Simulation of water flows in a tailings pile at the former uranium mine at Le Cellier (Lozère, France)

Ahmeda Ouédraogo[1],
Anne Jost[1], Valérie Plagnes[1], Pierre L'Hermite[1],
Isabelle Blanc-Potard[2], Camille Chautard[3],
Michael Descostes[3,4]

1 Sorbonne Université, CNRS, EPHE, METIS, F-75005 Paris, France

2 AMF, Orano Mining, France

3 Environmental R&D Department, Orano Mining, France

4 Centre de Géosciences, MINES ParisTech, PSL University, 35 rue St Honoré, 77300 Fontainebleau, France

Le Cellier open pit mine in operation (1974)

❖ Mine tailings

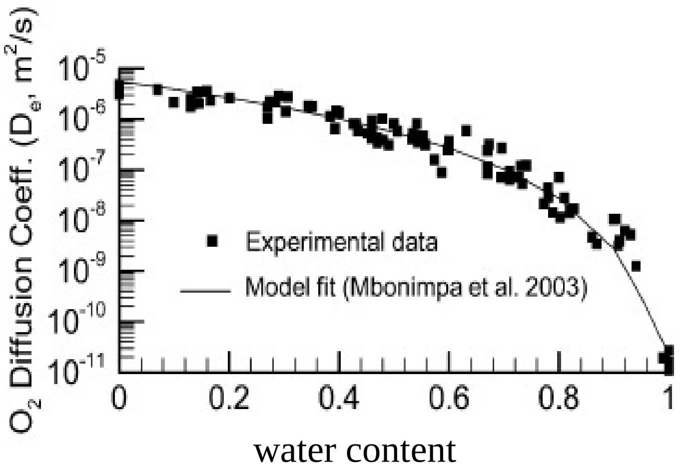
- Pile deposited (10 to 150 m) as a result of mining and/or ore treatment

https://www.srk.com/en/services/mine-waste-management

❖ Issues associated with tailings

- Sometimes exposed at the surface by atmospheric conditions
- Unsaturated area

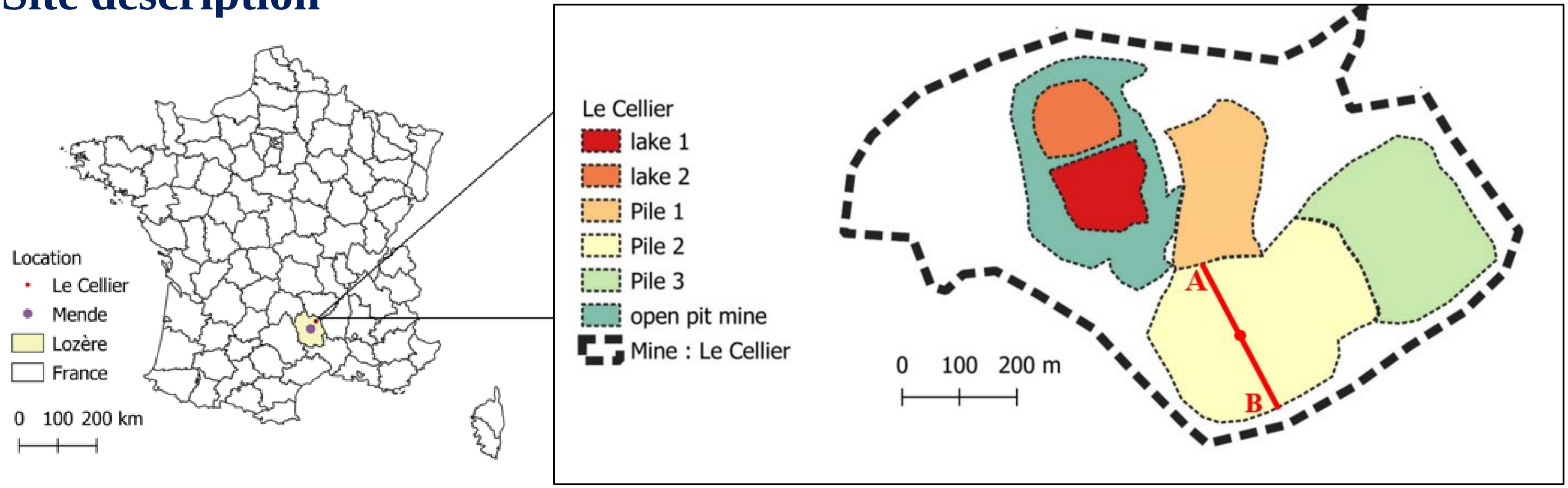
{ Transferts of pollutants
  Acid leaching
  Acid mine drainage



❖ Objectives

- ***Develop a 2D model that describes the flow in a tailings pile***
- ***Understand the water content repartition within the pile***

❖ Site description



- Le Cellier : a former uranium mine site managed by ORANO
- 2283 tons of uranium metal from 1956 to 1988

❖ Mining Activities

- Underground and open pit (OP) mining
- Ore processing (static and dynamic leaching)
- Tailings piles (Pile 1, Pile 2, Pile 3)

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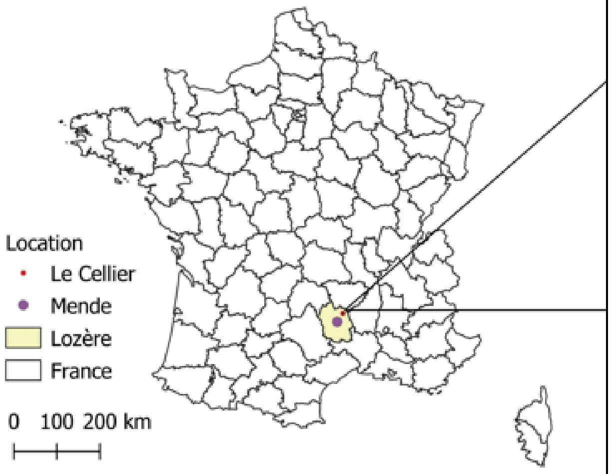

