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DE LA RECHERCHE À L'INDUSTRIE



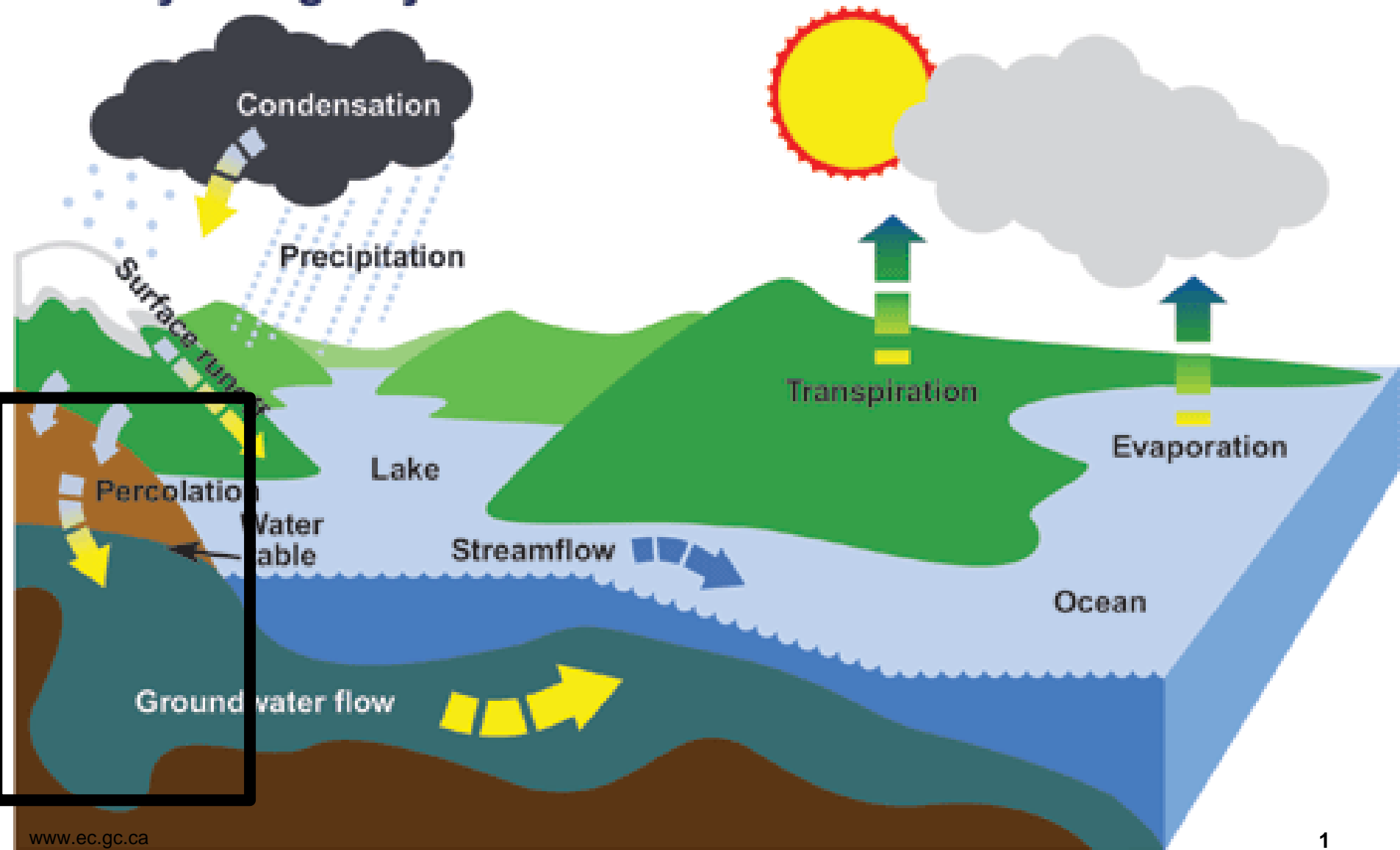
Laboratoire d'Hydrologie et
de Géochimie de Strasbourg



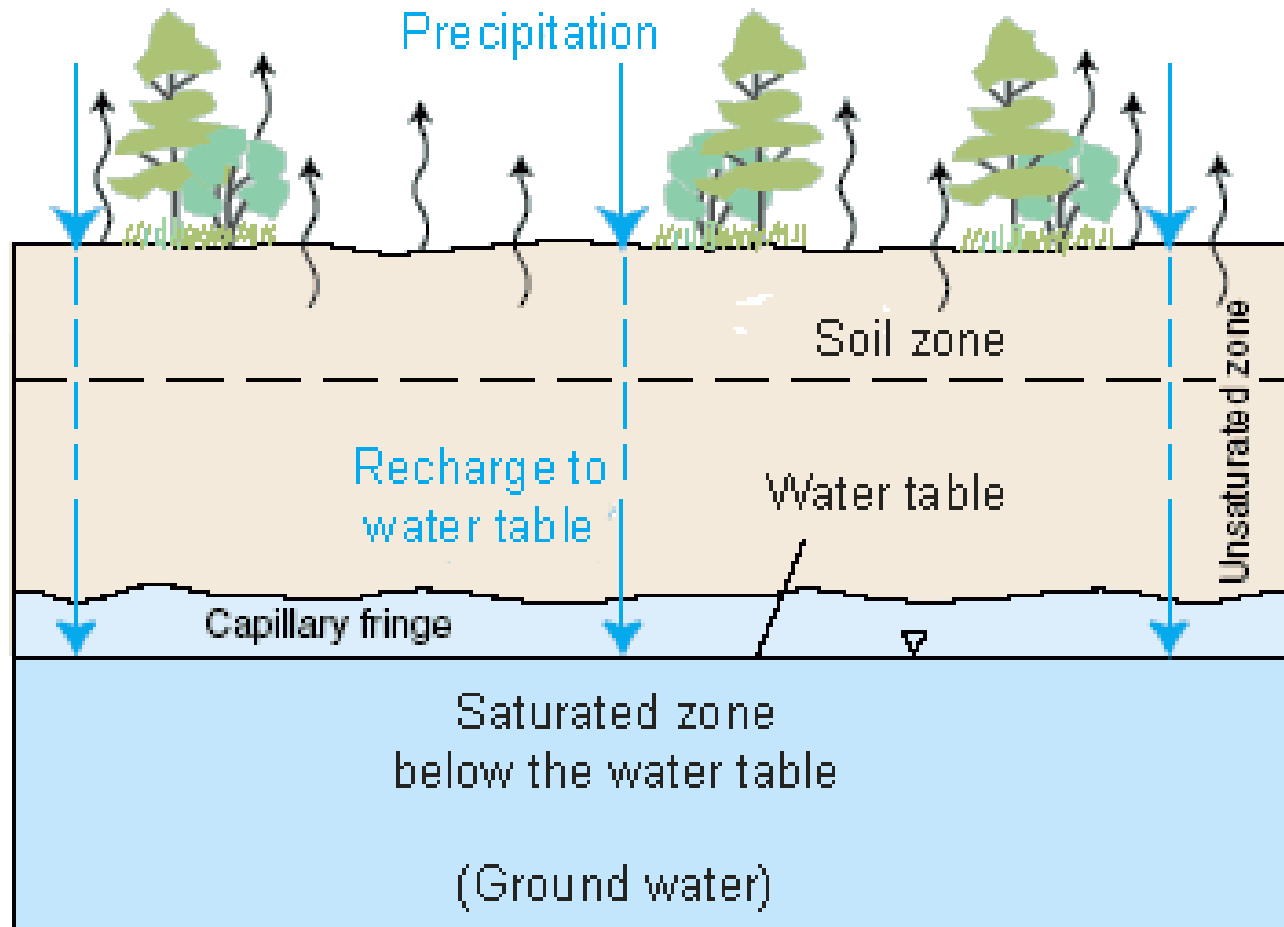
SIMULTANEOUS ESTIMATION OF GROUNDWATER RECHARGE AND HYDRODYNAMIC PARAMETERS FOR GROUNDWATER FLOW MODELING


Fadji HASSANE MAINA (Université de Strasbourg)
Philippe ACKERER (Université de Strasbourg)
Olivier BILDSTEIN (CEA Cadarache)

The hydrologic cycle



- **Groundwater (aquifers):** 3rd freshwater reservoir on the planet
- Replenished essentially by precipitation through **groundwater recharge**



- **Groundwater (aquifers):** 3rd freshwater reservoir on the planet
- Replenished essentially by precipitation through **groundwater recharge**
- The **main available water resources** for many countries
- Threatened by pollution and over-exploited
- Usually described by models  Simulations of piezometric levels (Hydraulic heads)
- **Physical Models are widely used**

1. **Continuity equation** (mass conservation): $S \frac{\partial H}{\partial t} + \nabla \cdot q = q_s$



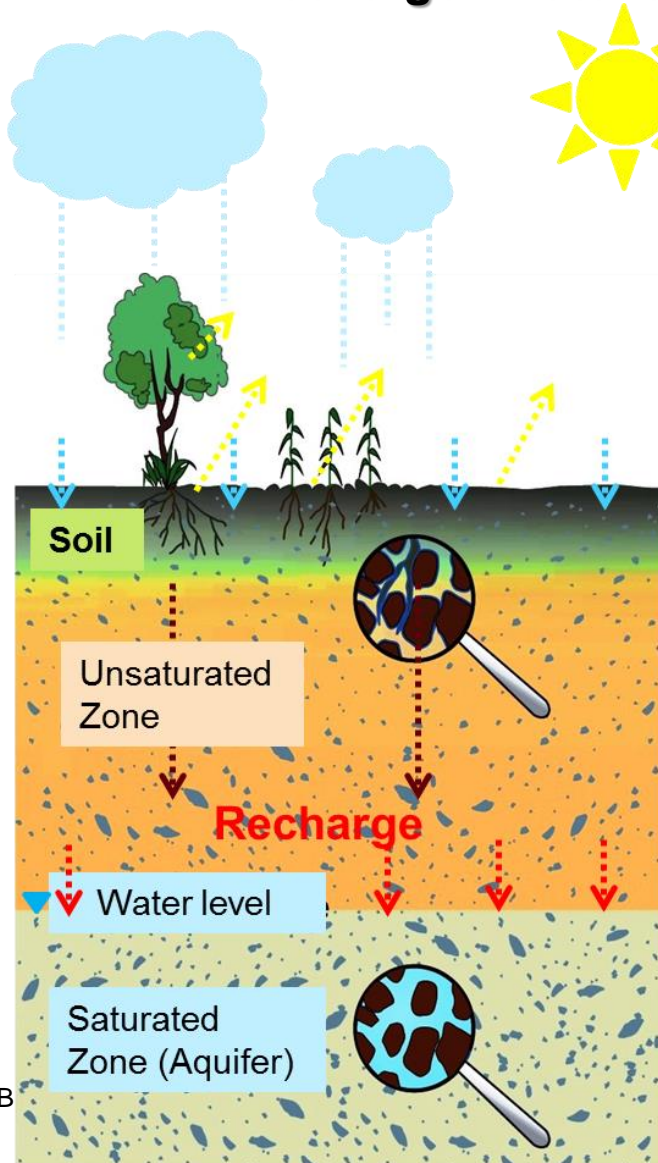
2. **Darcy's law** (computation of fluxes): $q = -K \nabla H$



Diffusivity equation (flow equation): $S \frac{\partial H}{\partial t} - \nabla \cdot [K \nabla H] = q_s$

Values of H knowing S, K and q_s → S and K are constant, q_s includes groundwater recharge

