Hydrodynamic and Hydrodispersive Behaviour of Chalk under Variably Saturated Conditions

Serge Brouyère
Hydrogeology Group
GEOMAC Department
University of Liège
Belgium
Serge.Brouyere@ulg.ac.be

Presentation Summary

- General context
- Description of the experiments
- Conceptual model for the chalk
- Mathematical and numerical model
- Conclusions

- The Hydrogeology Group at the University of Liège

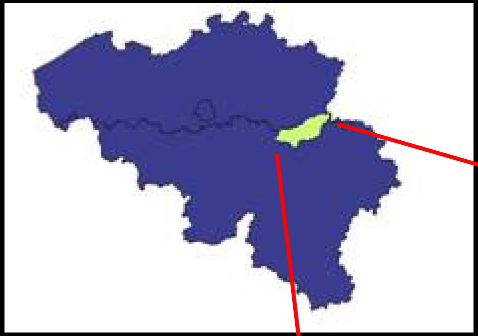
General context of the experiments

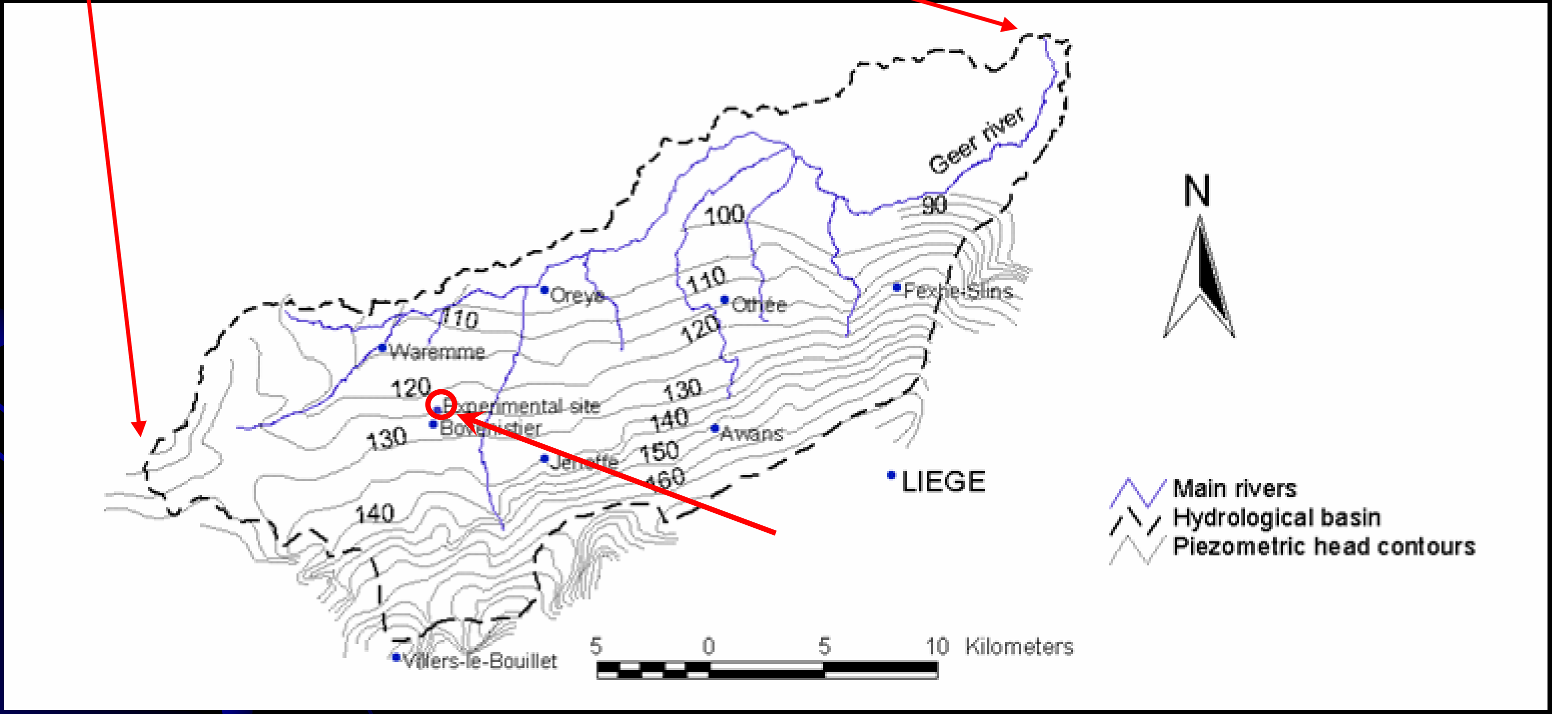
- The Hesbaye Aquifer is located in Senonian chalk formations of the Geer basin in Belgium
- 30 millions m³/year of drinking water to supply approx. 600,000 people
- Increase of nitrate contents at an annual rate of 0.1 mg/l in the semi-confined to 1 mg/l in the unconfined part of the aquifer
- Presently, around 35 mg/l; from 20 mg/l at the aquifer bottom to 175 mg/l in contaminated zones of the upper aquifer

