Geo-Electrical data fusion by stochastic co-conditioning simulations for delineating groundwater protection zones

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CMWR XVI - Computational Methods in Water Resources
XVI International Conference, Copenhagen, Denmark, June 19-22 2006

- … from a practical point of view : one of the classical questions of hydrogeology :

  delineation of protections zones around pumping wells in aquifers … integrating (as far as possible) all available data

- "… the future of « dealing with heterogeneity » in hydrogeology depends largely on a conscious decision to better characterize, describe and model the geology of the sites …"

  de Marsily et al., 2005

- " ... the central question of whether the stochastic method, which treats aquifer heterogeneity as a random field, is applicable to real aquifers under field conditions, has not been definitively answered"

  M.P. Anderson, 1995

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Outline

- Capture zones delineation in aquifers
  - Co-conditional stochastic method for delineation of time-related capture zone combined with an inverse modelling procedure
  - Application to a virtual (synthetic) study case
  - Application to a real case
- Conclusions/perspectives from a practical point of view

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Groundwater protection zones

- Time-related capture zone (protection zone)

→ delineation based on the concept of travel time

= area around the well from which water is captured within a certain time ***t***

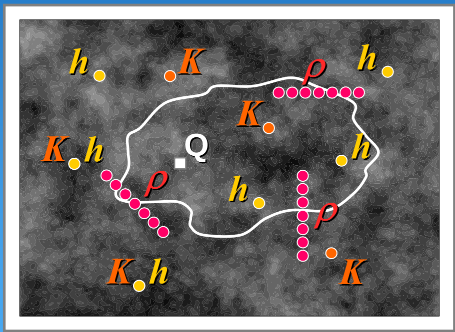
→ based on the reliability of the hydrogeological models

→ depends strongly on our ability to describe the aquifer system properties (K, n_e, ...)

→ based on our knowledge of the geology (limited by the existing field data)

Objectives

Propose a stochastic method to delineate protection zones, applicable to real study case
with fusion of data from geophysical prospecting



- ✓ quantification of the well capture zone uncertainty
- ✓ reduction of this uncertainty by fusion of direct and indirect measures of K

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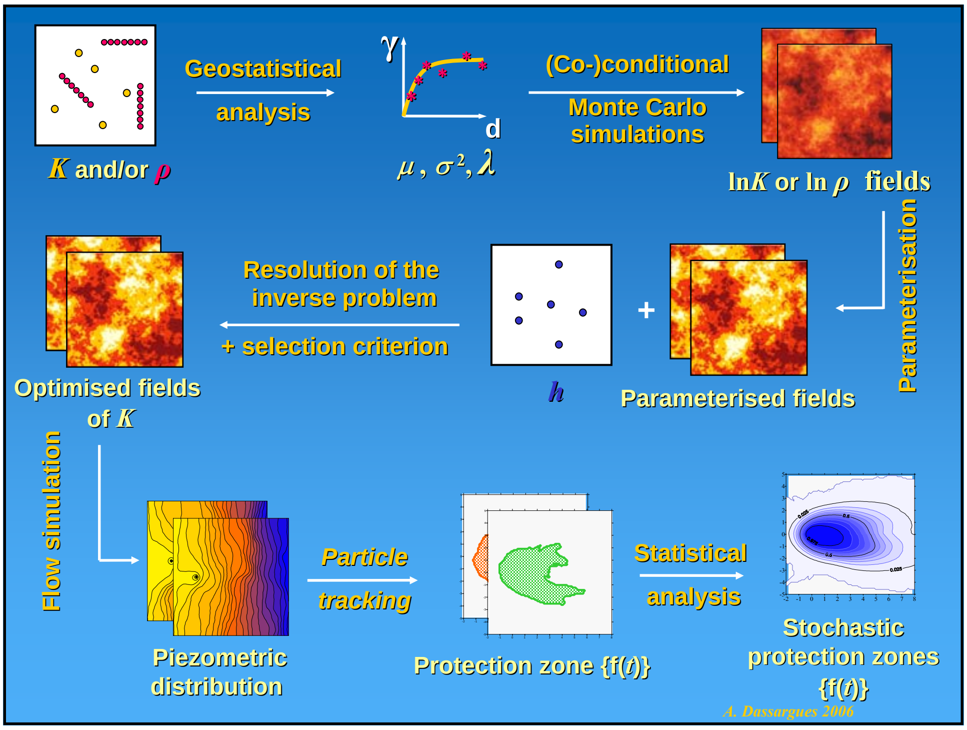