Recharge : water transfer from precipitation to groundwater

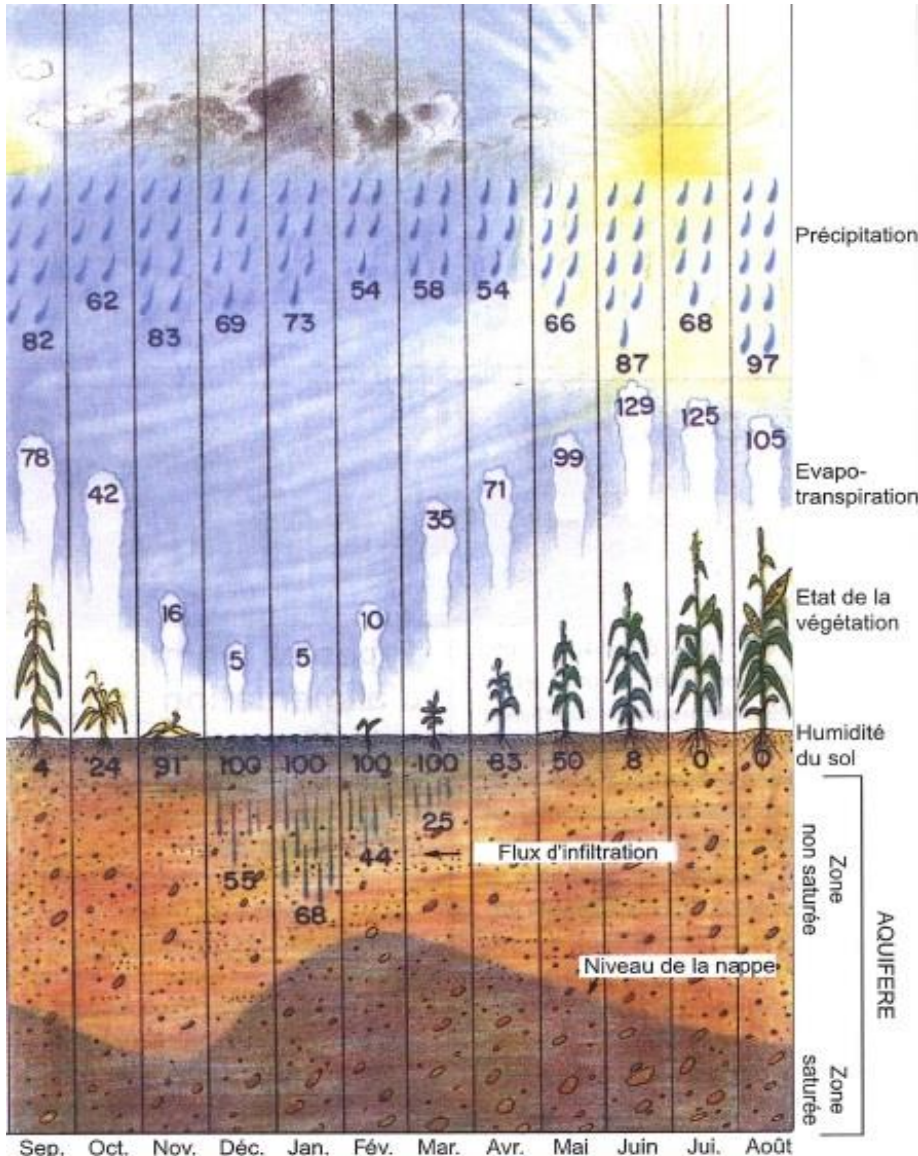


- ☺ Groundwater flow models: **Sophisticated and accurate**
- ☹ Recharge modeling: **Challenge**
 - **Complex hydrological component**

Groundwater recharge depends on:

- Climatic conditions
- Vegetation
- Soil and root zone
- Unsaturated zone

Recharge : water transfer from precipitation to groundwater



☺ Groundwater flow models: **Sophisticated and accurate**

☹ Recharge modeling: **Challenge**

- **Complex hydrological component**

Groundwater recharge depends on:

- Climatic conditions
- Vegetation
- Soil and root zone
- Unsaturated zone

Values can not be directly measured



Estimation

- Direct methods: lysimeters, TDR
- Empirical methods
- Tracers
- **Mathematical models**

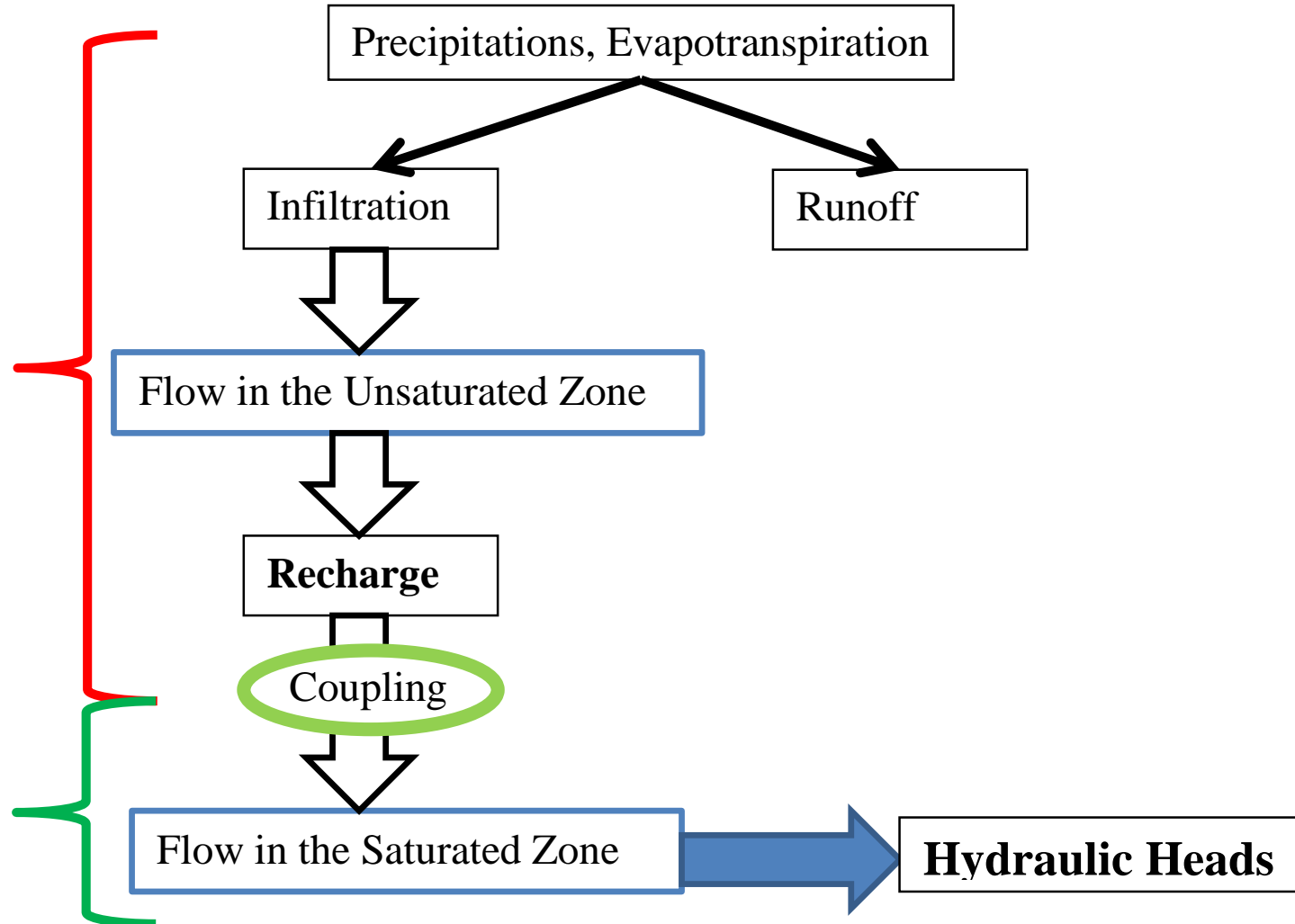
RECHARGE ESTIMATION: COUPLED MODEL

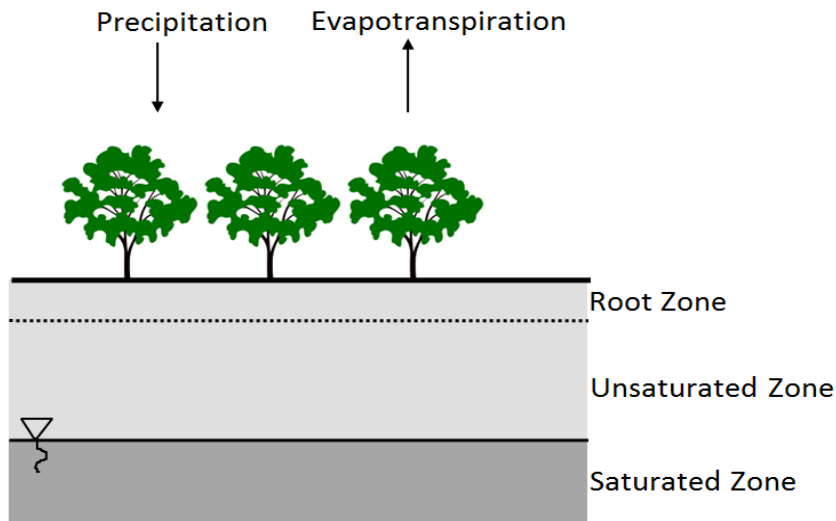
Simulation of flow in both unsaturated and saturated zones

Interactions between
Atmosphere and Soil
and Hydrodynamic in
the Unsaturated Zone :

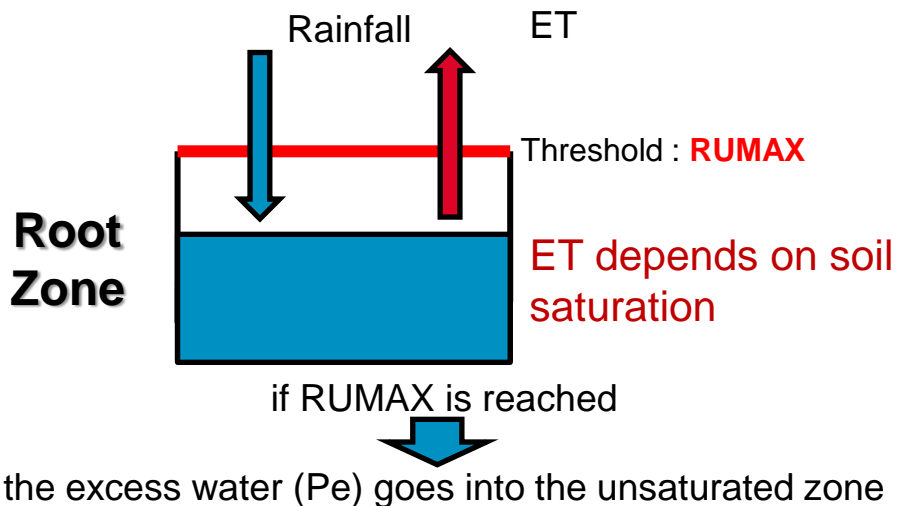
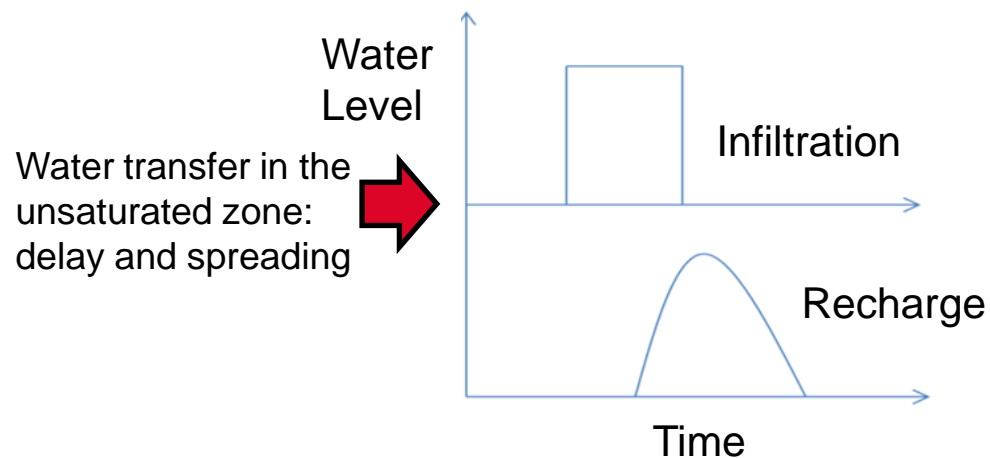
Nash