General context of the experiments

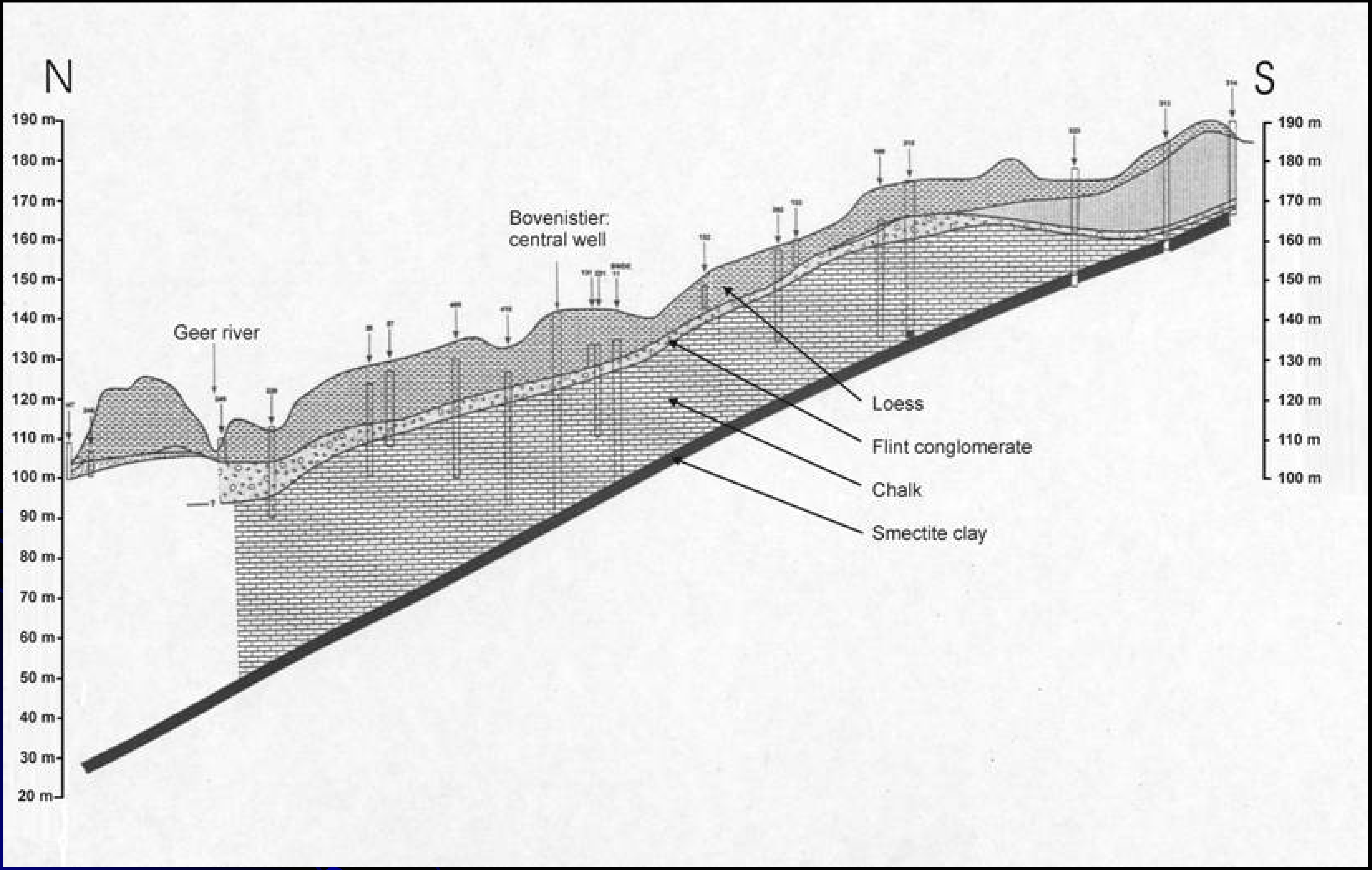
- Several projects and actions funded for studying and locating nitrate sources of groundwater contamination; however efforts were mostly devoted to model nitrate dynamics in soils (i.e. down to 1.5 m) and in the saturated zone
- Strong need for an investigation of hydrodynamic and hydrodispersive mechanisms governing the downward migration of water and contaminants across the unsaturated zone (i.e. from 1.5 m to the aquifer table)