Conditional simulations

$$z_j^{CS}(\underline{x}) = z^*(\underline{x}) + z_j^{NCS}(\underline{x}) - z_j^{NCS^*}(\underline{x})$$

Conditional Simulation (CS)	=	Kriging	+	Non-cond. simulation (NCS)	–	Kriging of the NCS

Turning Bands
(Matheron, 1973 – Mantoglou & Wilson,1982)

'Best Linear Unique Estimator' + smoothing

'Noise' (zero at the measurement points)

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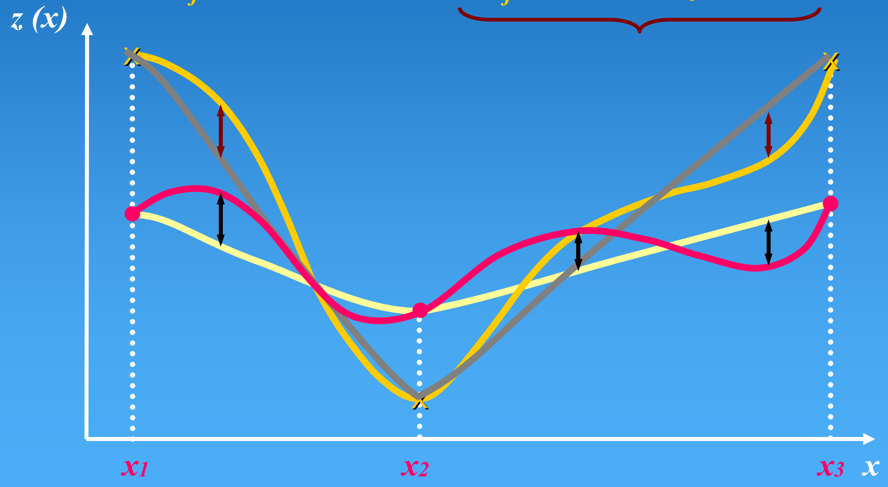
Conditional simulations

$$z_j^{CS}(\underline{x}) = z^*(\underline{x}) + z_j^{NCS}(\underline{x}) - z_j^{NCS^*}(\underline{x})$$



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Co-conditional simulations

$$z_j^{SC}(\underline{x}) = z^*(\underline{x}) + z_j^{SNC}(\underline{x}) - z_j^{SNC^*}(\underline{x})$$

Co-conditional simulation = Cokriging + Non cond. simulation NCS – Estimation by cokriging of the NCS

… by this cokriging (fusion of secondary data),

→ a better caracterisation of the spatial variability is obtained

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(Co-)conditional simulations

Data Availability

- K → **conditional simulations of ln$K$**
- K and ρ → **co-conditional simulations of ln$K$**
- ρ → **conditional simulations of lnρ**

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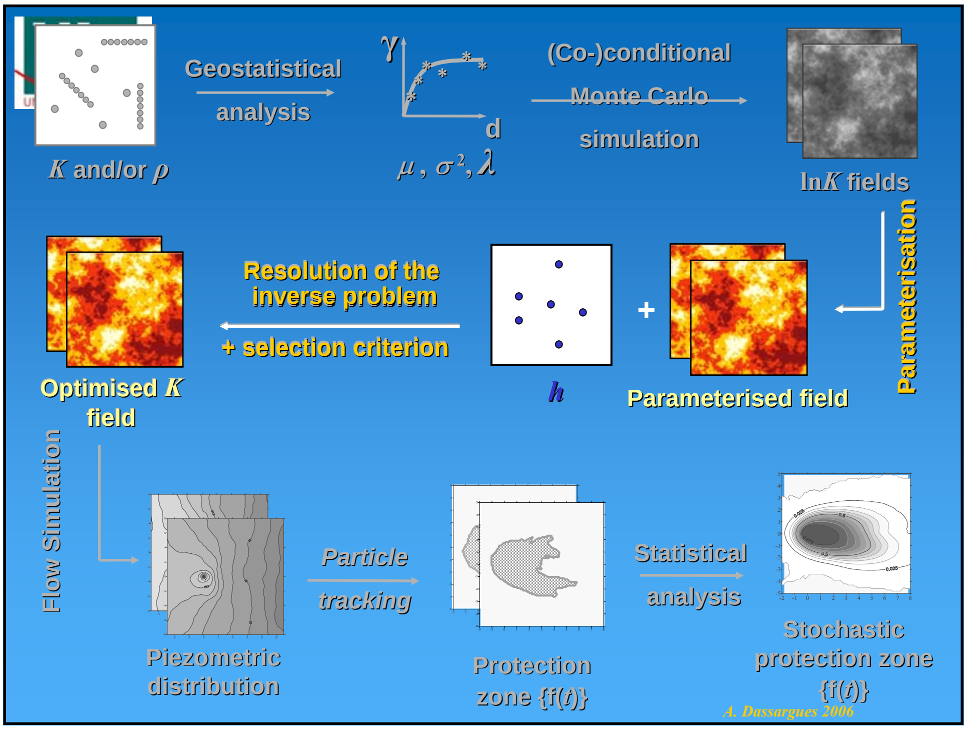