Groundwater Flow:
Diffusivity equation

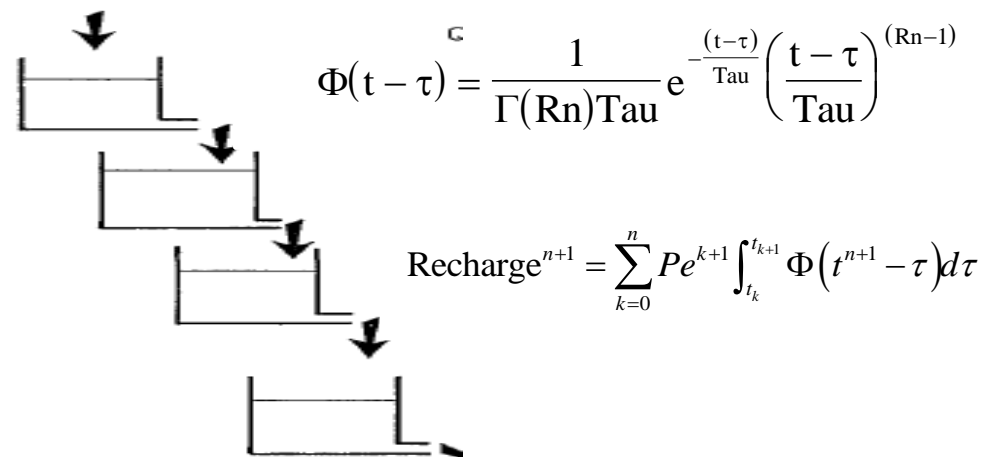




Hydrodynamic in the unsaturated zone



Modeling : propagation of a unit pulse signal

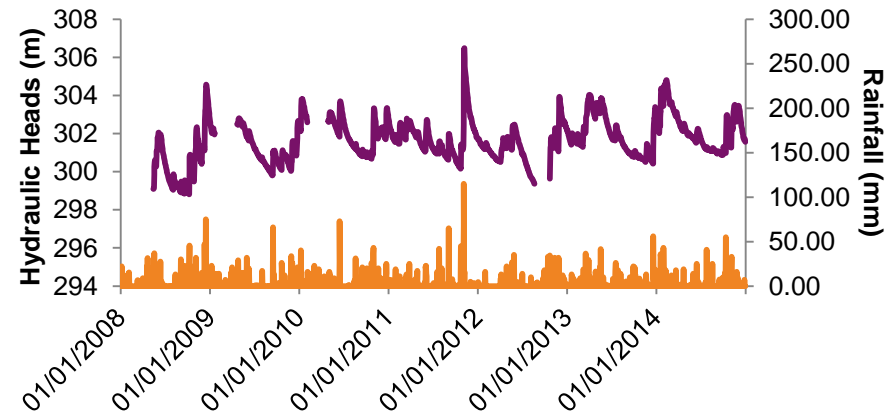
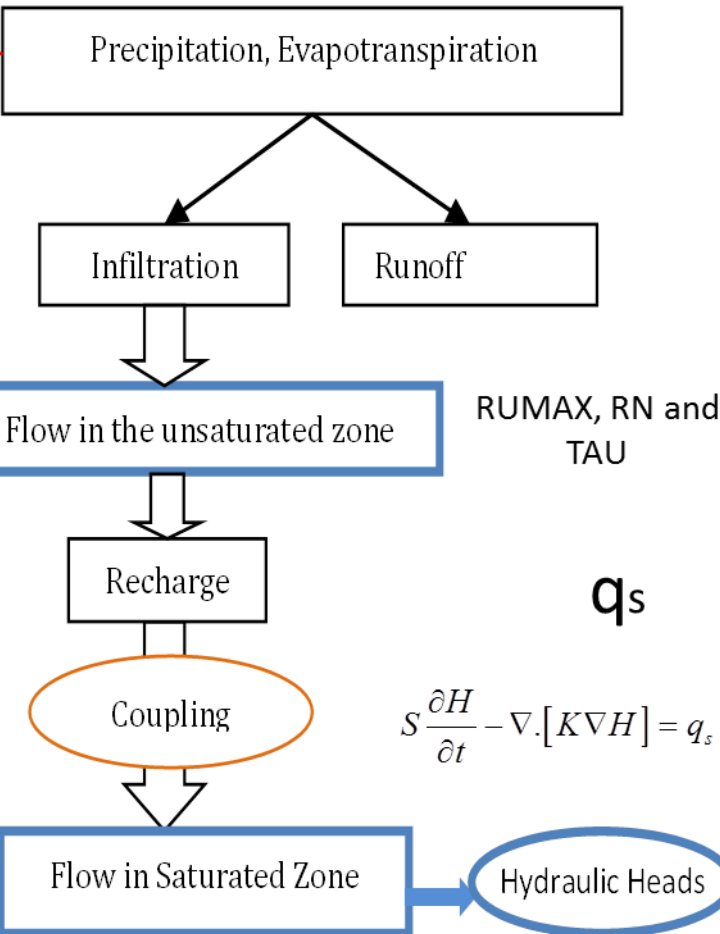


Nash parameters: **RUMAX, RN, TAU**

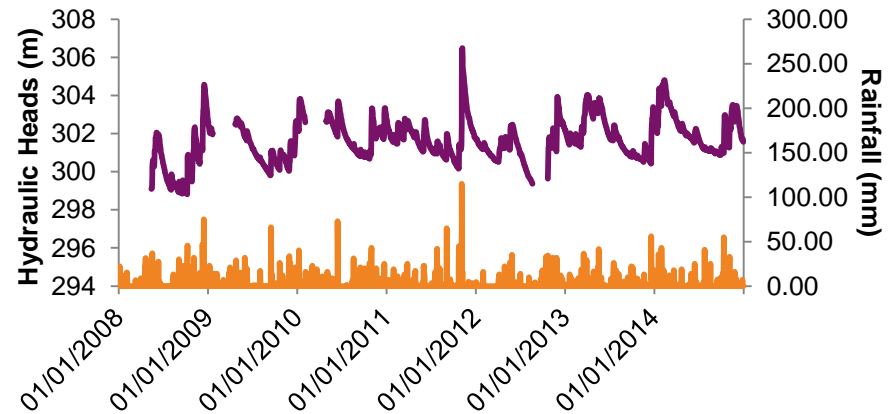
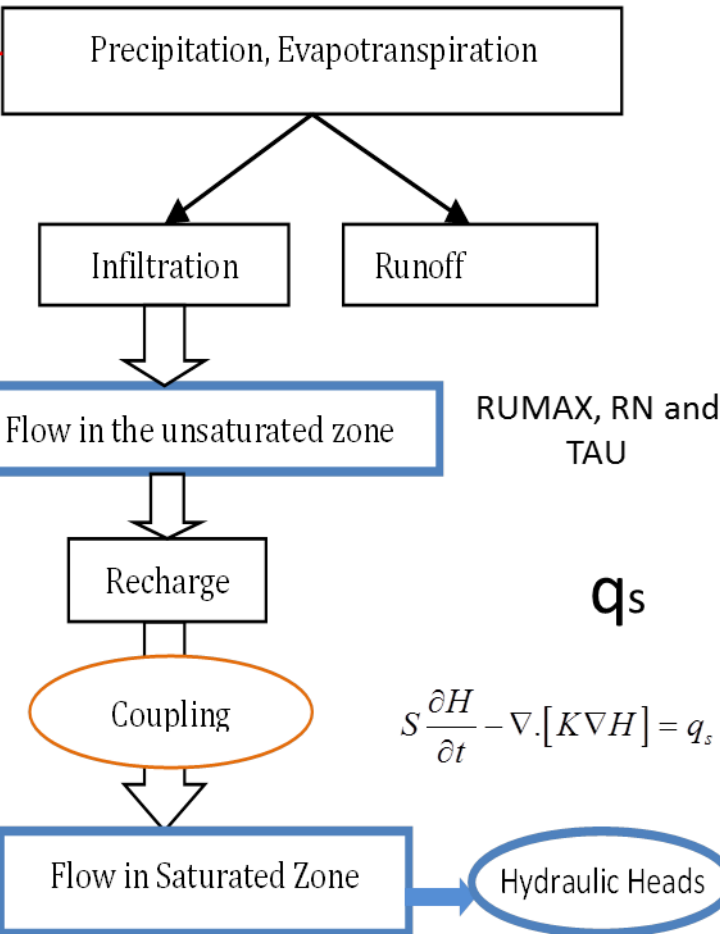
- ☹ Model uses constants called parameters
- ☹ **Aquifers are highly heterogeneous** → Parameters are not known accurately or even **unknown** in natural environments



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- Aquifers are highly heterogeneous** → Parameters are not known accurately or even **unknown** in natural environments
- Available data: **meteorological and piezometric levels**



- ☹ Model uses constants called parameters
- ☹ **Aquifers are highly heterogeneous** → Parameters are not known accurately or even **unknown** in natural environments
- ☹ Available data: **meteorological and piezometric levels**

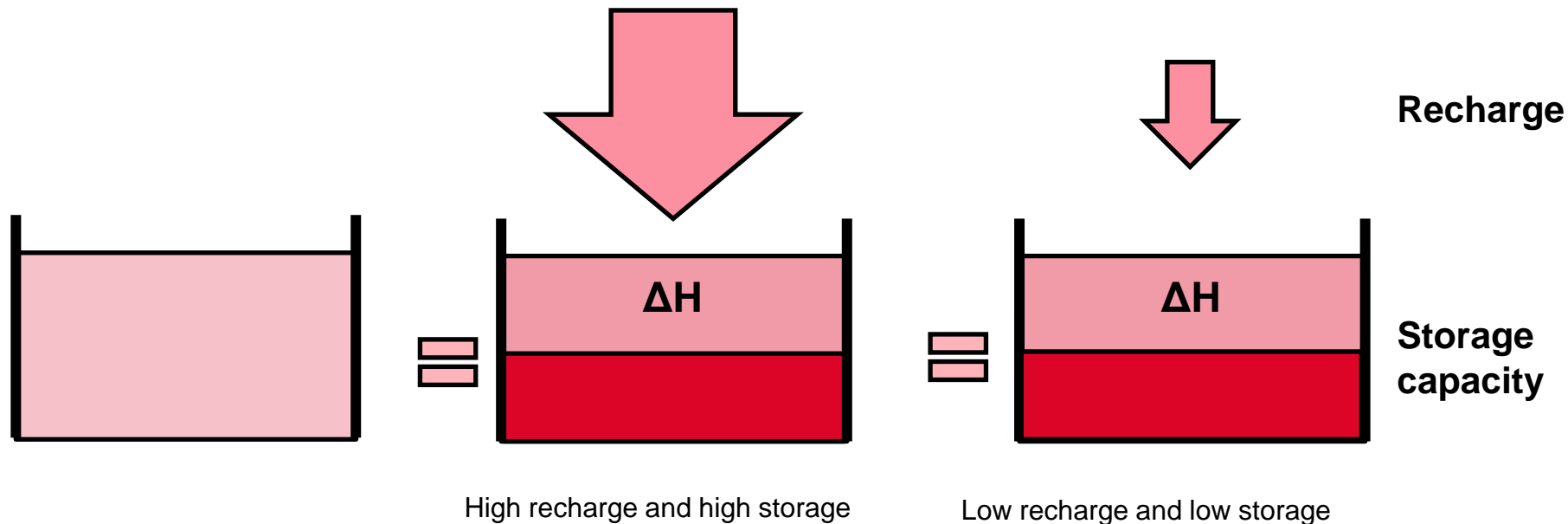


Recharge is estimated by calibrating piezometric levels

Simultaneous estimation of groundwater flow and recharge parameters from hydraulic heads variations