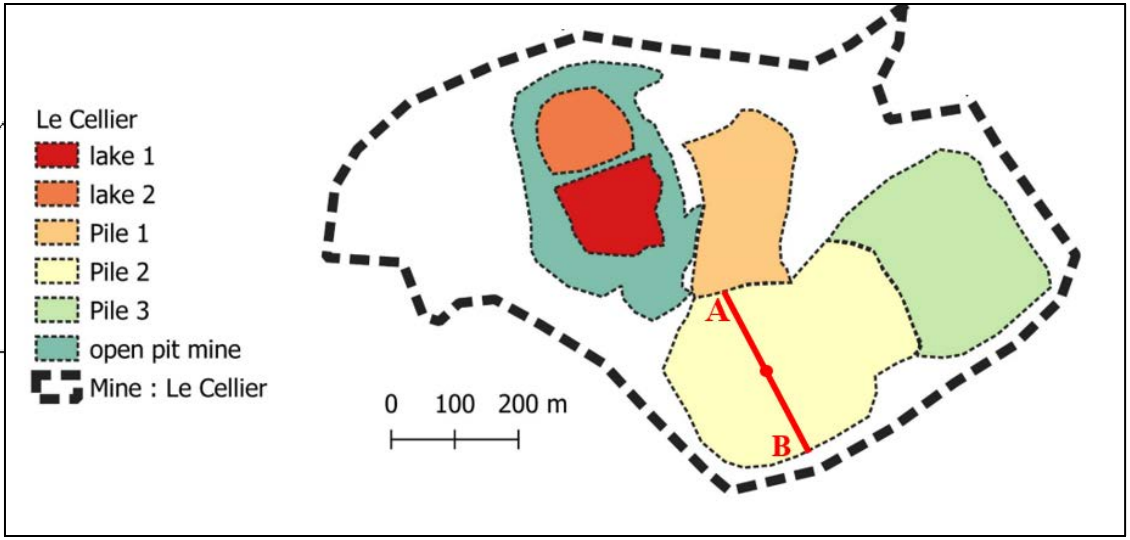

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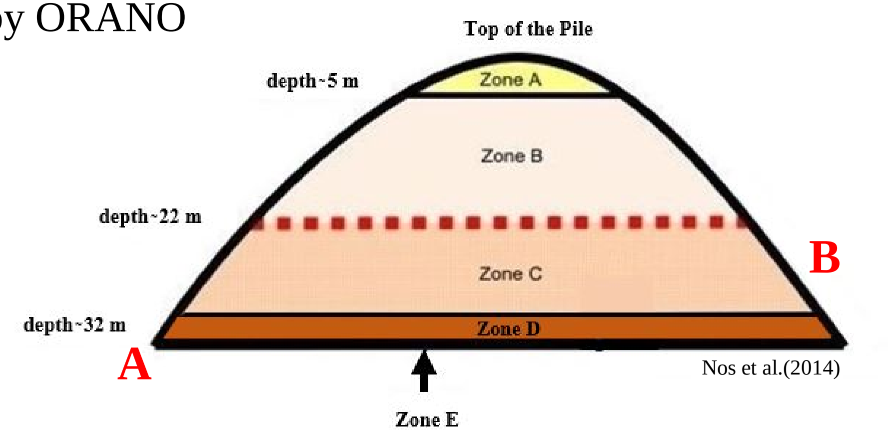
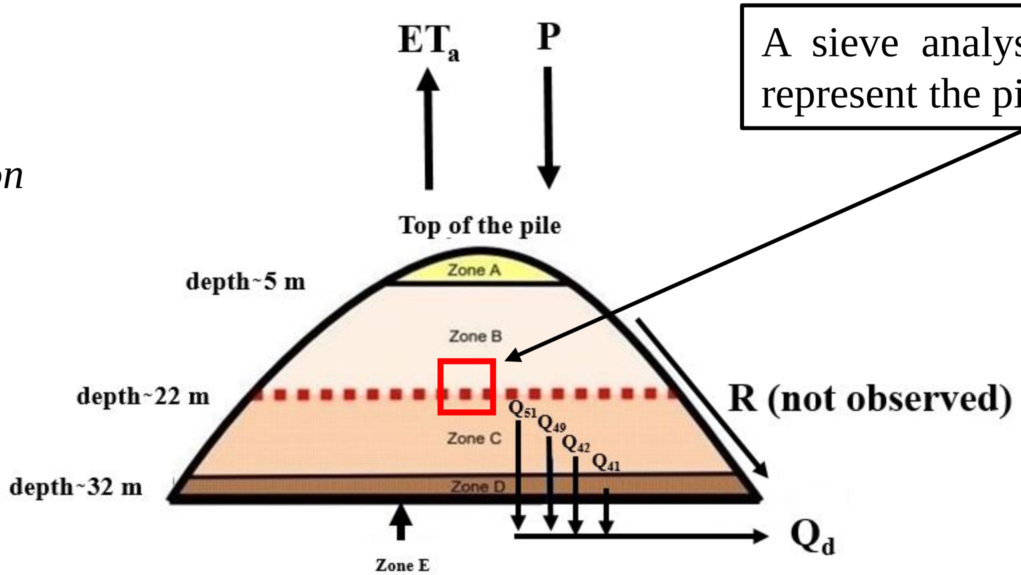


❖ Mining Activities

- Underground and open pit (OP) mining
- Ore processing (static and dynamic leaching)
- Tailings piles (Pile 1, Pile 2, Pile 3)
- Pile 2 →
  - Pile 2: a residual pile from static leaching
  - Impluvium (135 000 m²)
  - Materials: granite gravel, sand

❖ Available data from 2008- 2010

Climatic data:
P: *precipitation*
T : *temperature at daily step*
ET : *potential evapotranspiration*