Experimental site



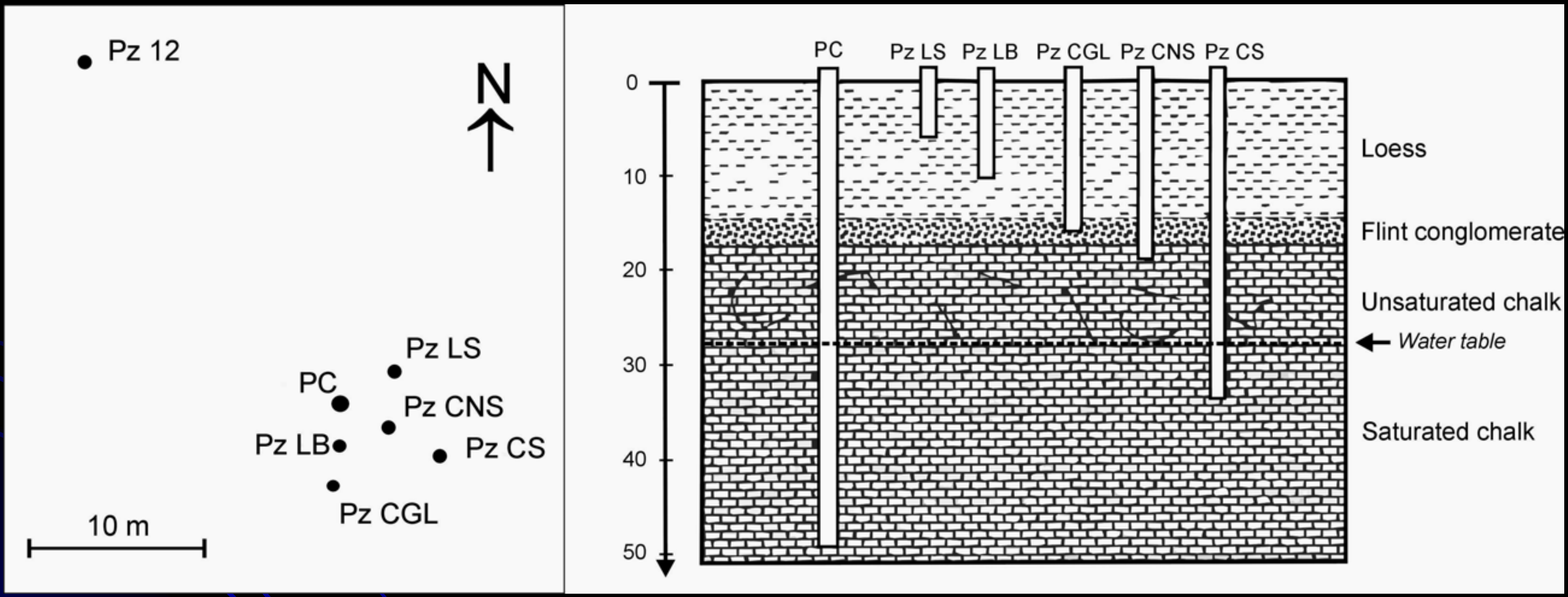


Experimental site



Experimental site

1 pumping well
+ 5 piezometers screened in the unsaturated and saturated zones



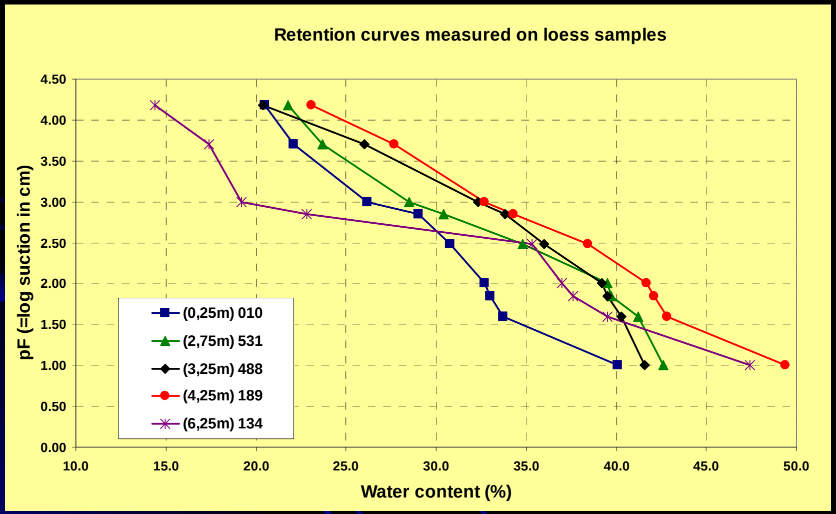
Experimental site

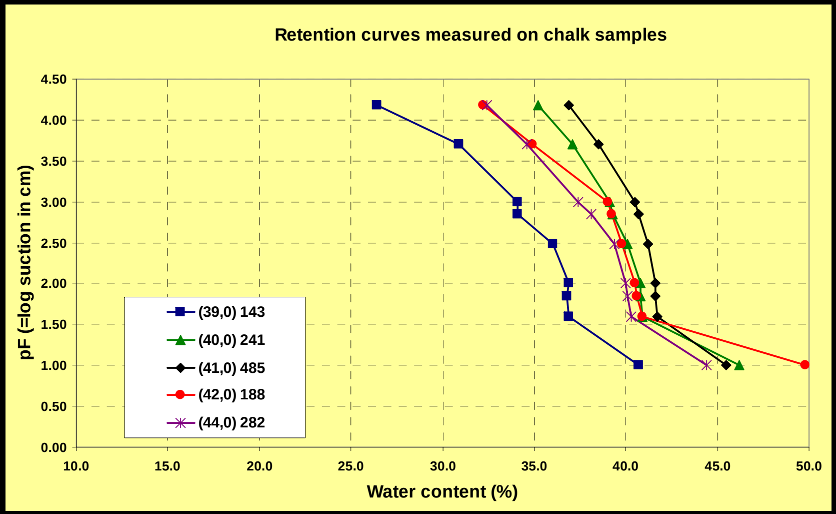
Planning of the experiments

- Boreholes drilled → various depths
- Undisturbed core samples taken for laboratory measurements
- Well logging (gamma-ray, gamma-gamma, neutron)
- Infiltration tests in the unsaturated zone
- Pumping tests in the saturated zone
- Tracer experiments in the saturated zone
- Tracer experiments in the unsaturated zone

Laboratory measurements

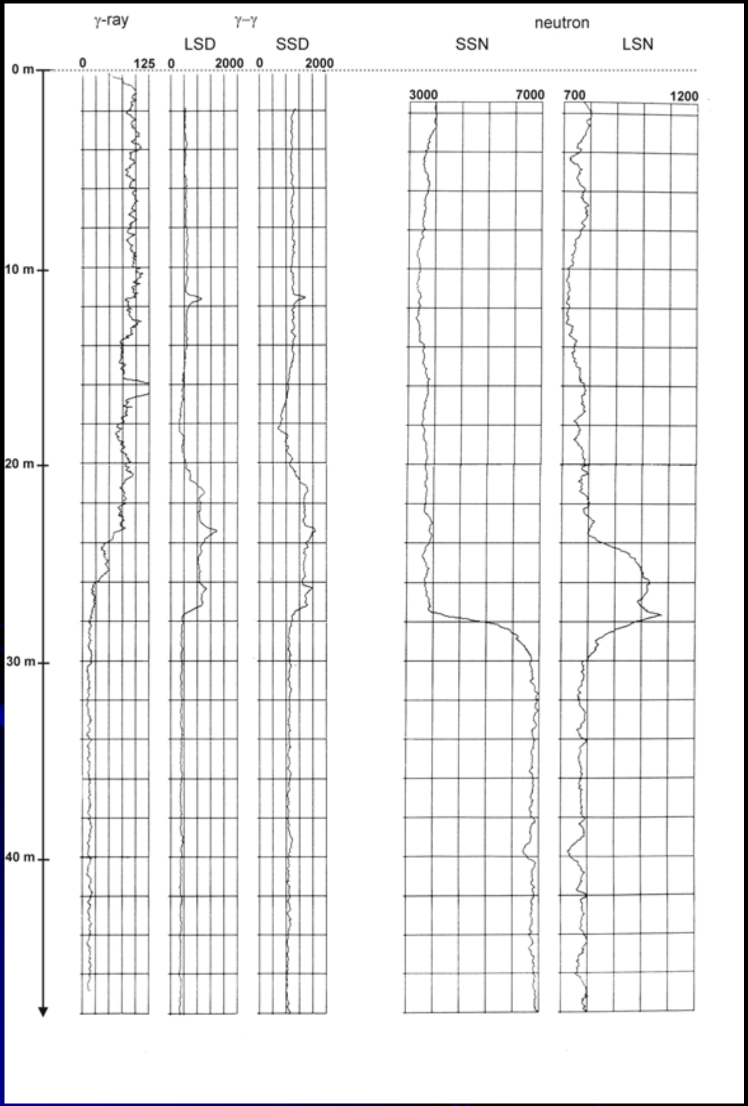
- Hydraulic conductivity measurements on core samples
  ➔ Chalk : ~1×10^{-8} m/s (matrix !)
- Textural analyses of loess formations
- Retention curves on loess and chalk samples