Correlation between recharge and storage capacity (S and q_s)

Recharge and storage capacity lead to the same effect



$$q = -K\nabla H \quad \text{Determine } q \text{ et } K \text{ knowing } H!$$

☺ Calibration is performed over time and space

☺ But... recharge is variable over time while the storage capacity is constant

When $q = 0 \rightarrow 0 = -K\nabla H \rightarrow$ Determination of K

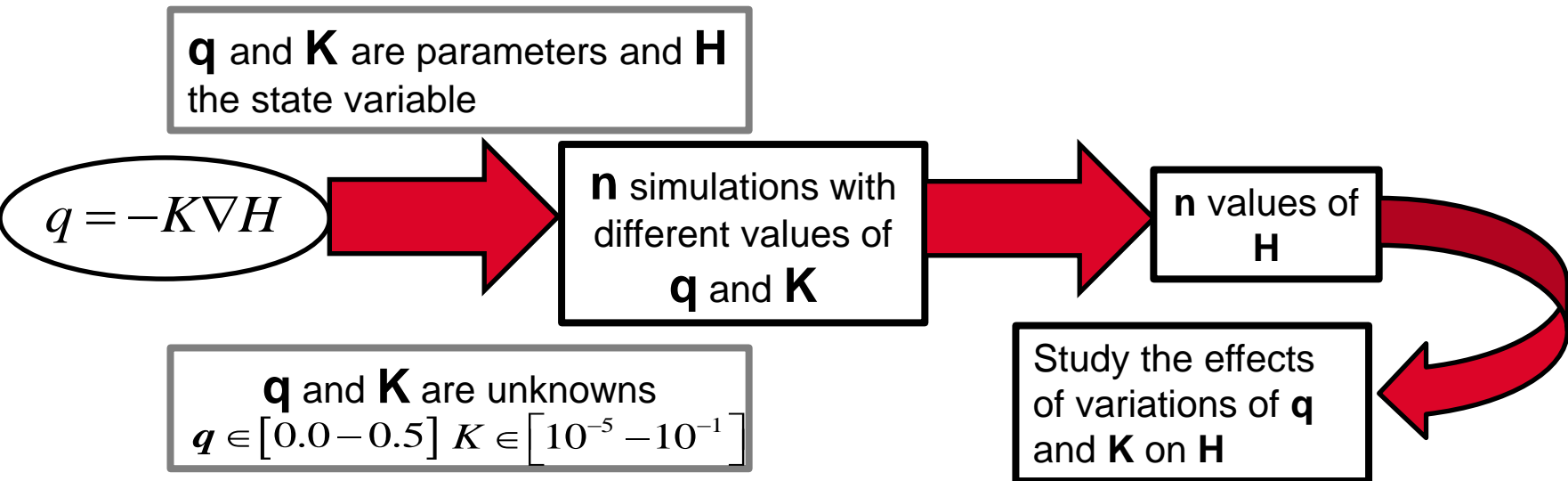
When $q \neq 0 \rightarrow$ Determination of q knowing K

☺ **Global sensitivity analysis**

Assess the calibration approach and guide the parameter estimation

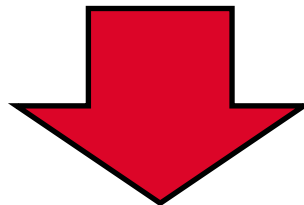
Uncertain parameters: variability ranges known → Quantify the effects of parameters uncertainty

Global sensitivity analysis: focuses on the output uncertainty over the entire range of values of the input parameters both single and in combination with one another



Variance based approach:

Sobol Indices



Surrogate model: Chaos polynomial expansion

SOBOL INDICES : CHAOS POLYNOMIAL EXPANSION


Let us consider a model with y as output and n input parameters, X the parameters vector

➤ **ANOVA decomposition** : $y = f_0 + \sum_{i=1}^n f_i(x_i) + \sum_{j>1}^n f_{ij}(x_i, x_j) + \dots + f_{1,2,\dots,n}(x_1, x_2, \dots, x_n)$


f_i : contribution of single parameter i to the output

f_{ij} : contribution of the combined effect of parameters i and j to the output

$$H = H_0 + f_S(S) + f_K(K) + f_{RN}(RN) + f_{RN,K}(RN, K) + f_{S,K}(S, K) + \dots$$

Orthogonality of f  $V = \sum_{i=1}^n V_i + \sum_{j>1}^n V_{ij} + \dots + V_{1,\dots,n}$

➤ **Sensitivity (Sobol) Indices** : $S_i = \frac{V_i}{V}$; $S_{ij} = \frac{V_{ij}}{V}$

Computation of f  **Polynomial expansion**

➤ **Chaos polynomial expansion**

$$y = \sum_{j=0}^{+\infty} a_j \Psi_j(x_1, \dots, x_n)$$

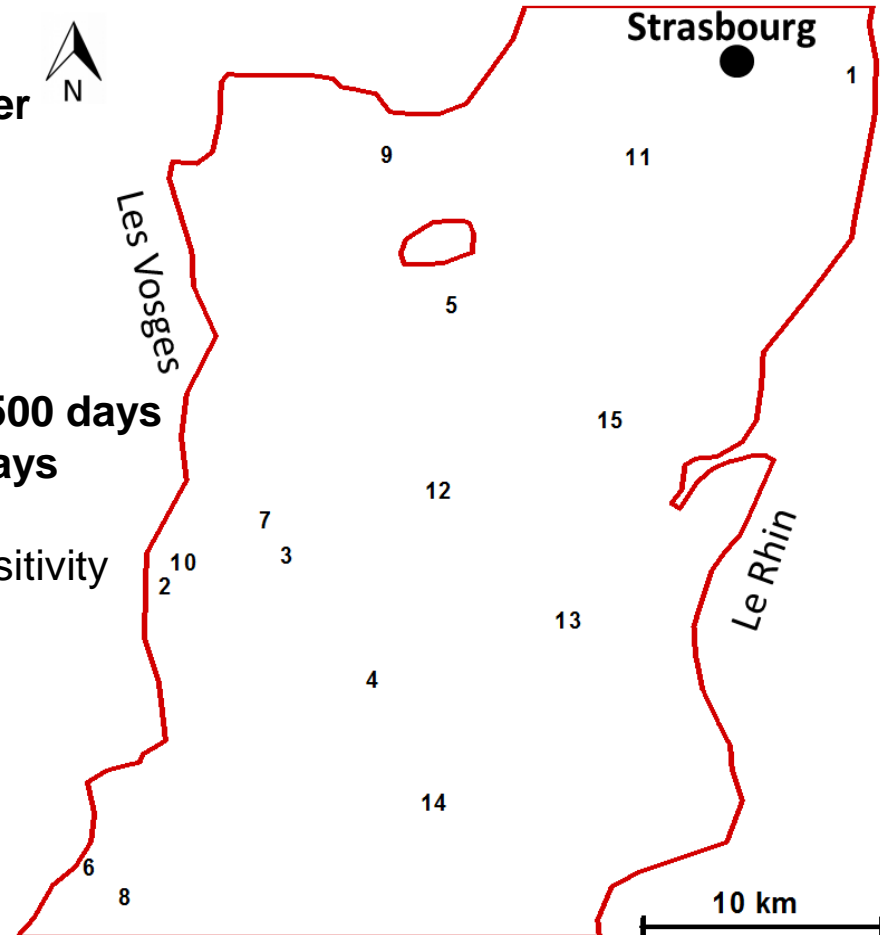
x : variable


Ψ : orthogonal polynomial (Legendre, Hermite)

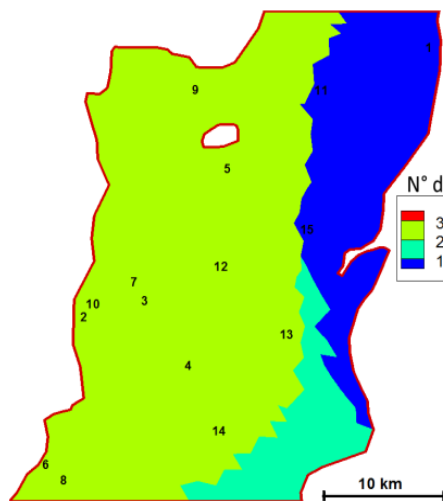
a : coefficients determined by least squares regression

Field based sensitivity analysis

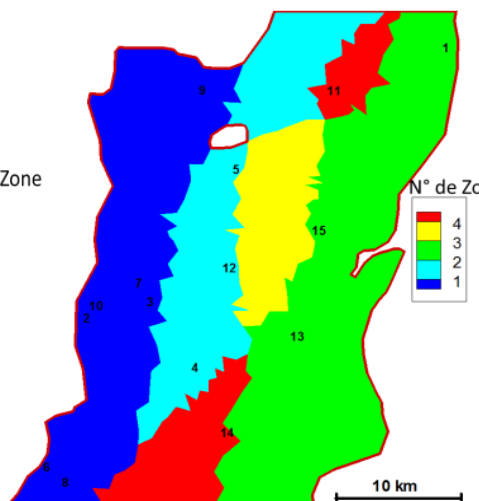
- **A subdomain of the Upper Rhine alluvial aquifer** widely studied at Université de Strasbourg
- Average rainfall per year: **1100 mm**
- Average of evapotranspiration per year: **900 mm**
- Simulate variations of piezometric levels during **1500 days**
- Sensitivity analysis performed over the last **450 days**
- Investigate spatial and temporal variations of sensitivity indices
- 1500 simulations of Quasi Monte Carlo



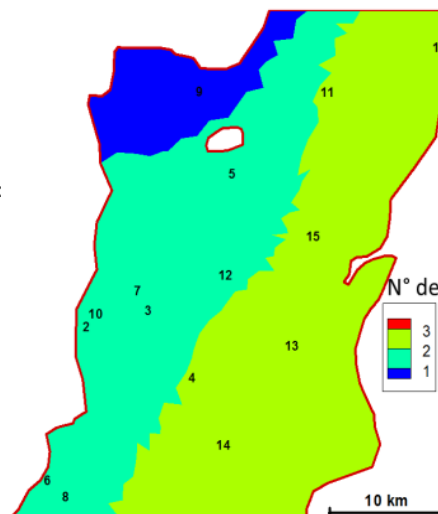
- Nash parameters for recharge: **RUMAX, RN, TAU**
- Aquifer parameters: **K and S**
- Parameters defined by zones (**Zonation**)  20 parameters