A sieve analysis supposed to represent the pile materials

Four drains discharges at monthly step

$$Q_d = Q_{51} + Q_{49} + Q_{42} + Q_{41}$$

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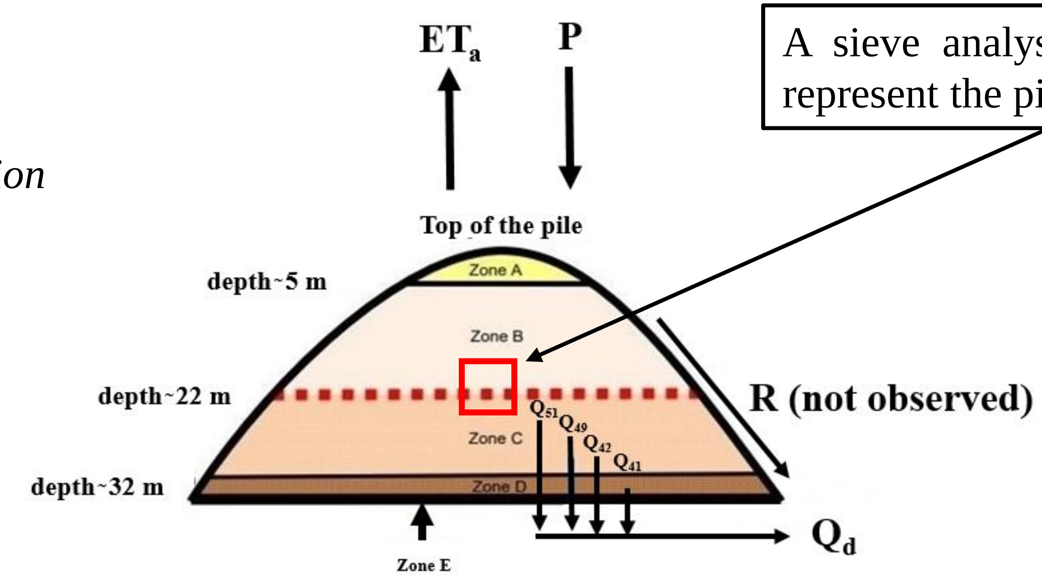
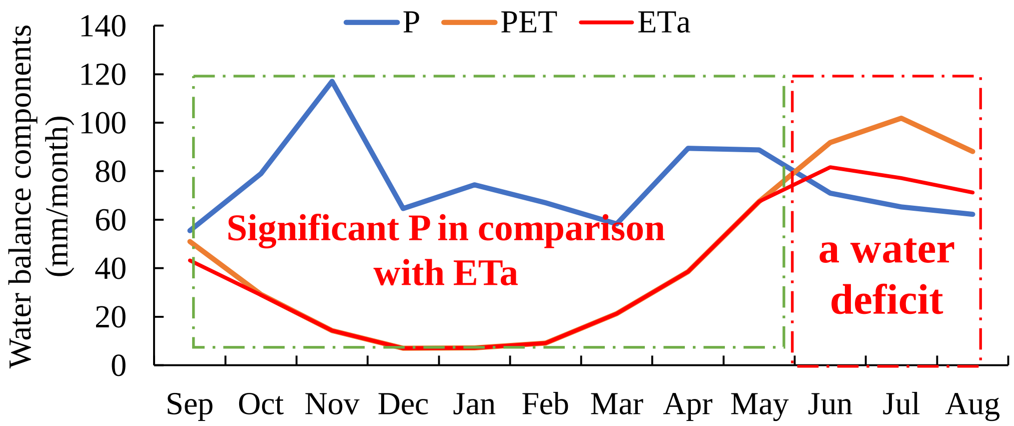


❖ Data analysis

Four drains discharges at monthly step

$$Q_d = Q_{51}+Q_{49} + Q_{42} + Q_{41}$$



- PET evaluated by Oudin (2004) formula
- Thornwaite water balance model
- Annual ETa (AWC = 120 mm) : 45% of precipitations.

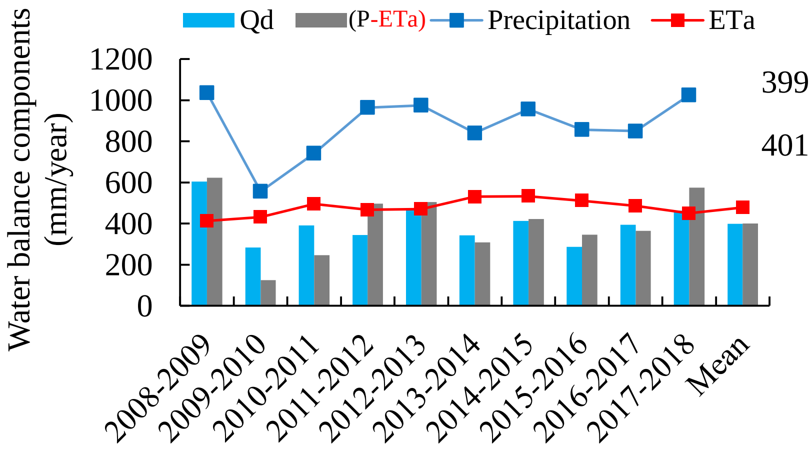
❖ Water balance of pile 2

At a pile scale :

$$P - ETa = R + I = Q_d$$

- **Budget is acceptable for most of the years**

Annual water balance



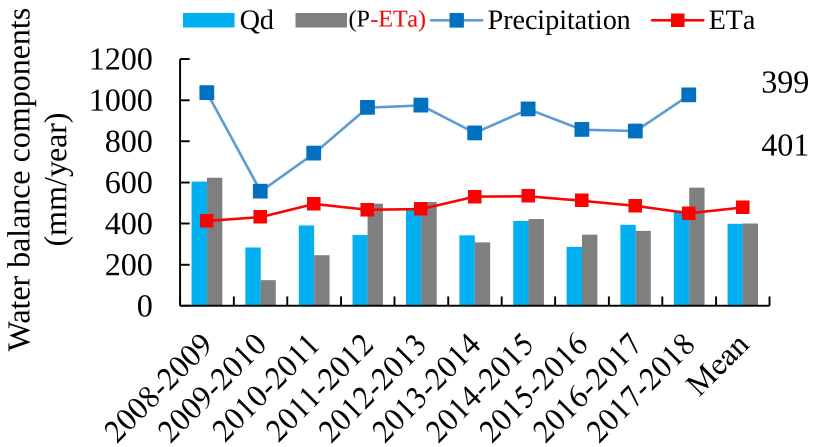
❖ Water balance of pile 2

At a pile scale :