Geostatistical
analysis
γ
d
μ, σ^2, λ
(Co-)conditional
Monte Carlo
simulation
K and/or ρ
ln$K$ fields
Parameterisation
Resolution of the
inverse problem
+ selection criterion
+
h
Optimised K
field
Parameterised field
Flow Simulation
Particle
tracking
Statistical
analysis
Piezometric
distribution
Protection
zone {f(t)}
Stochastic
protection zone
{f(t)}
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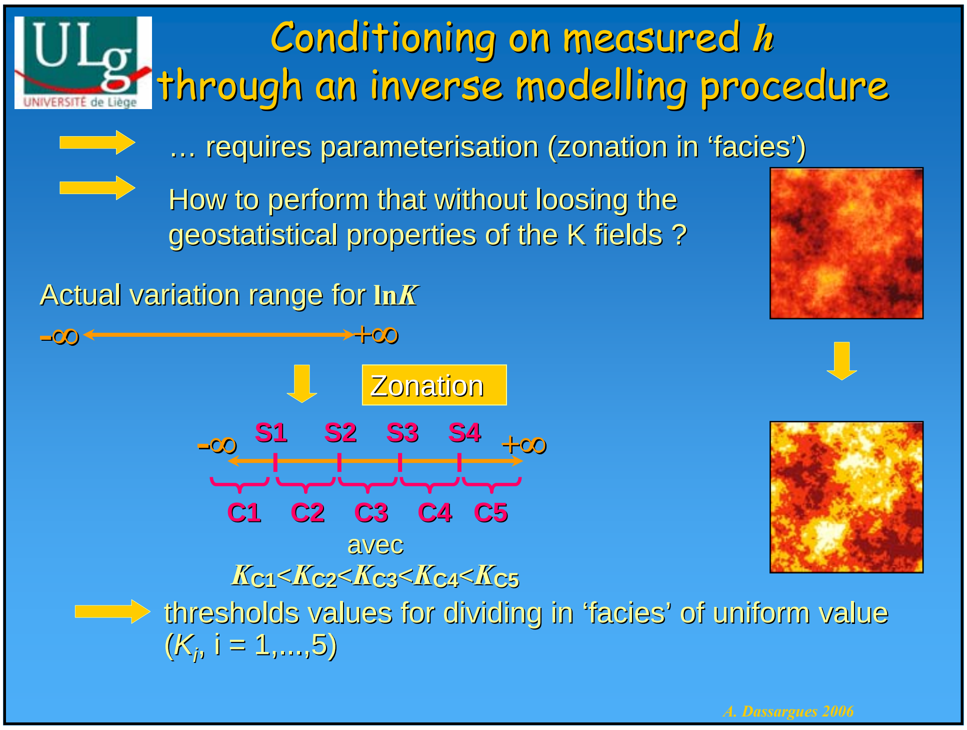

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Conditioning on measured h
through an inverse modelling procedure
… requires parameterisation (zonation in 'facies')
How to perform that without loosing the
geostatistical properties of the K fields ?
Actual variation range for ln$K$
-∞ +∞
Zonation
-∞ S1 S2 S3 S4 +∞
C1 C2 C3 C4 C5
avec
$K_{C1}<K_{C2}<K_{C3}<K_{C4}<K_{C5}$
thresholds values for dividing in 'facies' of uniform value
(K_i, i = 1,...,5)
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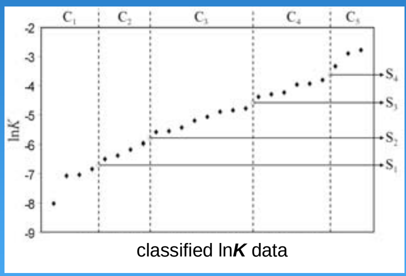
Which threshold values (S_i) ?

