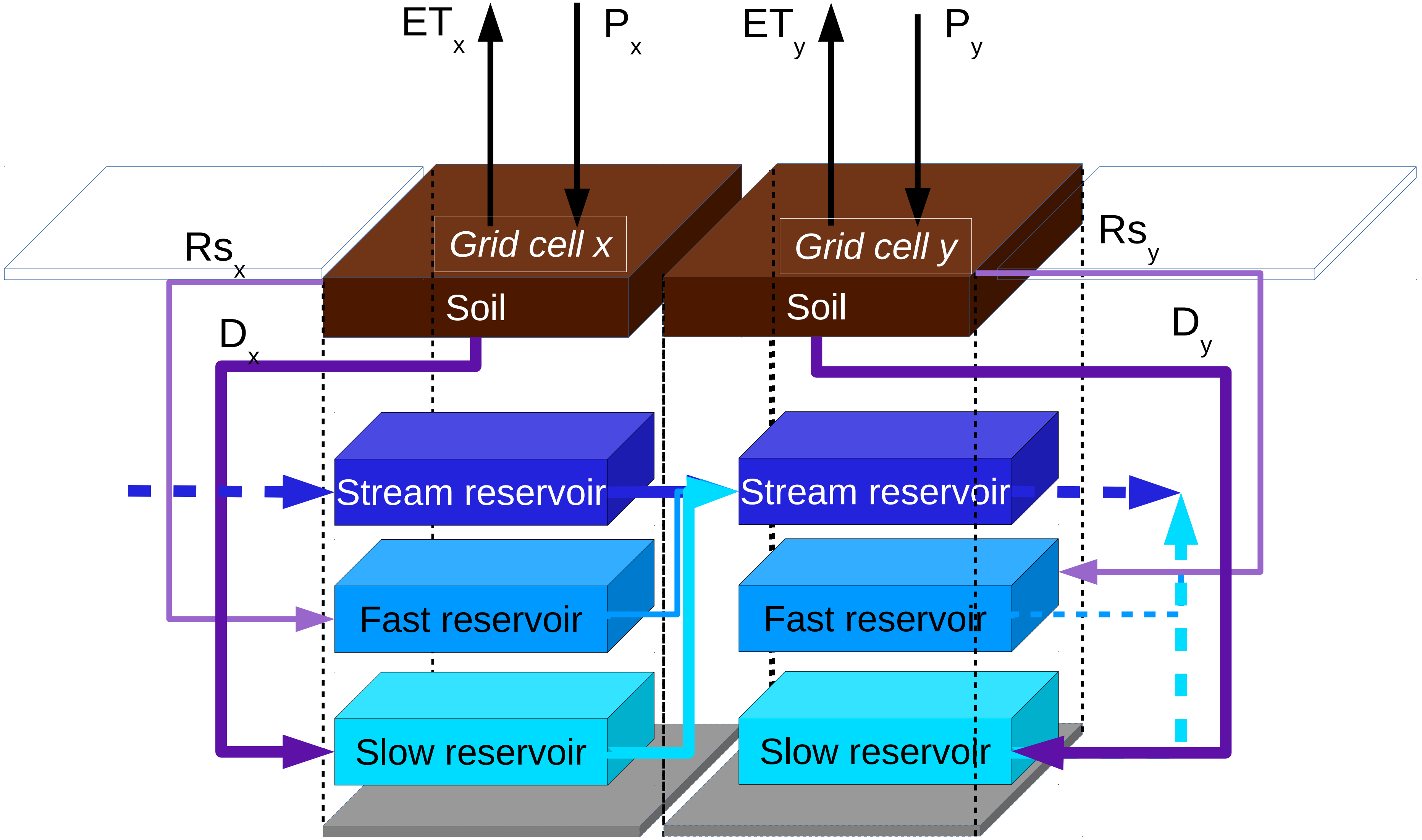
Transfer of runoff into the reservoirs



Transfer of runoff into the reservoirs



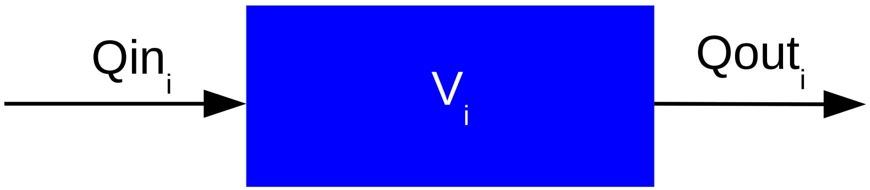
Transfer of runoff into the reservoirs

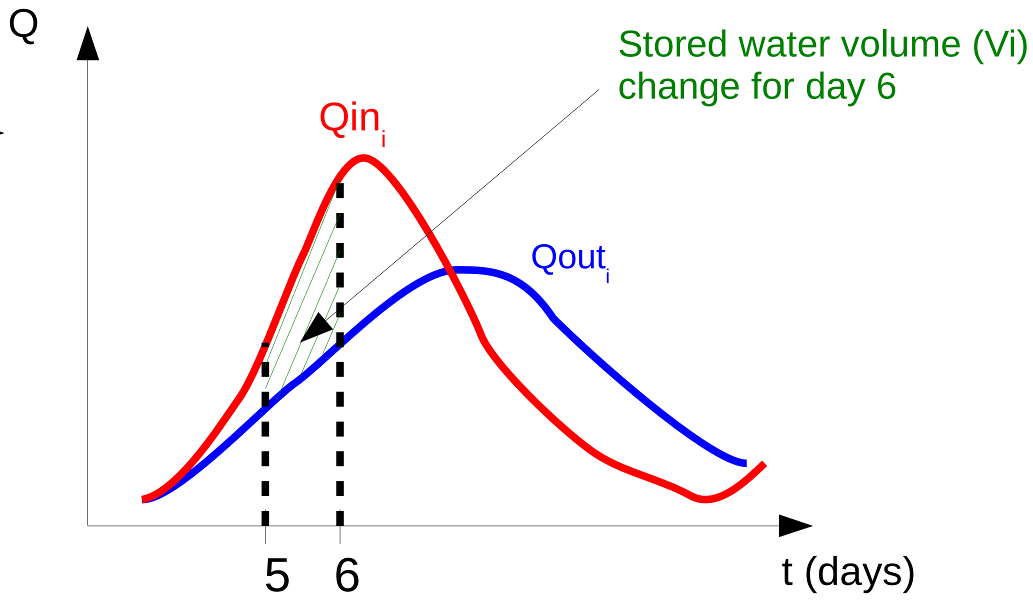


General equation of mass conservation (continuity equation)

$$\boxed{\frac{dV_i(t)}{dt}=Qin_i(t)-Qout_i(t)}$$