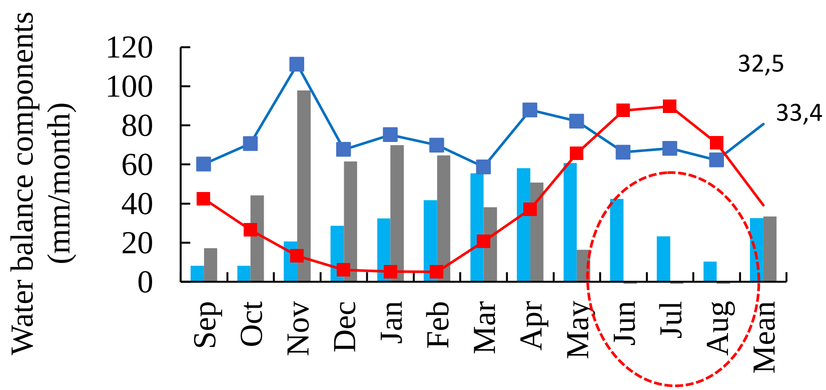
$$P - ETa = R + I = Q_d$$

- **Budget is acceptable for most of the years**
- **A reaction time of the pile?**

Annual water balance

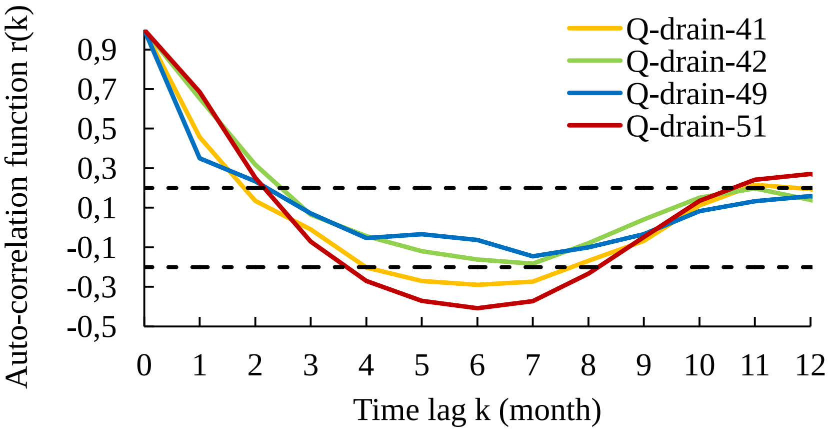


Monthly water balance



❖ Correlations of discharges (Q)

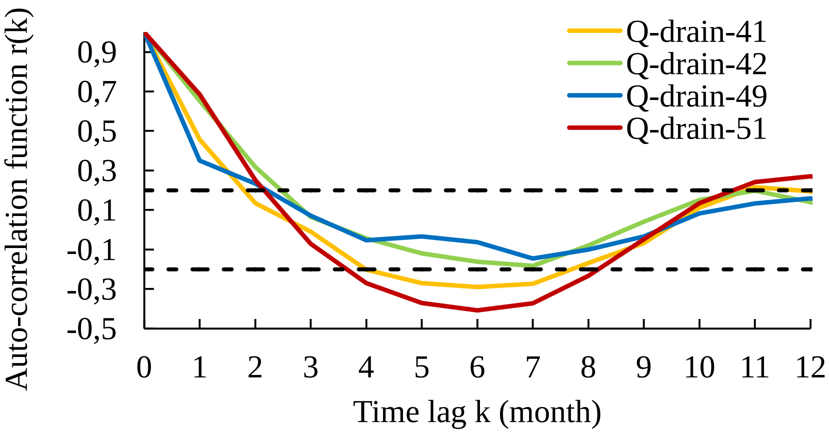
- Autocorrelation functions decrease synchronously on all drains , a cyclical pattern;

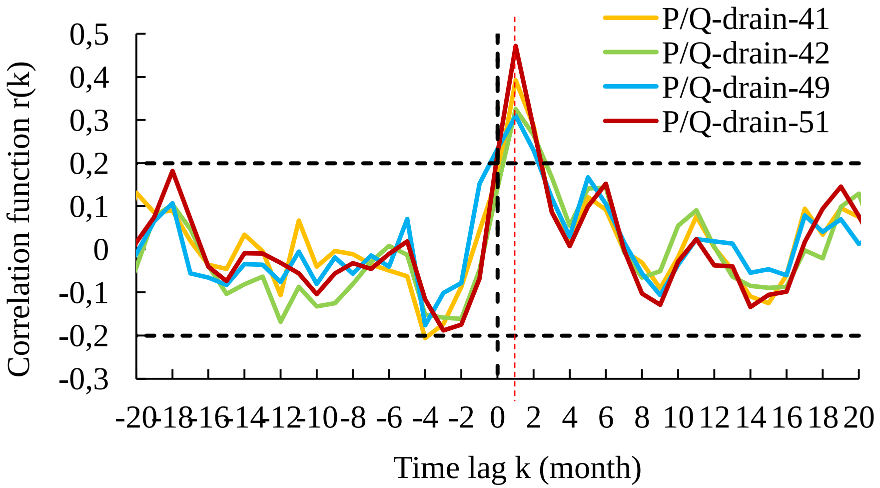


2008-2018: 120 observations

❖ Correlations of discharges (Q)