- Nitrate + pesticides concentrations measured in core samples

Well logging

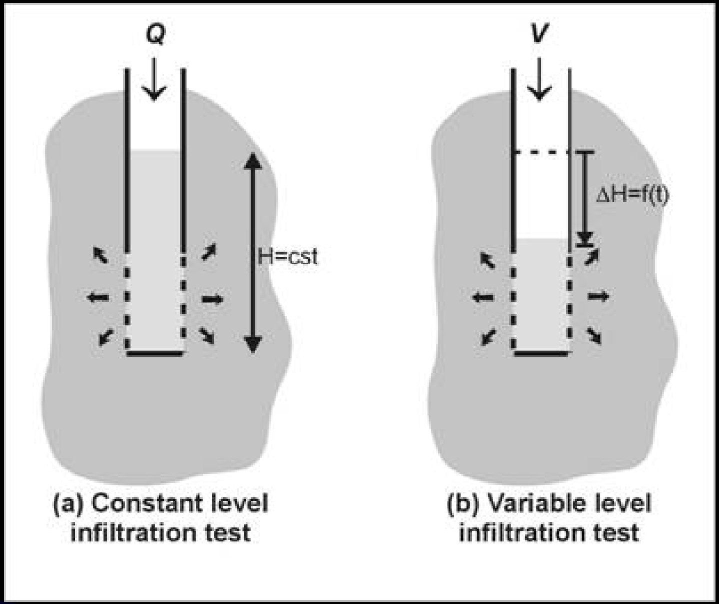


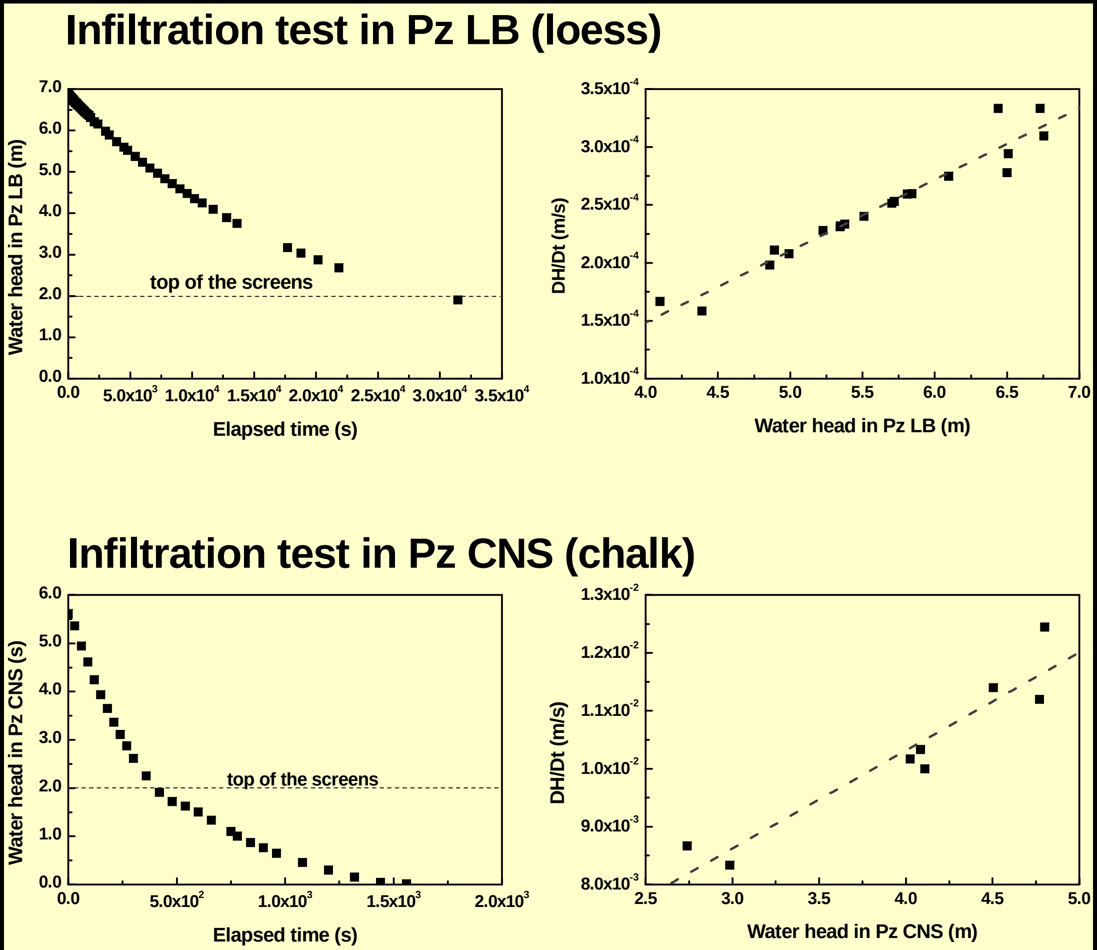
- Loess: high and variable radioactivity, relatively high density, variable water content in relation with rainy episodes
- Flint Cgl: low radioactivity + low water content → good drainage capacity
- Chalk: low radioactivity except at the top, low density between 20 and 28 m → alteration and dissolution in relation with water table fluctuations, capillary rise ~4m, limited by a low density level

Pumping tests in the saturated zone

Pumping well	Pumping rate (m^3/h)	Interpretation method	Chalk hydraulic conductivity estimated at the observation wells (m/s)					
			Pz 12		Pz CS		PC	
			drawdown	recovery	drawdown	recovery	drawdown	recovery
Pz 12	15.59	Theis	4.4×10^{-5} 8.8×10^{-5} 7.3×10^{-5}	1.46×10^{-4}	---	---	---	---
	8.1	Dupuit	7.5×10^{-5}	---	---	---	---	---
		Theis	1.26×10^{-4}	3.15×10^{-4}	---	1.26×10^{-5} 3.94×10^{-4} 1.26×10^{-4}	---	7.12×10^{-4} 3.78×10^{-3}
Pz CS	4.07	Dupuit	---	---	7.05×10^{-5}	---	---	---
		Theis	3.6×10^{-3} 9.22×10^{-4} 1.59×10^{-3}	2.84×10^{-3} 1.11×10^{-3}	2.8×10^{-6} 9.0×10^{-5}	2.52×10^{-4}	3.42×10^{-3} 1.37×10^{-3}	1.39×10^{-3}
PC	1.77	Dupuit	5.6×10^{-5}	---	---	---	---	---
	4.05	Dupuit	8.9×10^{-5}	---	---	---	---	---
	5.48	Dupuit	3.3×10^{-5}	---	---	---	---	---
	6.55	Dupuit	1.9×10^{-5}	---	---	---	---	---
	6.68	Dupuit	1.7×10^{-5}	---	---	---	---	---
	6.6	Dupuit	7.0×10^{-4} 3.29×10^{-4}	---	---	---	1.7×10^{-5}	---
		Theis		2.1×10^{-4} 7.8×10^{-5}	1.96×10^{-4} 9.4×10^{-5}	2.1×10^{-4} 7.8×10^{-5}	6.0×10^{-6} 1.4×10^{-5} 3.3×10^{-5}	4.63×10^{-4} 1.2×10^{-5} 3.0×10^{-6}

Infiltration tests in the unsaturated zone





Infiltration tests in the unsaturated zone

"Lefranc-Brillant" interpretation formulae used to estimate hydraulic conductivity of unsaturated formations

Well	Material	Constant head test			Falling head test
		Q_{inj} (m³/s)	H_{stab} (m)	K_S (m/s)	K_S (m/s)
Pz LS	Loess	1.80×10^{-6}	2.31	1.70×10^{-7}	2.34×10^{-6}
Pz LB	Loess	3.33×10^{-6}	6.89	1.04×10^{-7}	3.94×10^{-7}
Pz CGL	Flint conglomerate	11.67×10^{-6}	6.17	6.05×10^{-7}	1.95×10^{-6}
		16.70×10^{-6}	7.87	6.79×10^{-7}	
		25.00×10^{-6}	9.75	8.21×10^{-7}	
Pz CNS	chalk	66.67×10^{-6}	2.11	6.80×10^{-6}	1.66×10^{-5}
		142.83×10^{-6}	5.61	5.48×10^{-6}	

Tracer experiments in the saturated zone

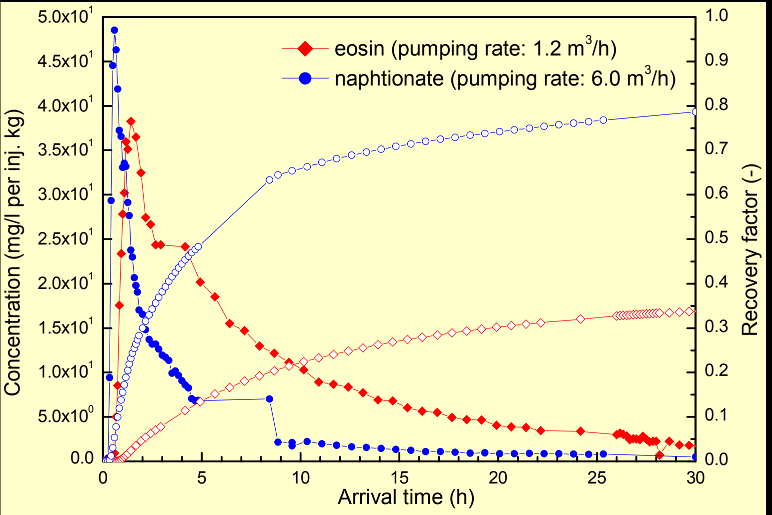
- Tracer experiments performed in order to estimate velocities and to quantify hydrodispersive properties in the saturated zone, close to the central well
- Two injections performed at well Pz CS, at different pumping rates
  - 1st injection with eosine yellowish (Q=1.2 m^3/h)
  - 2nd injection with naphtionate (Q=6.0 m^3/h)
- Tracers recovered at the central well + concentration evolution monitored at the injection well Pz CS

