HYDROLOGICAL MODELING: INTEGRATING THE IMPACT OF THE GROUNDWATER AND ANTHROPOGENIC EFFECT AT THE BASIN SCALE

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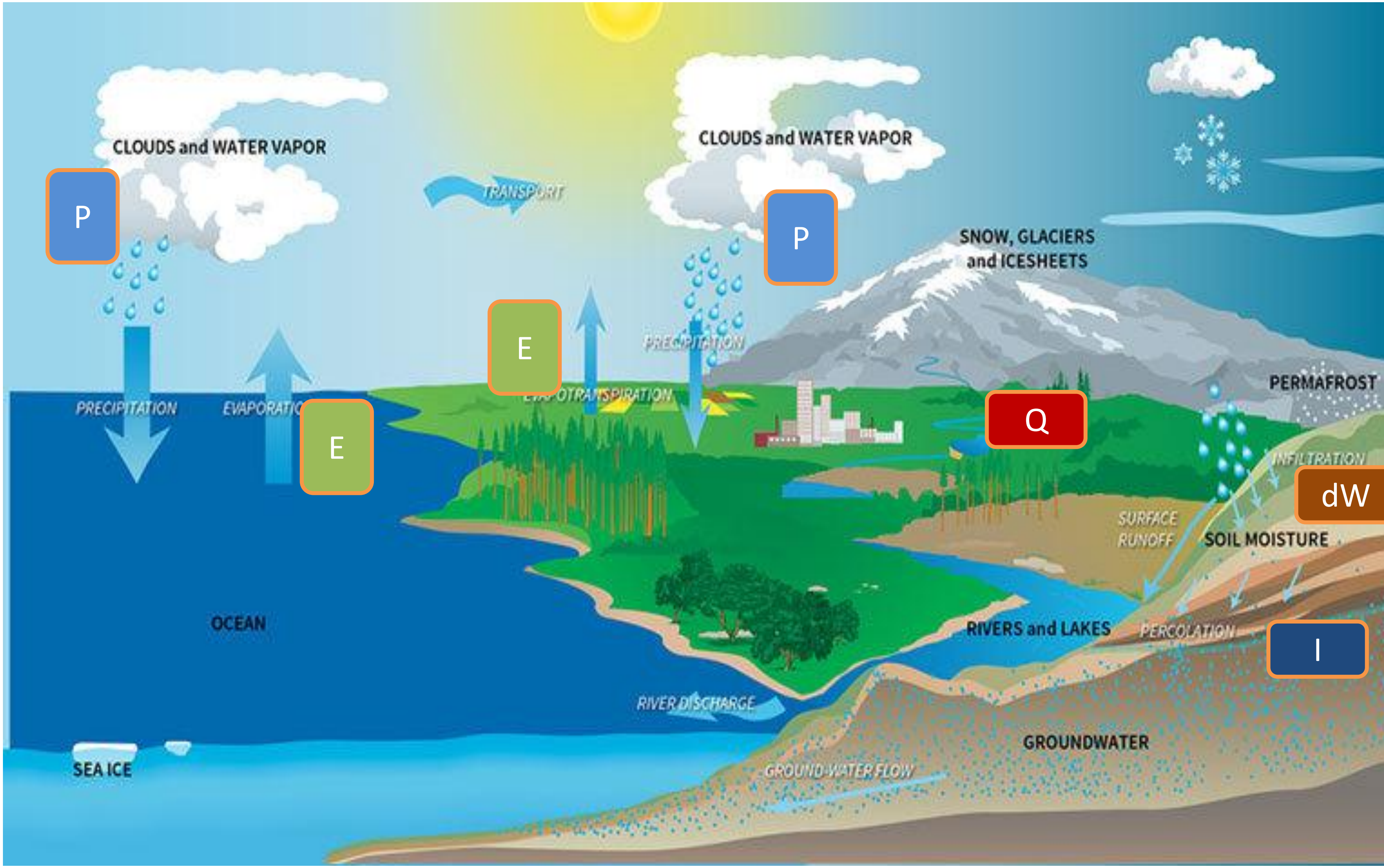
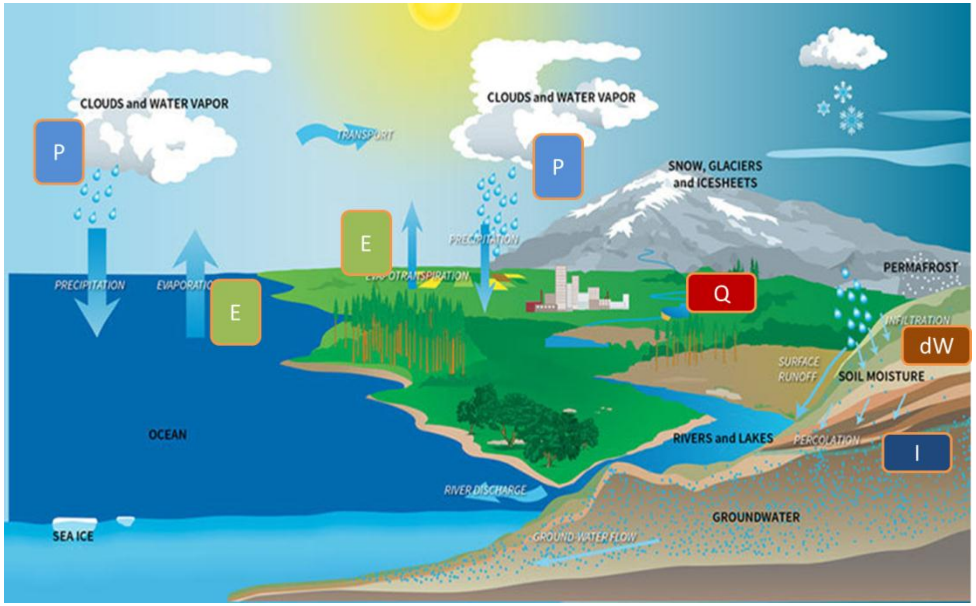
1. The Water Cycle



1. The Water Cycle



For an agronomist at daily scale

$\Delta w = P - E - Q$

For a hydrogeologist at annual scale

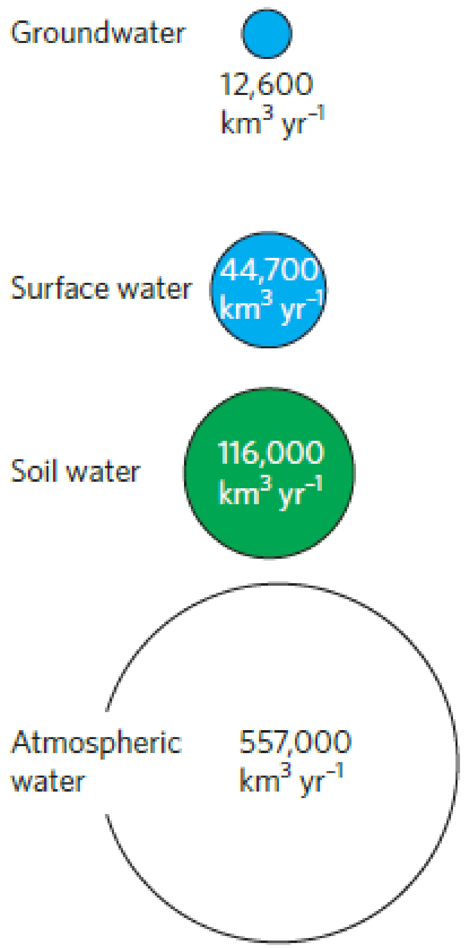
$I = P - E - Ro$

At global scale and decadal time scale

$P = E$

1. The global Water Cycle: composition

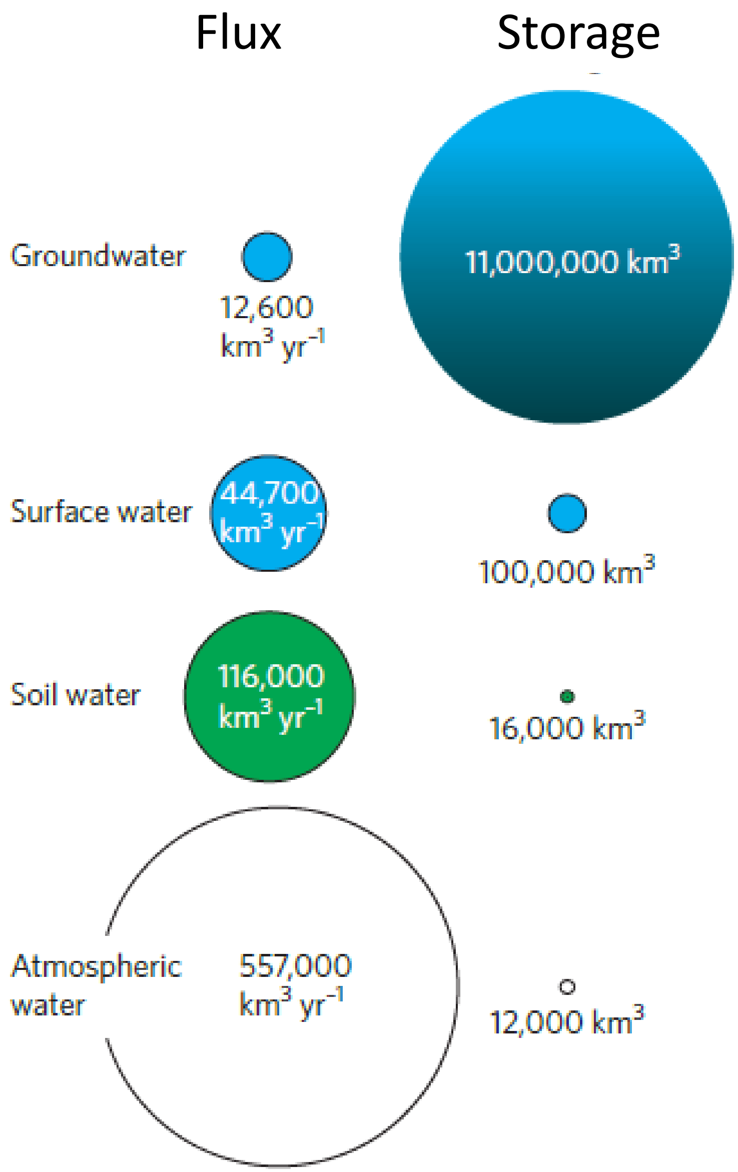
Flux



➔ Focus on atmospheric water: precipitation and evaporation

Aeschbach-Hertig & Gleeson, Nature Geoscience, 2012

1. The global Water Cycle: composition

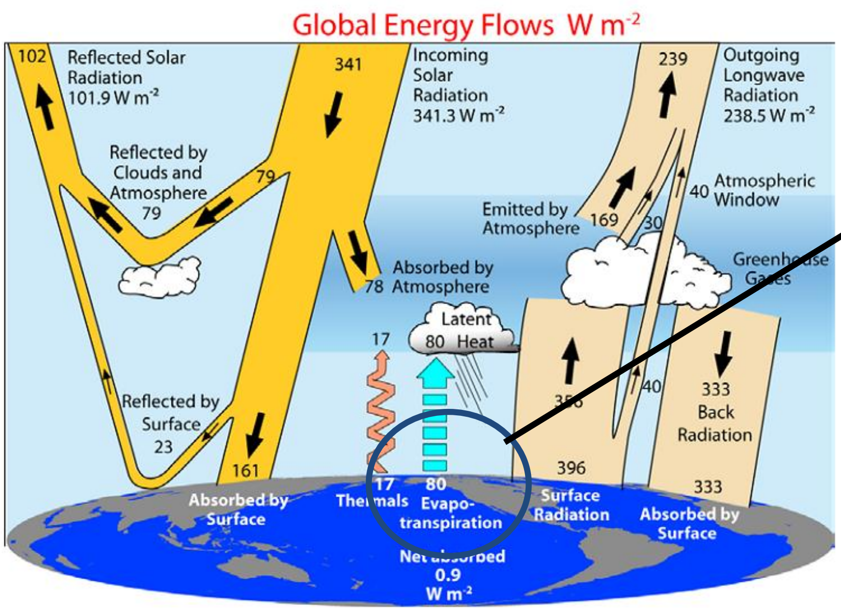


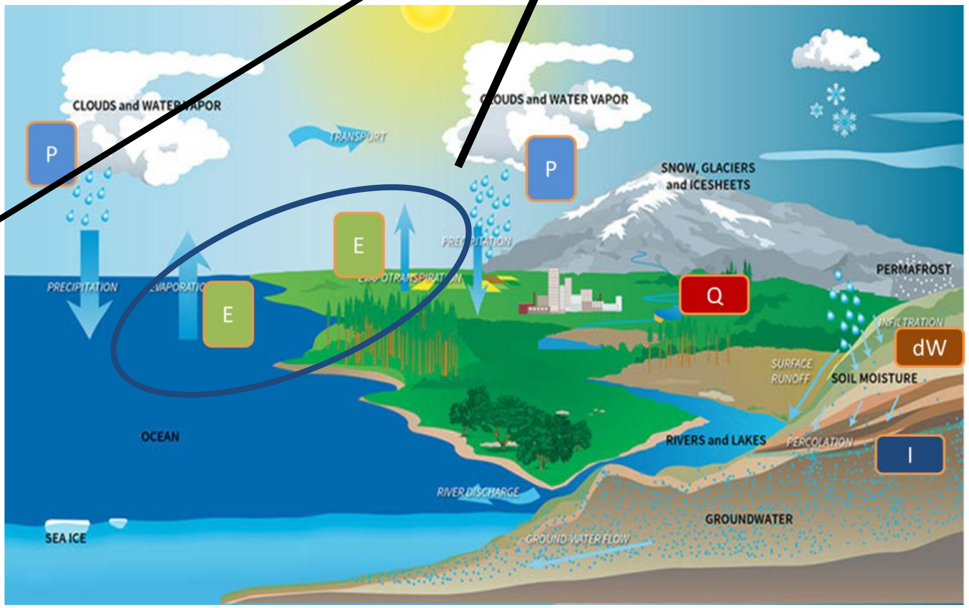
Aeschbach-Hertig & Gleeson, Nature Geoscience, 2012

1. Water and energy budgets

Energy budget : Rsol $(1-\alpha)+\varepsilon(\text{Ratm} - \sigma T_s^4) = H + LE + G$

Water balance : $\Delta w = P - Q - E$



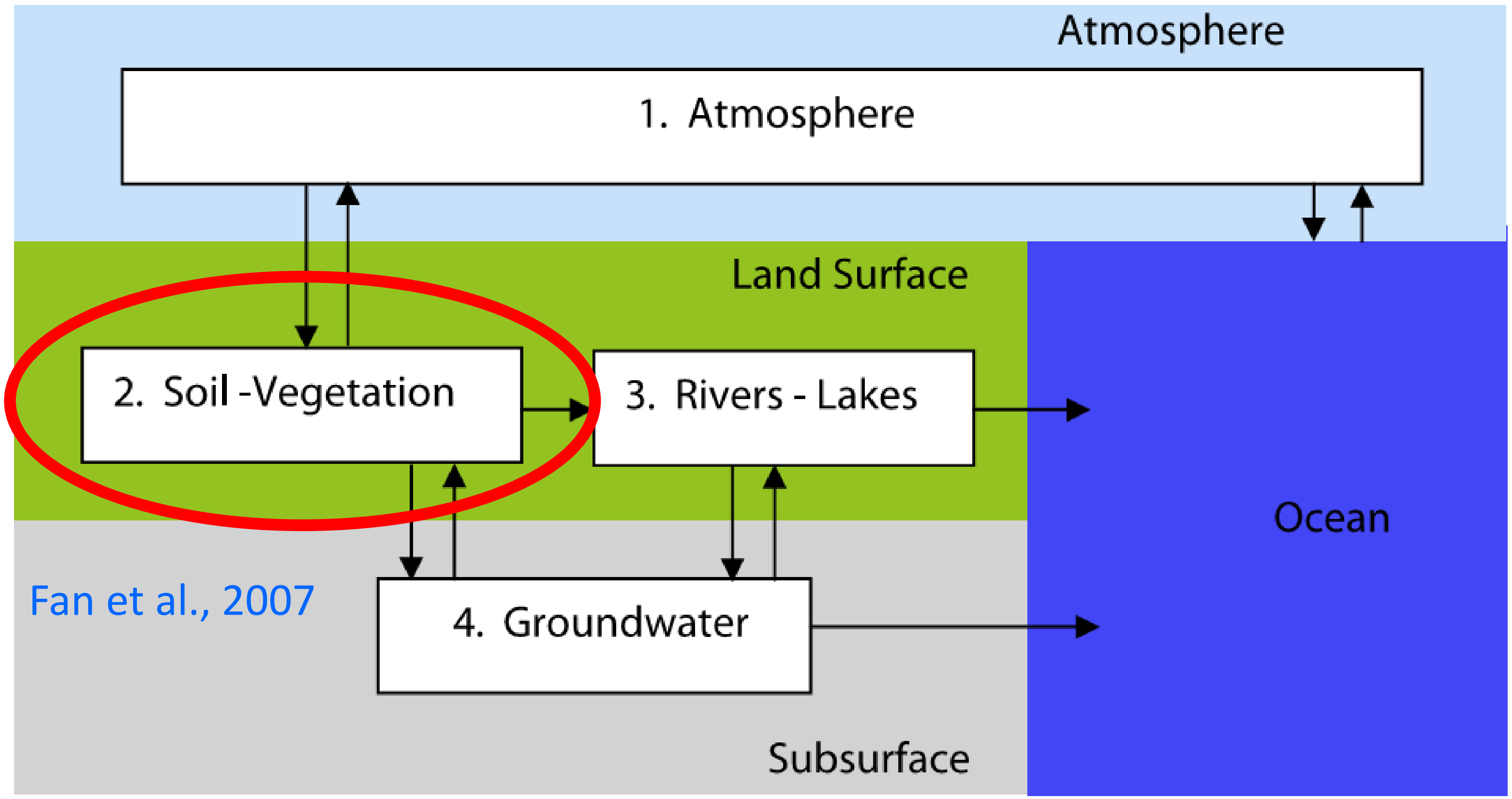


HYDROLOGICAL MODELING: INTEGRATING THE IMPACT OF THE GROUNDWATER AND ANTHROPOGENIC EFFECT AT THE BASIN SCALE

1. Some general patterns on the water cycle
2. **Zoom on the main processes**
3. Impact of human activities

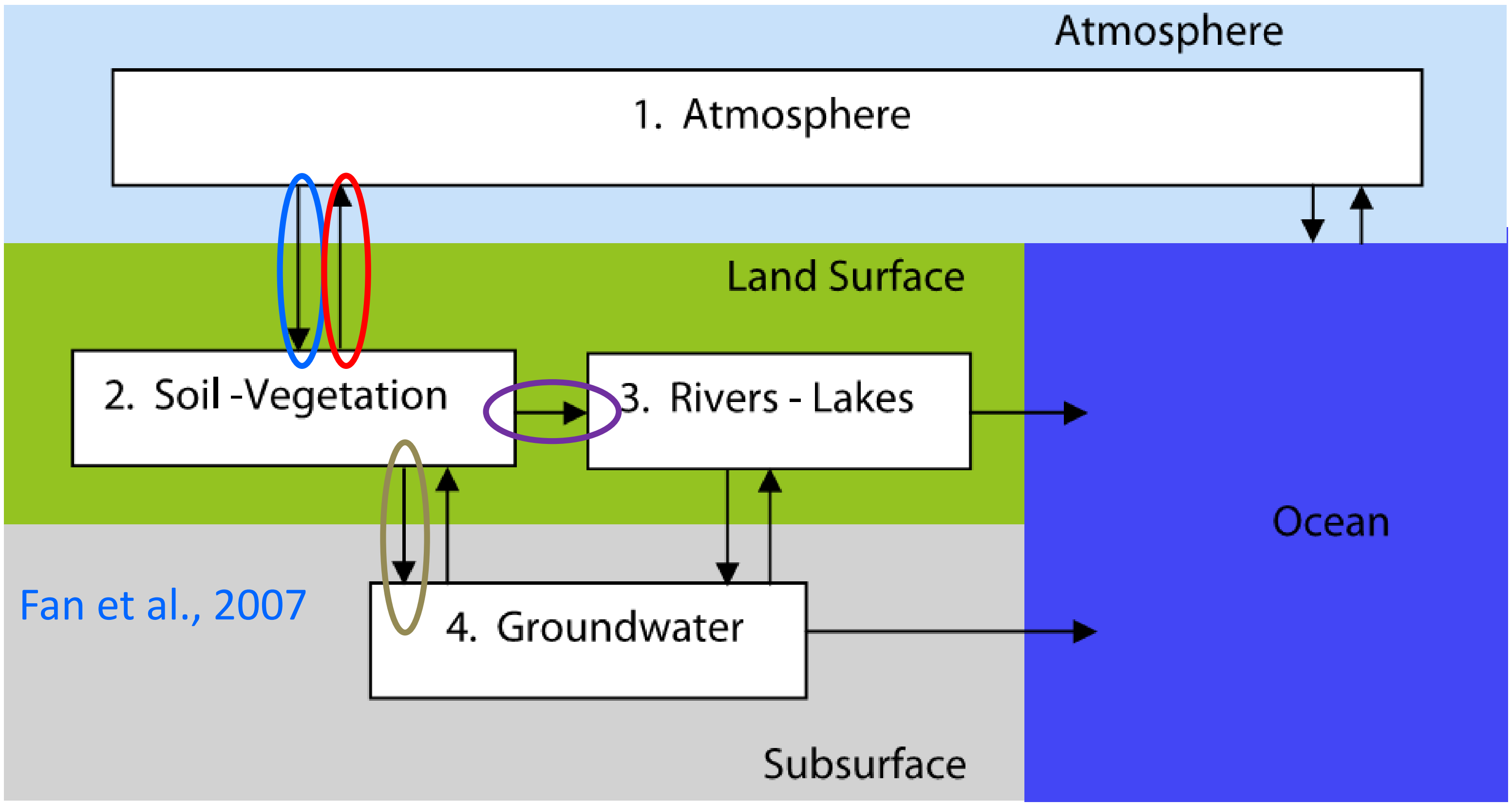
2. Water cycle: back to processes

Focus on the soil-vegetation interface



2. Water cycle: back to processes

Focus on the soil-vegetation interface

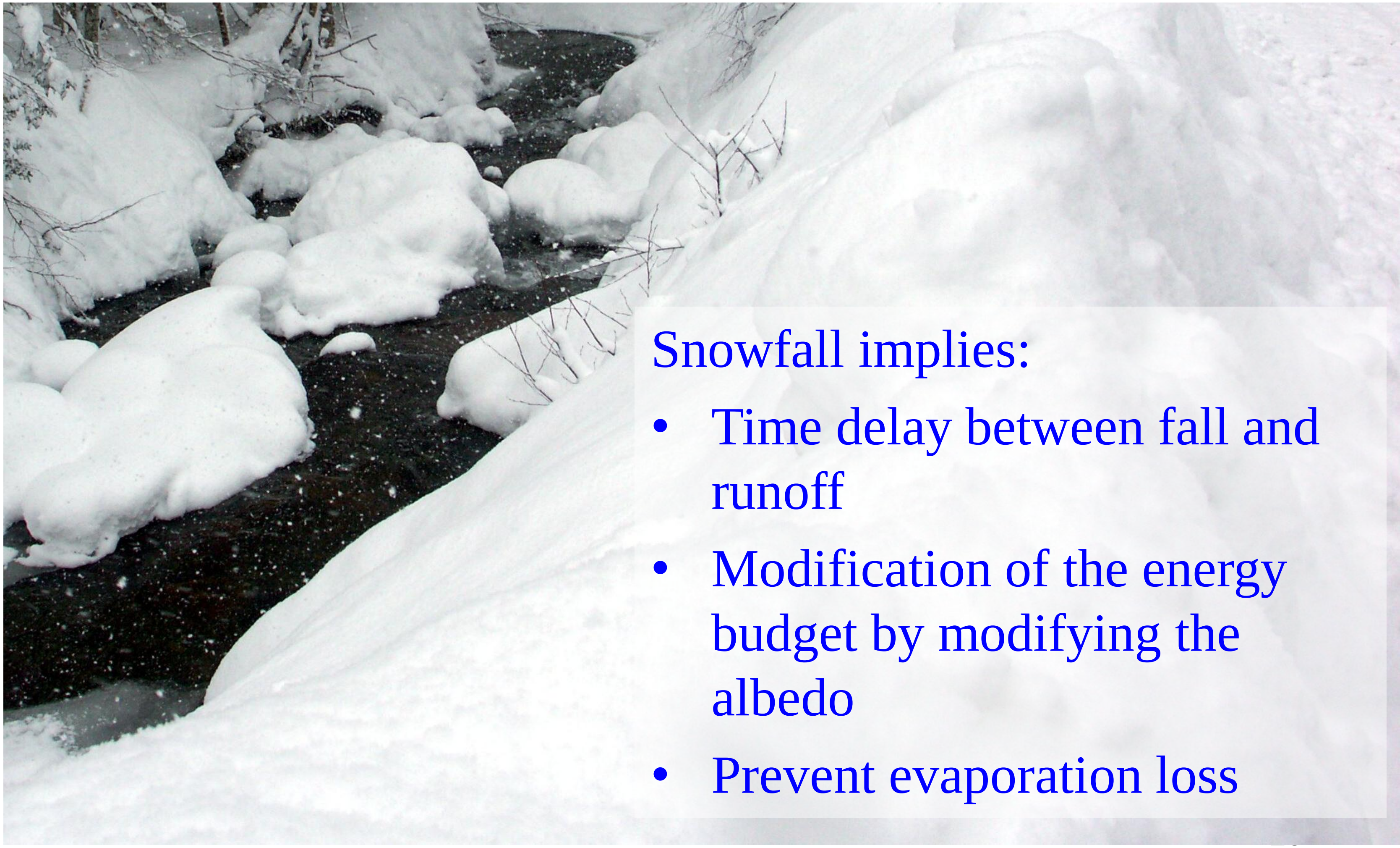


1. Precipitation
2. Evapotranspiration
3. Infiltration
4. Surface runoff

2. Water cycle: back to processes

1. Precipitation :

liquid and solid partition has a strong impact on water balance



Snowfall implies:

- Time delay between fall and runoff
- Modification of the energy budget by modifying the albedo
- Prevent evaporation loss

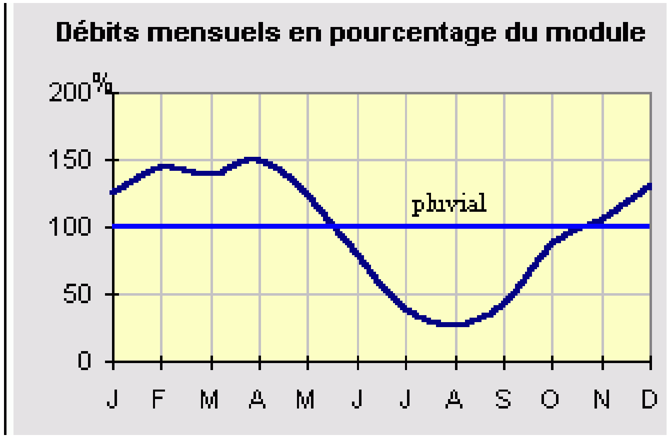
2. Water cycle: back to processes

1. Precipitation :

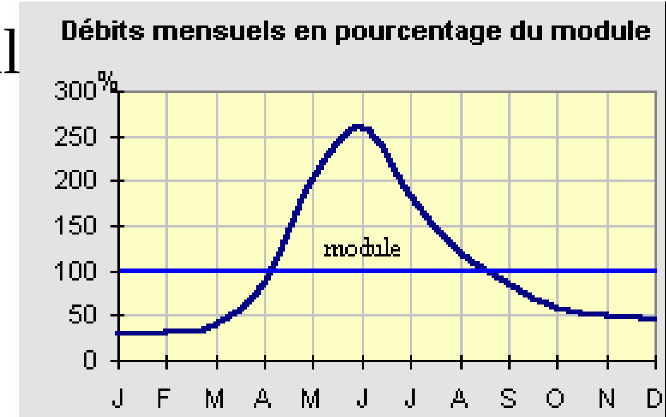
liquid and solid partition has a strong impact on water balance

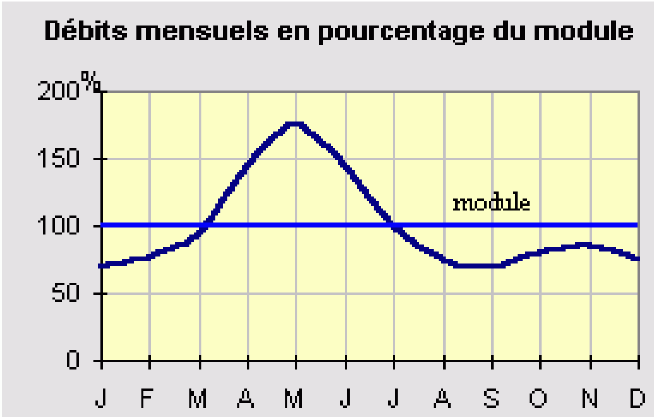
Hydrologic regime are associated to snowfall

Rainfall regime



Snowfall regime





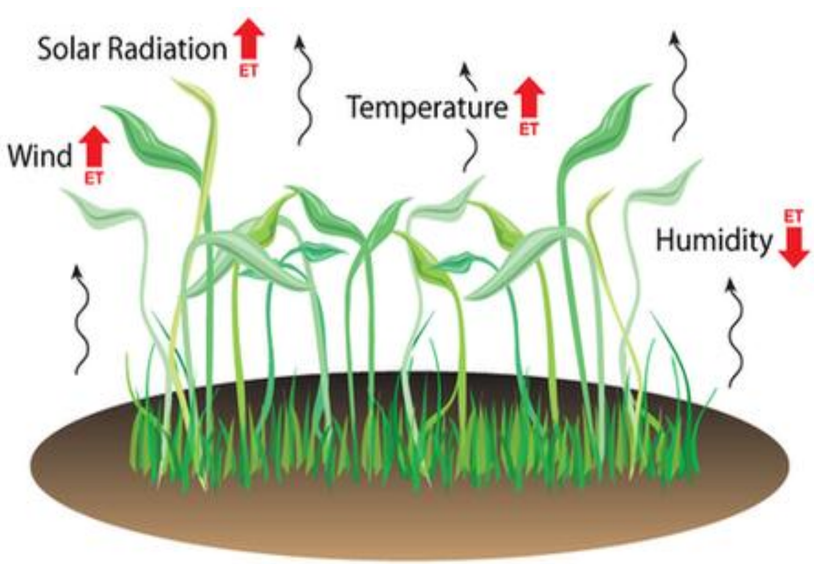
Mixed regime

2. Water cycle: back to processes

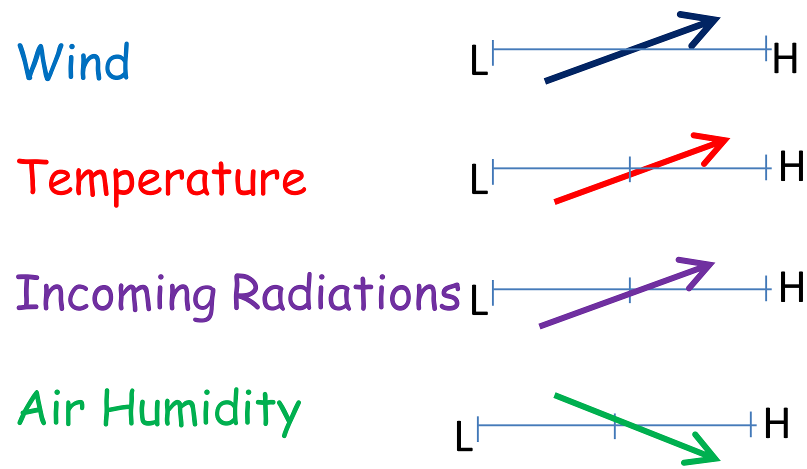
2. Evapotranspiration: dominant water flux over continent

Evapotranspiration=

Transpiration+Interception+Bare soil evaporation
+Sublimation



Sensitivity to the major atmospheric variables:



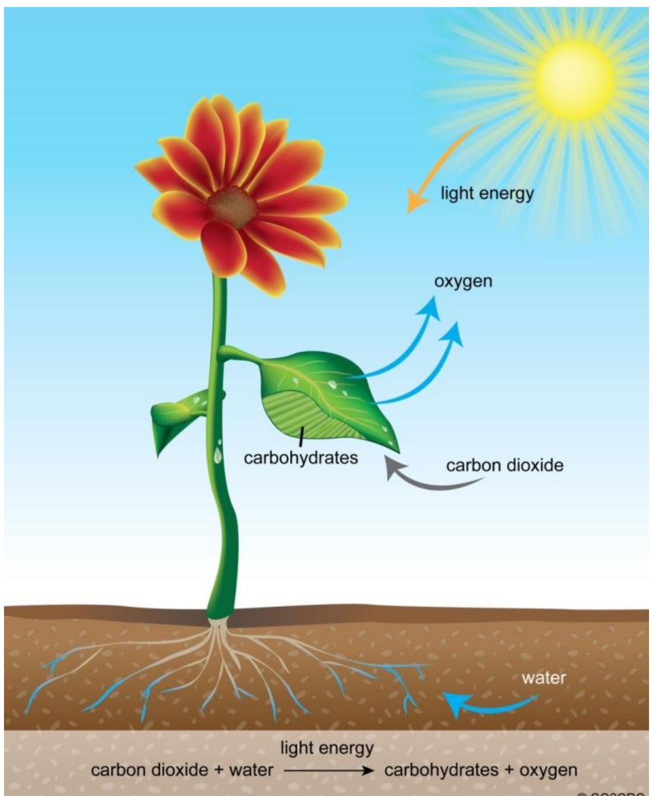
2. Water cycle: back to processes

2. Evapotranspiration: dominant water flux over continent

Evaporatranspiration=

Transpiration+Interception+Bare soil evaporation
+Sublimation

Focus on transpiration: connexion with C, N, P cycles…

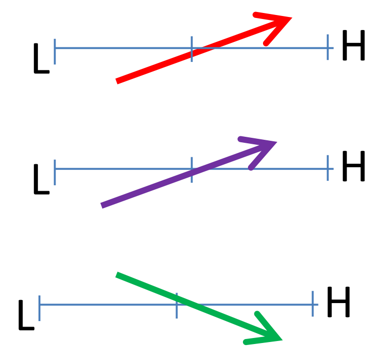


Sensitivity to other variables:

LAI

Soil moisture

CO_2

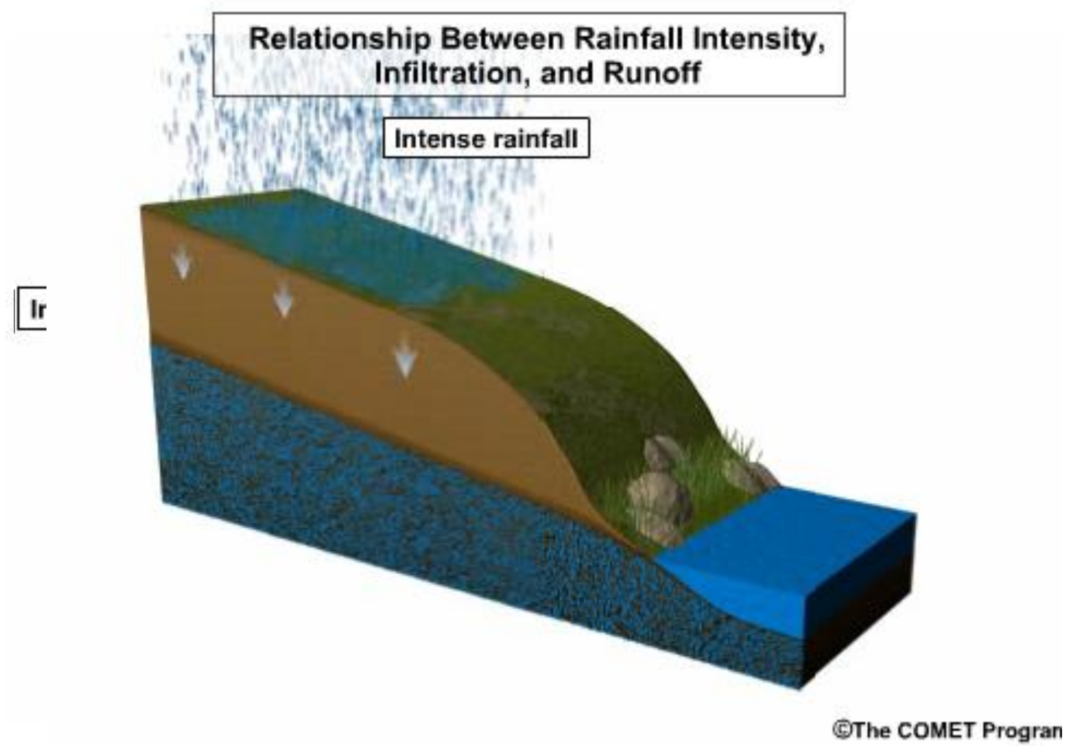


2. Water cycle: back to processes

3. Infiltration

4. Surface runoff

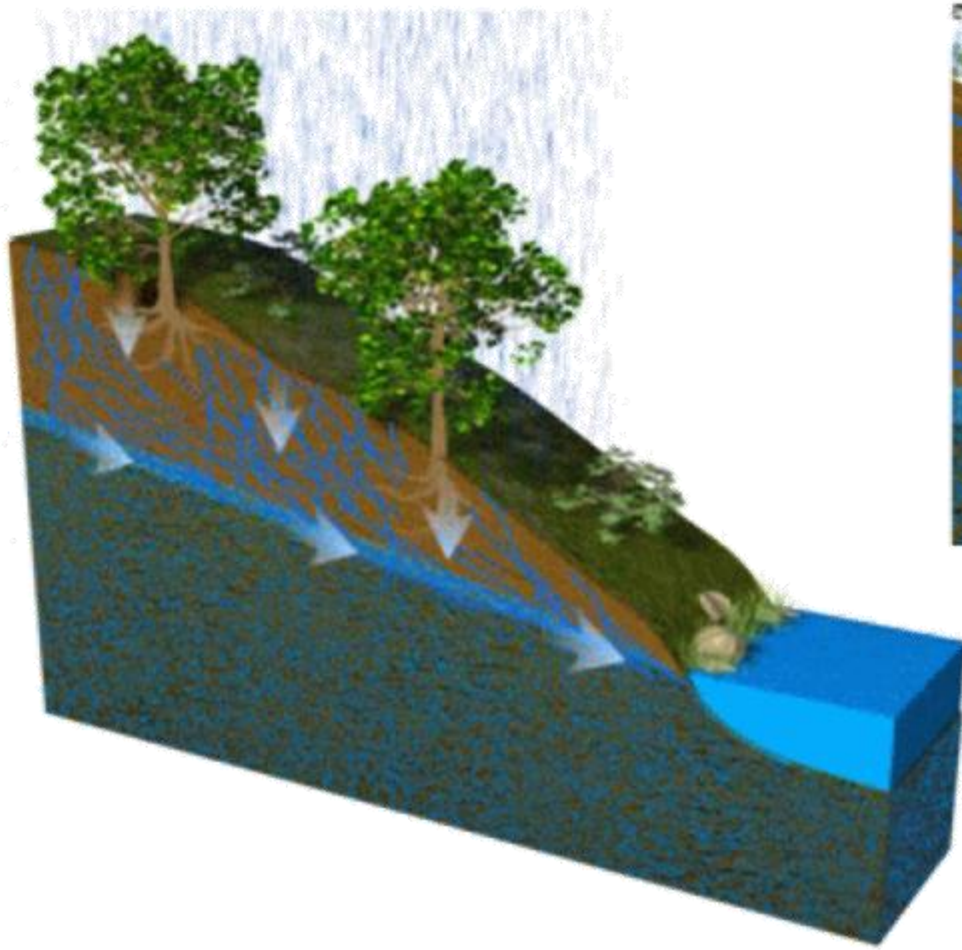
Surface Runoff and Infiltration can occur on the same time



2. Water cycle: back to processes

3. Infiltration

4. Surface runoff

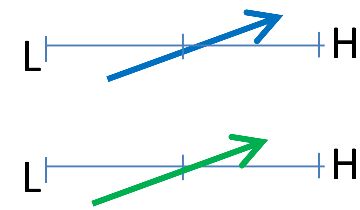


2. Water cycle: back to processes

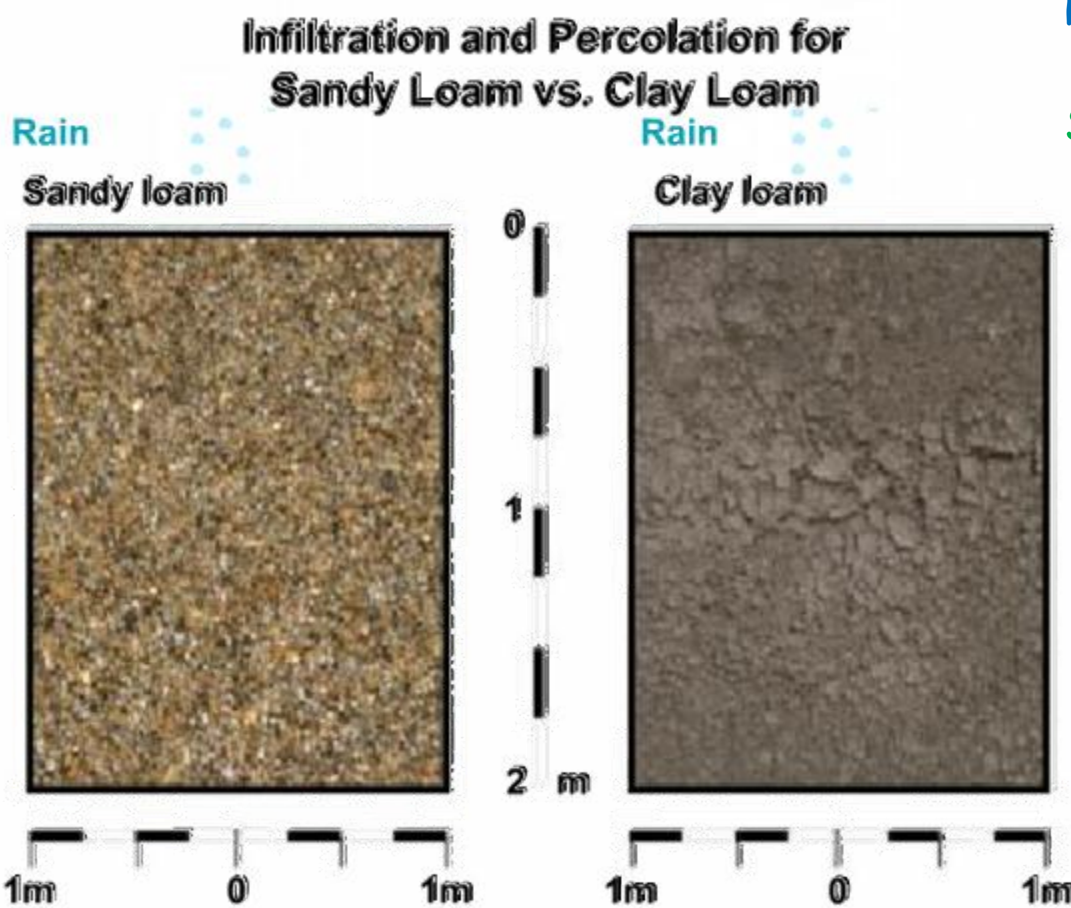
3. Infiltration

Sensitive to:

Rainfall intensity



Soil porosity

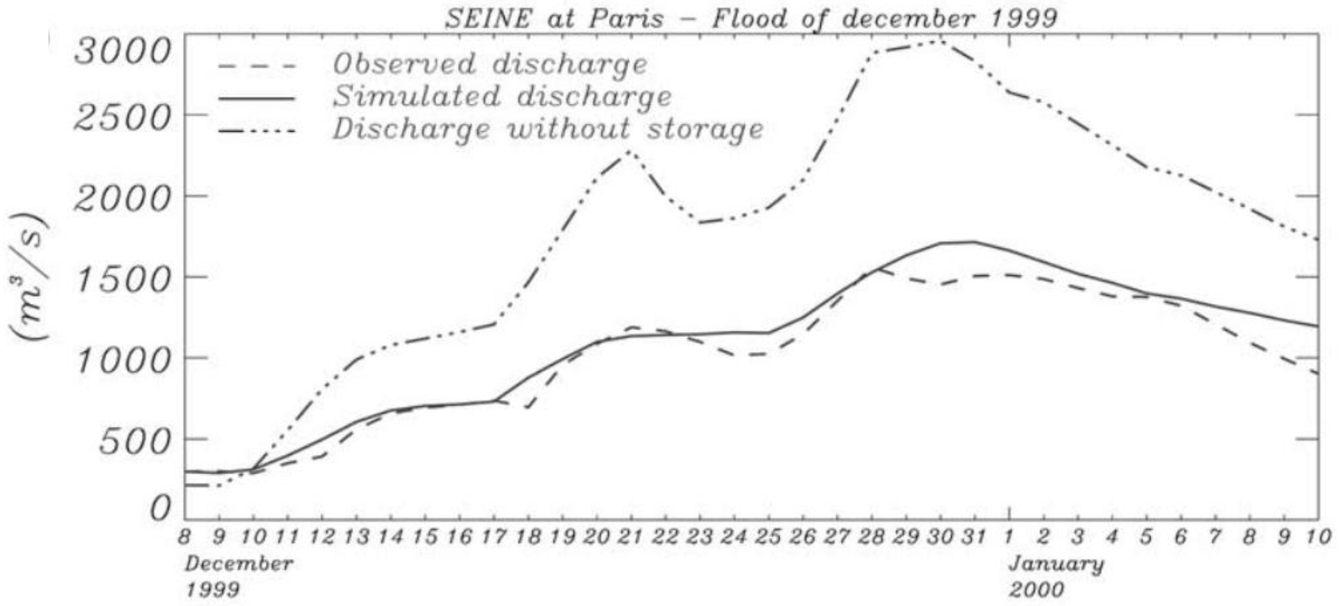


Simulated using Richards equation
or some simplifications :
Green & Ampt (1911) ➔ Infiltration front

2. Water cycle: back to processes

3. Infiltration

Infiltration to groundwater can decrease flood intensity
Example in the Seine Basin

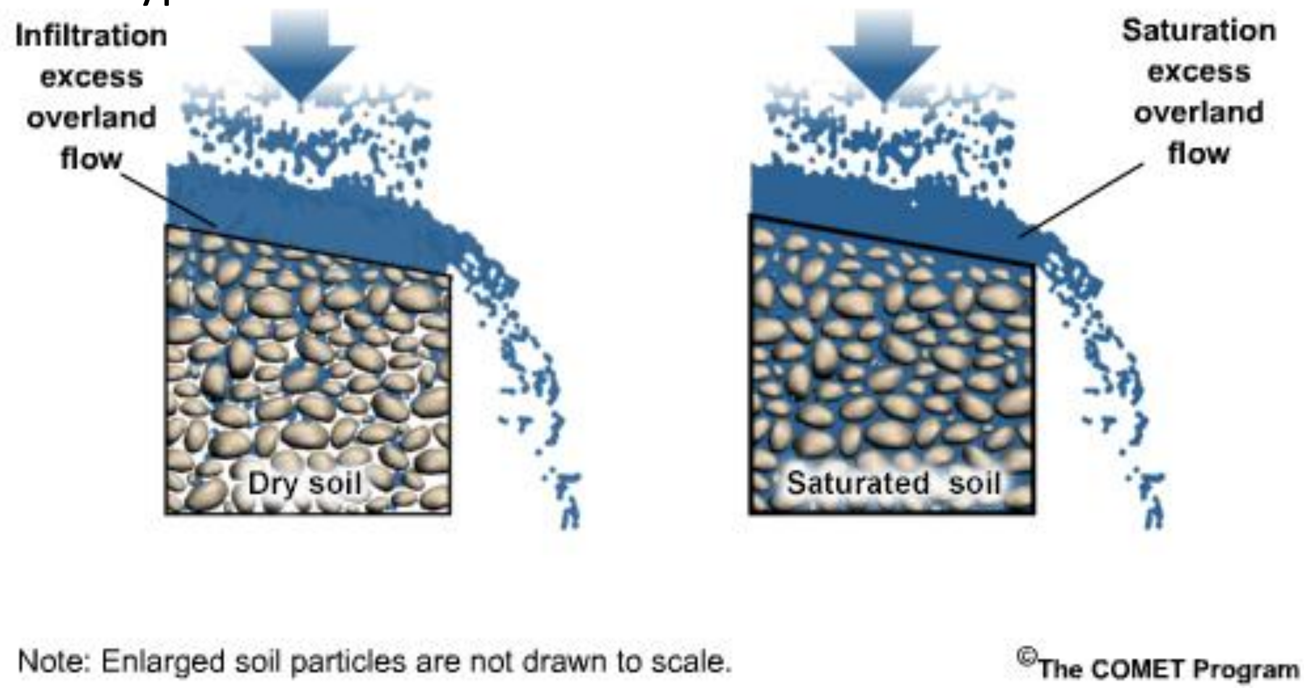


Rousset et al., 2004

2. Water cycle: back to processes

4. Surface runoff

Two types of surface runoff:

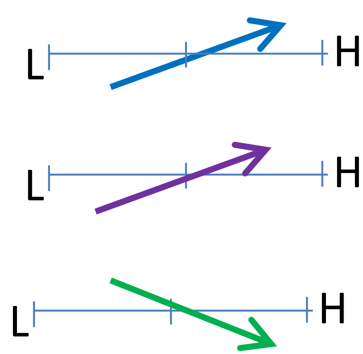


Sensitive to:

Rainfall intensity

Soil moisture

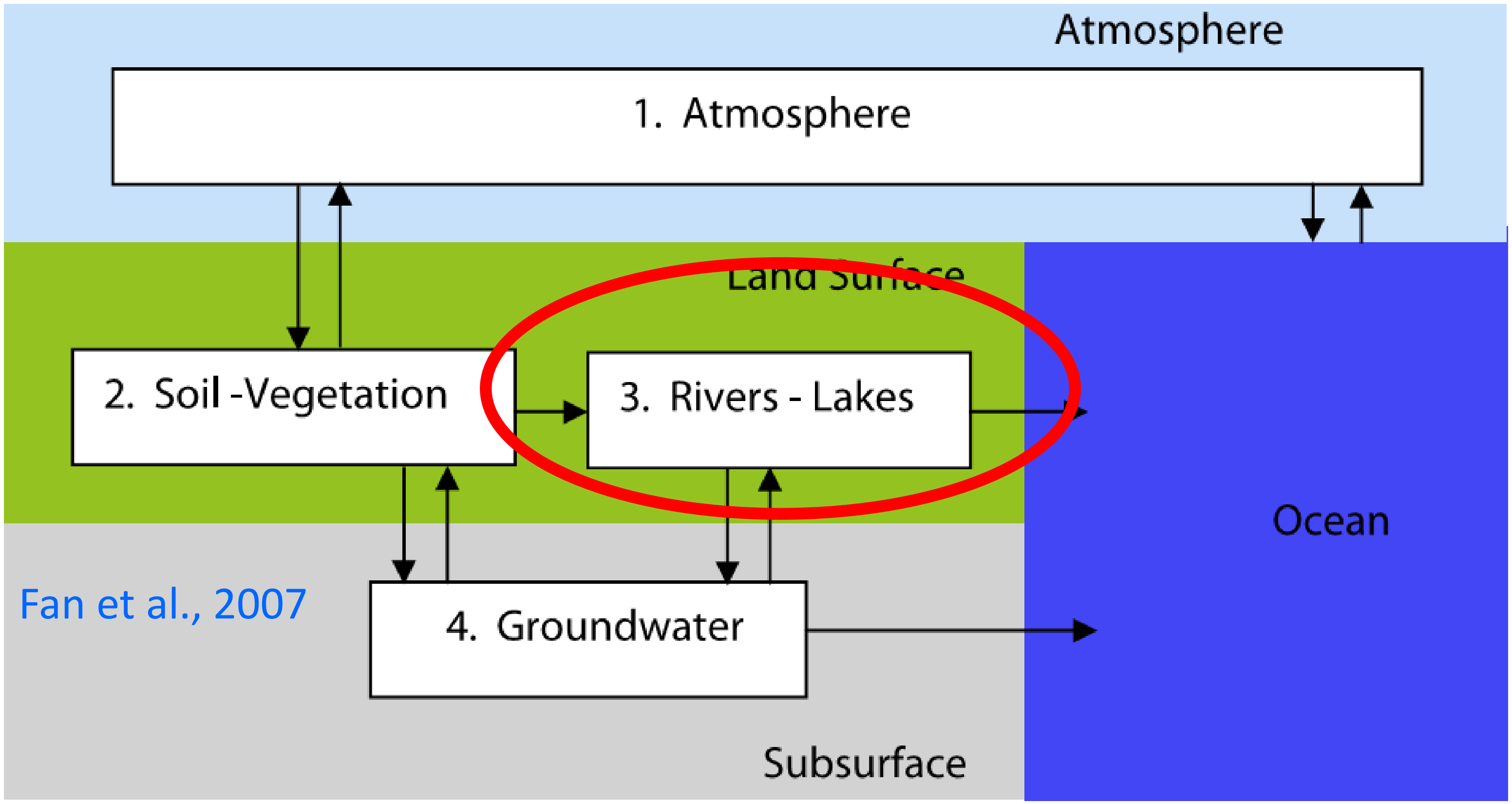
Soil porosity



Simulated using Horton (infiltration excess) or Dune (saturation excess) processes