- Principle : minimum variance within each ‘facies’

➡ minimising function f



$$f = \sum_{i=1}^{N_c} \sum_{j=1}^{N_{di}} (\ln K_{ij} - \overline{\ln K_i})^2$$

$$\overline{\ln K_i} = \frac{1}{N_{di}} \sum_{j=1}^{N_{di}} \ln K_{ij} \quad , i = 1, N_c$$

➡ then the value of K_{Ci} = average value / facies
➡ serve as initial value in (not adjoining) zones of the facies
➡ optimised by the inverse procedure

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After the inverse procedure: selection criterion (order criterion)

- after optimisation of the K values in each ‘facies’, we add the selection criterion that the initial respective order must be respected : $K_{Ci} < K_{C(i+1)}$
  or relaxing:
  ➡ only one permutation

➡ eliminating realisations not respecting this criterion as « irrealistic fields for a geological point of view »

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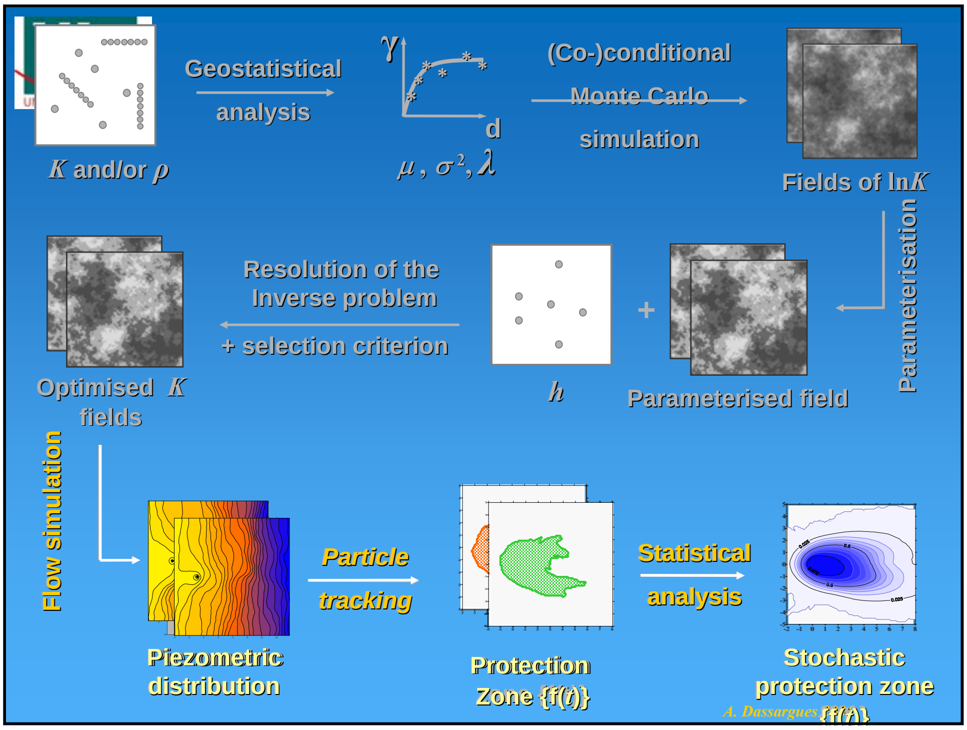


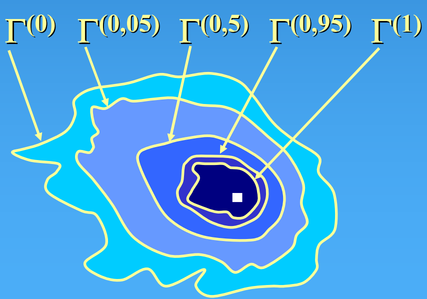
Statistical analysis

Capture zone probability distribution

$$[CAP(\underline{x},t)] = \frac{1}{n} \sum_{k=1}^{n} (I(\underline{x},t))_k$$

= probability that a tracer particle released at a particular location is captured by the well within a specified time