- Autocorrelation functions decrease synchronously on all drains , a cyclical pattern;
- Significant correlation functions (> 0.2) at a time lag equal to 1 month
- Heavy (above-average) rainfall can result in high discharge the next month
- Semi-annual cycle between rainfall and flow rates, in adequation with the time lag already observed between the calculated EXD and observed Q_d.
- Similar dynamic for all drains





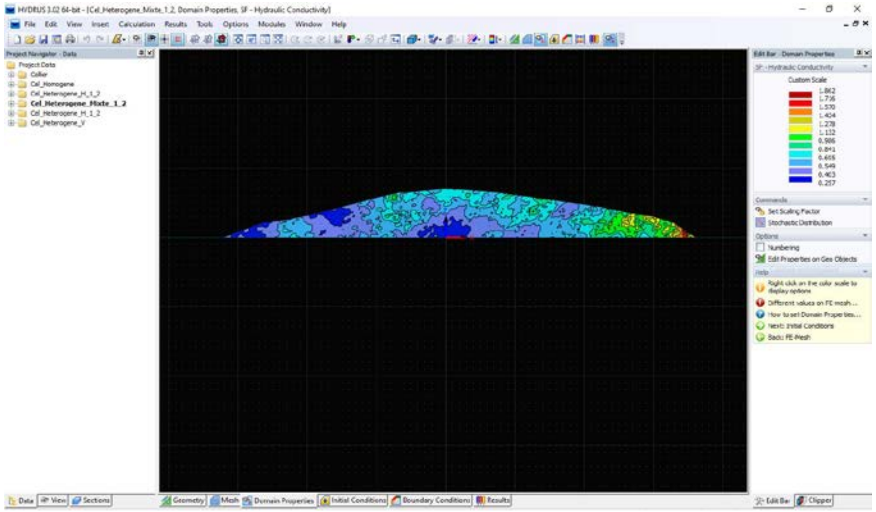
2008-2018: 120 observations

MODELING

Objective: *Reproduce the observed drains discharges and have a view on the water content evolution in the pile.*

❖ Software: HYDRUS 2D

- Richards (1931) equation governs water transfers in variably saturated porous media :



$$\frac{\partial}{\partial x}\left[K_x(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K_z(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K_z(h)}{\partial z} = -\mathrm{c(h)}\,\frac{\partial h}{\partial t}$$

$$c(h) = \frac{\partial \theta}{\partial h}$$

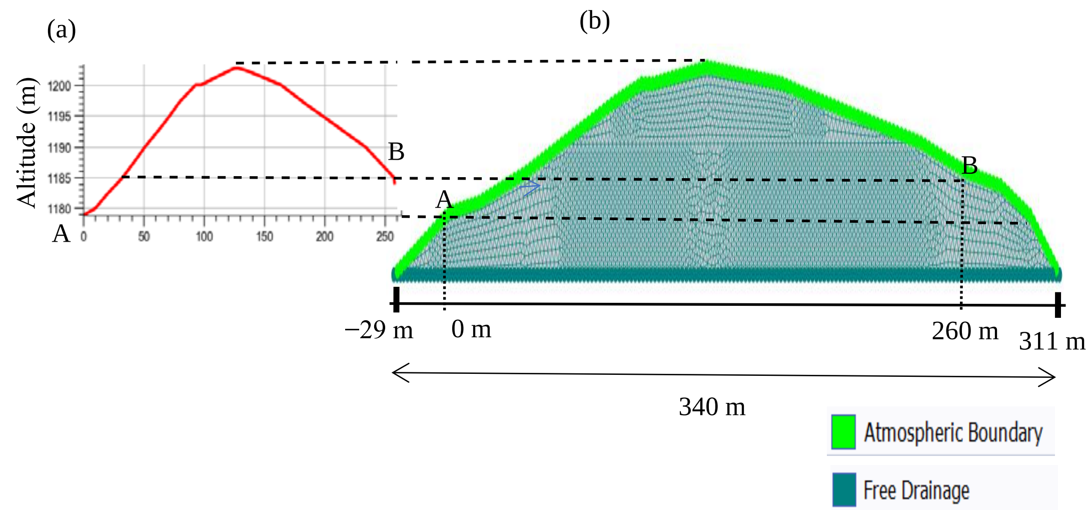
- Geometry of the pile

- Requires θ(h) and K(h) relationships

❖ Model geometry, boundary and initial conditions

- **Geometry**

Transversal topographic profile of pile 2 from A Digital Elevation Model (DEM)



- **Initial conditions**

h = -1,2 m which corresponds to a water content near to the residual water content

Number of mesh entities		
Nodes:	3764	
1D-Elements:	438	Discretization of Curves (edges)
2D-Elements:	7180	Discretization of Surfaces (faces)
3D-Elements:	0	Discretization of Solids (volumes)
Boundary mesh:		
Nodes:	346	Nodes on domain boundary
Elements:	346	Elements on domain boundary

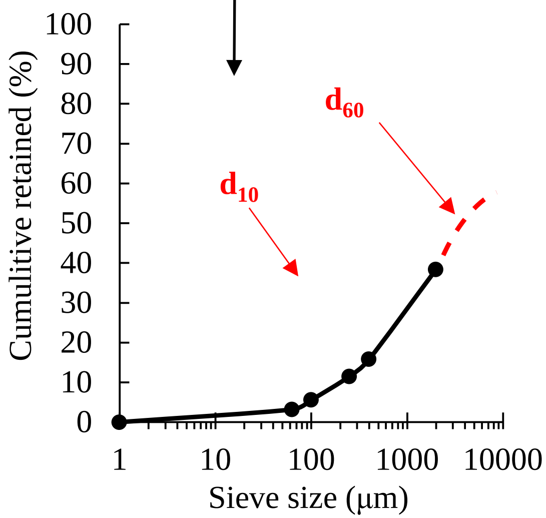
❖ Input data

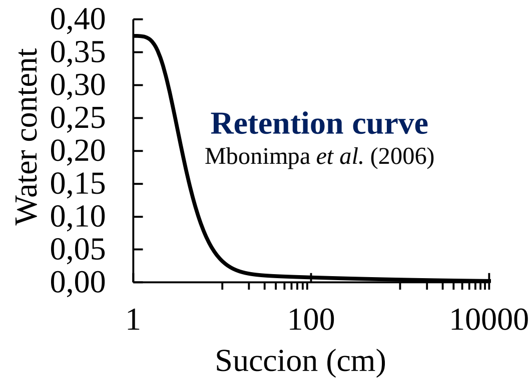
P, ETR at daily step but constrained with average monthly rainfall and evapotranspiration for each day