2. Water cycle: back to processes

Focus on river flow

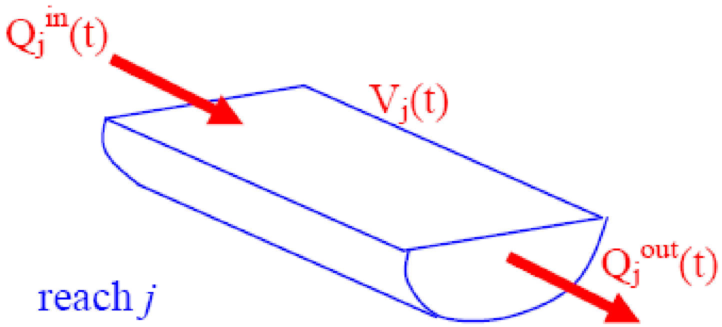


2. Water cycle: back to processes

River routing

Several approaches: Saint Venant equation, diffusive wave, Muskingum approach

$$V_j(t) = K_j.\left(x_j.Q_j^{in}(t) + (1-x_j).Q_j^{out}(t)\right)$$



(David et al., 2011, HP, JHM)

RAPID Routing model

- estimation of water volume and riverflows on every reaches
- adapted to large scale basin with high spatial resolution

➔Few parameters, inversion process included

➔ numerical efficiency (parallel computation)

2. Water cycle: back to processes

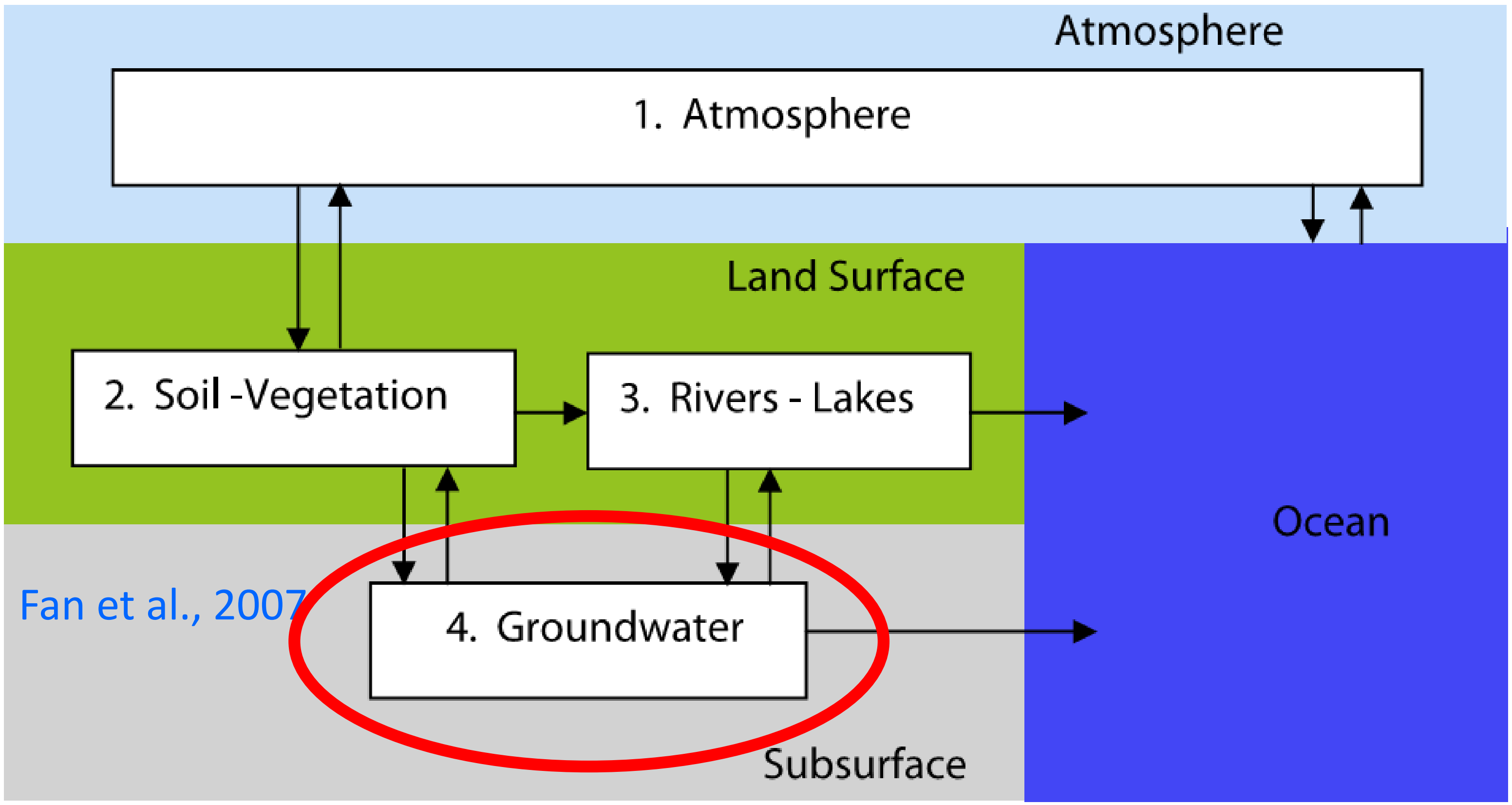
River routing

Illustration of the Rapid Model

(David et al., 2011, HP, JHM)

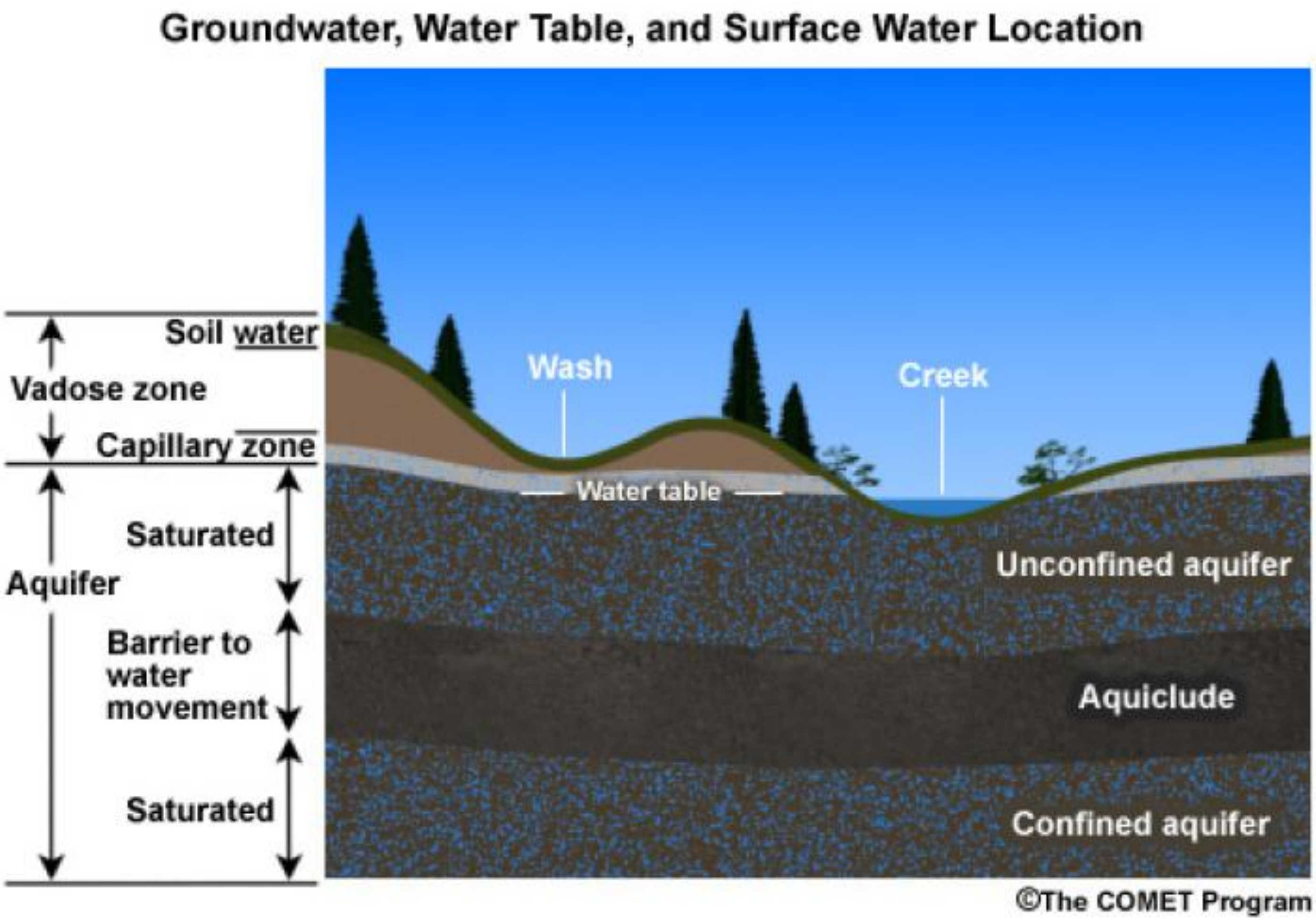
2. Water cycle: back to processes

Focus on groundwater



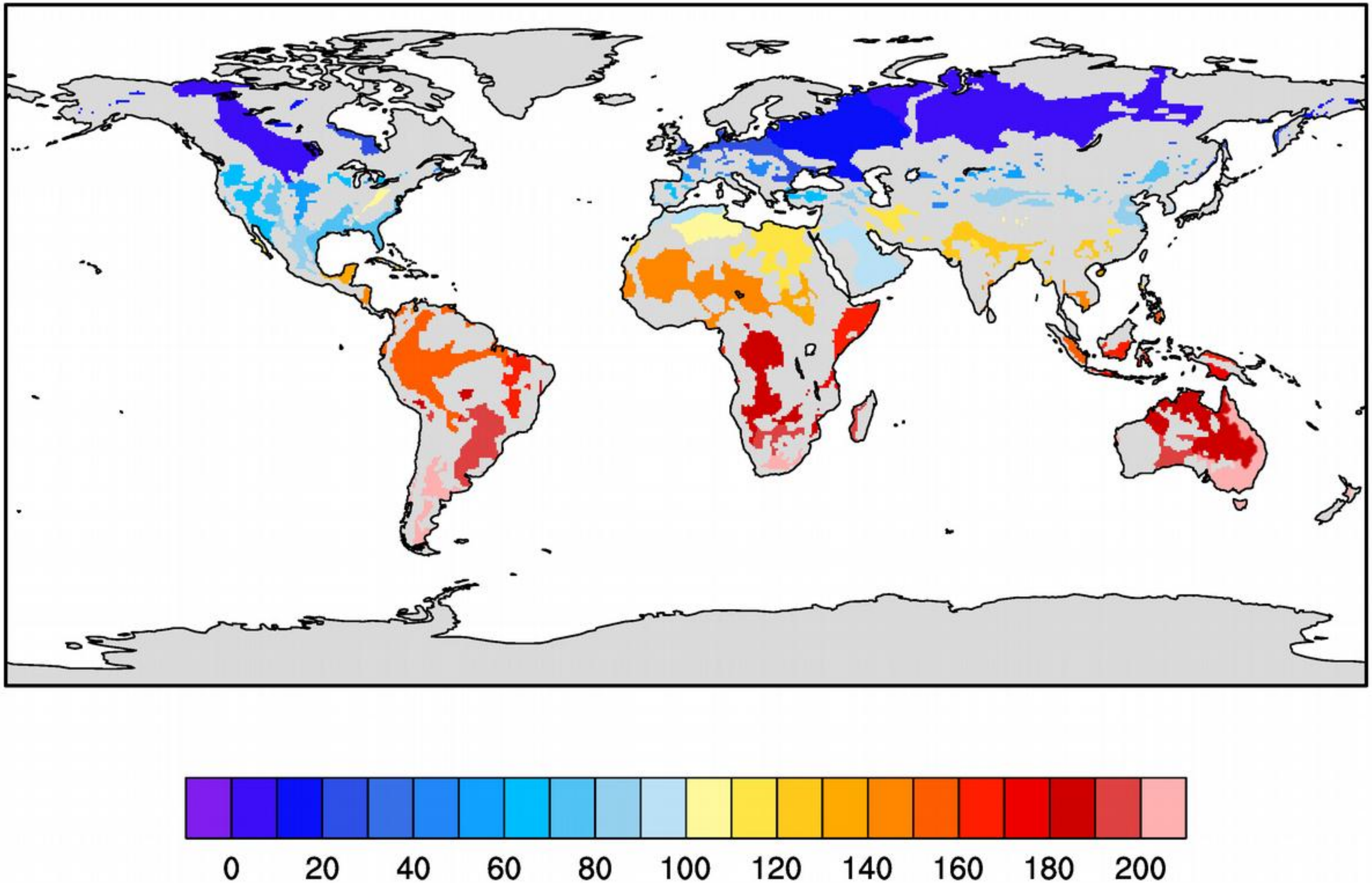
2. Water cycle: back to processes

Zoom on groundwater



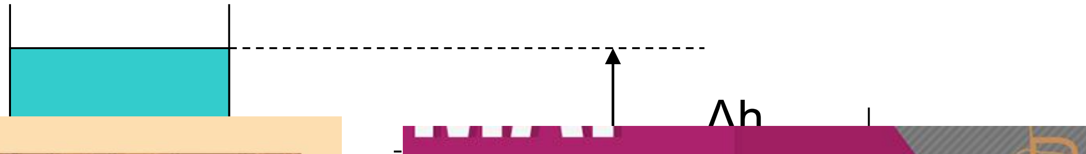
2. Water cycle: back to processes

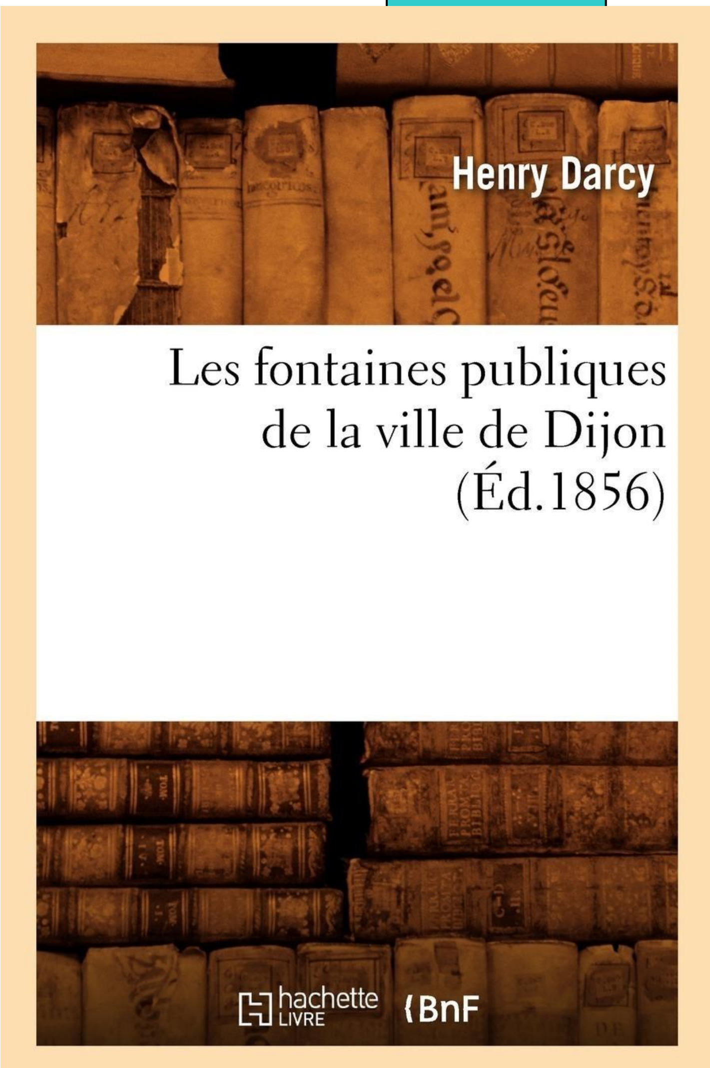
Main groundwater basins

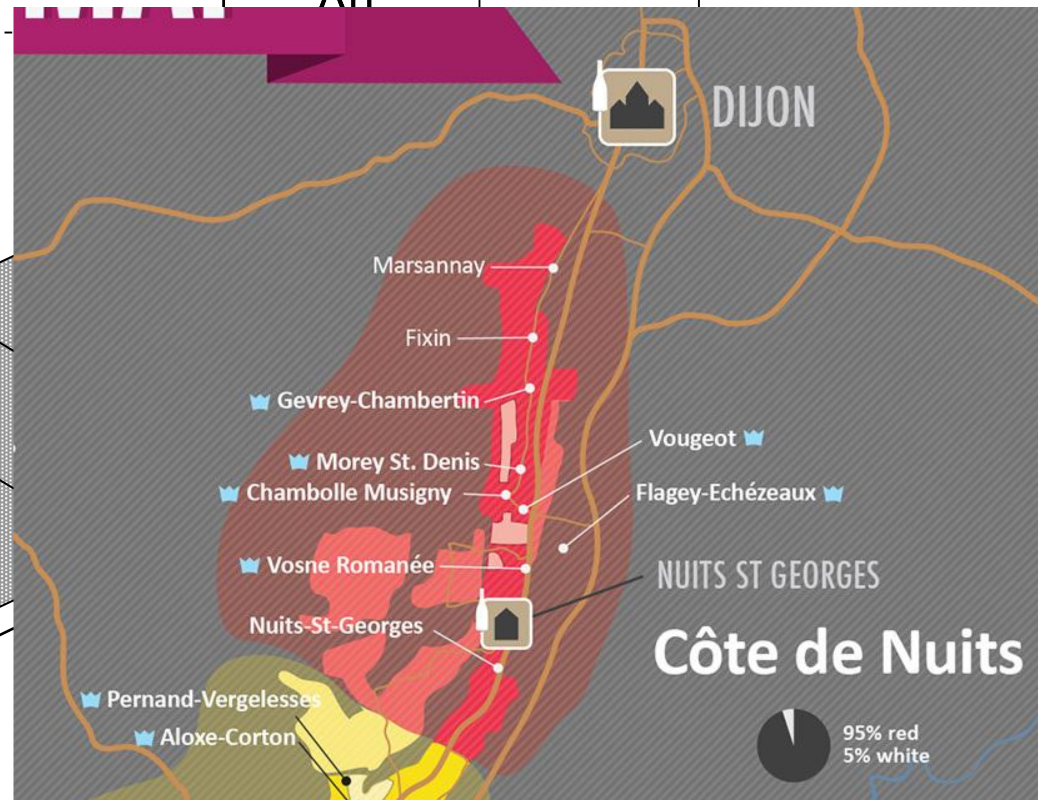


2. Water cycle: back to processes

Darcy's law







y

adient

$$V = -K\,\mathrm{grad}(h)$$

2. Water cycle: back to processes

Groundwater flow (2D)

Confined or uncondined aquifer

$$\omega \frac{\partial \mathrm{h}}{\partial \mathrm{t}} = \frac{\partial}{\partial x}(\bar{K}(h - z_{sub})\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(\bar{K}(h - z_{sub})\frac{\partial h}{\partial y}) + \bar{f}$$

Parameters

ω : Porosity or storage coefficient (x)

K: Hydraulic conductivité hydraulique ou transmissivité (x)

z_{sub} : substratum elevation (unconfined aquifer) (x)

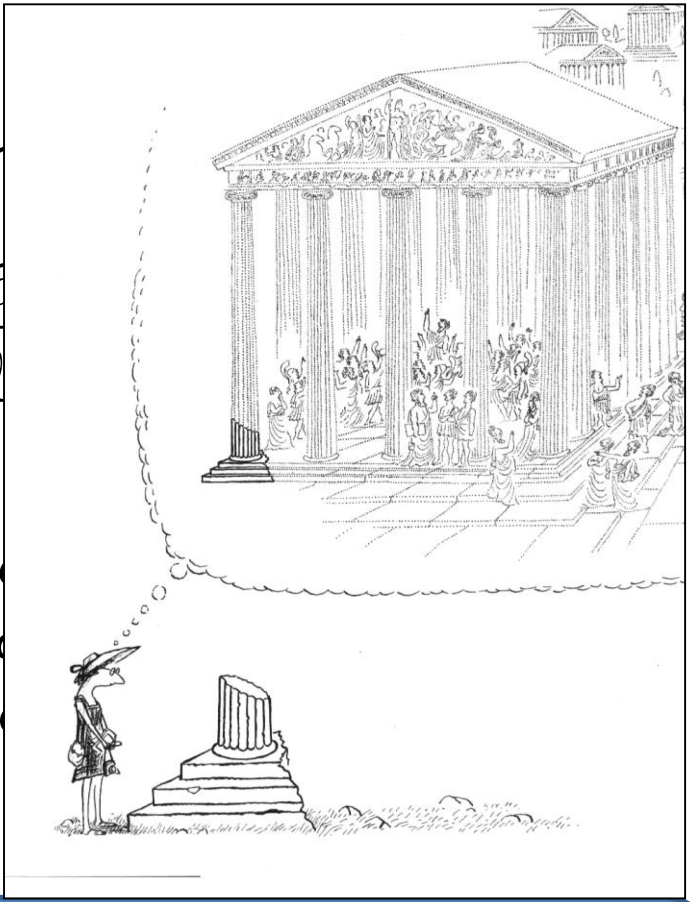
f : sink and source (x,t)

2. Water cycle: back to processes

Groundwater flow (2D)

Confined or uncondined aquifer

$$\omega \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\bar{K}(h - z_{sub})\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial \ldots}$$



Parameters

ω : Porosity or storage coeffici

K: Hydraulic conductivité hydr

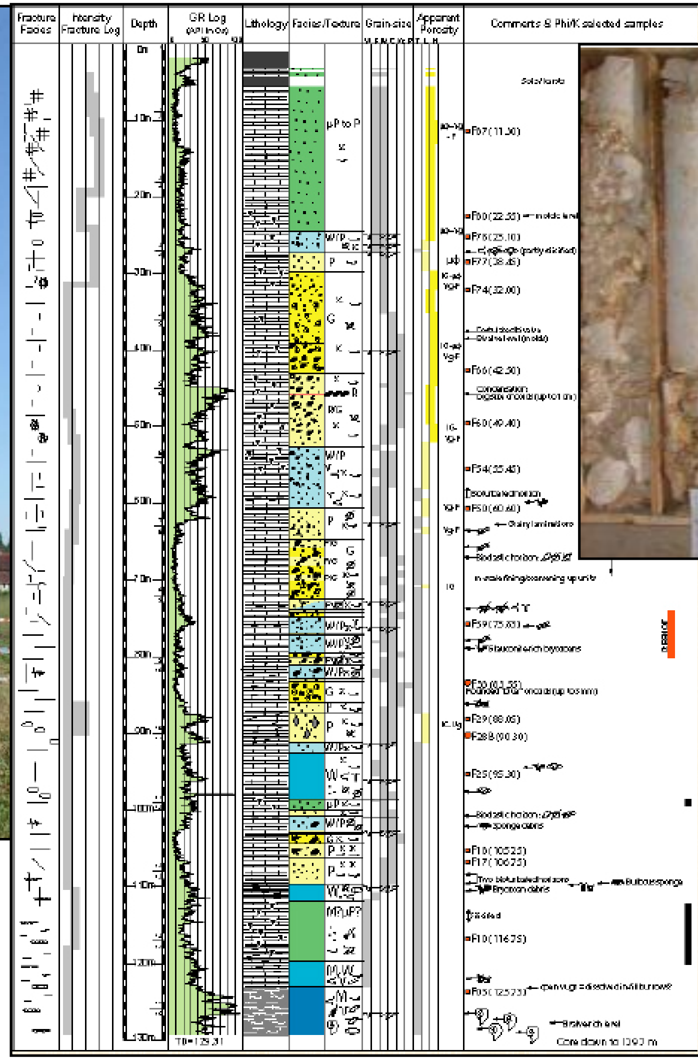
z_{sub} : substratum elevation (unc

f : sink and source (x,t)

Problem: how to determine the value of the parameters?