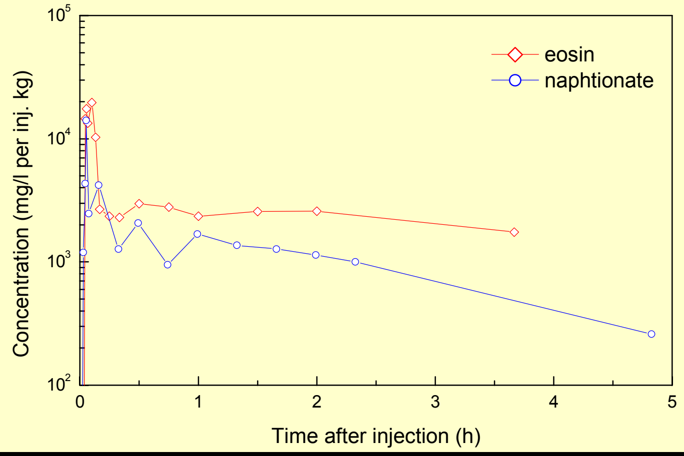
Tracer experiments in the saturated zone



Tracer experiments in the saturated zone

	Phase 1	Phase 2
Tracer	**eosin Y**	**naphtionate**
Date of injection	**2/7/1998 14:50**	**4/7/1998 9:40**
Pumping rate (m^3/h)	**1.2**	**6.0**
Injected quantity (kg)	**0.0053**	**0.0051**
Tracer volume (m^3)	**0.010**	**0.010**
Tracer injection duration (h)	**0.031 (1min53s)**	**0.036 (2min11s)**
Water flush volume (m^3)	**0.127**	**0.132**
Water flush duration (h)	**0.29 (17min20s)**	**0.22 (12min56s)**
Date of 1st arrival	**2/7/1998 15:25**	**4/7/1998 9:55**
Minimum transit time (h)	**0.58 (35min)**	**0.25 (15min)**
Maximum velocity (m/h)	**10.2**	**24**
Date of modal restitution	**2/7/1998 16:15**	**4/7/1998 10:15**
Modal transit time (h)	**1.42 (85min)**	**0.5 (30min)**
Modal velocity (m/h)	**4.2**	**1.2**
C_{mod}/C_{inj} (-)	**1.93×10^{-3}**	**3.44×10^{-3}**
Recovery factor (%)	**35 (after 40 h)**	**87 (after 77 h)**





Tracer experiments in the unsaturated zone

- Tracer experiments performed in order to evaluate transit times from the land surface to the water table and to identify mechanisms driving water and solute mobility and retardation in the unsaturated zone
- Tracer injections performed in Pz LS & LB (loess), in Pz CGL (flint cgl) and in Pz CNS (chalk)
- Tracers recovered by pumping permanently at the central well (Q: 3 to 6 m^3/h) during 2 years
- Here: presentation of tracer experiments performed from Pz CNS

Tracer experiments in the unsaturated zone

- Tracer injection performed in Pz CNS under "intense artificial" recharge conditions