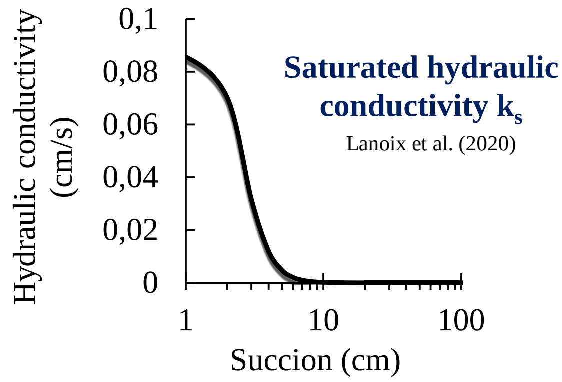
❖ Hydraulic parameters: θ(h) and K(h) relationships

1

Sieve analysis 21-22 m (d10, d60, e)







RETC Code

van Genuchten et al.(1991)

Parameters	θ_r	θ_s	α (m^{-1})	*n*	k_s ($m.j^{-1}$)	*l*
Cellier 1	*0. 001*	*0. 37*	*30*	*3. 3*	*73. 44*	*0. 5*

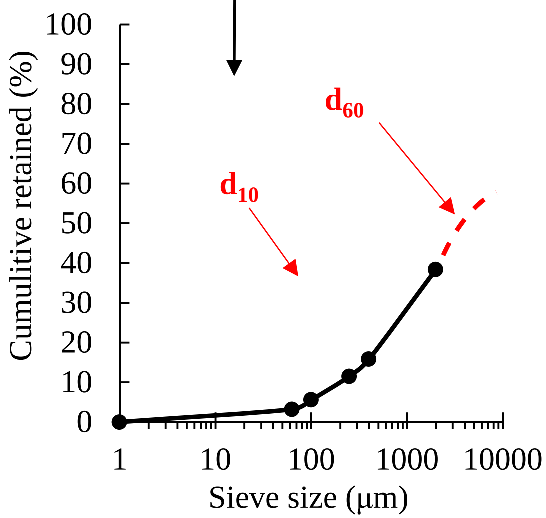
Compared simulated discharges with these parameters to the observed discharges, the Nash Criterion (NSE) is 0.4

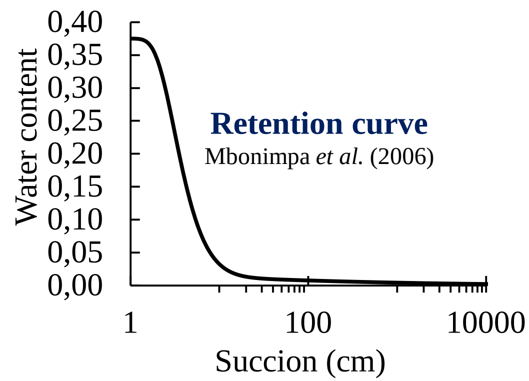
$$NSE = 1 - \frac{\sum_1^n (Q_{si} - Q_{oi})^2}{\sum_1^n (Q_{oi} - \overline{Q_o})^2}$$

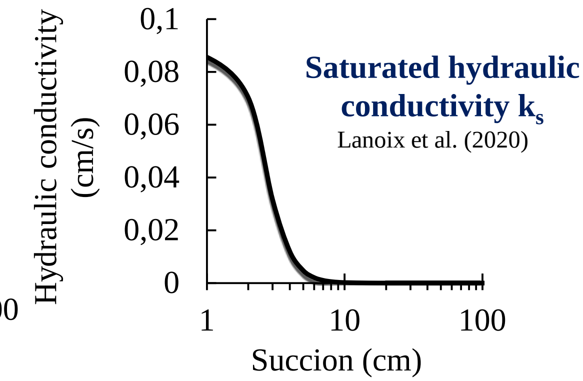
where n is the total number of data, Q_{si} is the simulated value, Q_{oi} is the observed value and $\bar{Q}_o$ is the average of observed data.

❖ Hydraulic parameters: θ(h) and K(h) relationships

1 **Sieve analysis 21-22 m (d10, d60, e)**







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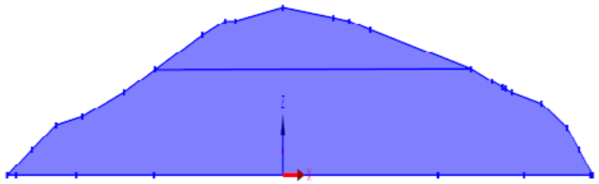
2 **2nd set of parameters from inverse method with observed flows**

Parameters	θ_r	θ_s	$\alpha\ (m^{-1})$	*n*	$k_s\ (m.j^{-1})$	*l*
Cellier 2	*0*	***0. 29***	*30*	*3. 4*	*73. 44*	*0. 5*

❖ Model geometry, boundary and initial conditions



- ***Homogeneous materials***

Parameters	θ_r	θ_s	α (m^{-1})	n	k_s $(m.j^{-1})$	l
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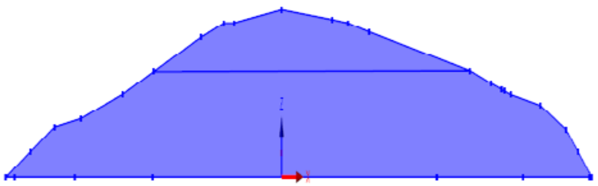
- ***Homogeneous materials***