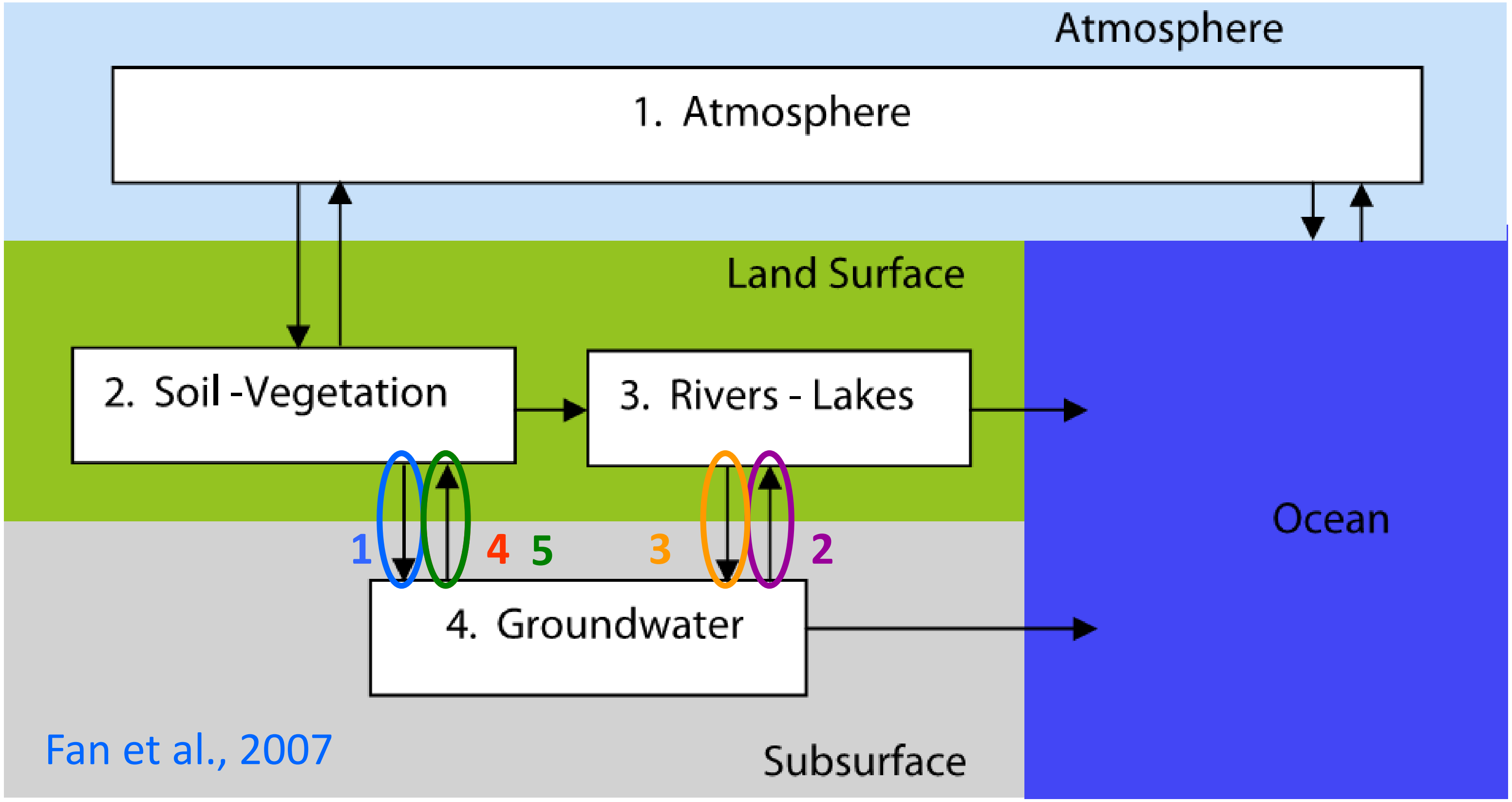
2. Water cycle: back to processes

Determining groundwater parameters: direct observation



Or (and) assimilation/inversion techniques

2. Water cycle: back to processes

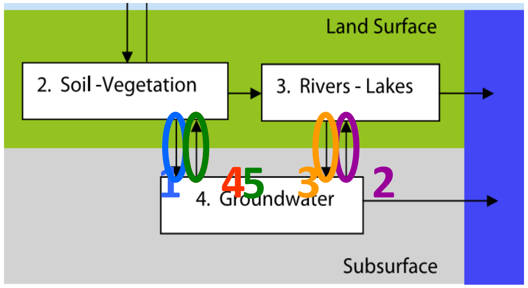


1. **Infiltration to the Aquifer**
2. **Aquifer to river exchange**
3. **River loss to aquifer**
4. **Groundwater evaporation loss**
5. **Groundwater abstraction**

2. Water cycle: back to processes

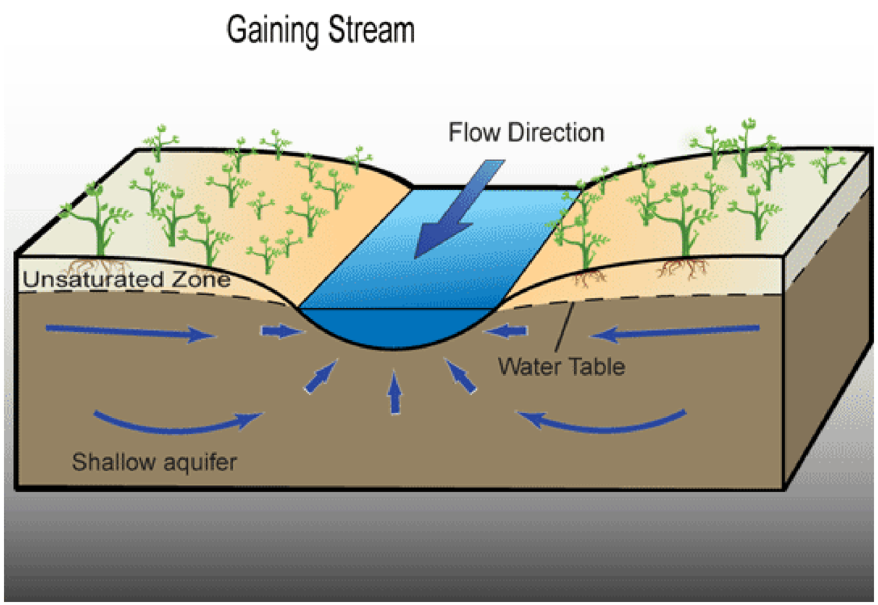
2. **Aquifer to river exchange**

3. **River loss to aquifer**



River aquifer interactions are not easy to handle, because of:

- High spatial and temporal variabilities
- Badly known distribution of the effective parameters



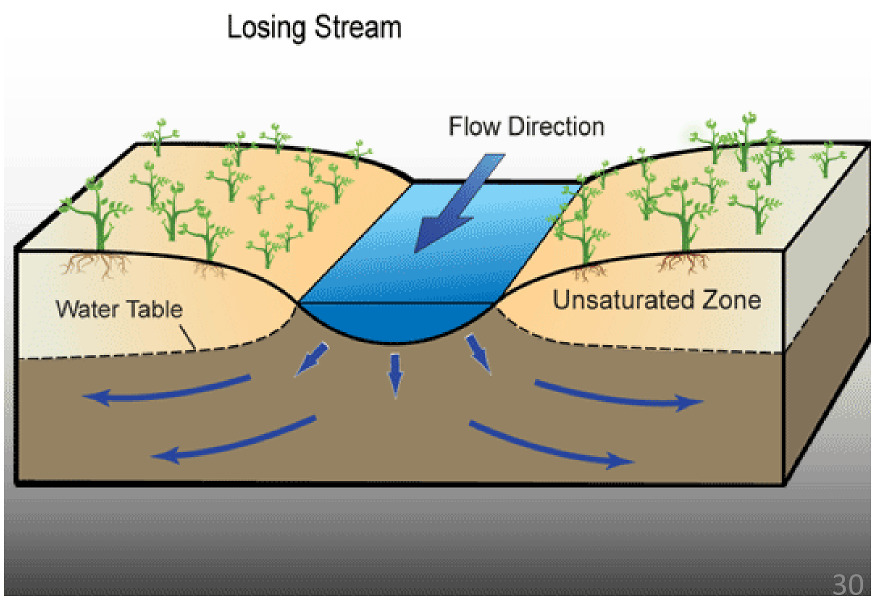
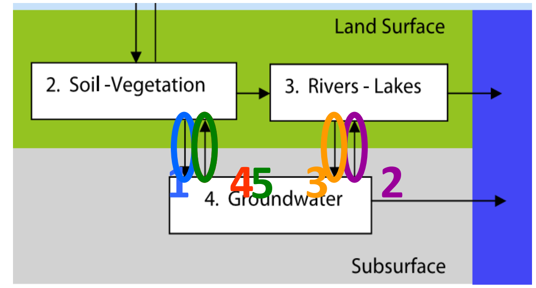


Figure connectedwatergov.au, Winter et al., 1998

2. Water cycle: back to processes



2. Aquifer to river exchange

3. River loss to aquifer

Evidence from observation:

Water balance in the Rhine upper alluvial basin
Aquifer to river exchange volume during a **flood event** in 1986

(Estèves, 1988)

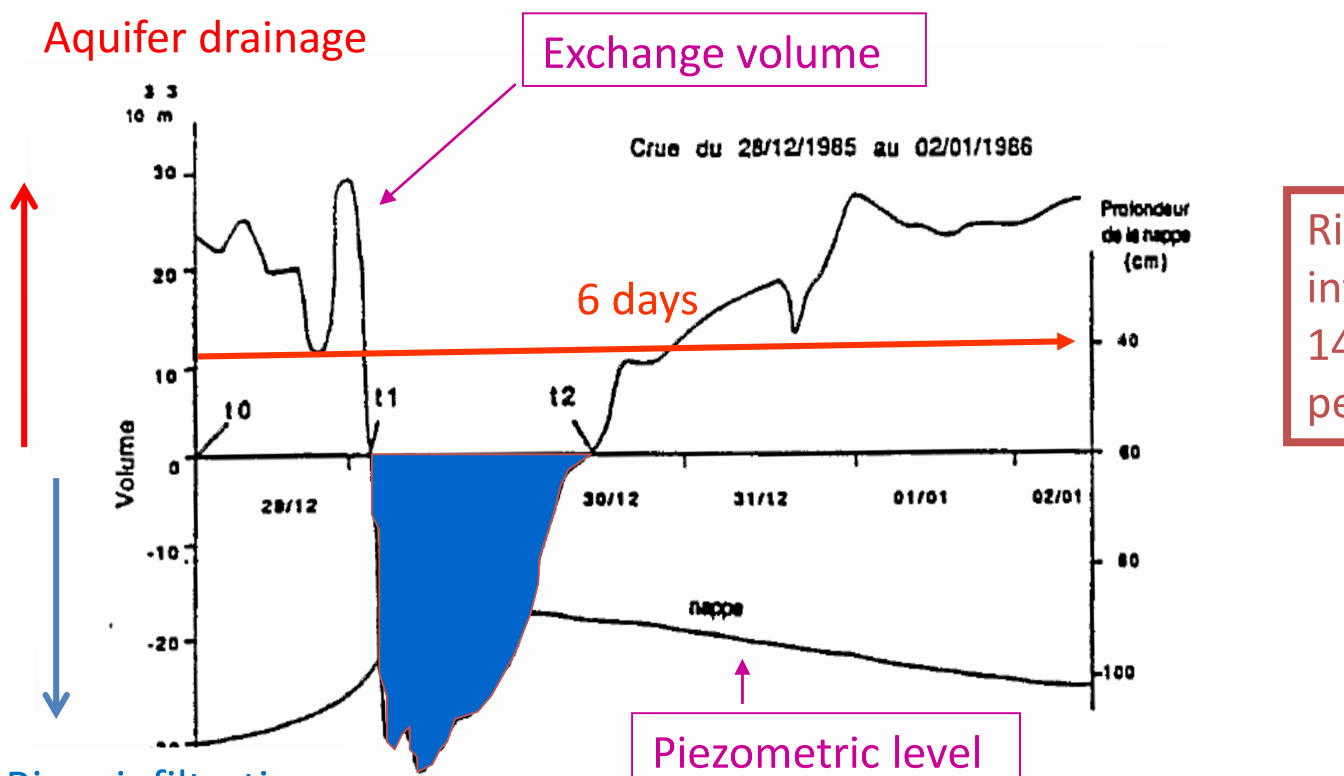


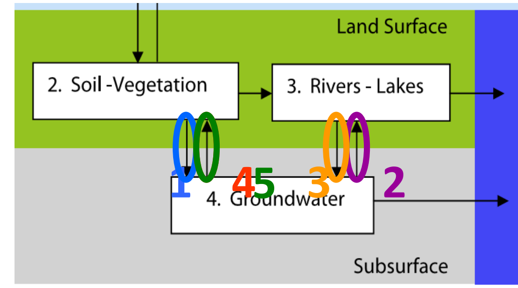
Figure 6 : Volumes d'eau échangés et variations du niveau piézométrique de la nappe au point P2 lors d'une crue.

River to aquifer infiltration:
14% of the river flood peak

2. Water cycle: back to processes

2. Aquifer to river exchange

3. River loss to aquifer



Transfer coefficient

River level

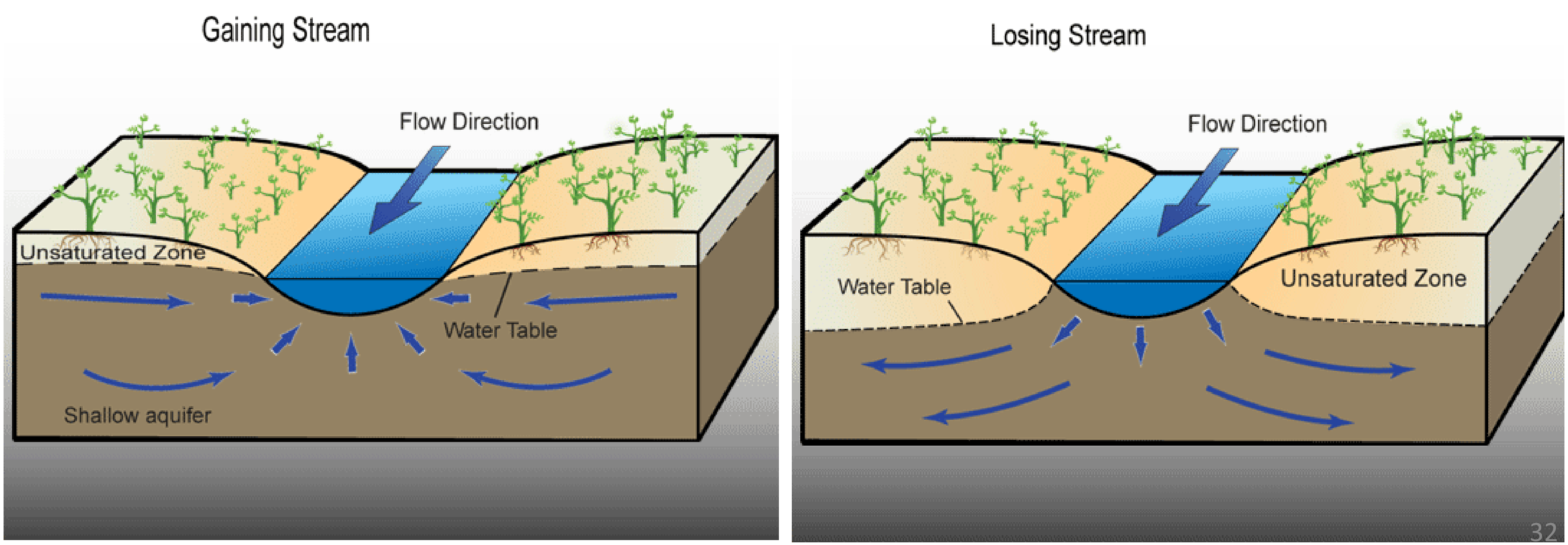
Piezometric level

$$Qexch_{river-aquifer} = \min \begin{cases} C_{riv} \cdot (H_0 - h) \\ Q_{\max} \\ V/\Delta t \end{cases}$$

Maximum infiltration rate

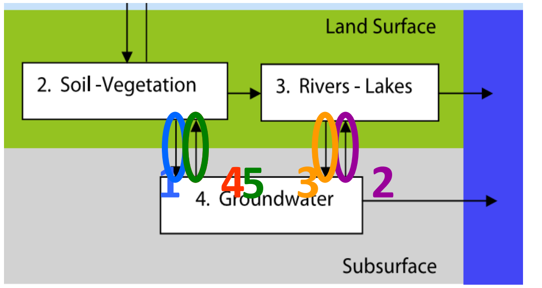
Volume of water in the river

Figure connectedwatergov.au, Winter et al., 1998



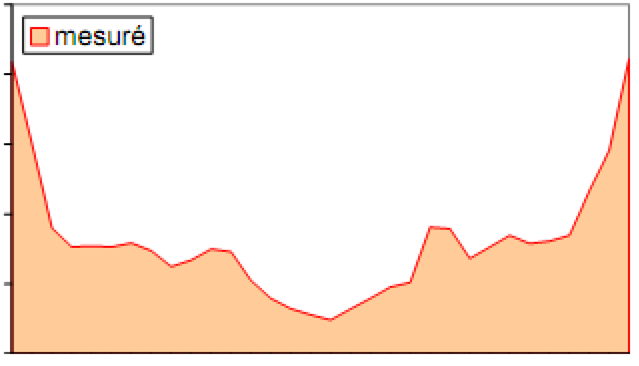
2. Water cycle: back to processes

2. Aquifer to river exchange
3. River loss to aquifer

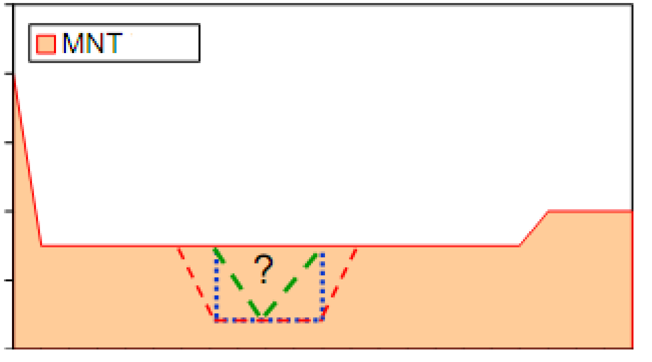


Sensitivity of the river level simulated by an hydraulic model to the river bed geometry

Observed river bed geometry

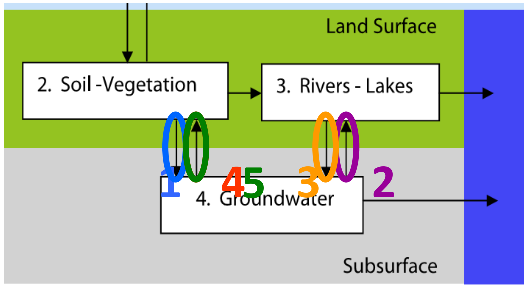


Data from DEM



Saleh et al, 2011

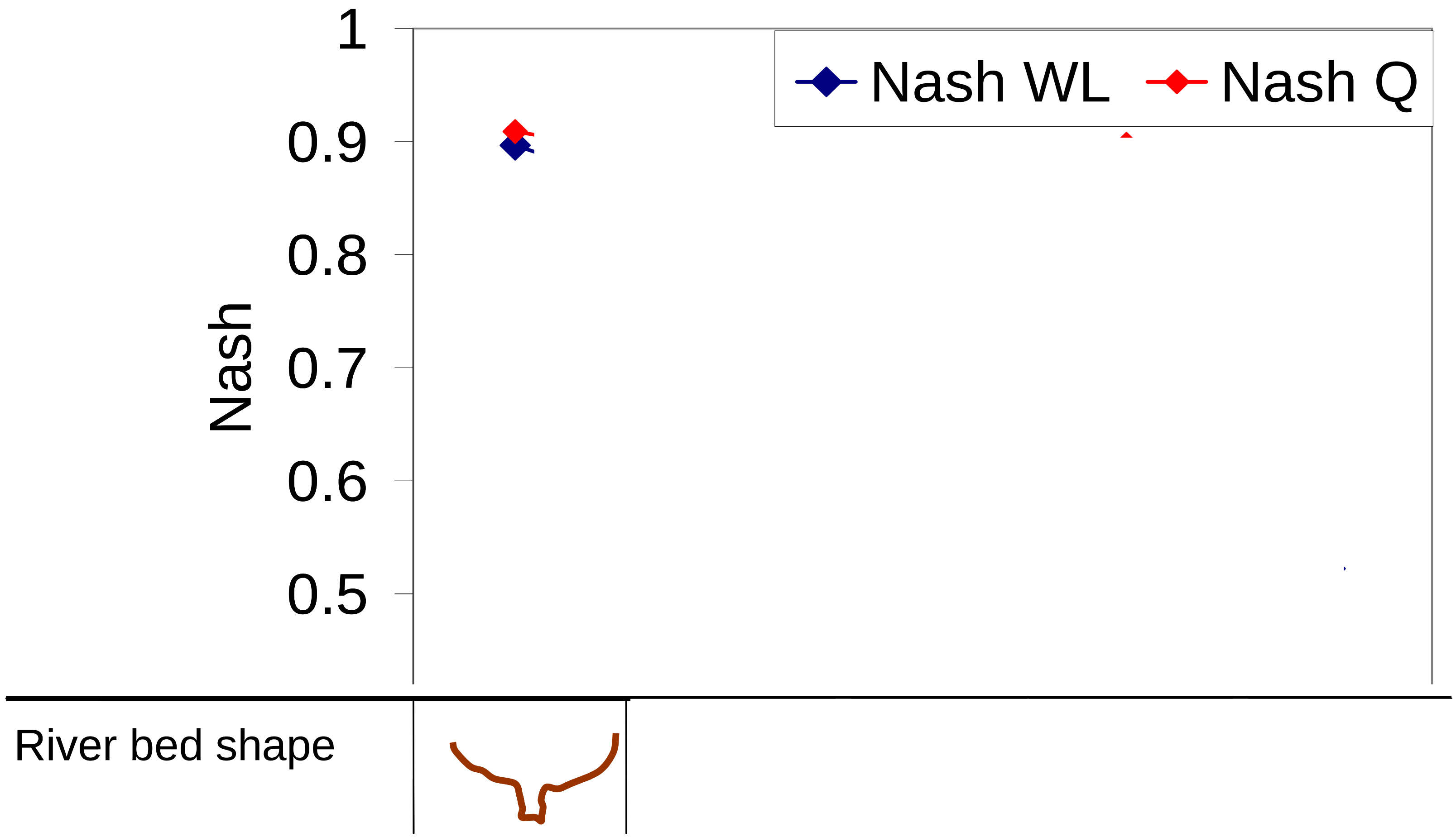
2. Water cycle: back to processes



2. Aquifer to river exchange

3. River loss to aquifer

Sensitivity of the river level simulated by an hydraulic model to the river bed geometry



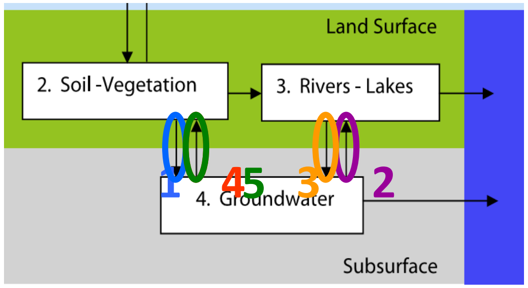
Saleh et al, 2011

2. Water cycle: back to processes

2. Aquifer to river exchange

3. River loss to aquifer

River level estimation at regionale scale

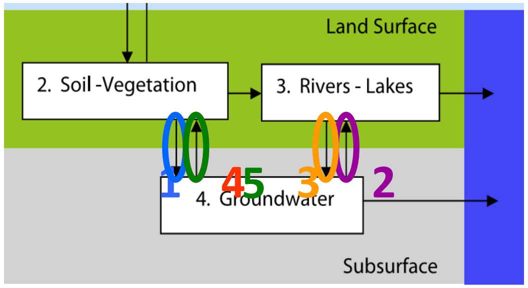


SWOT mission : Surface Water and Ocean Topography

This satellite mission will provide high resolution water level

http://swot.jpl.nasa.gov/

2. Water cycle: back to processes



2. Aquifer to river exchange

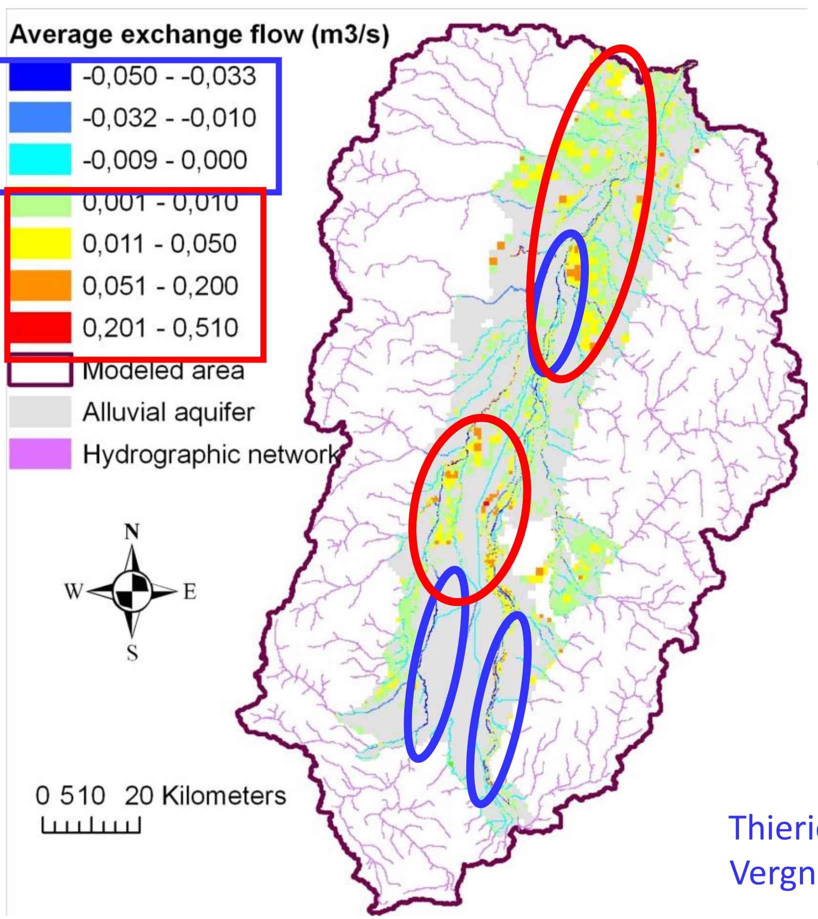
3. River loss to aquifer

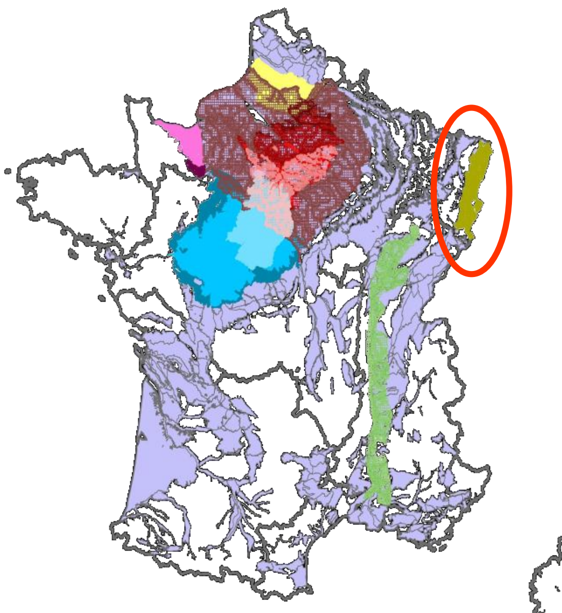
Spatial variabilities:

Simulation of the river aquifer exchange with variable river levels

River infiltration

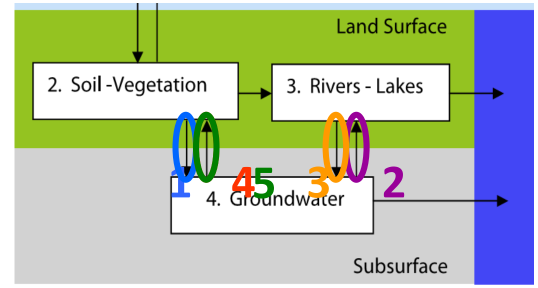
Aquifer drainage





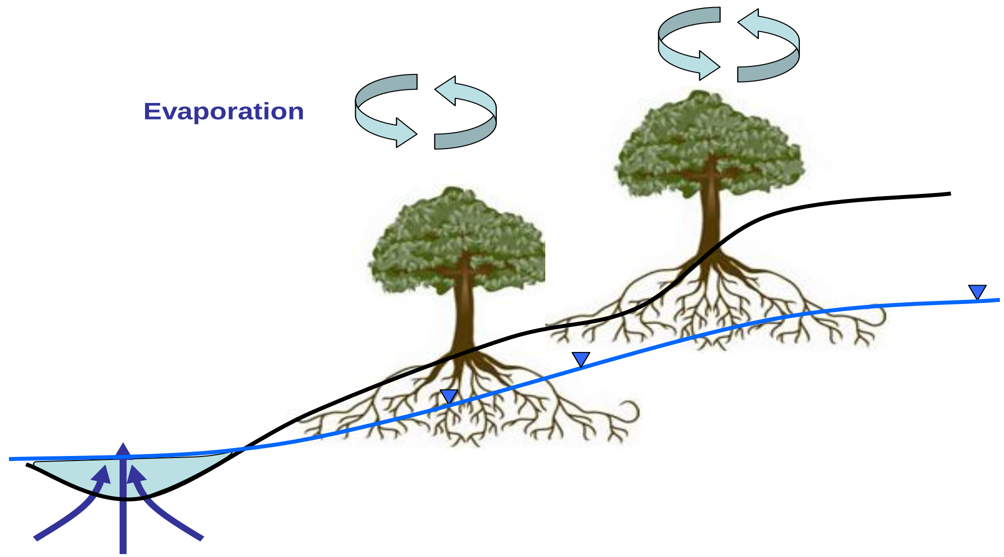
Thierion et al., 2012, JH
Vergnes & Habets, 2018

2. Water cycle: back to processes

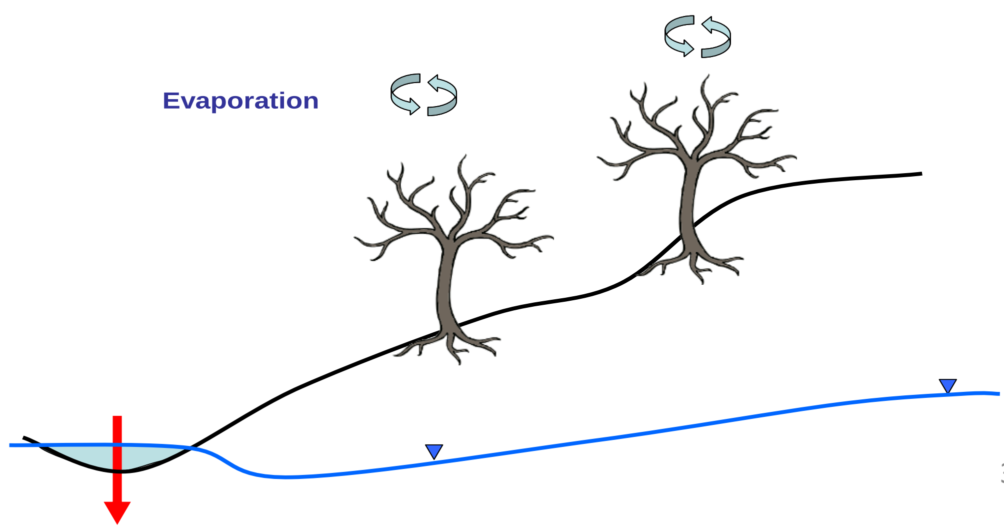


4. Groundwater evaporation loss

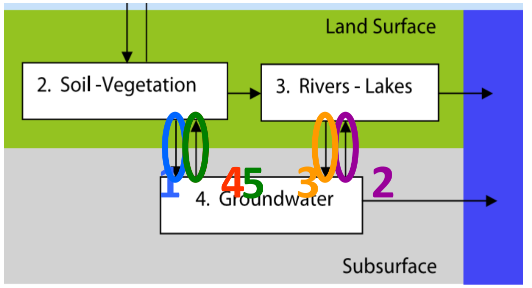
Most of the time, this flux is neglected:
➔ It is implicitely taken into account in the groundwater study



➔ What will happen if the groundwater conditions evolve?



2. Water cycle: back to processes



4. Groundwater evaporation loss

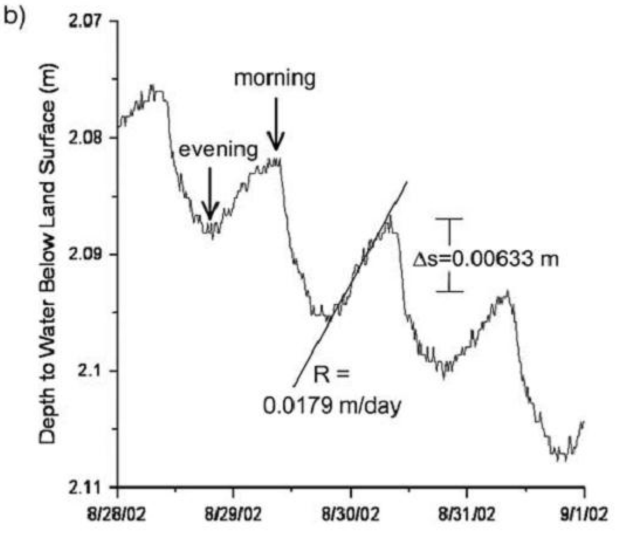
Estimation based on observations

High frequency analysis of piezometric change

Biochemistry & Isotopic observations

High evaporation losses in the Rhine wetlands

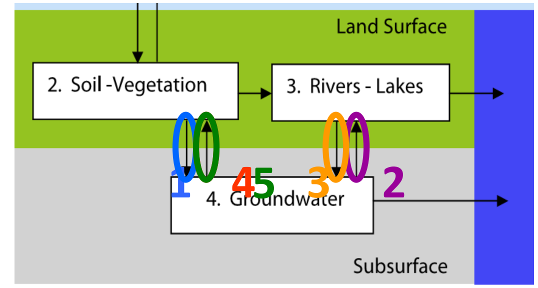
Sanchez Pérez et al., 2008



~50% of ETR in the Tagon basin

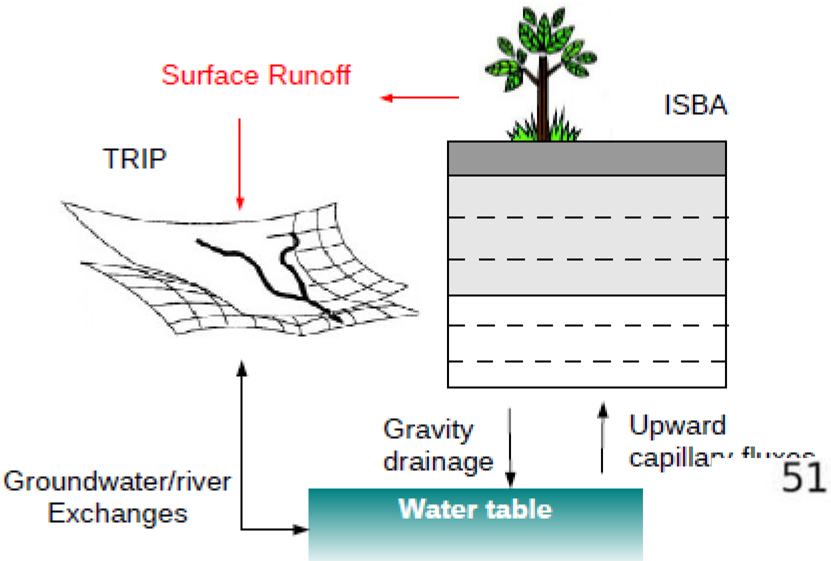
Guillot, 2011, Ephyse

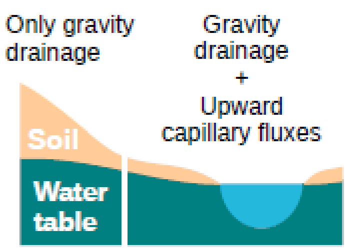
2. Water cycle: back to processes



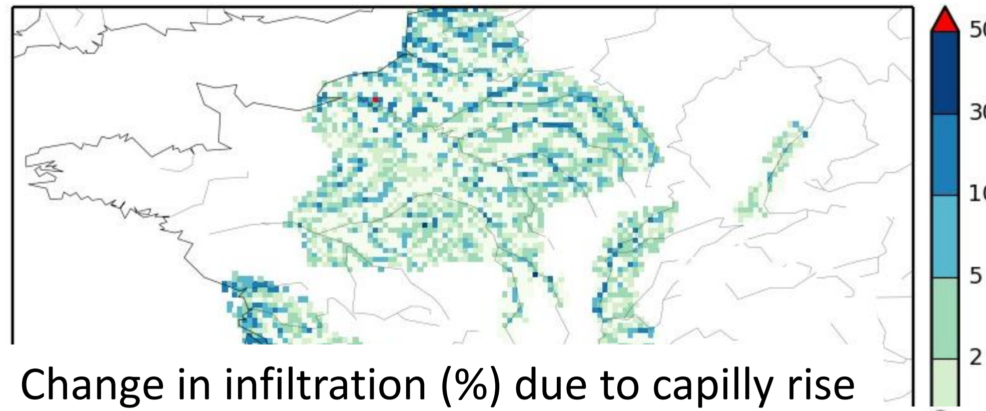
4. Groundwater evaporation loss

Estimation based on modeling

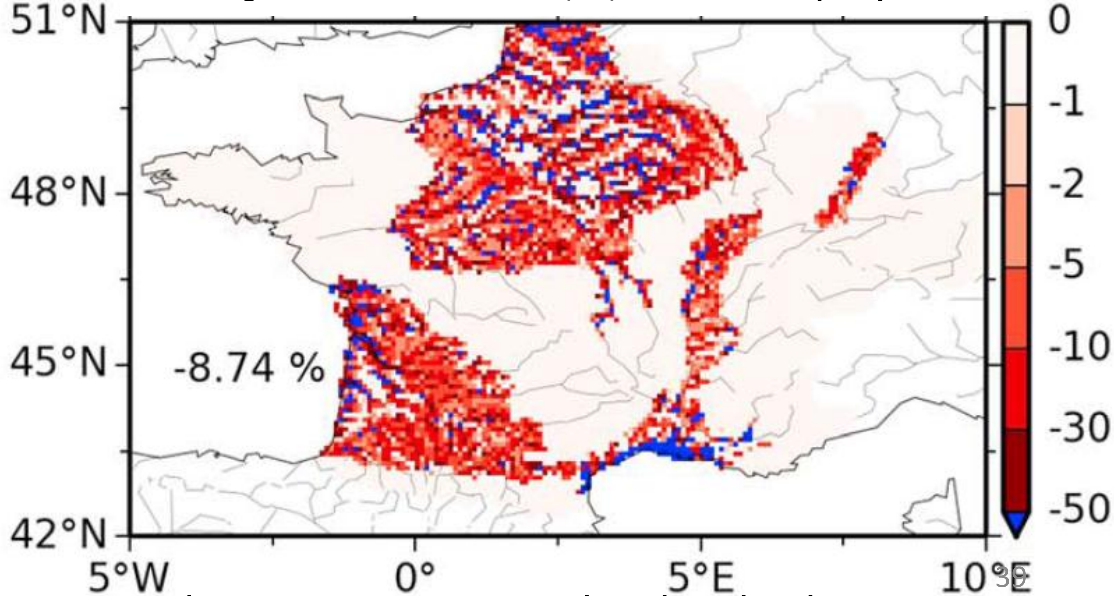




Change in evaporation (%) due to capilly rise



Change in infiltration (%) due to capilly rise



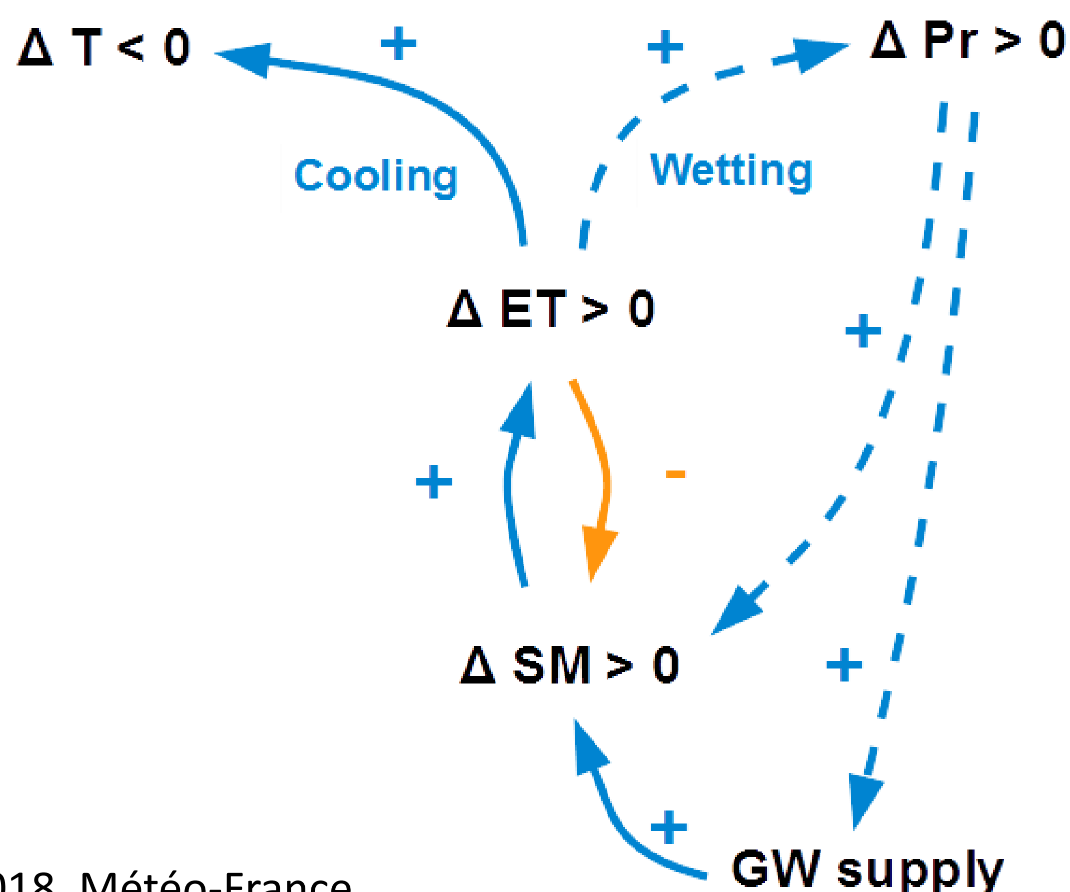
Vergnes et al., 2014 JGRA

About 9% on average but localy above 50%

2. Water cycle: back to processes

4. Groundwater evaporation loss➔ Feedback to atmosphere

Cooling and wetting effects : mechanism



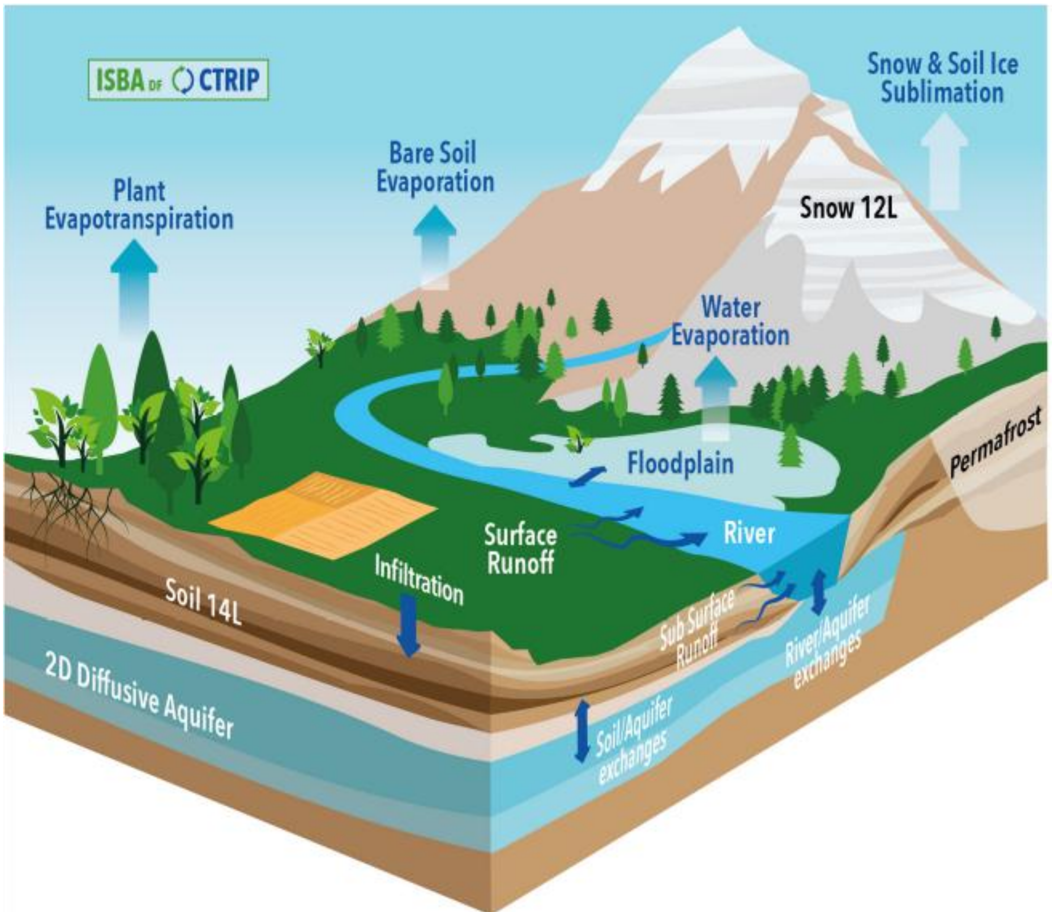
Colin et al., 2018, Météo-France

2. Water cycle: back to processes

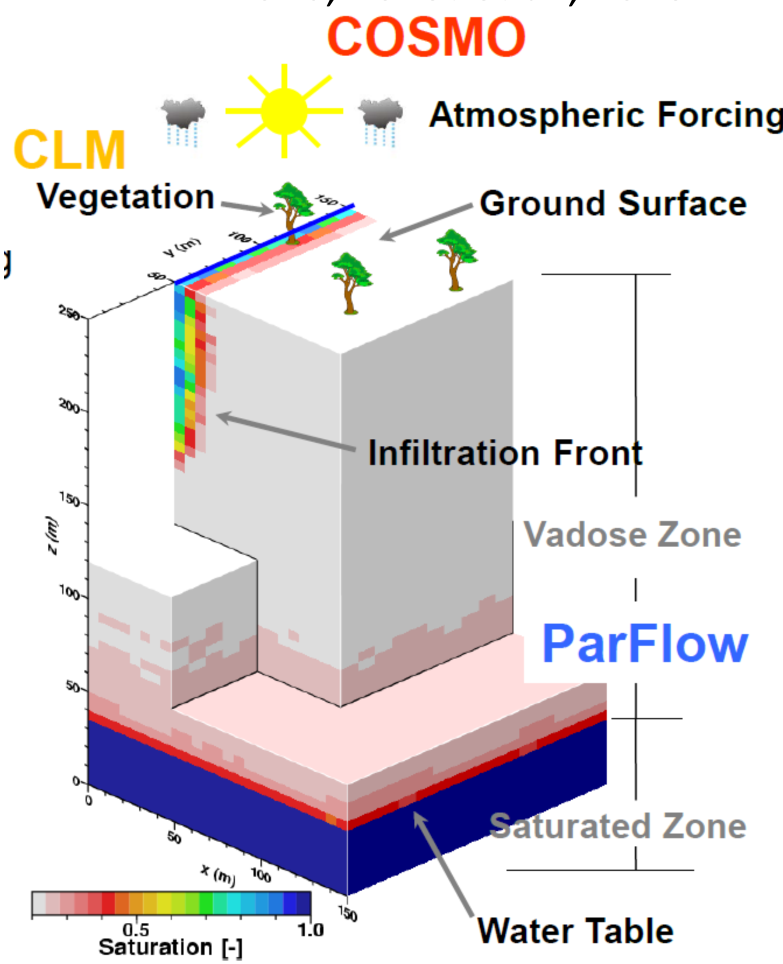
4. Groundwater evaporation loss➔ Feedback to atmosphere

Several coupled Groundwater Atmosphere model are getting developped

Decharme et al. 2018 (in prep)
CNRM-CM



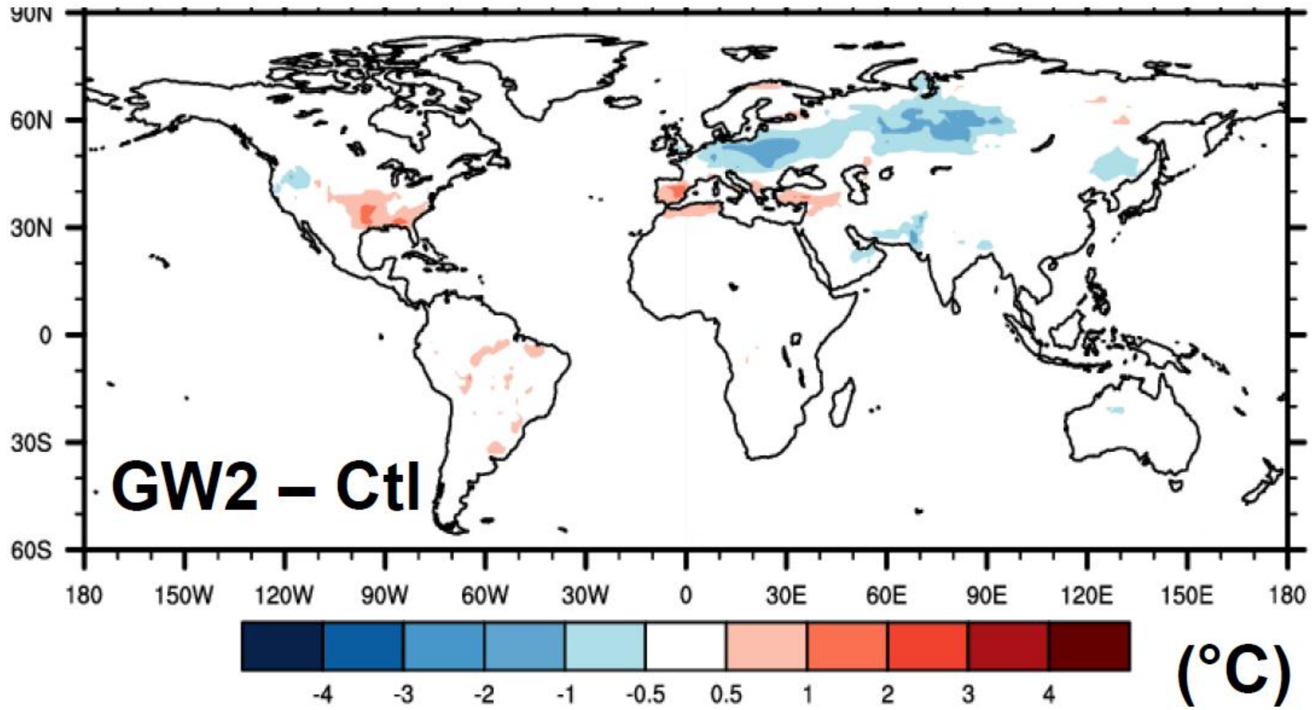
TerrSysMP Kuntz et al., 2016, Kollet et al., 2018



2. Water cycle: back to processes

4. Groundwater evaporation loss➔ Feedback to atmosphere

Impact of Groudwater in the context of climate change with CNRM-CM



=> Up to -2 °C

Colin et al., 2018, Météo-France

HYDROLOGICAL MODELING: INTEGRATING THE IMPACT OF THE GROUNDWATER AND ANTHROPOGENIC EFFECT AT THE BASIN SCALE

1. Some general patterns on the water cycle
2. Zoom on the main processes
3. **Impact of human activities**

3. Anthropogenic impacts on the water cycle

Direct impacts:

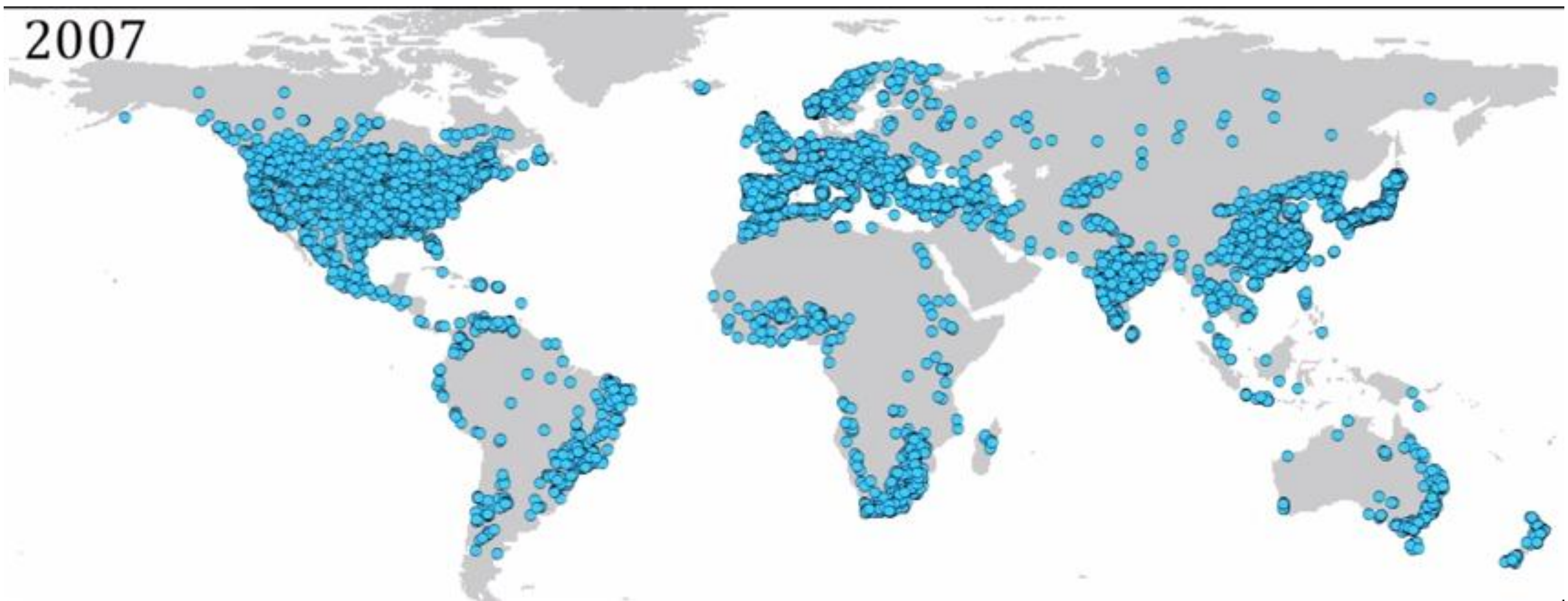
- River Dams
- Groundwater abstraction

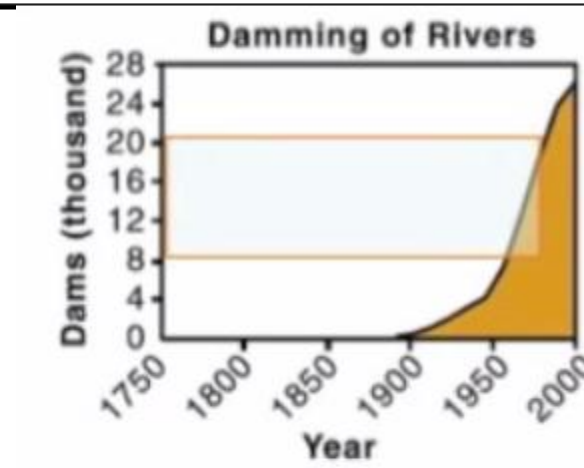
Indirect impacts:

- Land Use change
- Sea Level Rise
- Erosion and subsidence
- Climate change
- Pollution…

3. Anthropogenic impacts on the water cycle

Damming of river



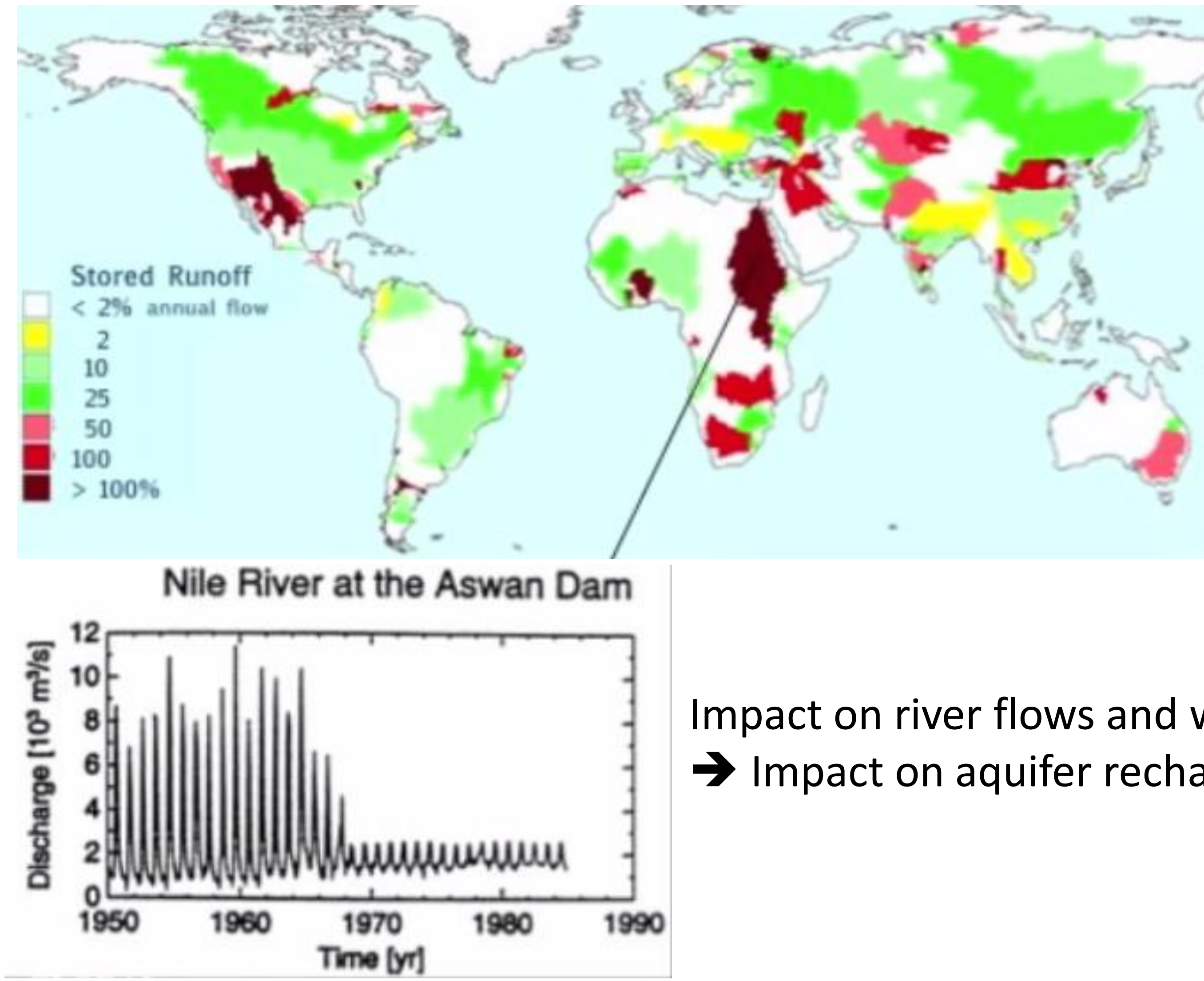


Global Reservoir and Dam (GRanD) database
Lehner et al., 2011
Dams with reservoirs larger than 0.1 km3

➔ 6,862 large dams, 6.1 km3 water store

3. Anthropogenic impacts on the water cycle

Damming of river



Impact on river flows and wetlands

➔ Impact on aquifer recharge

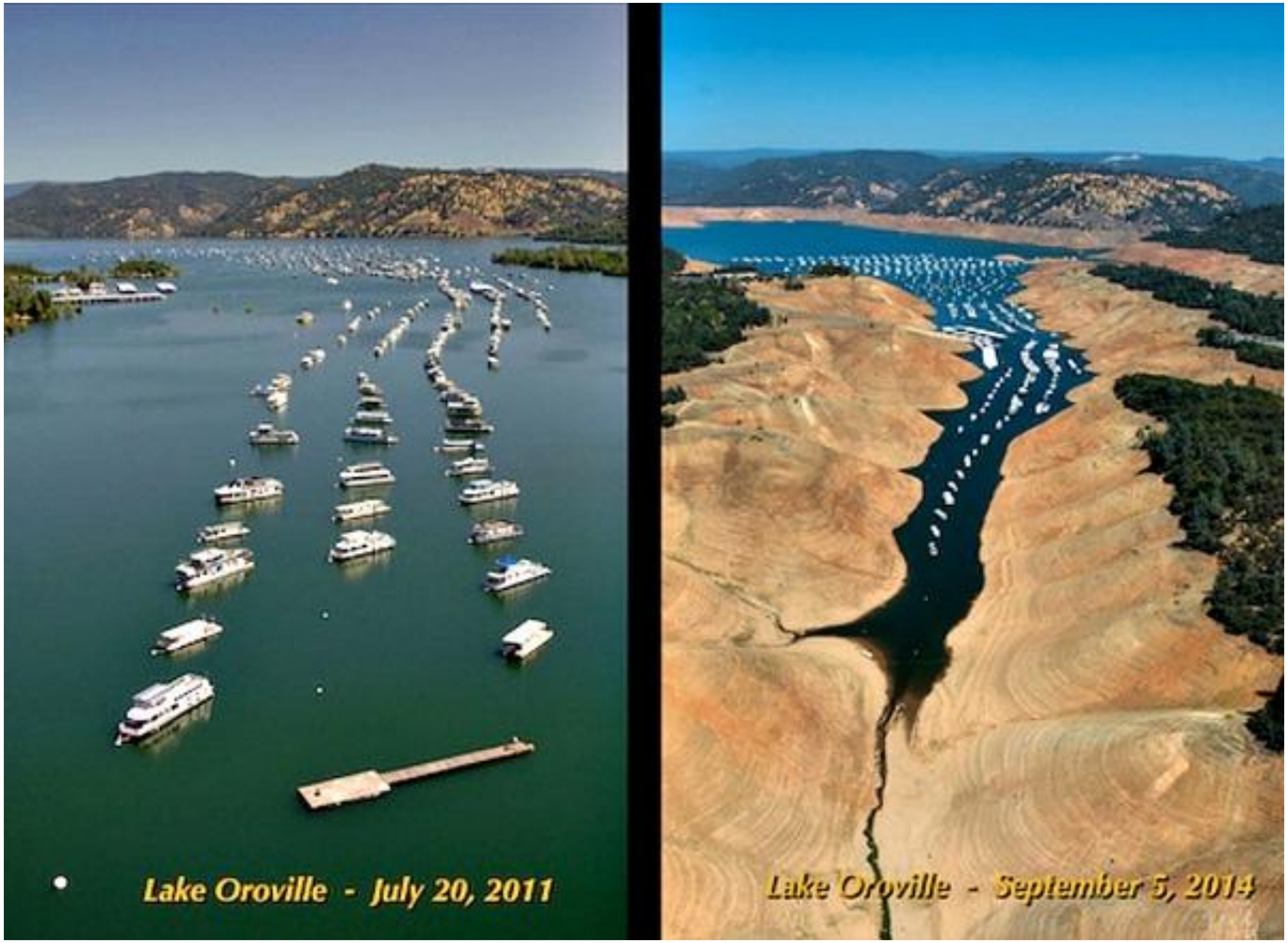
Global Reservoir and Dam (GRanD) database

3. Anthropogenic impacts on the water cycle

Damming of river The limits of managing the water resource by the o

Difficulty to fill up the dams

Building new dams will not necesseraly provides more water



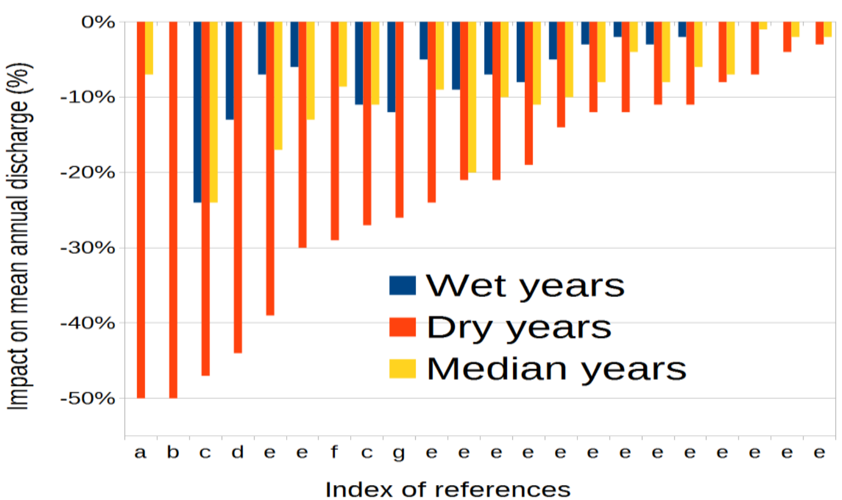
3. Anthropogenic impacts on the water cycle

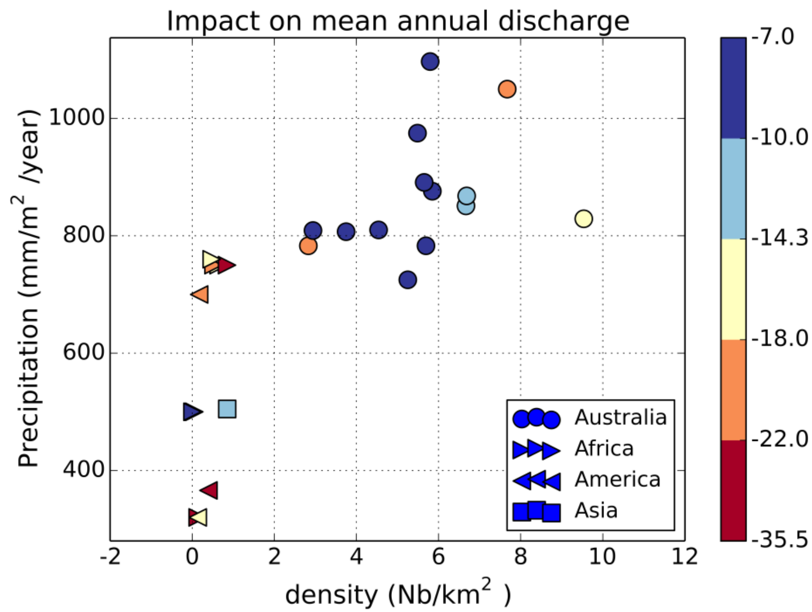
Damming of river: small dams

Strong impact on riverflows

Impact of the small dam network difficult to anticipate due to the various managment of the dams

Evolution of annual riverflow of watershed higly equiped with small dams(%) as a function of the humid/dry years



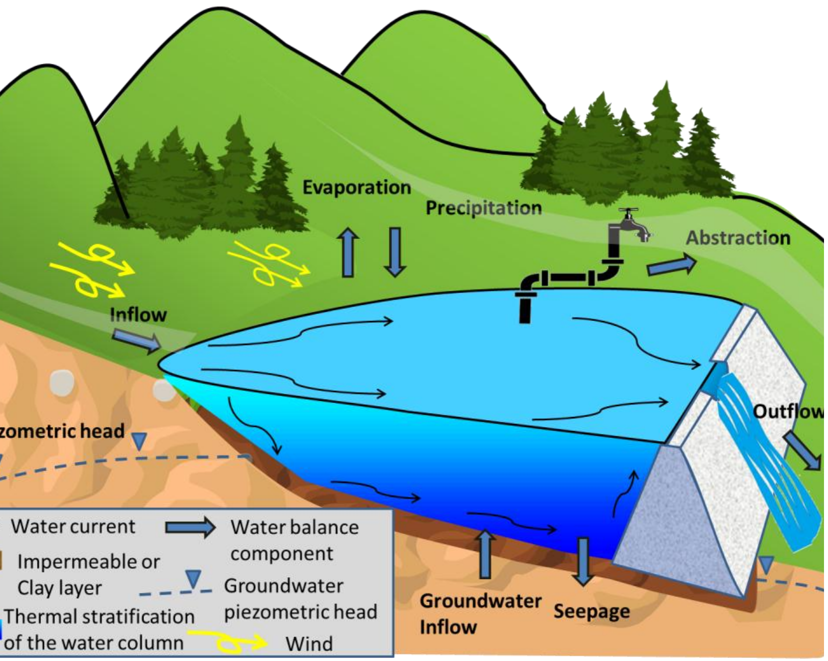


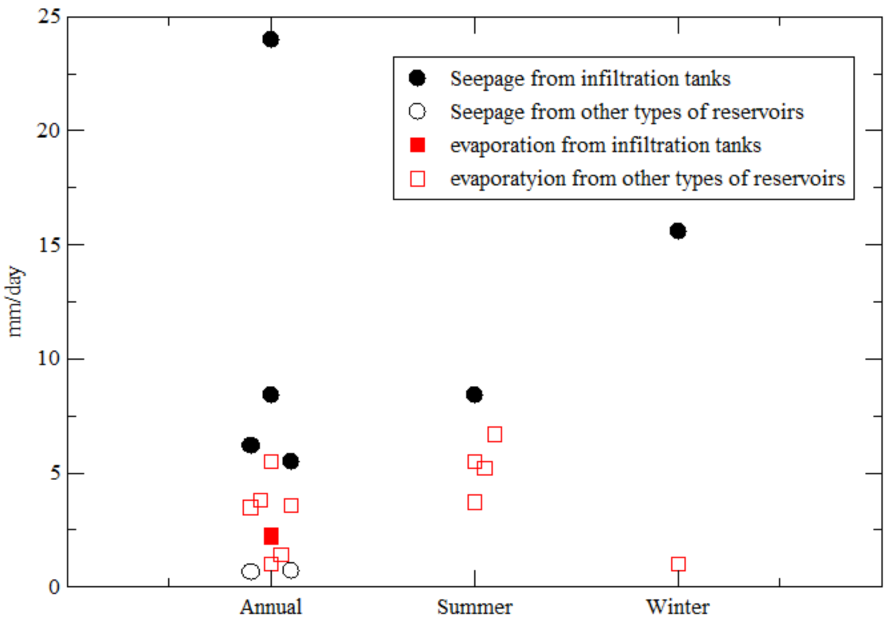
On average, small dams reduce annual discharge by 10%
But far more the dry year….

Habets, Molénat et al., 2018

3. Anthropogenic impacts on the water cycle

Damming of river: small dams

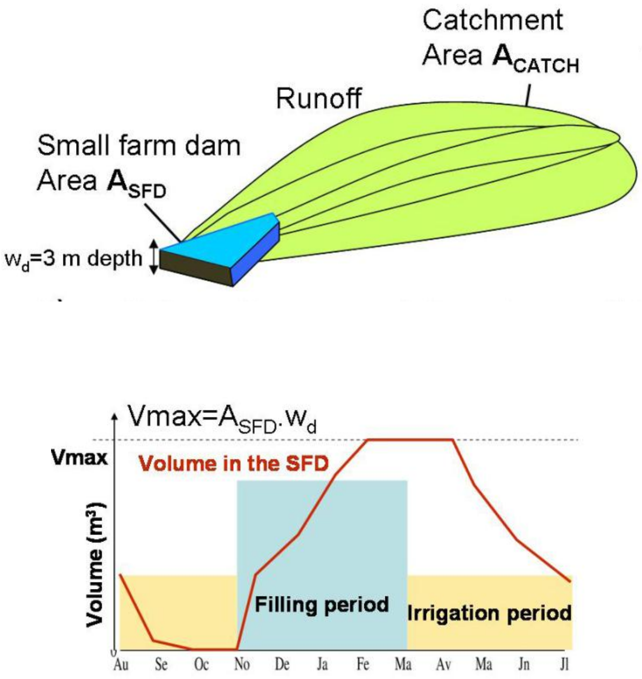


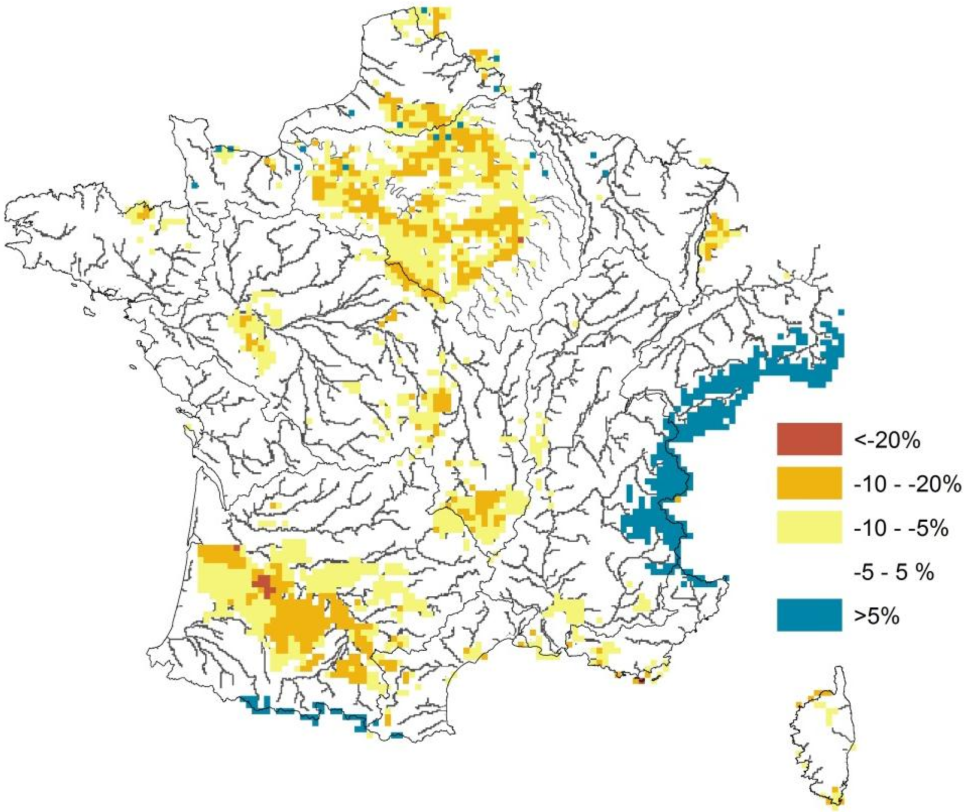


Habets, Molénat et al., 2018

3. Anthropogenic impacts on the water cycle

Damming of river: small dams:
modeling allow to project the efficiency (dam's filling)