The isolines $\Gamma^{(i)}$ connect the locations in the *CAP* with the same probability $p(CAP(x,t)) = i$



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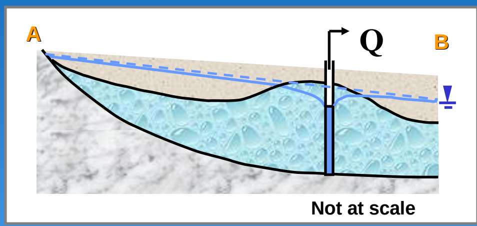
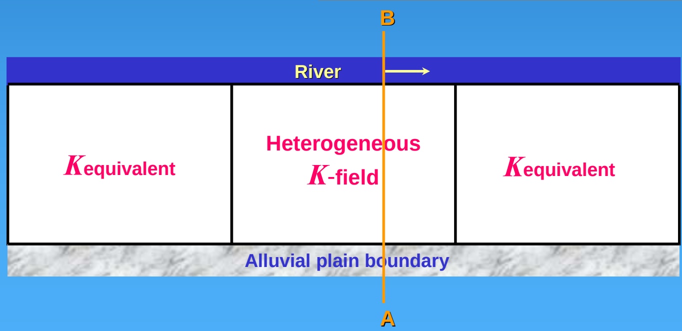
Synthetic study case

Groundwater model
representing
« a reference situation »

very similar to alluvial aquifer conditions





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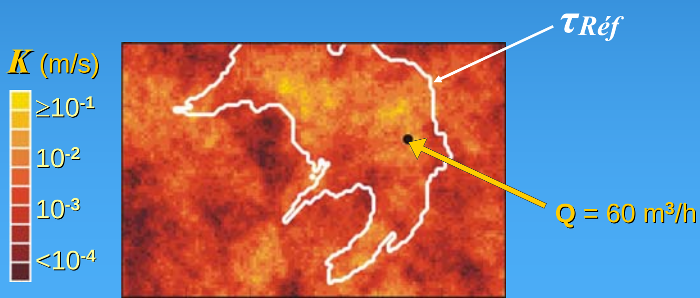
Construction of a reference capture zone

One non-conditional ***K***–field generation: reference medium

- Reference protection zone f(*t*)
  (by direct groundwater flow simulation and particle tracking)
- Create sets of 'measured data' ***K***, ***h*** and ***ρ***



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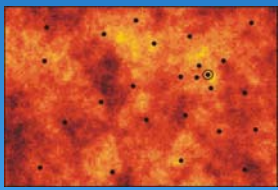
Creating realistic 'measured data sets'

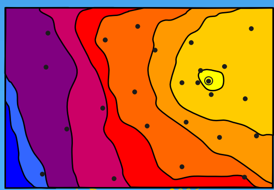
- Creating a (K) hydraulic conductivity data set

  ➡ in few 'measurement points': value from the K field



- Creating a (h) piezometric heads data set

  ➡ in few 'measurement points': value from the reference flow field



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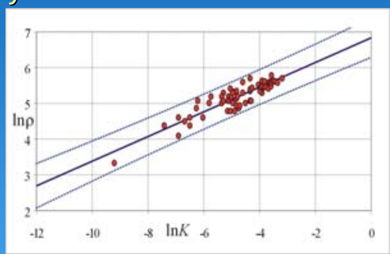
Creating realistic 'measured data sets' (following)

- Creating a (ρ) geoelectrical resistivity data set



Data measured and collected in many sites of the alluvial sediments of the River Meuse

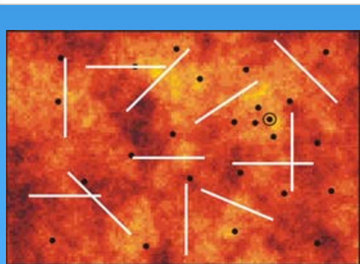
➡ correlation between $\ln K$ and $\ln \rho$

➡ artificial generation of a ρ data set from the reference K field

considering N(0,1) as a random draw within a standard normal distribution and $\hat{\sigma}$ the standard deviation of the regression residual,

$$\ln \rho_i = b_0 + b_1 \ \ln K_i + \sigma . N_i(0,1)$$

300 resistivity values, distributed on 12 tomographic profiles



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Application to the synthetic study case