- $V_i(t)$ $[L^3]$, volume of water stored in the reservoir i
- Qin_i $[L^3.T^{-1}]$, rate of inflow of the reservoir i
- $Qout_i$ $[L^3.T^{-1}]$, rate of outflow of the reservoir i





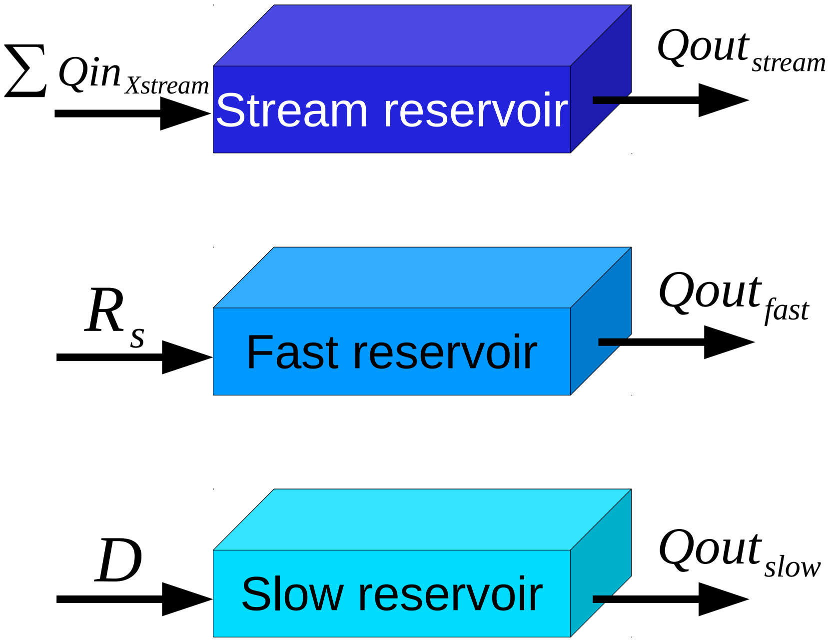
$$\frac{V_{i_{t+1}}-V_{i_t}}{\Delta t}=Qin_{i_t}-Qout_{i_t}$$

Δt = 1 day, time step for the routing procedure in ORCHIDEE

General equation of mass conservation (continuity equation)