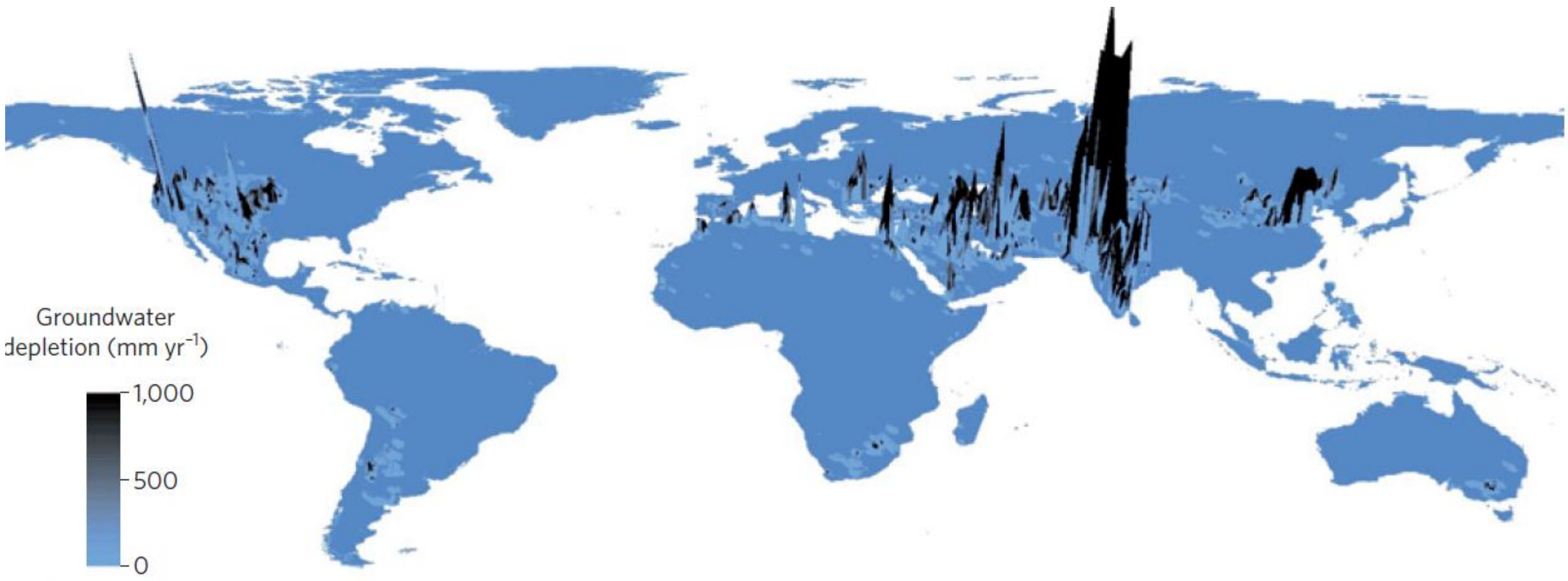




Habets et al., 2014

3. Anthropogenic impacts on the water cycle

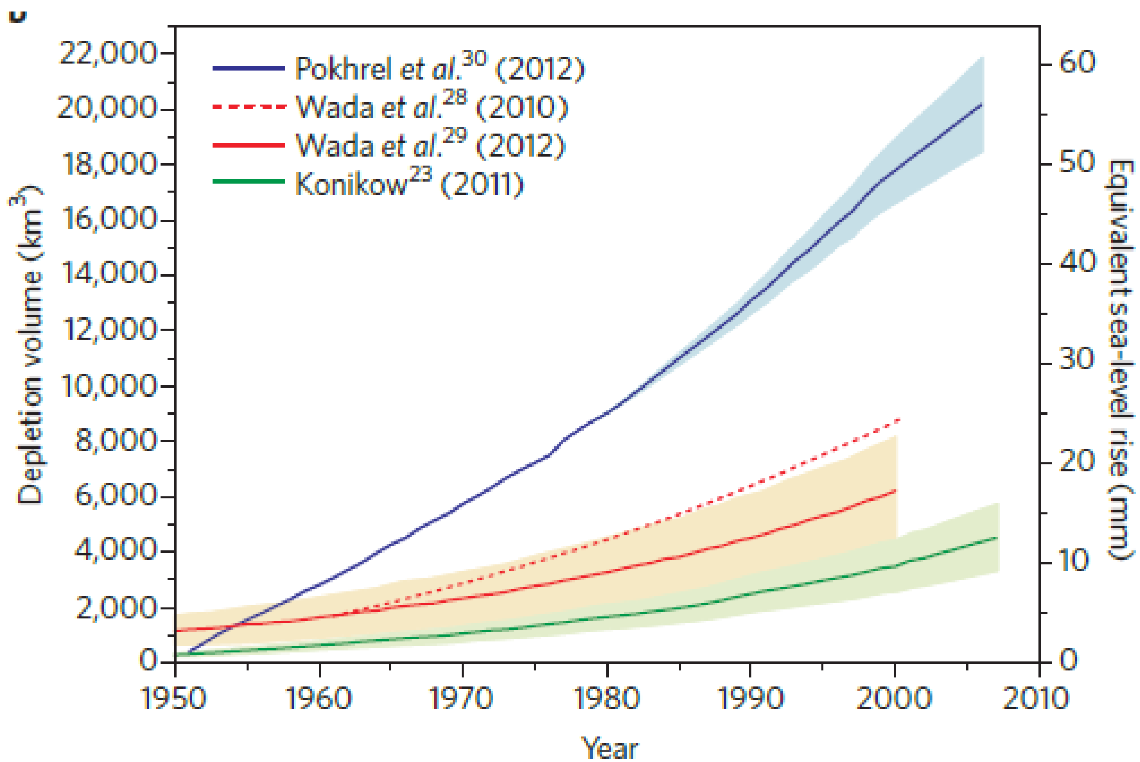
Groundwater abstraction



Aeschbach-Hertig & Gleeson, Nature Geoscience, 2012

3. Anthropogenic impacts on the water cycle

Groundwater abstraction



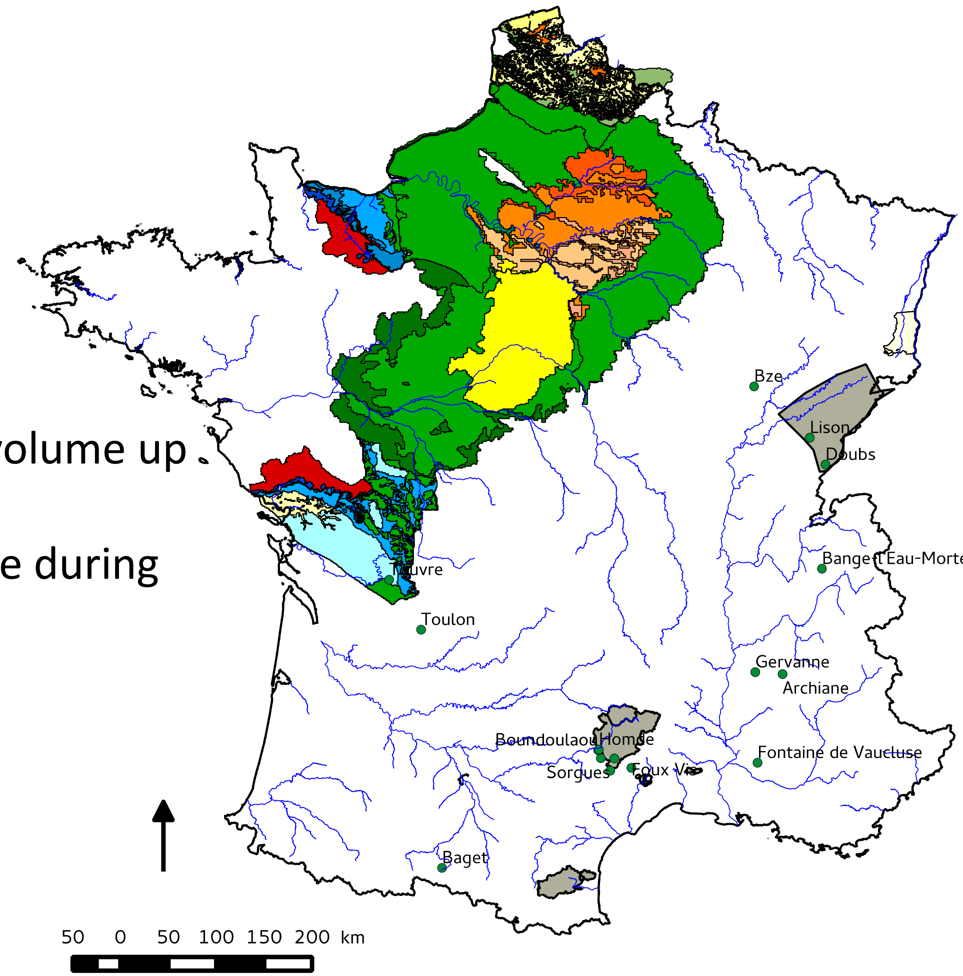
Estimated groundwater depletion and corresponding sea-level rise

Aeschbach-Hertig & Gleeson, Nature Geoscience, 2012

3. Anthropogenic impacts on the water cycle

Groundwater abstraction

Example within the Aqui-FR project



- Over **16 000** GW abstractions points, for a volume up to **2.4 billion** m^3
- Pumpings can represent half or the recharge during dry year
- Pumpings affect low flow

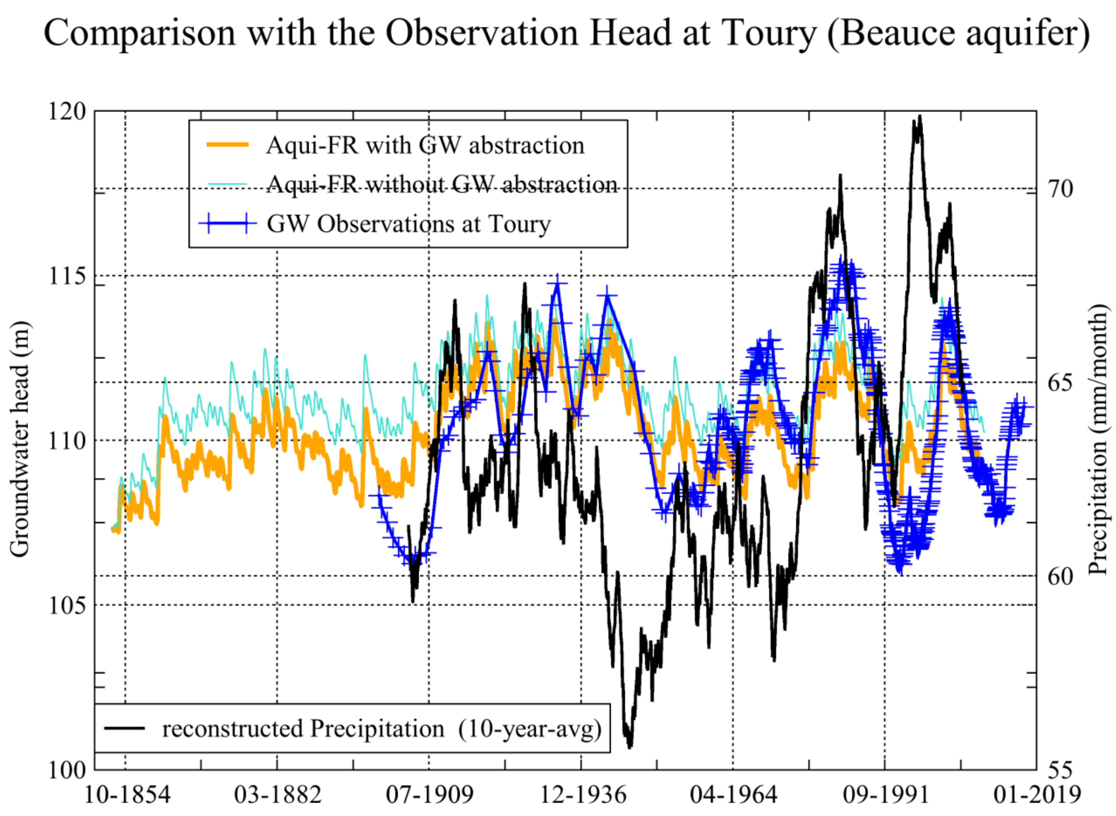
Roux et al., 2018 (CMWR); Vergnes et al., 2018 (CMWR)

www.metis.upmc.fr/~aqui-fr

3. Anthropogenic impacts on the water cycle

Groundwater abstraction

Example within the Aqui-FR project and the XXth century reconstruction by Bonnet et al. 2018 (CERFACS)



4. Climate change & Anthropogenic impacts cycle

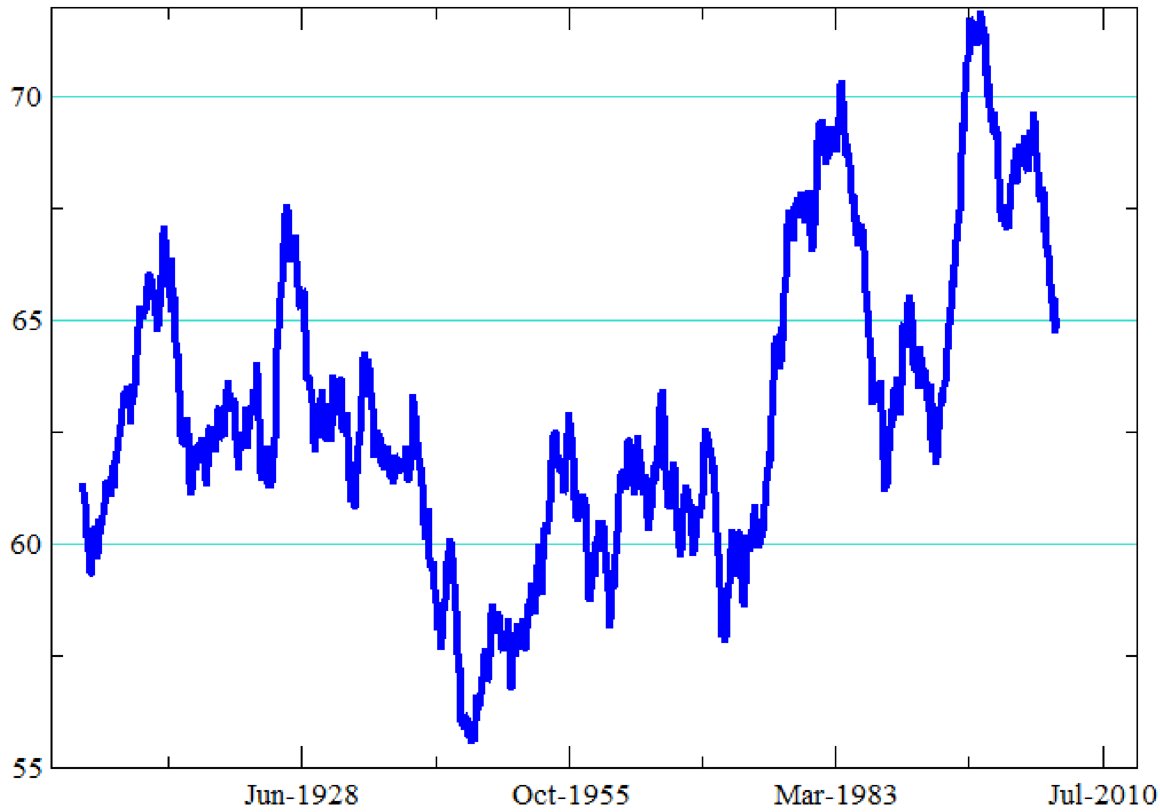
Climate change !

Still difficult to disentangle climate change and anthropogenic change
In the last 70 years:

- There are climate variabilities + changes
- Change in land Use
- Change in agricutural practises : yield of wheat increase by 700%!

4. Climate change & Anthropogenic impacts cycle

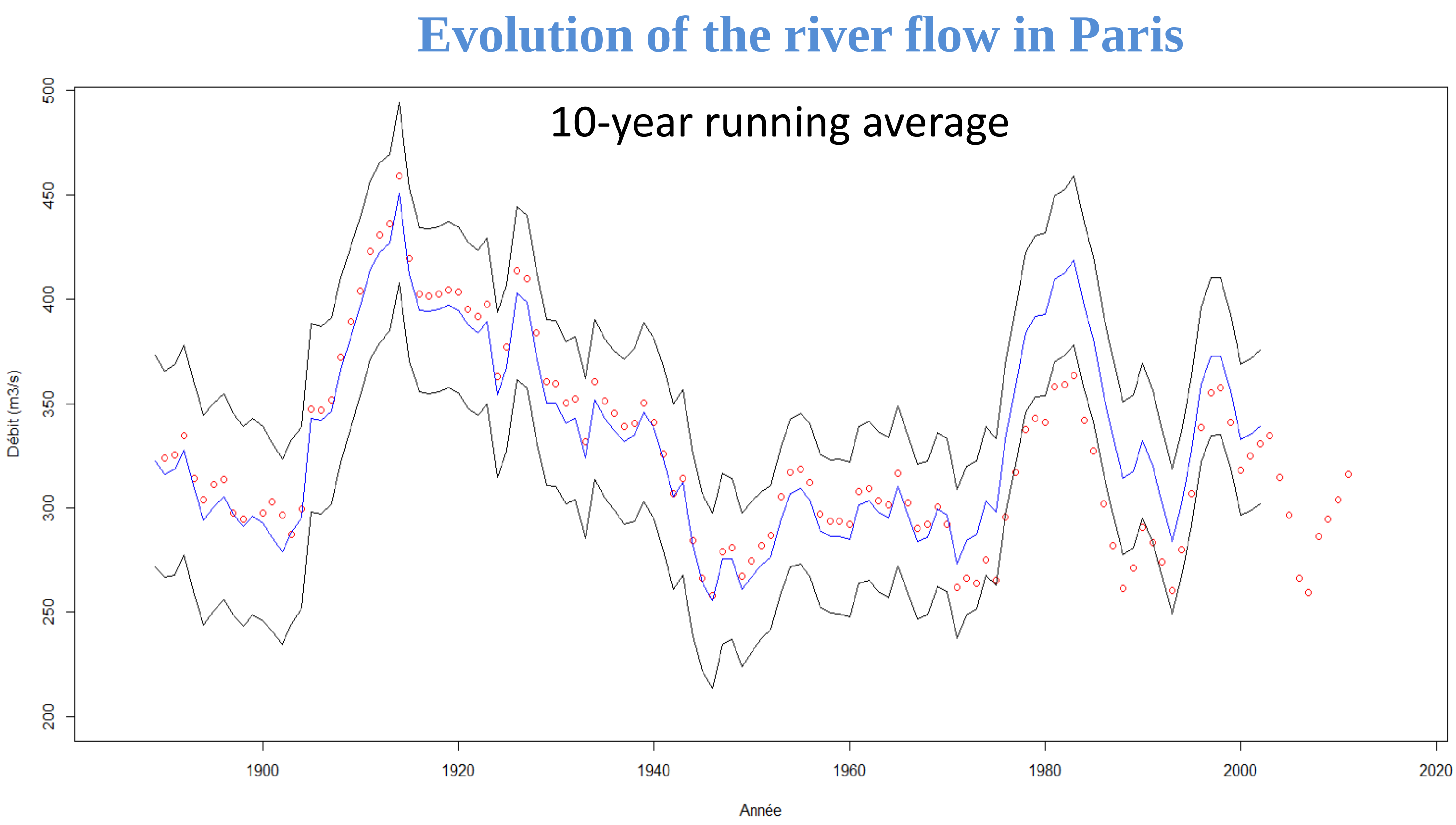
Evolution of monthly precipitation in the Seine Basin



Strong pluri-annual variabilities
Trend of an increase of precipitation

Source: GPCC

4. Climate change & Anthropogenic impacts cycle

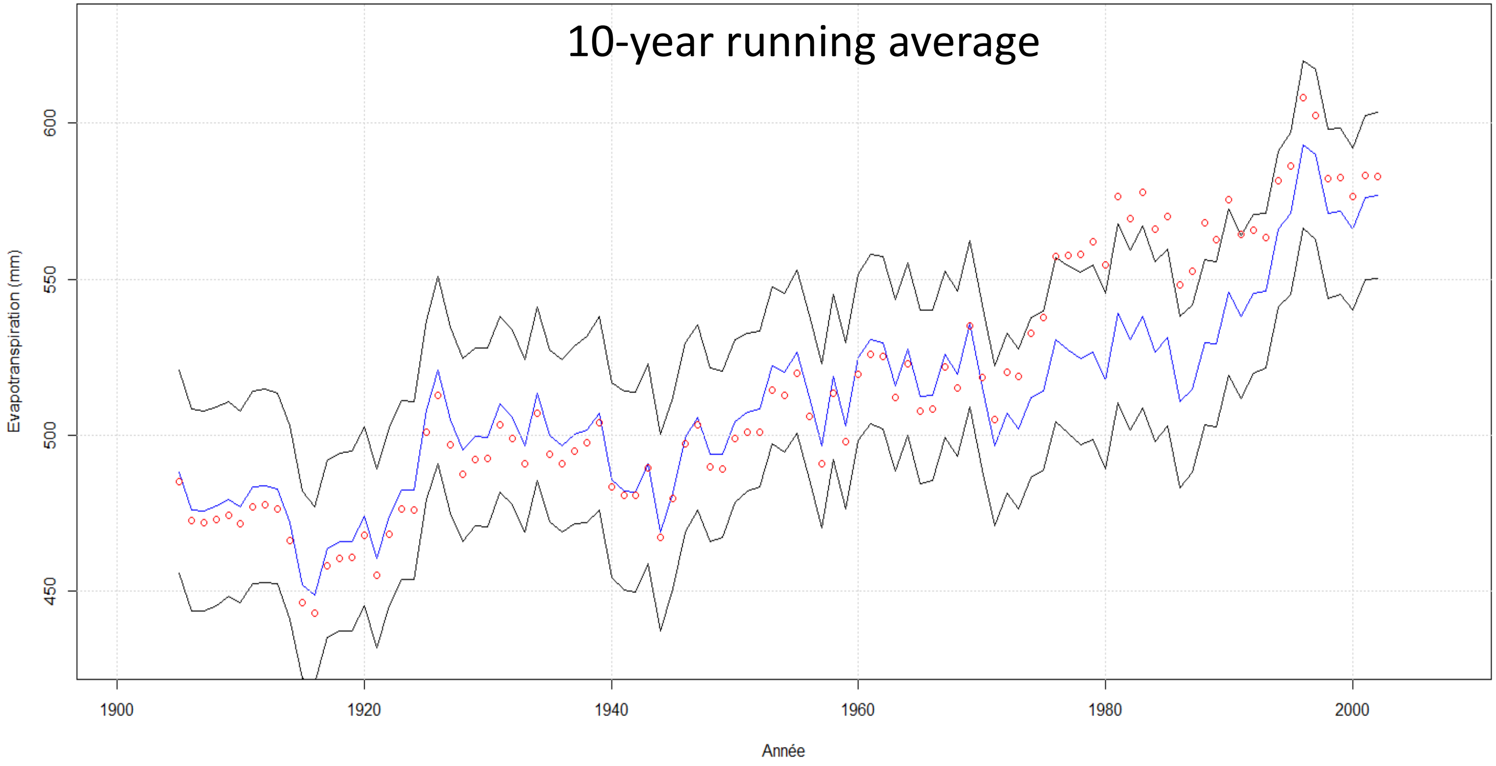


➔Strong variabilities, no increase trend

Source: LEFE project Vitesse, Boé et al.

4. Climate change & Anthropogenic impacts cycle

Estimation evolution of the actual evapotranspiration in the Seine basin
E=P-Q

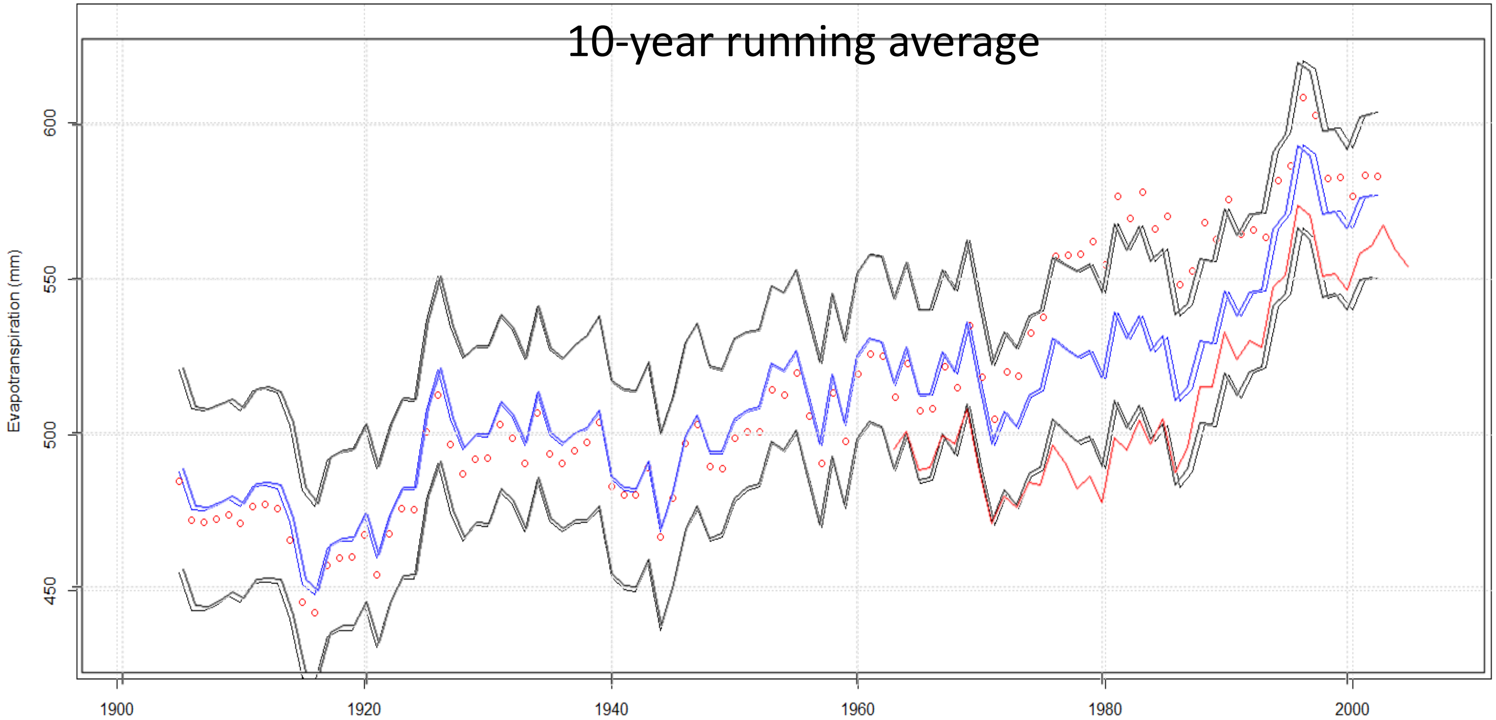


➔strong increase !

Source: LEFE project Vitesse, Boé et al.

4. Climate change & Anthropogenic impacts cycle

Estimation of the evolution of the actual evapotranspiration in the Seine basin E=P-Q



The model reproduces the trend on evaporation although it doesn't take into account the change in land use, agricultural practices, nor damming….

Is it error compensation (luck?)
Or is it that anthropogenic change is already weaker than climate change ?