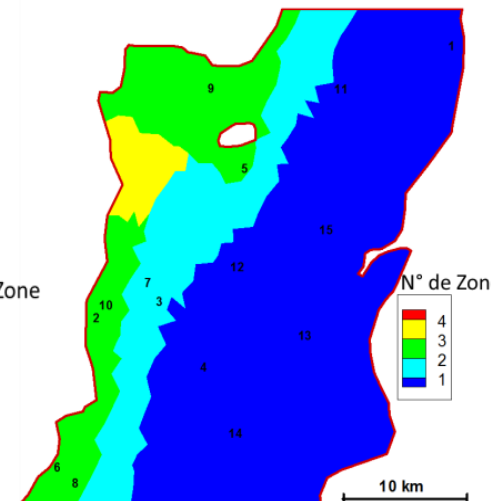
RUMAX




RN and TAU



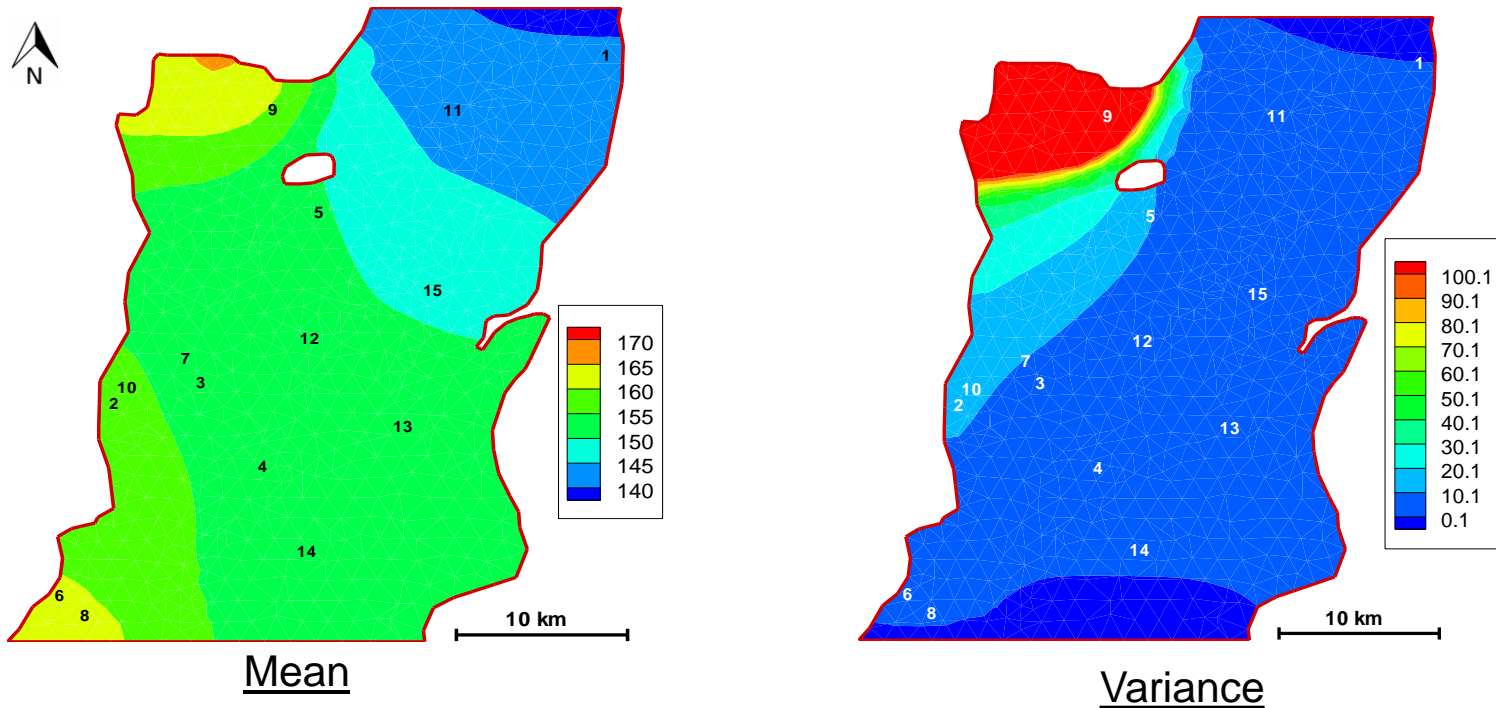
Permeability



Storage capacity

- Nash parameters for recharge: RUMAX, RN, TAU
- Aquifer parameters: **K** and **S**
- Parameters defined by zones (**Zonation**)  20 parameters

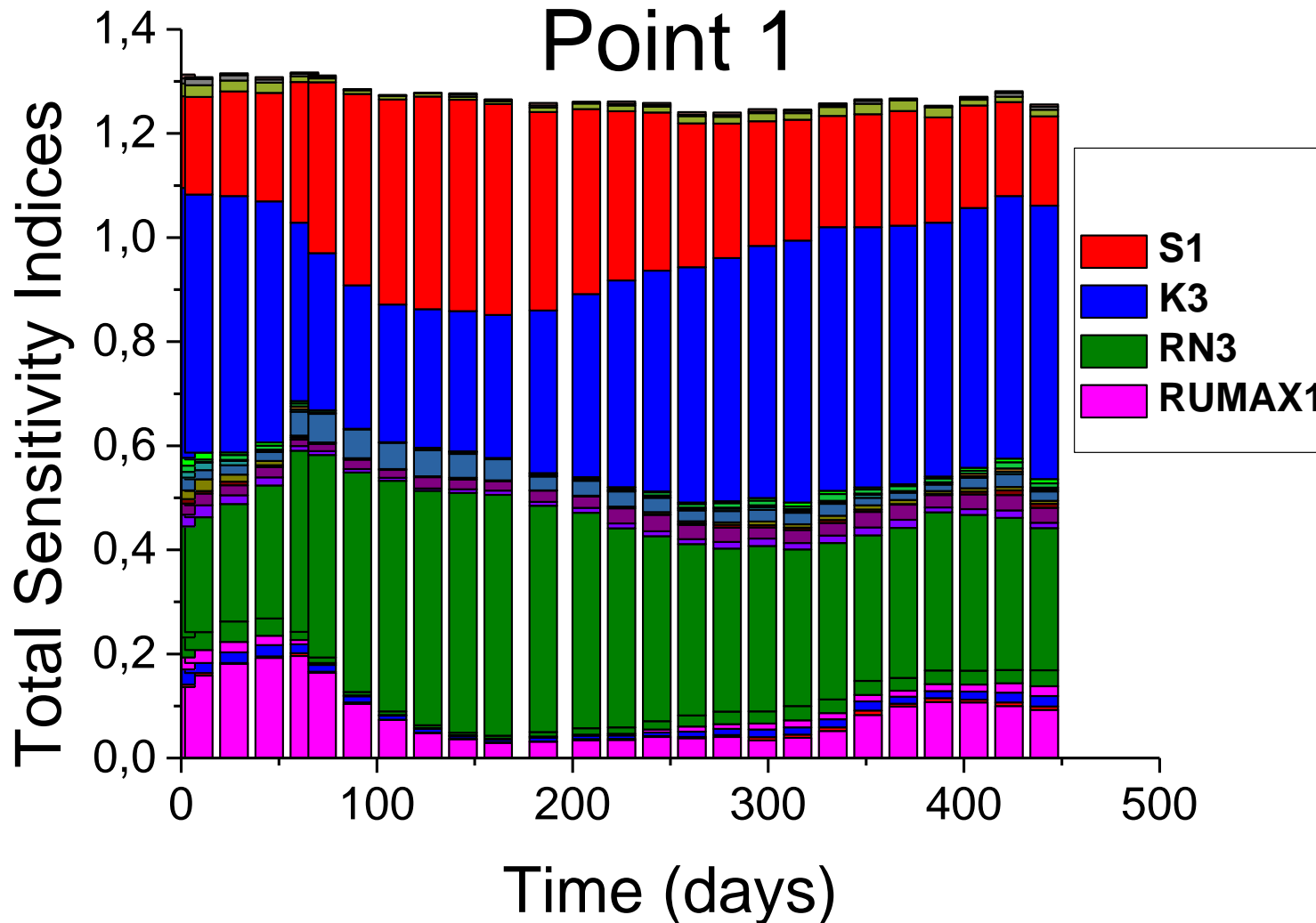
Mean and Variance of the hydraulic head



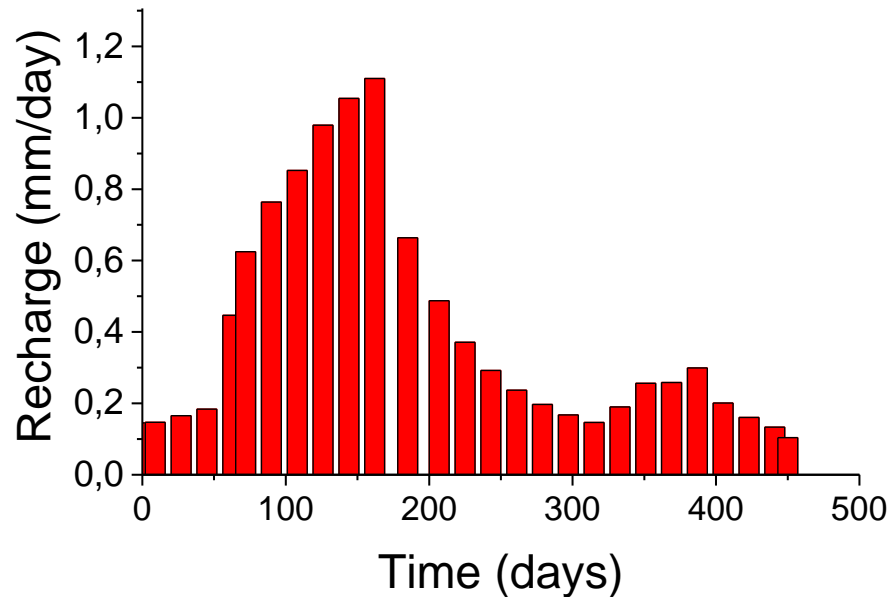
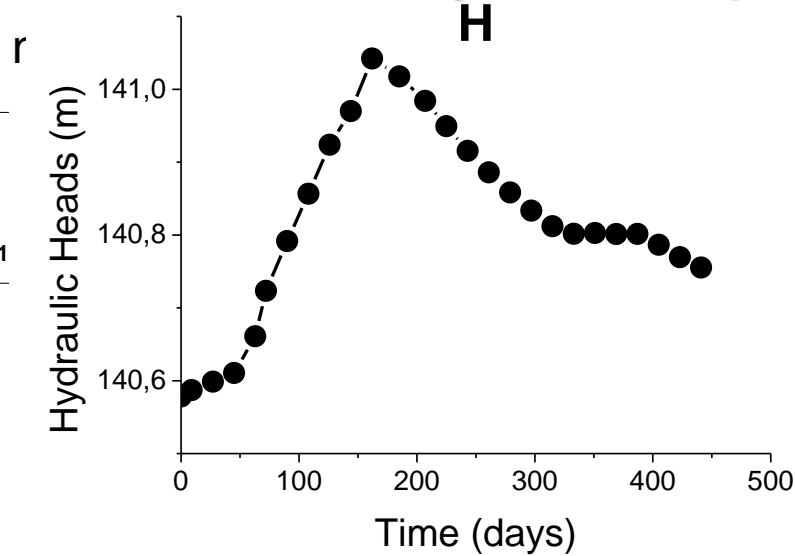
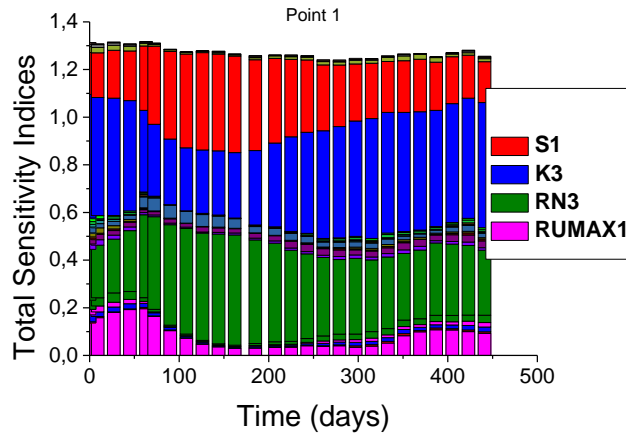
- Hydraulic heads range between 140 and 165 m
- Variance ranges between 0 and 100: the imposed boundaries have the lowest variance