Equation of mass conservation applied for each reservoir of the grid cell:

$$\begin{cases} \dfrac{dV_{stream}(t)}{dt} = \sum Qin_{Xstream}(t) - Qout_{stream}(t) \\[2ex] \dfrac{dV_{fast}(t)}{dt} = Rs(t) - Qout_{fast}(t) \\[2ex] \dfrac{dV_{slow}(t)}{dt} = D(t) - Qout_{slow}(t) \end{cases}$$



- Qin_{stream} [kg/day], sum of all inflow from the stream reservoirs of neighbor cells ($Qin_{Xstream}$) that flow into that cell direction
- V_i [kg], Qin_i [kg/day], $Qout_i$ [kg/day]
- Rs [kg/day], surface runoff
- D [kg/day], drainage

Outflow-storage relation

$$\boxed{Qout_i(t) = \frac{1}{T_i} . V_i(t)}$$

T_i [day], the time of a water waves to travel through a reach

(also called “time constant”, “residence time”)

with: $T_i = g_i . k$

The residence time in the reservoir i depends on 2 parameters:

- g_i [10^{-3} day/km], the property of the reservoir i
- k [km], the topographic index of the corresponding grid cell

Outflow-storage relation

Property of the reservoir (g_i)

- g_i is constant for all grid cells and is unique for each reservoir:
    - g_{stream} = 0.24 10^{-3} day/km
    - g_{fast} = 3.00 10^{-3} days/km
    - g_{slow} = 25.0 10^{-3} days/km
- The values were obtained during a calibration of river discharge over the Senegal basin and then generalized to all the worldwide basins (Ngo-Duc et al., 2007)

Outflow-storage relation

Topographic index (k)

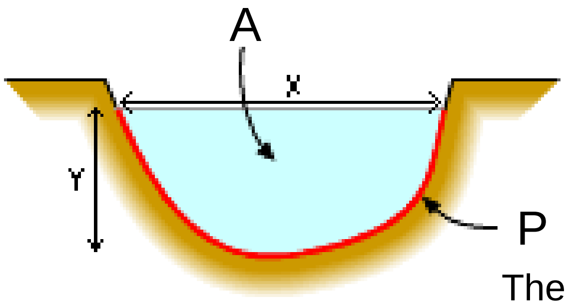
- k varies spatially and does not depend on the reservoir
- Its formulation is a simplification of Manning's formula (from Ducharne et al., J. Hydrol, 2003)

Manning equation: computes the velocity of open-channel flows

$$U = \left(\frac{u_m}{n}\right) . R_h^{2/3} . \sqrt{\tan\beta}$$

U [m/s],	open-channel flow velocity
u_m [$m^{1/3}$/s],	unit-conversion factor
n,	Manning coefficient which characterizes channel resistance
R_h [m],	hydraulic radius
tanβ,	water-surface slope

Hydraulic radius: measures the channel flow efficiency



$$R_h \equiv \frac{A}{P}$$

A [m²],	cross-sectional area of the flow
P [m],	length of the wetted portion of the flow boundary (“wetted perimeter”)

The greater R_h, the greater the efficiency of the channel and the more volume it can carry. For channels of a given width (x), R_h is greater for the deeper channels (y is high).

Outflow-storage relation

Topographic index (k)

$$\boxed{U=\left(\frac{u_m}{n}\right).R_h^{2/3}.\sqrt{\tan\beta}}$$

Manning equation

$$\downarrow$$

$$\frac{1}{U}=\left(\frac{n}{u_m.R_h^{2/3}}\right)\cdot\left(\frac{1}{\sqrt{\tan\beta}}\right)$$

$$\downarrow$$

$$\frac{d}{U}=\left(\frac{n}{u_m.R_h^{2/3}}\right)\cdot\left(\frac{d}{\sqrt{\tan\beta}}\right)$$

$$\downarrow$$

$$t_{adj}=\alpha.\left(\frac{d}{\sqrt{\tan\beta}}\right)$$

- $t_{adj}=d/U$ [s], transfer time between two adjacent grid cells. Equivalent to T_i.
- d [m], distance between two adjacent grid cells.
- α [s/m], a scaling parameter, including the influence of roughness of the river bed (influence of the water stage being neglected). Equivalent to g_i.