Tracer: KCl

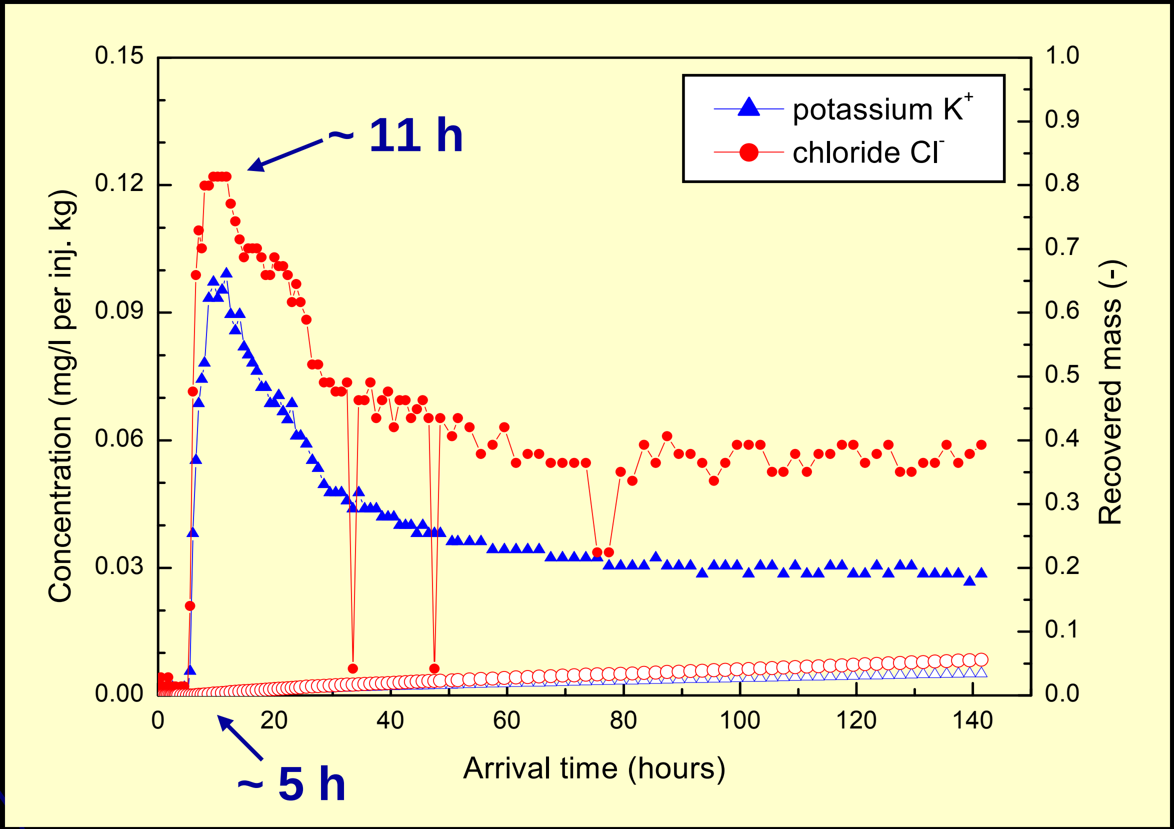
M_{inj}: 100 kg

V_{inj}: 300 l

T_{inj}: ~1 h

$Q_{recharge}$: ~0.3 m³/h

Distance ~10m



Tracer experiments in the unsaturated zone

- Tracer injection performed in Pz CNS under “natural” recharge conditions

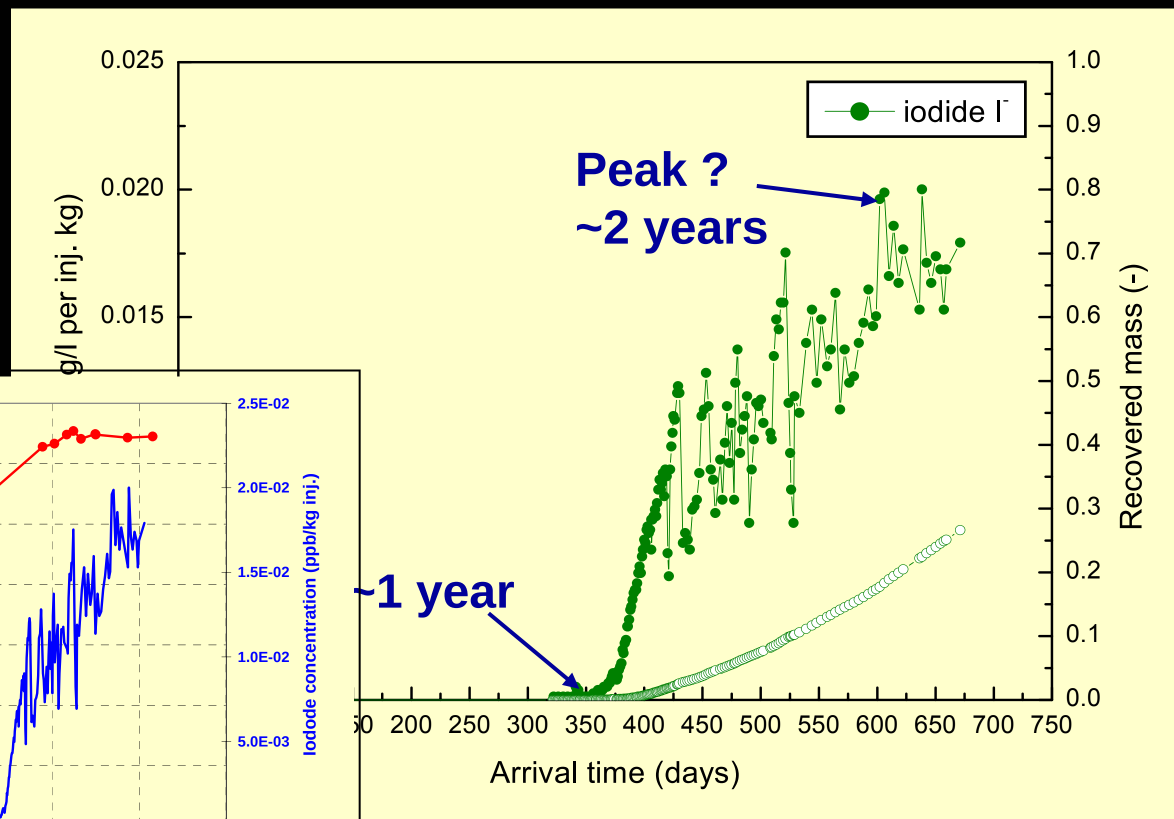
Tracer: I^-

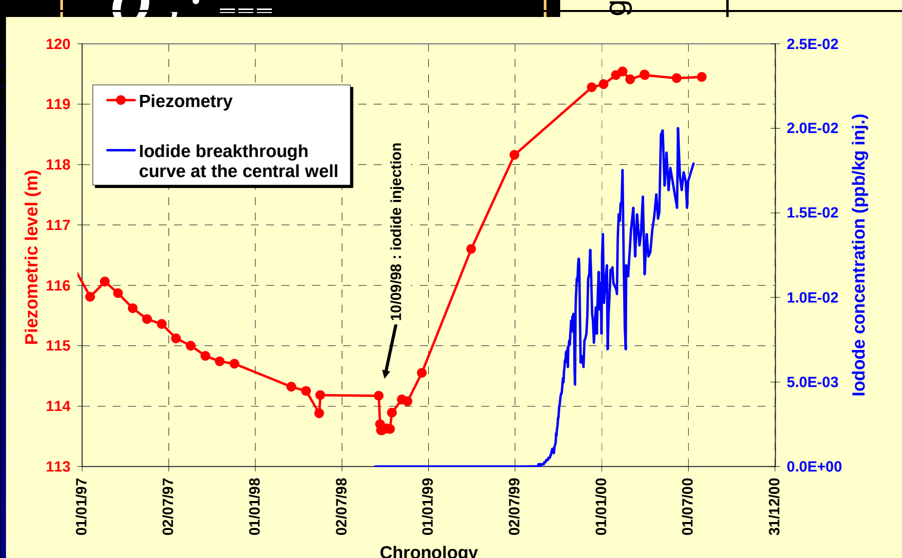
M_{inj}: 10 kg

V_{inj}: 30 l

T_{inj}: ~ 6 min

Q_{inj}: ===





Tracer experiments in the unsaturated zone

Tracer	KCl	I^-
Date of injection	8/7/1998 11:40	11/11/1998 9:35
Pumping rate (m^3/h)	6.5	3 to 6
Injected quantity (kg)	100	7.64 (10 of KI)
Tracer volume (m^3)	0.3	0.03
Injection/ recharge conditions	Constant recharge: 0.1 m^3/h	No recharge
Date of 1st arrival	8/7/1998 16:55	17/8/1999
Minimum transit time (h)	5.25	8184 (341 days)
Unsaturated thickness at the date of 1st arrival (m)	+/- 9.15	+/- 4.22
Maximum transit velocity (m/h)	1.74	0.052
Date of modal restitution	9/7/1998 00:10	9/6/2000?
Modal transit time (h)	11,5	15312 (638 days) ?
Mean unsaturated thickness (m)	+/- 9.15	+/- 3.7
Modal velocity (m/h)	0.788	2.42×10^{-4} (0.58 cm/day)
C_{mod}/C_{inj} (-)	$\sim 6.0 \times 10^{-7}$	$\sim 3.0 \times 10^{-5}$
Recovery factor (%)	K^+: 3.1 Cl^-: 5.1	+/- 26.6

Hydrodynamic & hydrodispersive behaviour of variably saturated chalk

- Tracer transit time across the unsaturated zone: Factor 1000 between the 2 tracer test results (several hours → 1 year)

  → Dual porosity / dual permeability of chalk

  - Chalk matrix
    - High porosity (n_M ~ 30 → 45 %)
    - Microporosity (~1μm) → high capillary tensions
    - Low saturated hydraulic conductivity $K_{s,M} \sim 1\times10^{-8}$ m/s
  - Fissures
    - Low associated porosity ($n_F \leq 1\%$)
    - Relatively large opening → low capillary tensions
    - High saturated hydraulic conductivity $K_{s,F} \sim 1\times10^{-5} \rightarrow 1\times10^{-4}$ m/s