Temporal variation of sensitivity indices at point 1

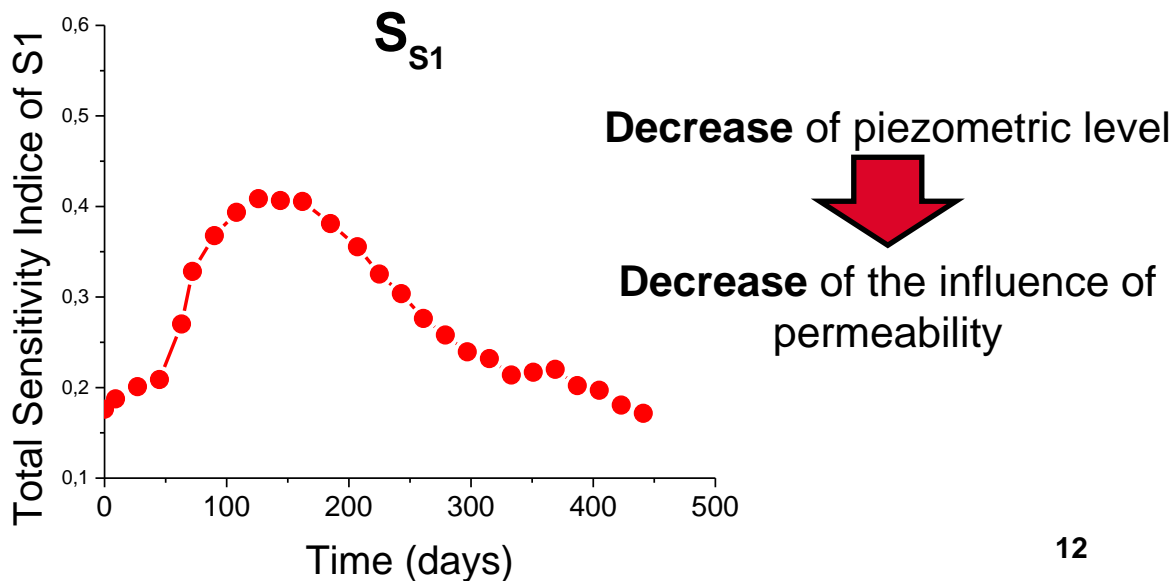
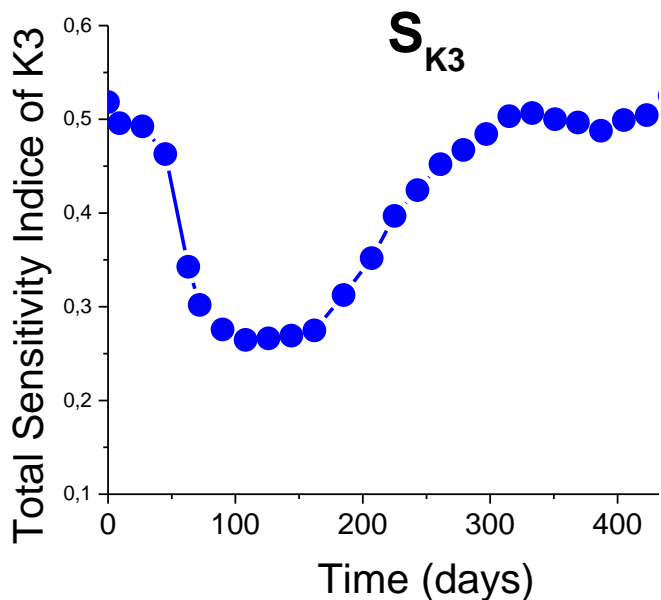
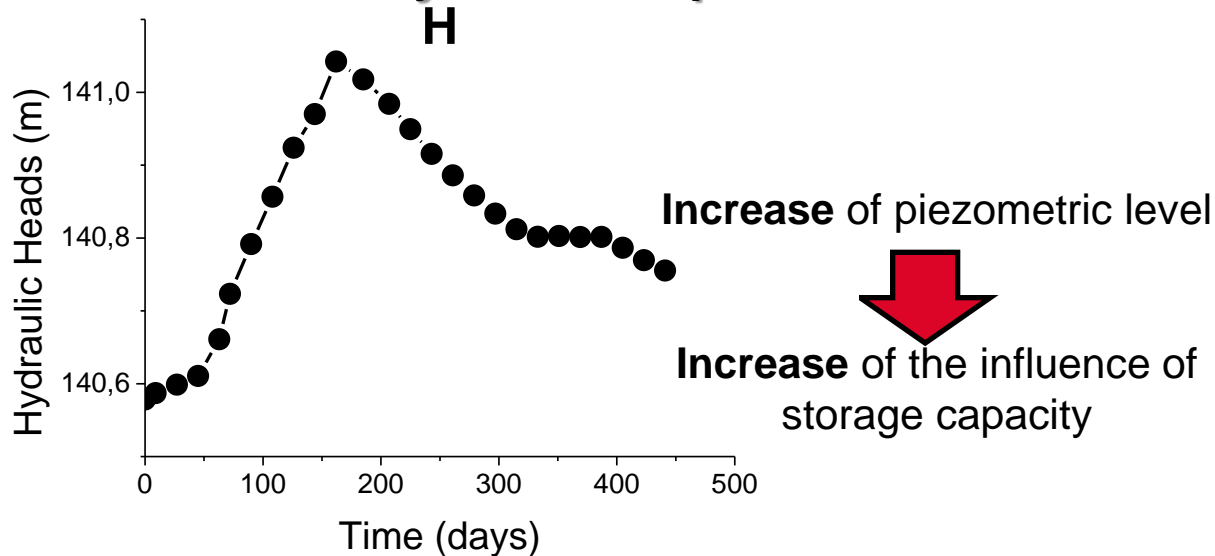
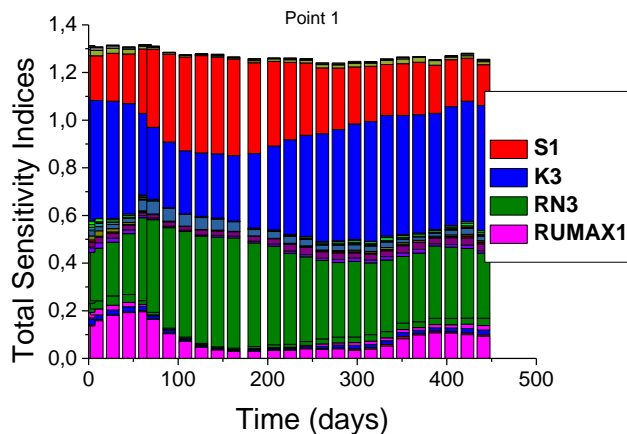
Influential parameters: S, K, RUMAX, RN



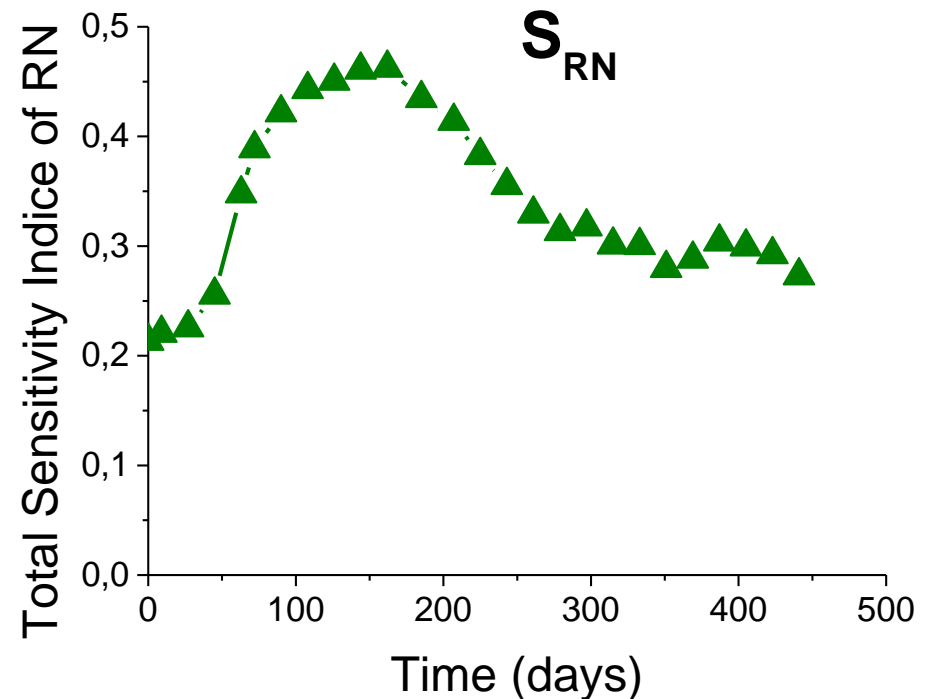
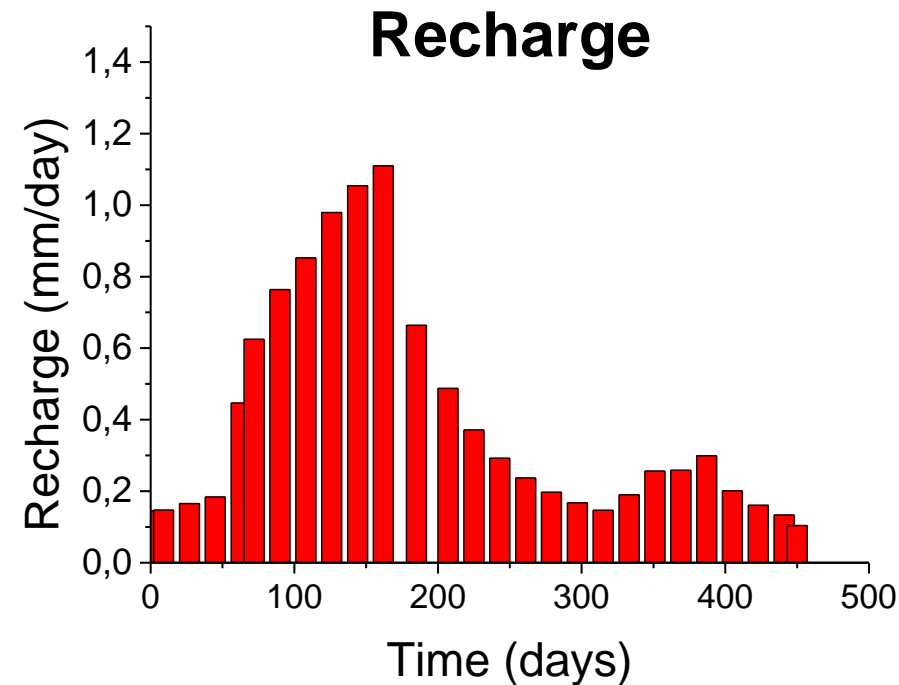
Temporal variation of sensitivity indices at point 1