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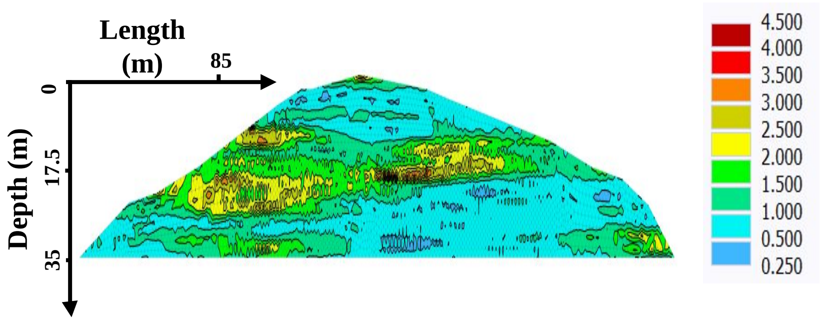
Cellier	*0*	*0. 29*	*30*	*3. 4*	*73. 44*	*0. 5*

- ***Heterogenous materials***

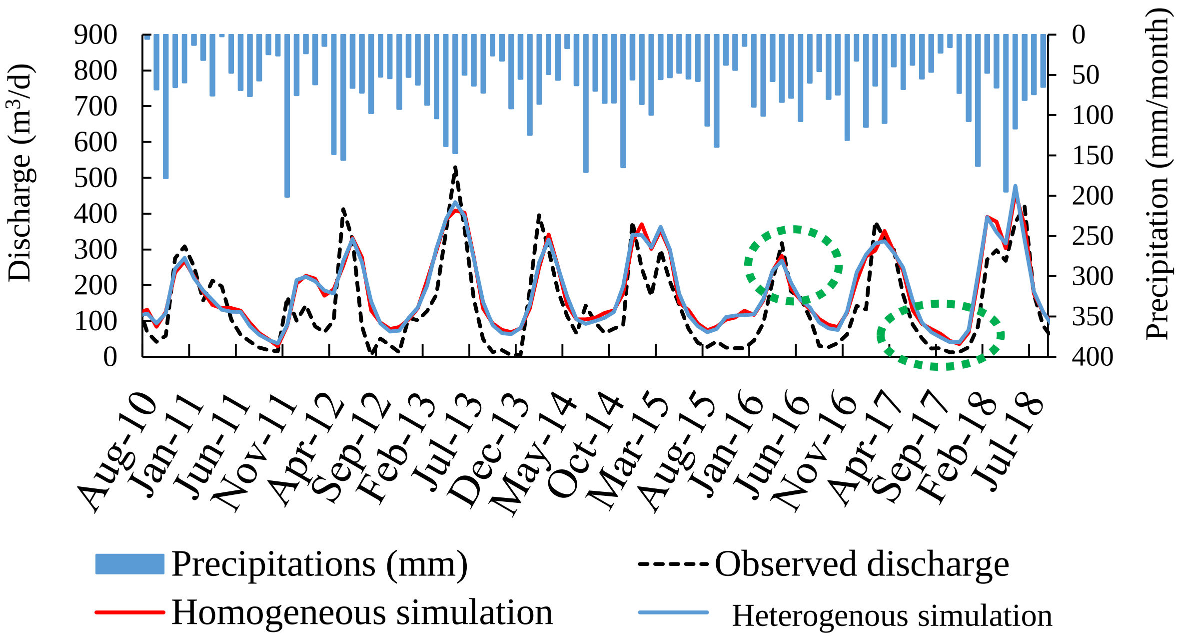
due to acid injection through horizontal deposits during static leaching ***: stochastic vertical correlation approach***

Log σ	Correlation	Heterogenous materials
0.25	Cor X	100
	Cor Y	5



Scaling factors for horizontal related to hydraulic conductivity

❖ Observed and simulated discharges are compared

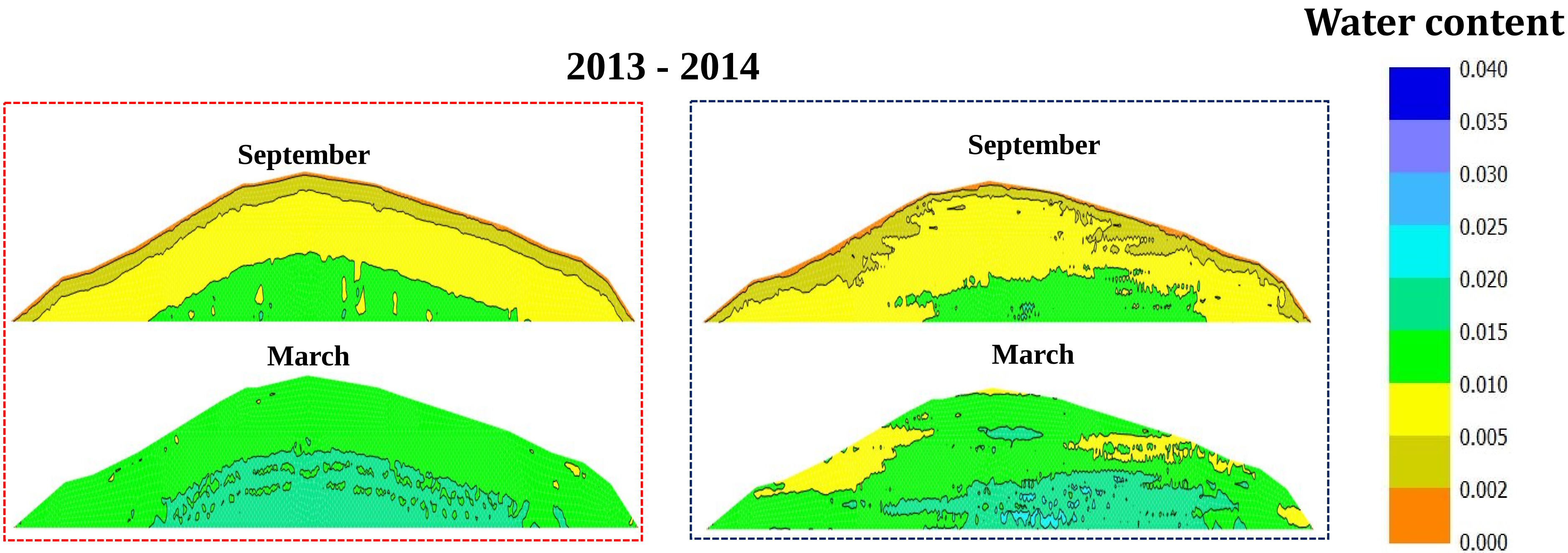


Statistics Criterion	Homogeneous	Horizontal
NSE Q	0,64	0,64
NSE $ln\ (Q)$	0,36	0,37
NSE $(\sqrt{Q})$	0,56	0,57