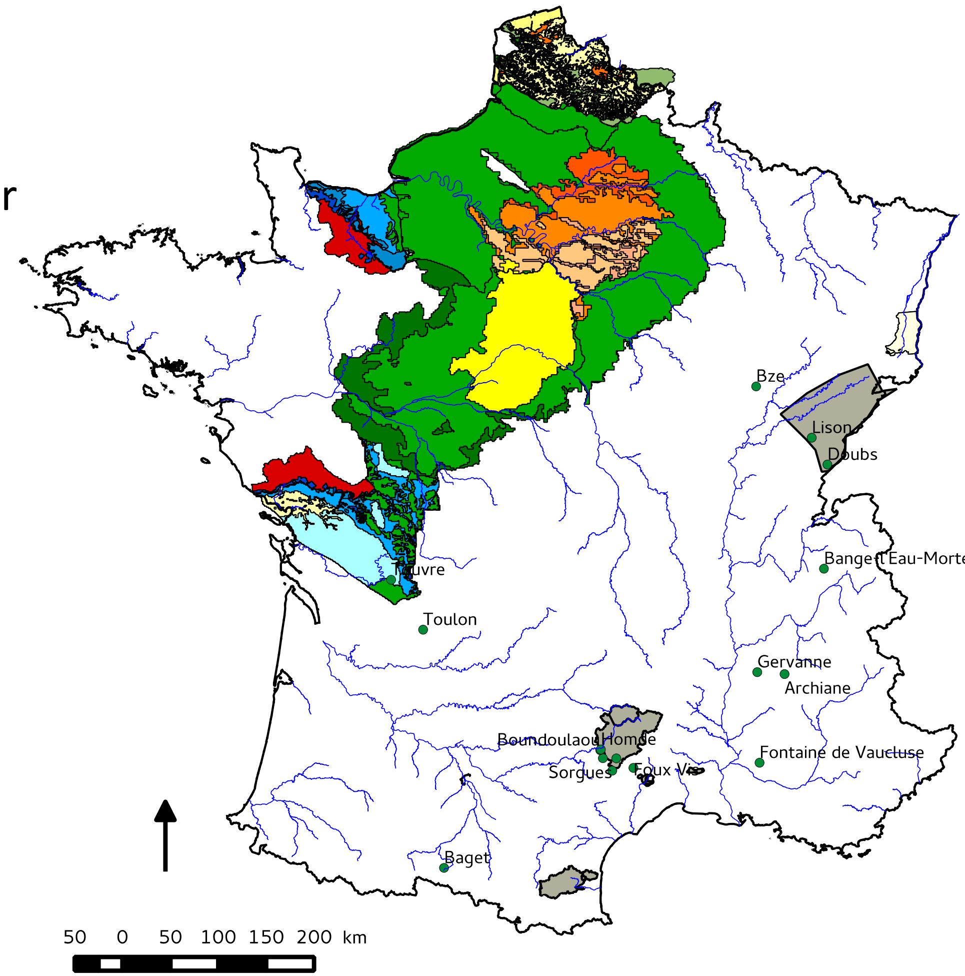
Source: LEFE project

5. Climate change & groundwater

Impact on River & groundwater with the Aqui-FR model

Assessment of present day simulation over

- **554** river gages (**BD Hydro**)
- **629** piezometric gages (**ADES**)



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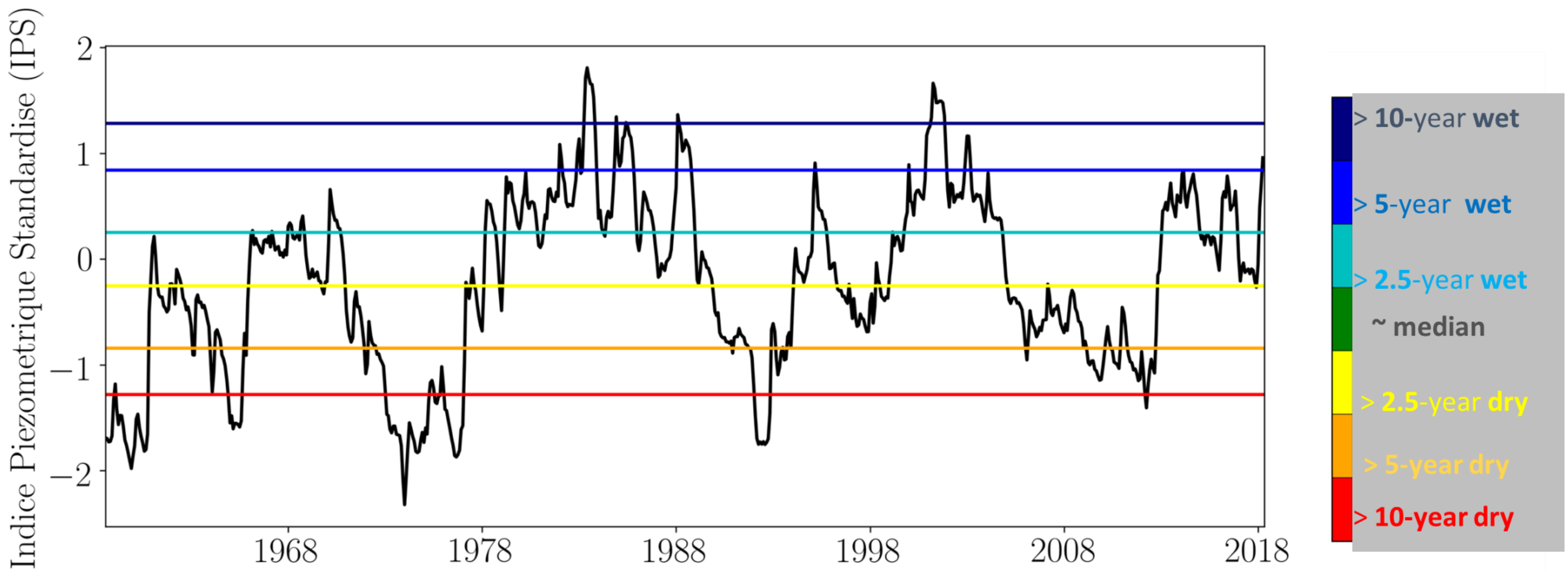
Roux et al., 2018 (CMWR); Vergnes et al., 2018 (CMWR)

5. Climate change & groundwater

Impact on River & groundwater with the Aqui-FR model

- Present day evolution of the standardised piezometric level index (SPLI)



Roux et al., 2018 (CMWR); Vergnes et al., 2018 (CMWR)

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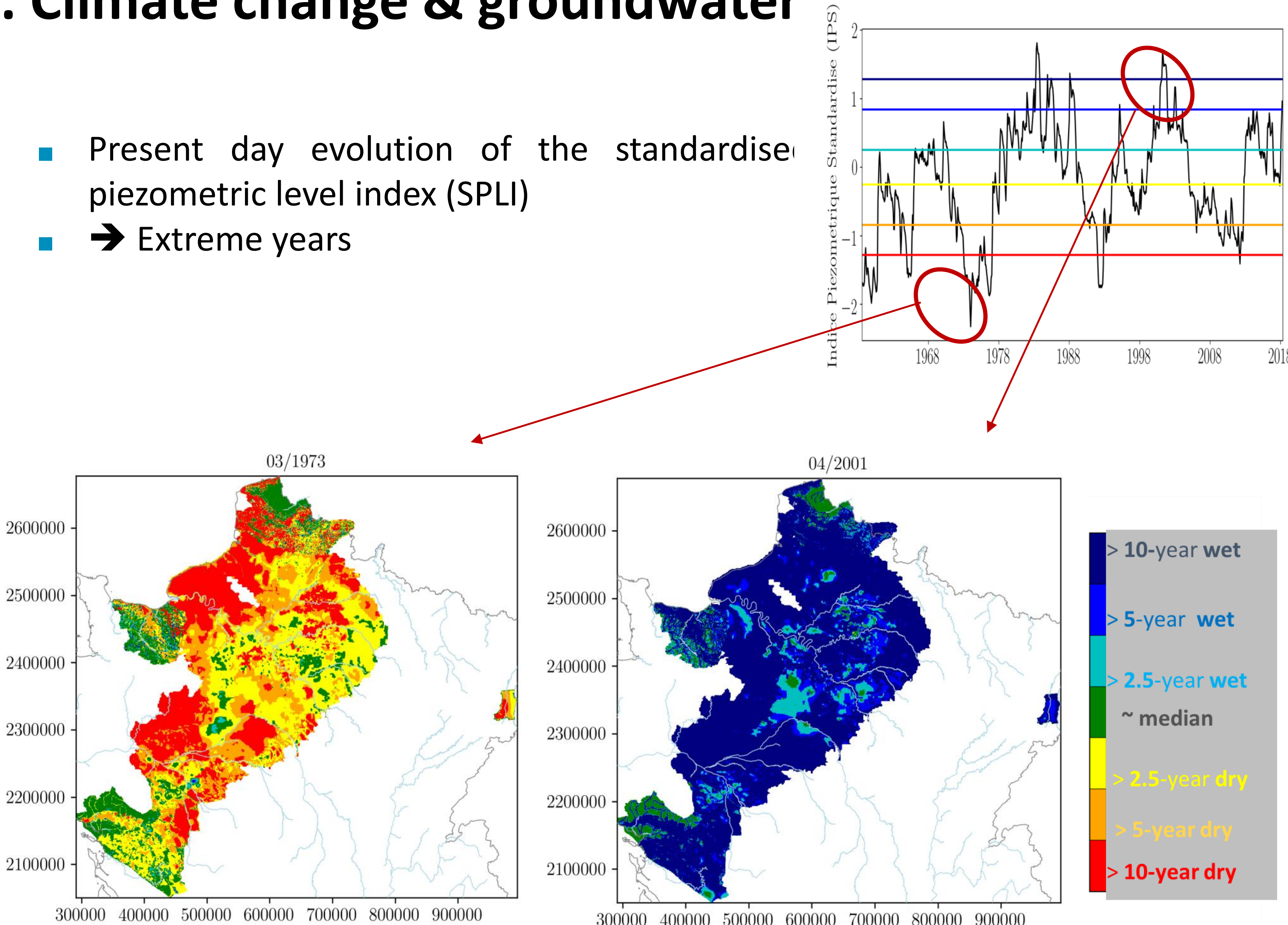
5. Climate change & groundwater

- Present day evolution of the standardised piezometric level index (SPLI)
- ➔ Extreme years



Roux et al., 2018 (CMWR); Vergnes et al., 2018 (CMWR)

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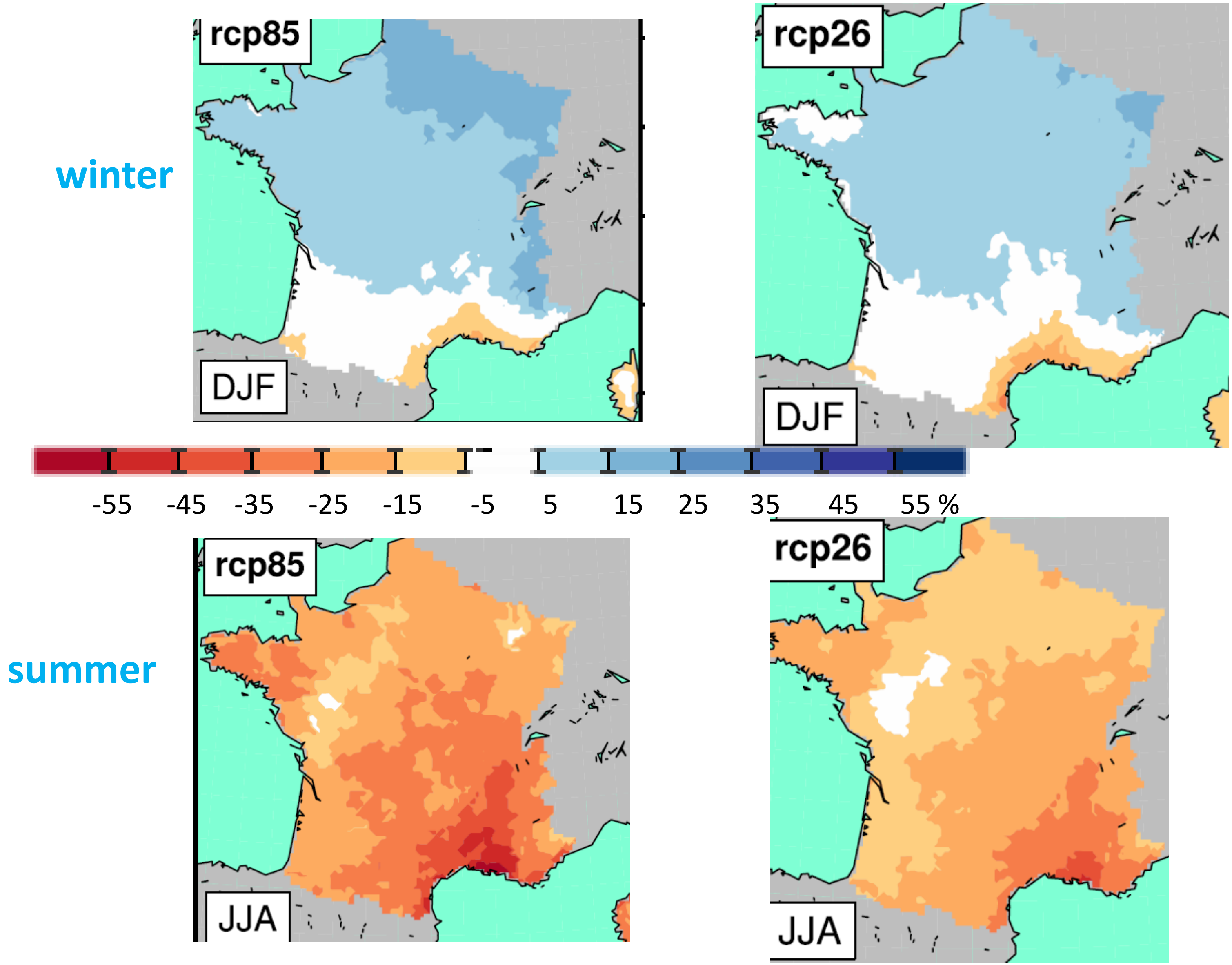
5. Climate change & groundwater

Change in precipitations in France in 2070-2099

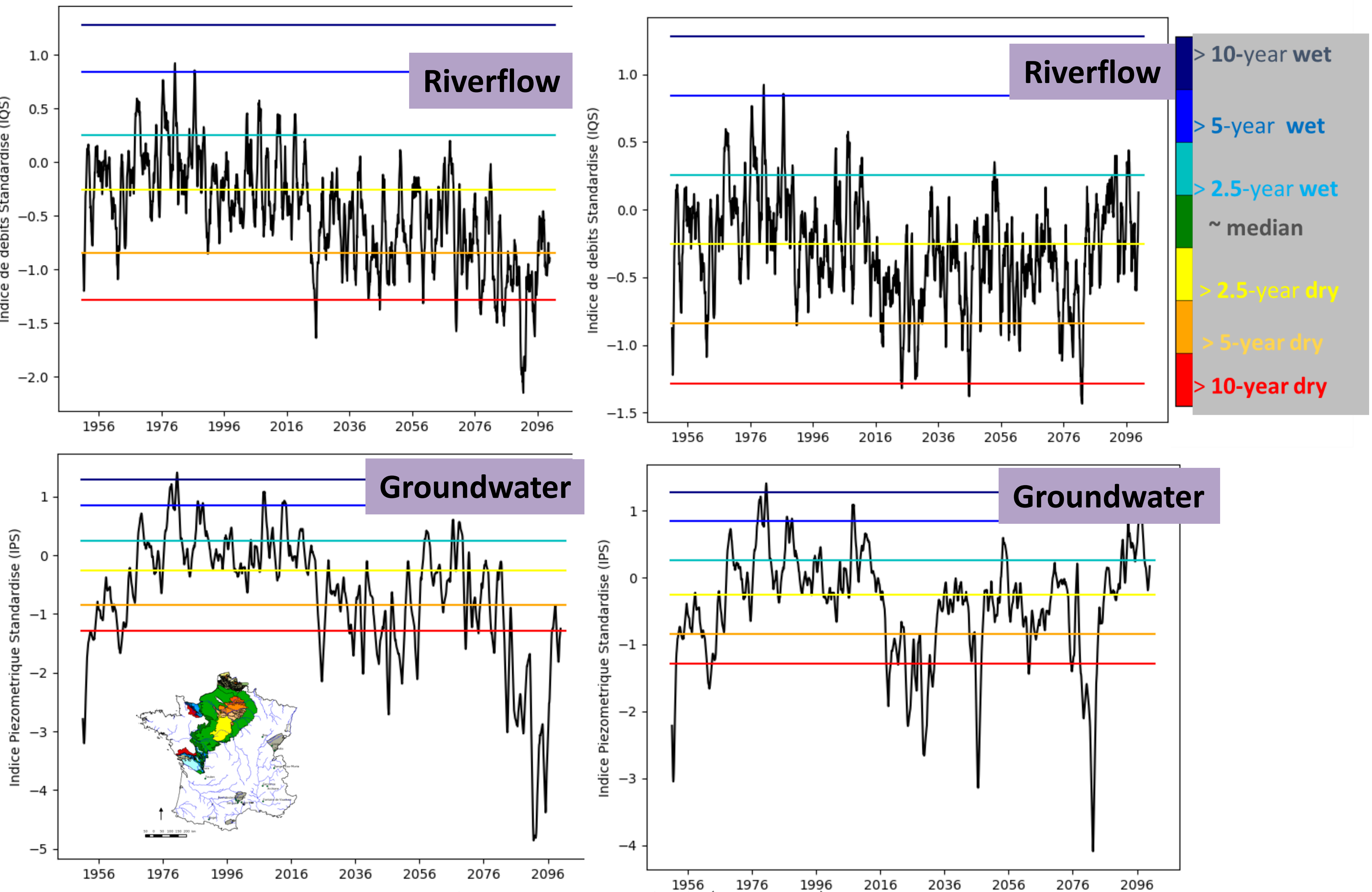


Dayon 2015

5. Climate change & groundwater

RCP8.5

RCP2.6

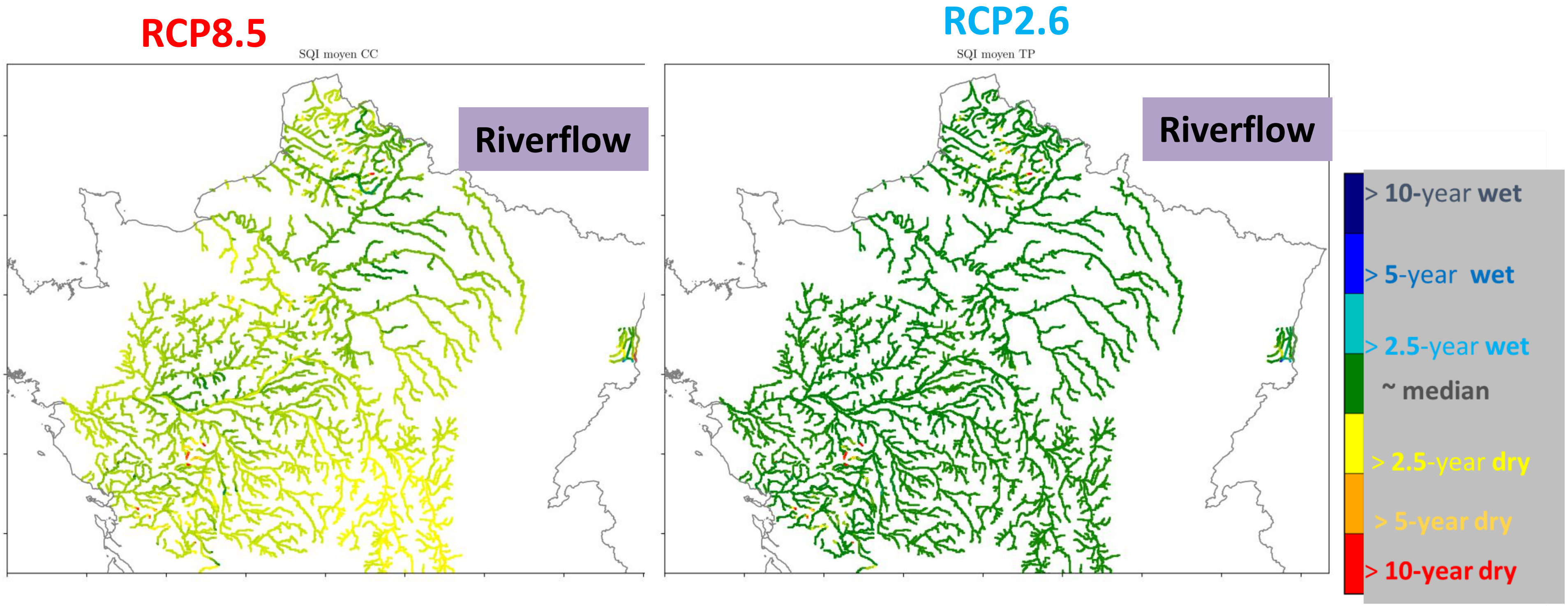


Habets., 2018 (CMWR) One climate model (NOR1) www.metis.upmc.fr/~aqui-fr

5. Climate change & groundwater

Evolution of the standardized riverflow

2070-2100 compared to 1960:1990



Habets., 2018 (CMWR) **Multi-climate model mean**

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5. Climate change & groundwater

Evolution of the standardized riverflow

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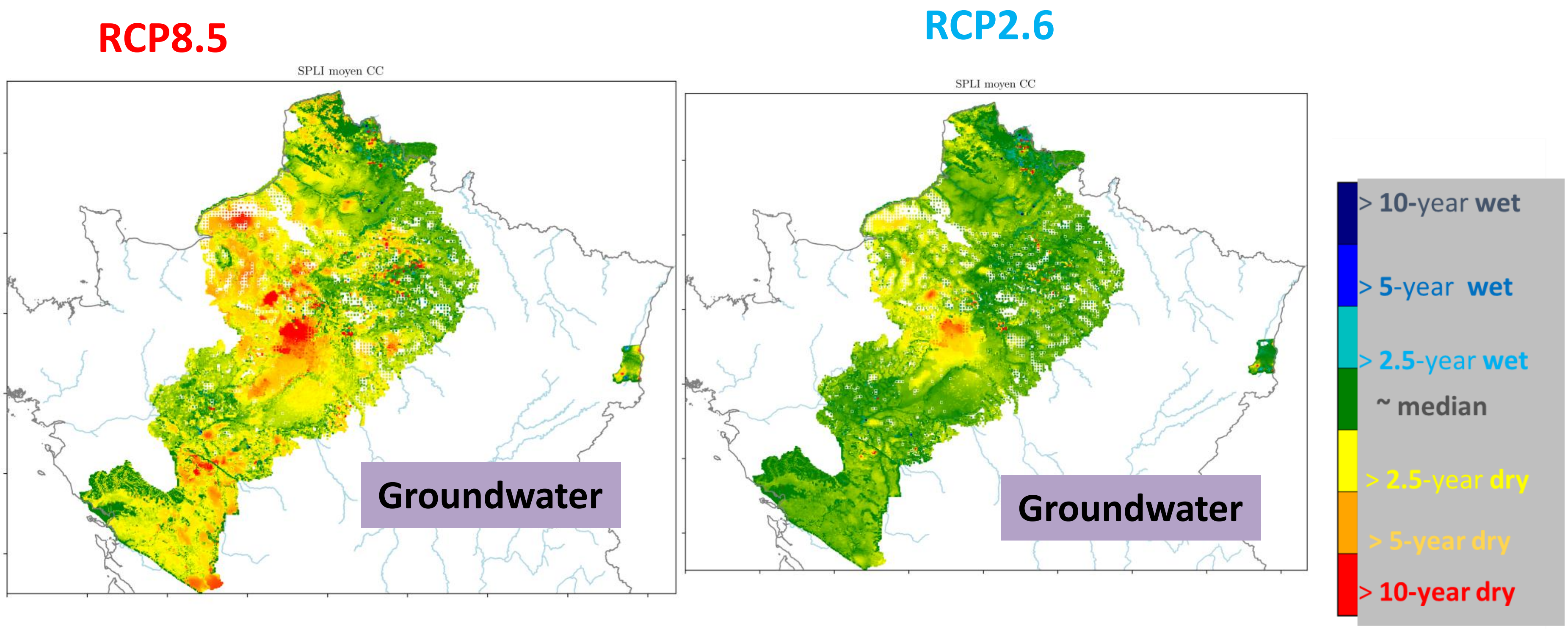

Habets., 2018 (CMWR) **Multi climate model mean**

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HYDROLOGICAL MODELING: INTEGRATING THE IMPACT OF THE GROUNDWATER AND ANTHROPOGENIC EFFECT AT THE BASIN SCALE

The strategies to adapt to climate should take into account groundwater:

- Improving infiltration to the groundwater reduces the risk of (fast) flood and help providing water resource during the period of scarcity
- Groundwater storages have a small evaporation loss compare to dam
- Filtration of the water to the aquifer improves groundwater quality

BUT:
- Risk of long duration flooding exists when aquifer levels are high
- Aquifer management, including artificial recharge and reuse can have impact on the groundwater quality
- Abstraction of groundwater should be controled to be sustainable….

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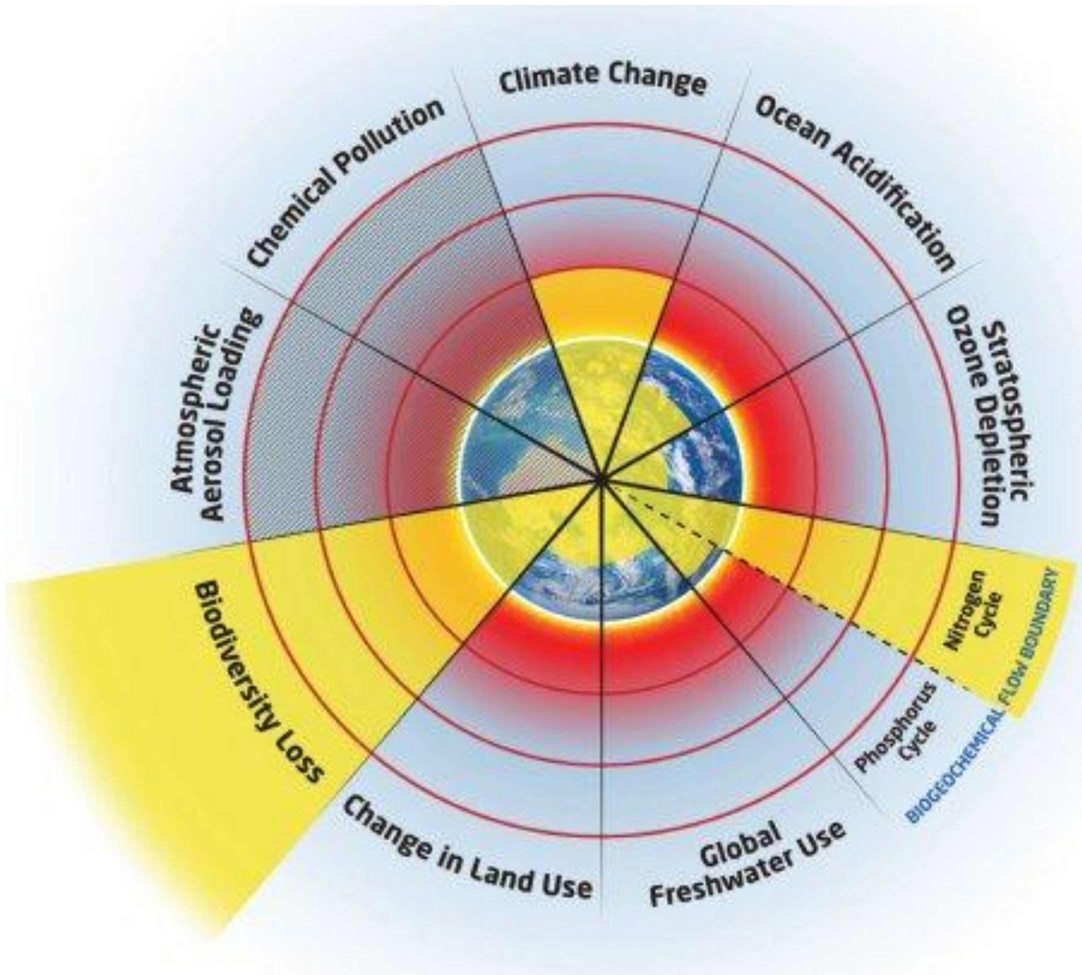
Conclusion

The planetray boundaries



Rockstrom et al., 2009, modified by IGBP