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Temporal variation of sensitivity indices at point 1

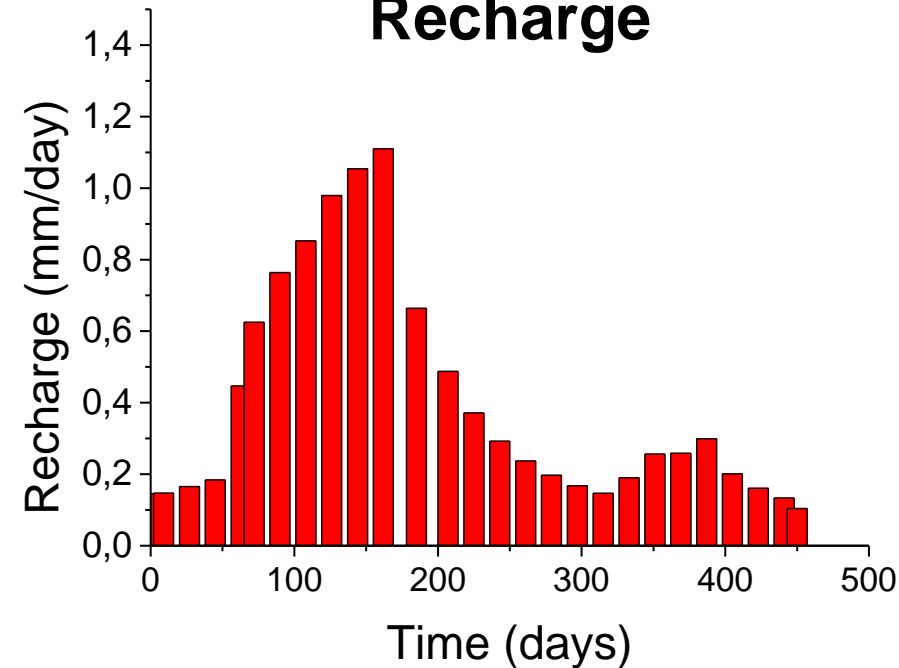


RN: water transfer in the unsaturated zone
(delay and spreading)

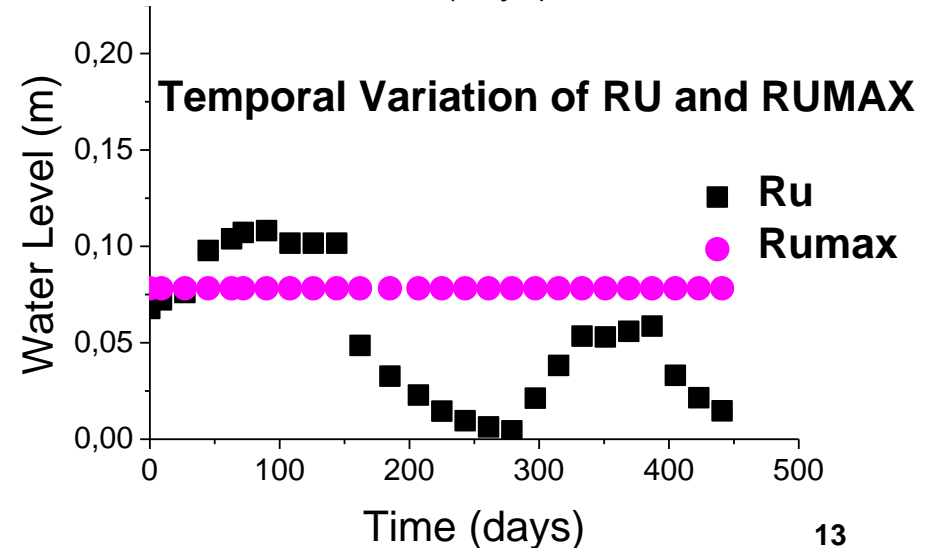
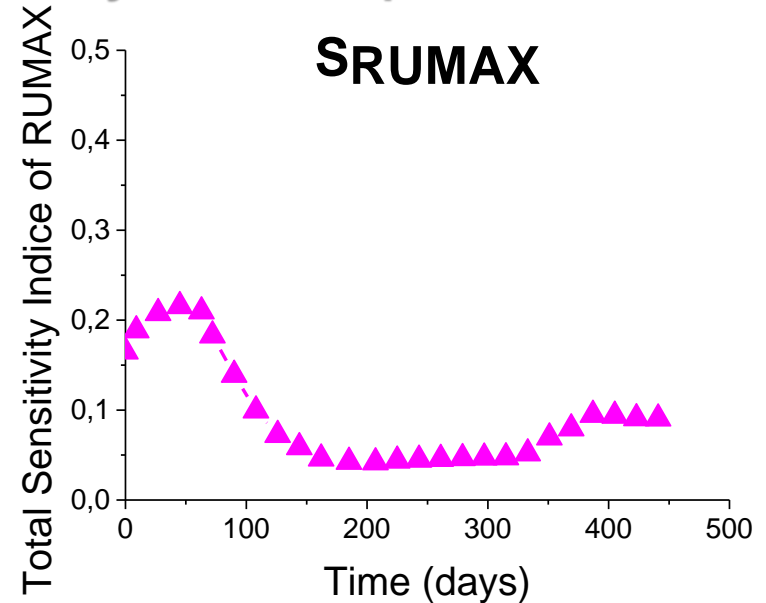
RUMAX: threshold parameter

Temporal variation of sensitivity indices at point 1

Recharge



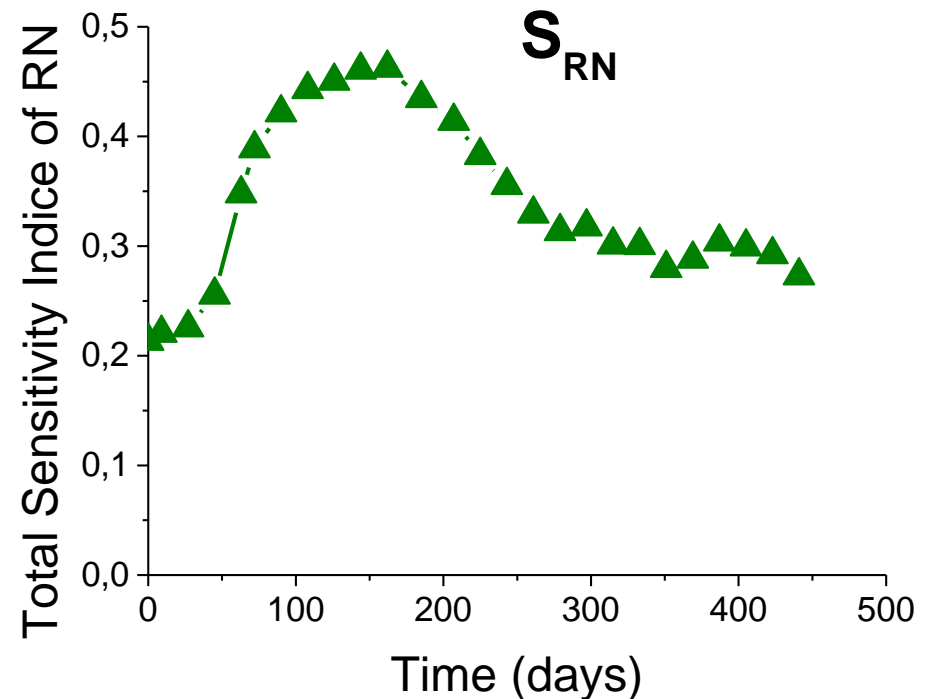
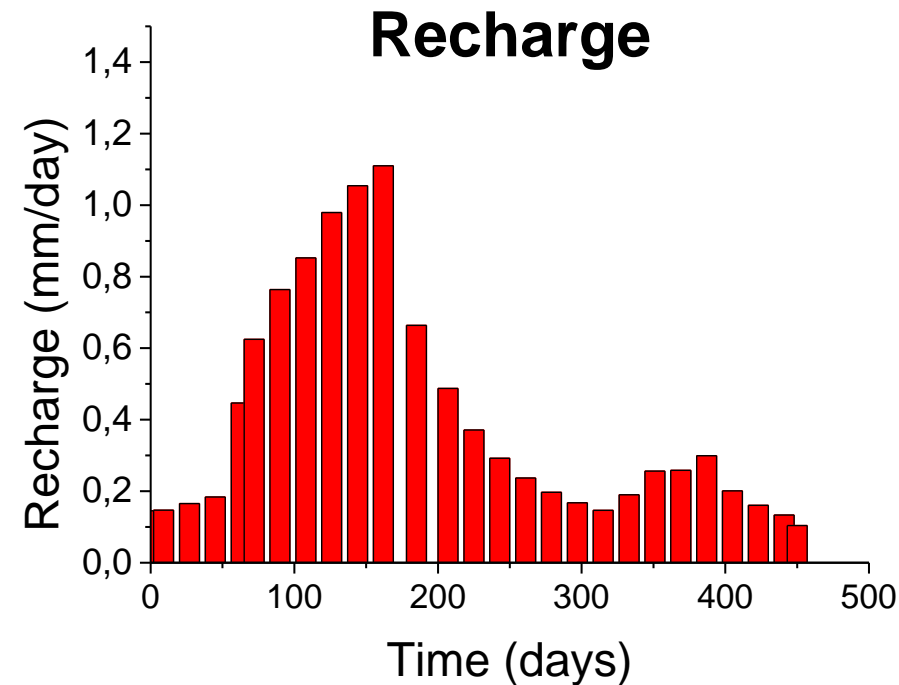
SRUMAX



RN: water transfer in the unsaturated zone (delay and spreading)