good

- Flow dynamics reproduced
- High and low flow periods not reproduced very well in some periods throughout the simulations
- Small difference between homogeneous et heterogenous approaches (not significant statistically)
  - Low Hydraulic conductivity sensitive to discharges

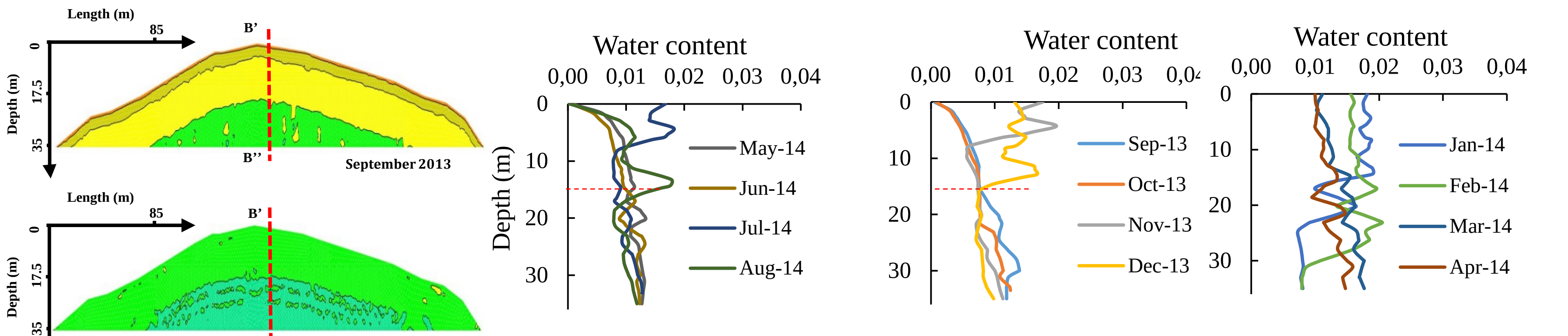
❖ Simulation of water content



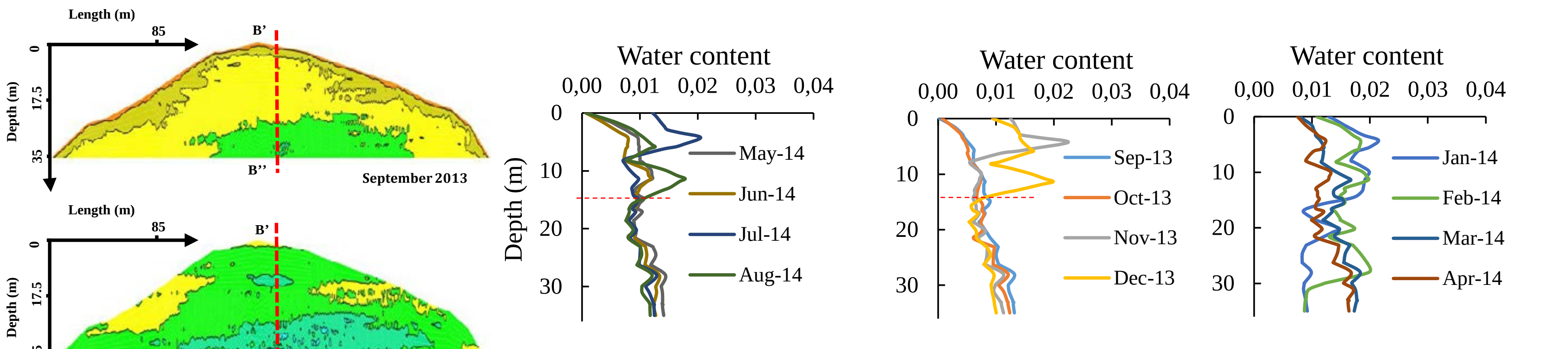
Homogenous simulation **Heterogeneous simulation**

- **Low water content (Max : 2.9 % homogeneous and 3.2 % heterogenous simulations)**
- **Seasonal distribution of water content**
- **Water retention areas in heterogeneous simulation**

❖ Simulation of water content



Homogenous simulation



Heterogenous simulation

- **From May to December, low impact of the atmospheric conditions on the water content below 15 m**
- **More fluctuation of water content from January to April**

❖ Conclusion

- **Knowledge of the site** (history of deposits, granulometry)
- **Daily / Monthly data of the site** (P, T et Q)
- **Flow simulation with Hydrus en 2D**
    - Simulation of discharges from pile 2
    - Low water content in the pile
    - Seasonal distribution of water content

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❖ Next steps: NEEDS 2021-2022

- **Model improvement**
  - Additional field study (geophysics and material characteristics)
  - Daily measurements on site (P, Q)
  - Coupling with reactive transport, heat transfer and gas movements
- **Other modeling approaches**
  - Dual porosity
  - Fractured aquifers (macro-pores)

Measurements of discharges

Open pit mining (1974)

Le Cellier site (1978)

Le Cellier site (1981)

Le Cellier site (1991)

THANK YOU FOR YOUR ATTENTION

Current view of Le Cellier Site (2010)