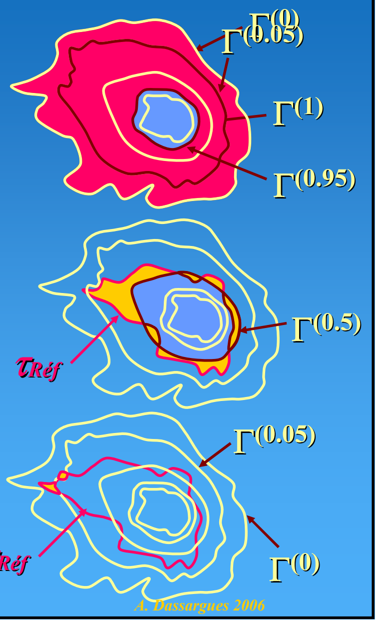
	0 K	15 K	25 K
0 ρ	$[CAP(x,t)]$	$[CAP(x,t) \mid K_{15}, h_{15}]$ $[CAP(x,t) \mid K_{15}, h_{25}]$	$[CAP(x,t) \mid K_{25}, h_{15}]$ $[CAP(x,t) \mid K_{25}, h_{25}]$
150 ρ	$[CAP(x,t) \mid h_{15}, \rho_{150}]$ $[CAP(x,t) \mid h_{25}, \rho_{150}]$	$[CAP(x,t) \mid K_{15}, h_{15}, \rho_{150}]$	$[CAP(x,t) \mid K_{25}, h_{25}, \rho_{150}]$
300 ρ	$[CAP(x,t) \mid h_{15}, \rho_{300}]$ $[CAP(x,t) \mid h_{25}, \rho_{300}]$	$[CAP(x,t) \mid K_{15}, h_{15}, \rho_{300}]$	$[CAP(x,t) \mid K_{25}, h_{25}, \rho_{300}]$

t = 1, 5, 10, 20 days

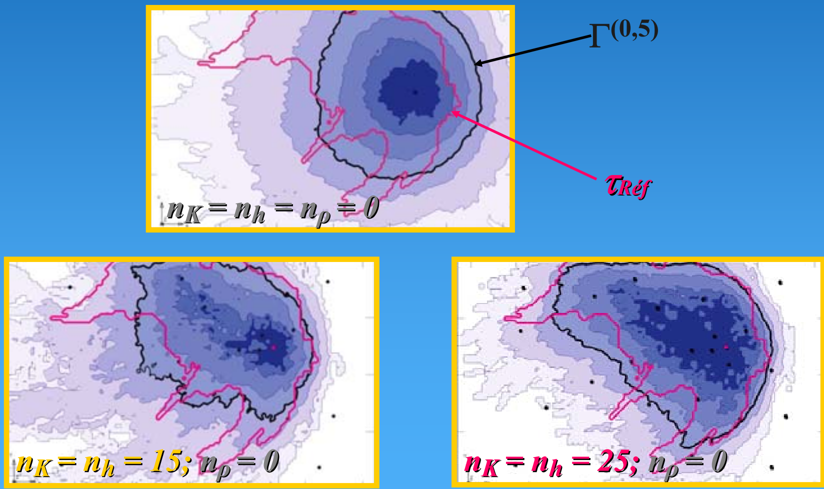
Performance quantification

(after van Leeuwen *& al.*, 2000)

- w_{a1} and w_{a2} = a measure of the surface between $\Gamma^{(0)}$ and $\Gamma^{(1)}$; and between $\Gamma^{(0.05)}$ and $\Gamma^{(0.95)}$
- w_b = deviation of $\Gamma^{(0.5)}$ with regards to $\tau_{Réf}$
- w_{s1} and w_{s2} = how far $\tau_{Réf}$ is well included in the zone $\Gamma^{(0)}$ and $\Gamma^{(0,05)}$