RUMAX: threshold parameter

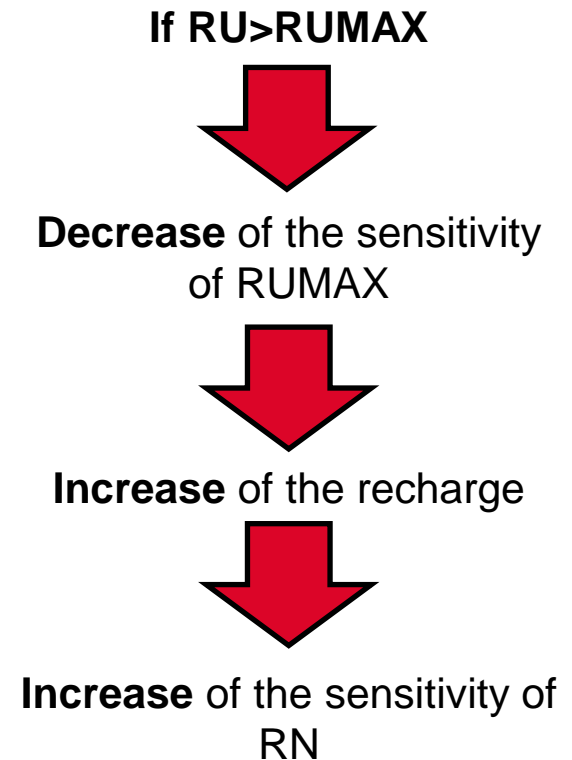
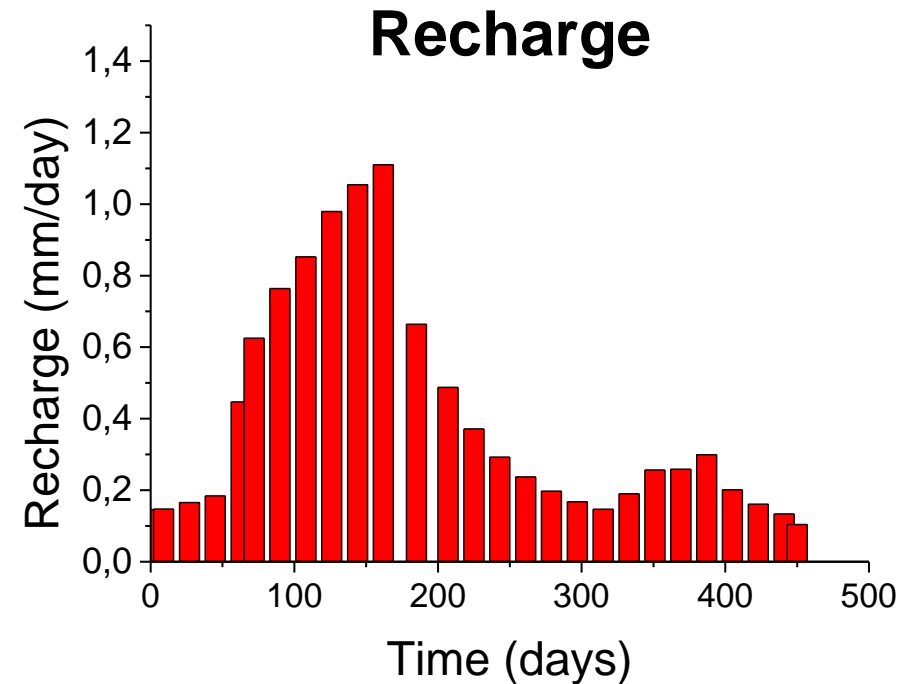
Temporal variation of sensitivity indices at point 1



RN: water transfer in the unsaturated zone
(delay and spreading)

RUMAX: threshold parameter

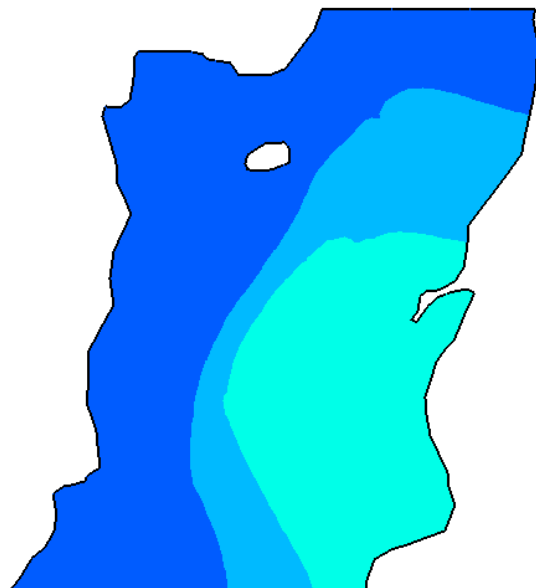
Temporal variation of sensitivity indices at point 1



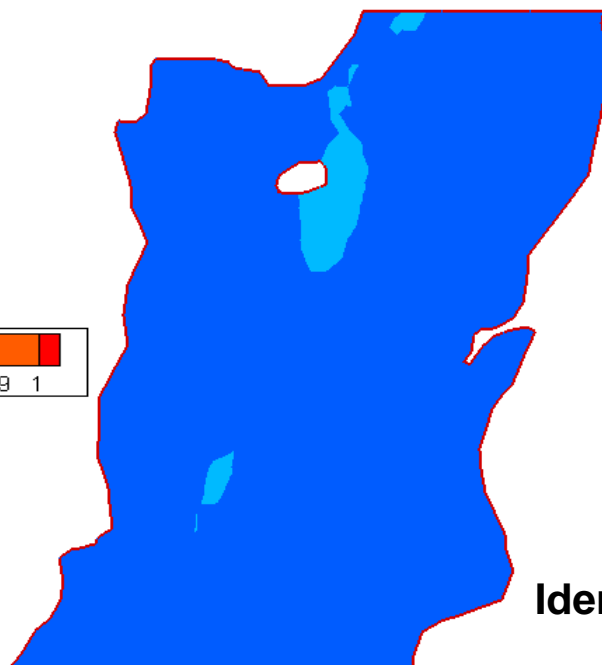
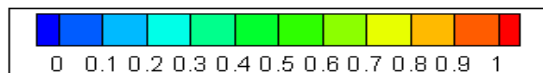
R_N : water transfer in the unsaturated zone (delay and spreading)

R_{UMAX} : threshold parameter

Sensitivity maps over time



S1

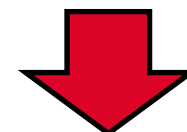


RUMAX3

RUMAX3: sensitive from the **1st** to **185th** day
S1: influential between the **185th** and the **346th** day



Weak or even negligible correlations between the
185th and the 346th day



Identification of S



During the first days



Identification of RUMAX and RN knowing S

- Determination of influential parameters

Nash: RUMAX and RN

Groundwater flow: K and S

- Temporal variation of parameter sensitivity

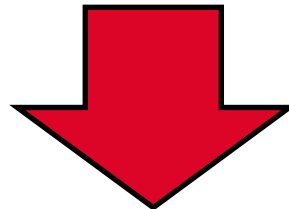
Nash: saturation of the 1st reservoir (RUMAX) and recharge (RN)

Permeability: decrease of the hydraulic heads

Storage capacity: increase of the hydraulic heads

- Weak interactions between aquifer and recharge parameters

$$q = -K\nabla H \quad K \text{ constant, } q \text{ variable} \rightarrow q=0, \text{ détermination of } K$$



Confirmation of the feasibility of simultaneous estimation of recharge and groundwater flow parameters

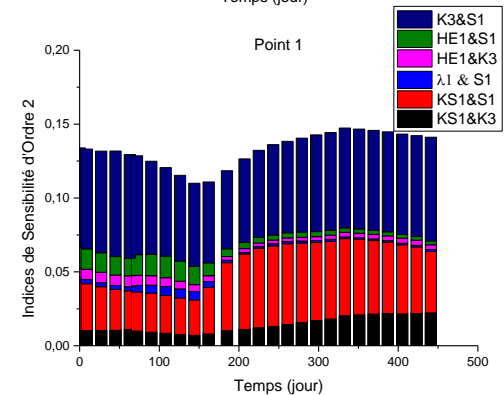
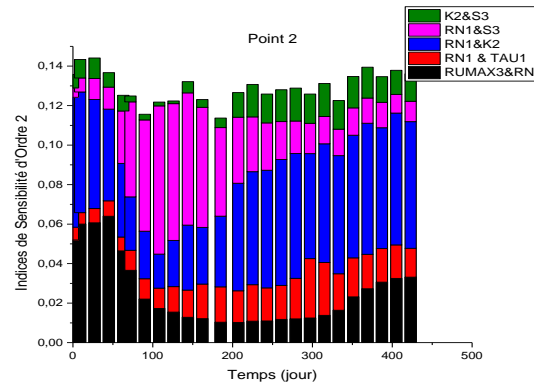
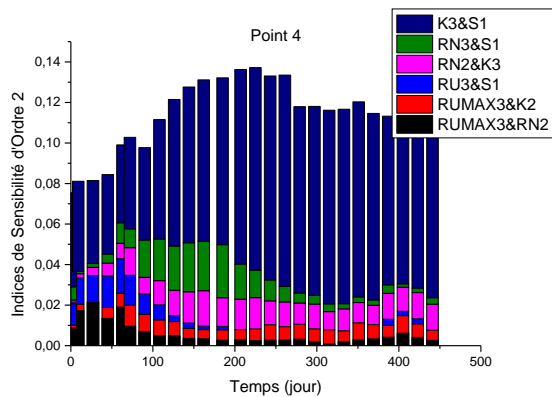
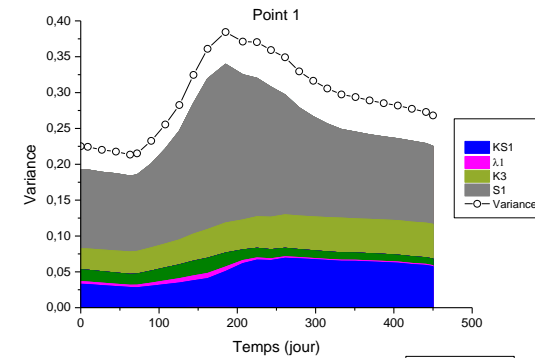
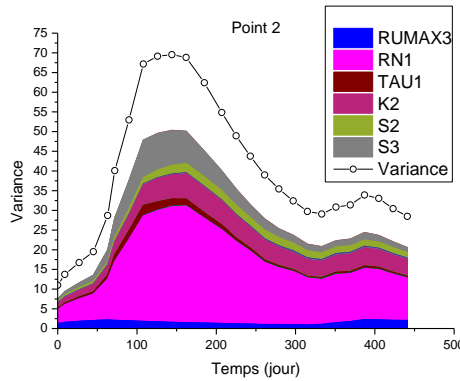
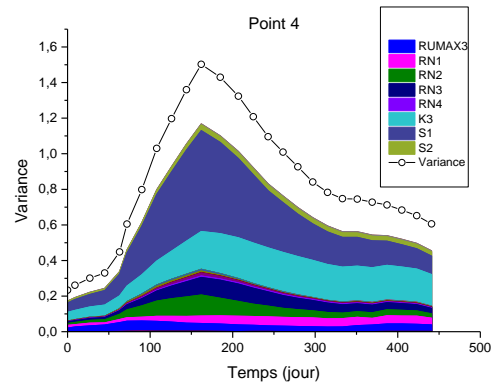
A high-speed photograph of a water splash on a blue background. The splash is centered, with several droplets captured in mid-air above the main impact point. The water surface shows concentric ripples spreading outwards. The overall color palette is various shades of blue, from light to deep navy.

*Thank you for
your attention*

Parameters Interactions

Nash model

Richards model



Diffusivity equation (Transient state with recharge)

$$S \frac{\partial H}{\partial t} - \nabla \cdot [K \nabla H] = q_s$$

Steady state without recharge

$$-\nabla \cdot [K \nabla H] = 0$$

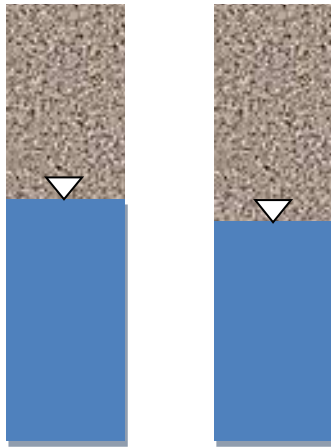
Steady state with recharge

$$-\nabla \cdot [K \nabla H] = q_s$$

Transient state without recharge

$$S \frac{\partial H}{\partial t} - \nabla \cdot [K \nabla H] = 0$$

Assumption of constant hydraulic head over decade



$$q_i^n = -K \frac{\partial}{\partial z} (h - z) = K \left(h_{i+\frac{1}{2}} \right) \left(\frac{h_i^n - h_{i+1}^n}{\Delta z_i} + 1 \right)$$

If the hydraulic heads decreases, the imposed pressure decreases, and the flux calculated is positive and strong

If the hydraulic heads increases, the imposed pressure increases, and the flux calculated is negative

RESOLUTION OF RICHARDS EQUATION