$$\downarrow$$

$$k=\frac{d}{\sqrt{\tan\beta}}$$

- $k=t_{adj}/\alpha$ [m], topographic index

$$\downarrow$$

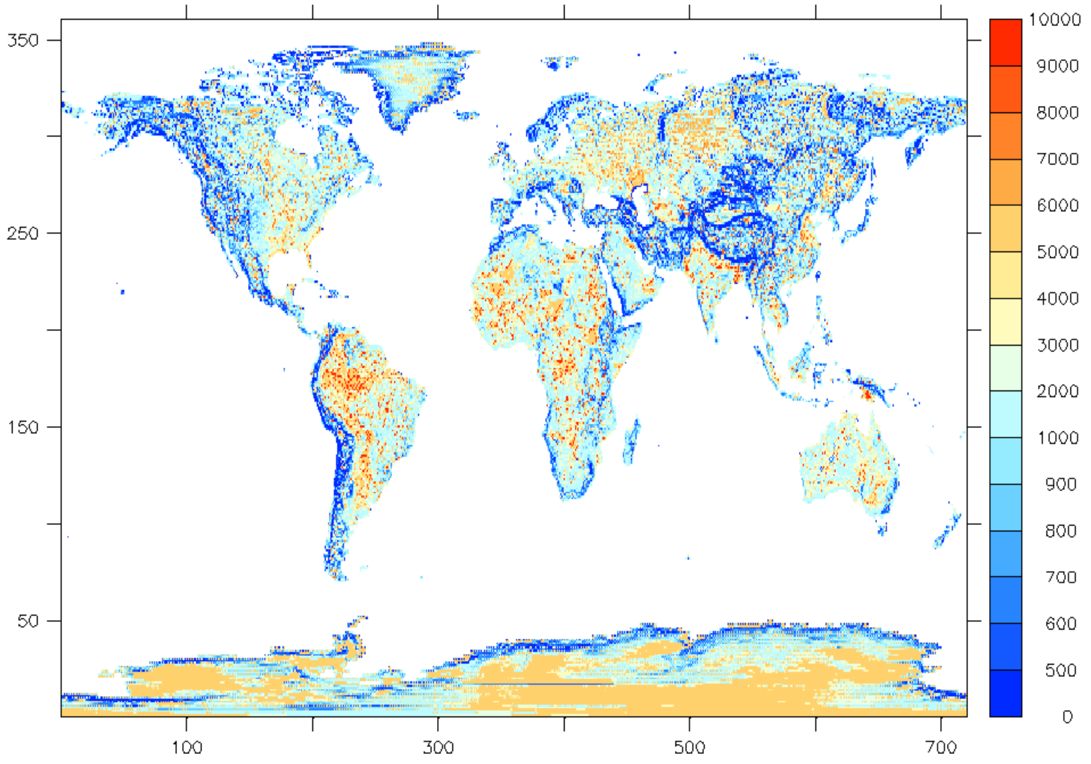
Topographic index in ORCHIDEE

$$k=\sqrt{\frac{d^2}{\tan\beta}}\rightarrow k=\sqrt{\frac{d^2}{\frac{\Delta z}{d}}}\rightarrow k=\sqrt{\frac{d^3}{\Delta z}}$$

then: $\boxed{k=\sqrt{\frac{d^3}{\Delta z.10^6}}}$ to put k in km

Outflow-storage relation

Topographic index (k)



Topographic index [km]

0.5°x0.5° spatial resolution

$$T_i = g_i . k$$

$$12.5 \text{ days} < T_{slow} < 250 \text{ days}$$

Groundwater residence time estimated in the literature: 10-300 days

2.2.4

The routing scheme

See my training course 2014

Modeling in ORCHIDEE:
inland and man-made wetlands (irrigation, floodplains, swamps, ponds and endorheic lakes)

Parameters used in routing.f90

Name	Value	Unit	Description
General			
diagunit	87	*unitless*	Diagnostic file unit
dt_routing	one_day	s	Routing time step
nbasmax	7	*unitless*	Maximum number of basins per grid cell
nbvmax	440	*unitless*	
num_largest	50	*unitless*	Number of largest basins
fast_tcst	3	day/m	Fast reservoir property
slow_tcst	25	day/m	Slow reservoir property
stream_tcst	0.24	*day/m*	Stream reservoir property
Swamp subroutine			
swamp_cst	0.2		Swamp constant
Floodplain subroutine			
beta	2	*unitless*	Fix the shape of the floodplain
floodcri	2000	mm	Potential height for which all the basin is flooded
flood_tcst	4	day/m	Flood reservoir property
Pond subroutine			
betap	0.5	*unitless (0-1)*	Ratio of the basin surface intercepted by ponds and the maximum surface of ponds
pondcri	2000	mm	Potential height for which all the basin is a pond
Endoheric lake subroutine			
maxevap_lake	7.5/86400	mm/s	Maximum evaporation rate from lakes

2.2.5

The routing scheme

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Where you can find informations about the routing module of ORCHIDEE

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LAND SURFACE MODEL

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