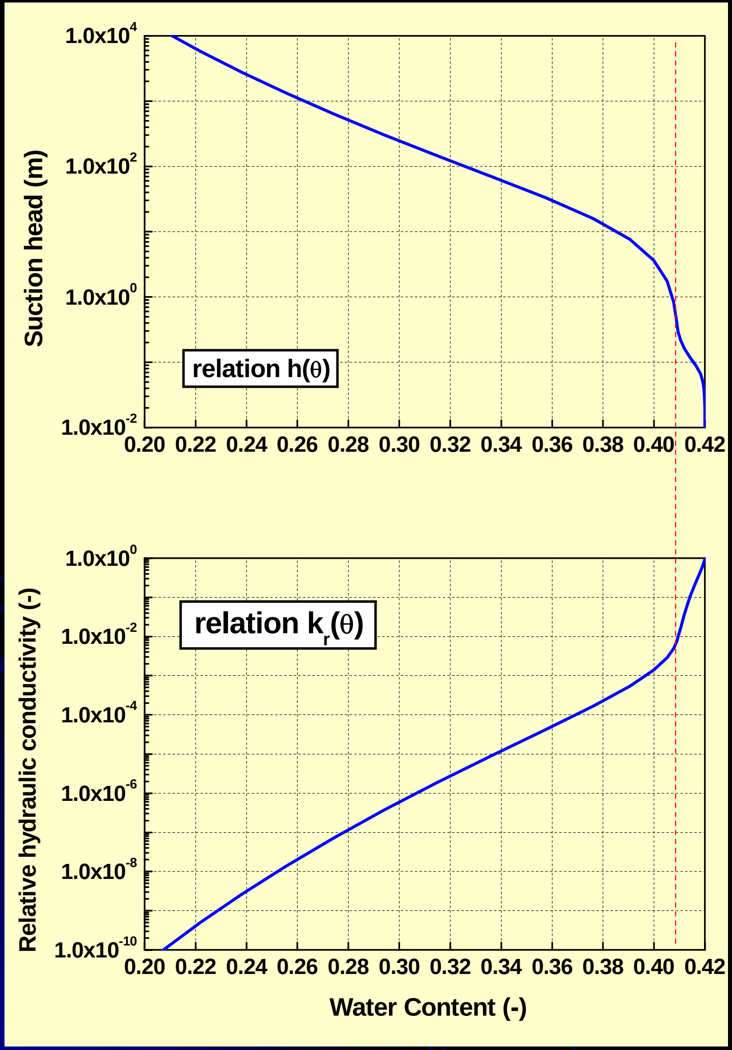
Hydrodynamic & hydrodispersive behaviour of variably saturated chalk

- Consequences → groundwater flows
  - Saturated conditions:
    - ➔ $K_{s,M} << K_{s,F}$ → water drainage through the fissures; water storage in the matrix
  - Unsaturated conditions:
    - ➔ Quick desaturation of the fissure network with groundwater flow restricted in the matrix
- Consequences → contaminant transport
  - Saturated conditions:
    - ➔ Fast migration along the fissures ($K_{s,F}$ >> and n_F <<); physical retardation in the matrix (immobile water)
  - Unsaturated conditions:
    - ➔ Slow migration of contaminants across the matrix ($K_{s,M}$<< and n_M >>)

Hydrodynamic & hydrodispersive behaviour of variably saturated chalk

- Mathematical model
  - Chalk rock assimilated to a single continuum
  - New relationship $\theta(h)$ used to model the retention curve of the chalk rock adapted to account for the bi-modal distribution of the porosity (fissures and matrix); hydraulic conductivity curve $K(\theta)$ derived analytically from $\theta(h)$
  - Variation of effective porosity (transport) and dual-porosity (retardation) in function of the saturation degree S_w of the chalk rock considered using a dynamic partitioning of the water content between mobile and immobile water in f(S_w)

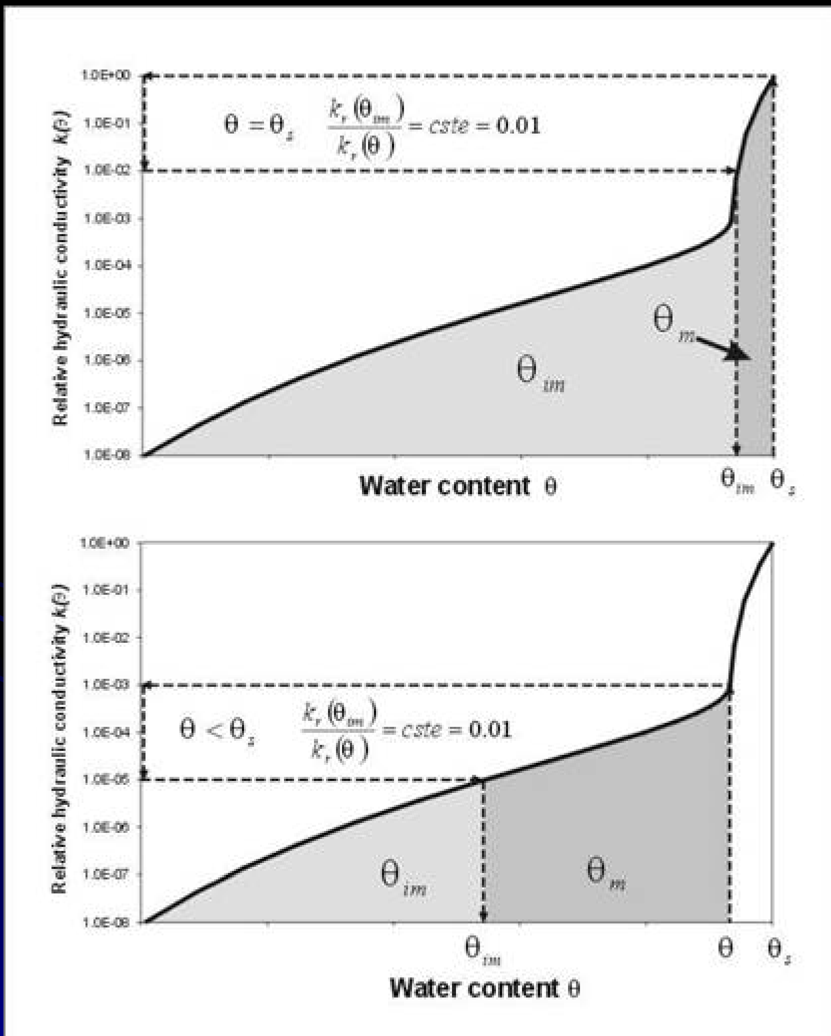
Hydrodynamic & hydrodispersive behaviour of variably saturated chalk



- Relationships developed to represent the unsaturated properties of the fissured chalk
  - 2 van Genuchten relationships + a continuity condition at the transition
  - Mualem's model used to derive analytically $K(\theta)$ from $\theta(h)$

Example with estimations drawn from field & lab experiments

Hydrodynamic & hydrodispersive behaviour of variably saturated chalk

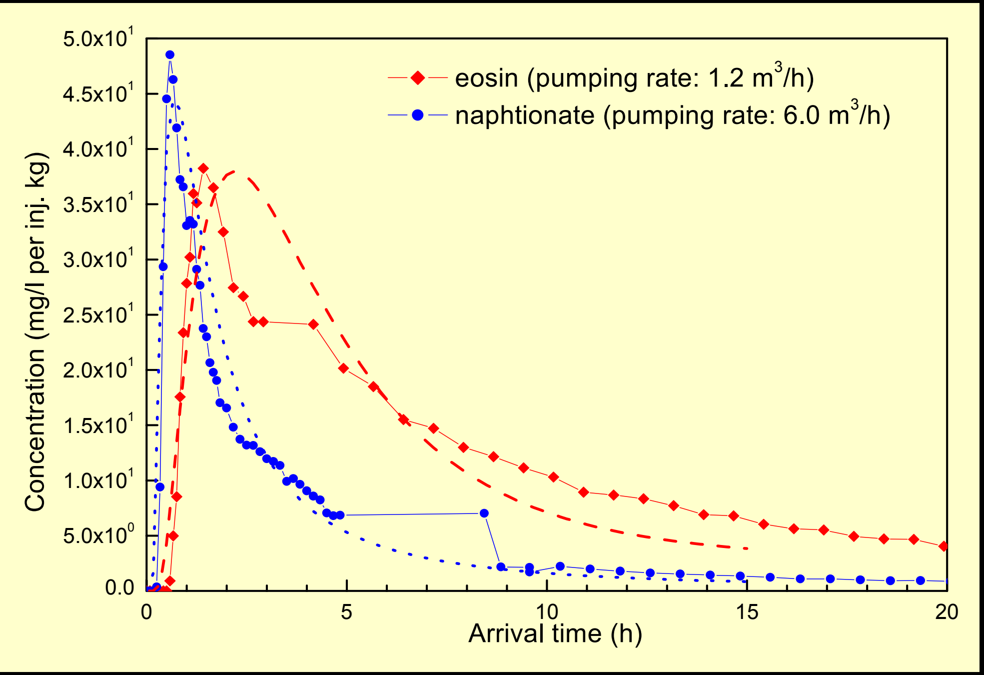


- Water partitioning between mobile & immobile water in function of the saturation degree (Zurmühl & Durner)
  - Traditional MIM model: θ_{im}=cst ➔ problems in the unsaturated zone
  - $k_r(\theta)$ reflects the distribution of flow velocities in the medium, in function of the saturation degree ➔ relationship used to distribute the water content θ between θ_m and θ_{im} en $f(S_w)$ using a partitioning coefficient:

    $C_{part}=K(\theta_{im}) / K(\theta)$

Modelling results

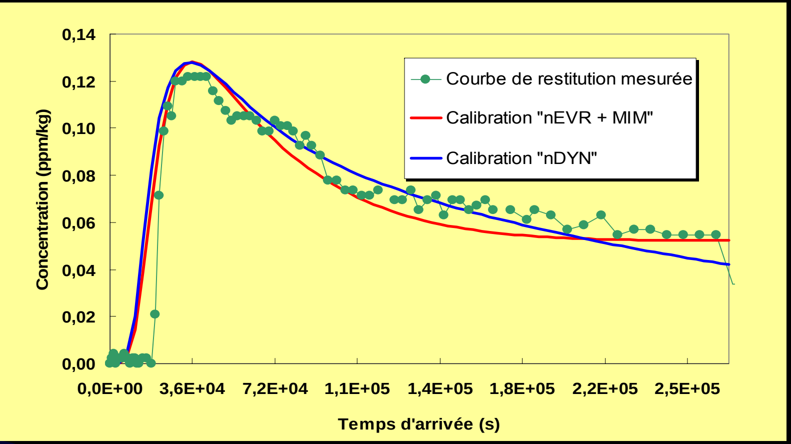
- Saturated zone (Pz CS)



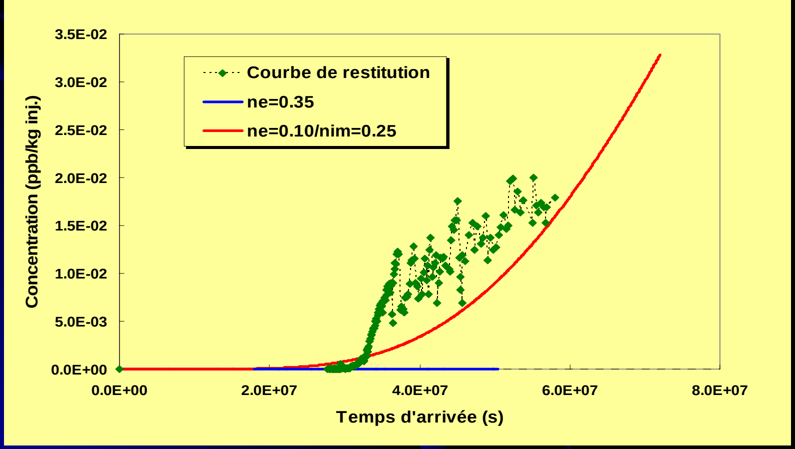
θ_m (-)	a_L (m)	α (s^{-1})	θ_{im} (-)
0.004	1.0	2.0×10^{-7}	0.05

Modelling results

- Unsaturated zone (Pz CNS)



	θ_m (-)	θ_{im} (-)	a_L (m)	α (s^{-1})
MIM	**0.01**	**0.08**	**1.0**	**2.3×10^{-7}**
DYN	**C_{part}= 0.02**		**1.0**	**9.0×10^{-8}**



Difficult to deal with water table variations…
Test with parameters representative
of the matrix (high porosity)

Conclusions

- Tracer experiments clearly highlight the importance of the dual-porosity/ dual-permeability of the chalk in both the saturated zone and the unsaturated zone
- New conceptual and mathematical approach proposed to model the hydrodynamic and hydrodispersive behaviour of chalk in variably saturated conditions
- Vulnerability of chalk to contamination occurring at the land surface: strongly dependent of the existence or not of a protective cover that attenuates the recharge intensity at the top of the unsaturated chalk !

The Hydrogeology Group at ULg (Belgium)

- Department of Georesources, Geotechnologies and Building Materials (**http://www.ulg.ac.be/geomac**)
- Head of the group: Prof. A. Dassargues
- Team of ~10 researchers in the field of Hydrogeology
- Main research topics:
  - Integrated modelling (soil – rivers – groundwater)
  - Groundwater vulnerability assessment and mapping
  - Hydrogeological database and GIS developments
  - Field investigations (tracer experiments, multi-parameter monitoring …)
  - Stochastic modelling of protection zones