For each realisation, computation of the 20-day capture zone → CaPD



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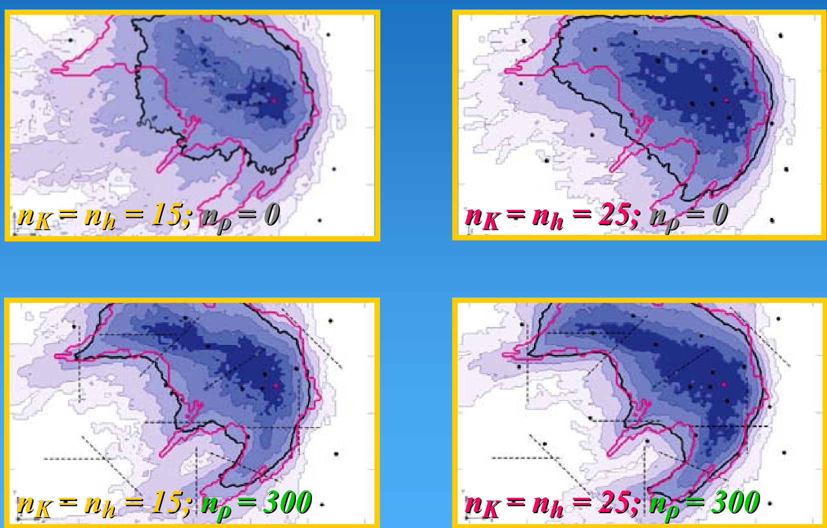
… strong effect of the co-conditioning



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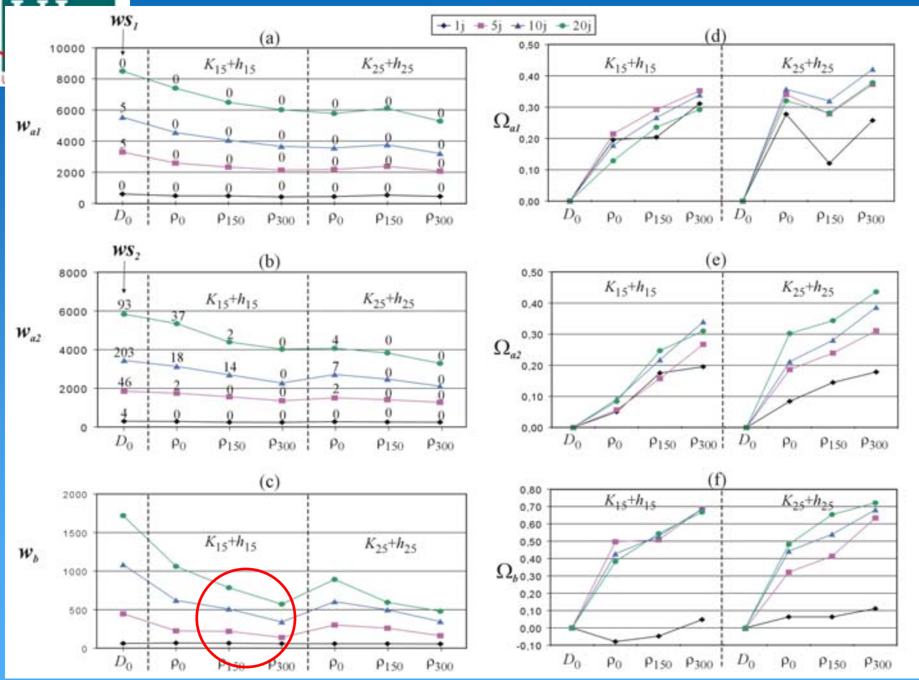

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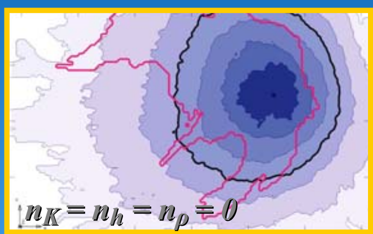
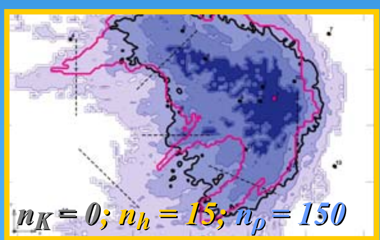
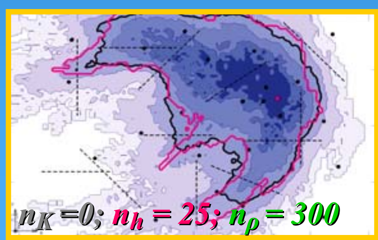
Synthetic case: summary







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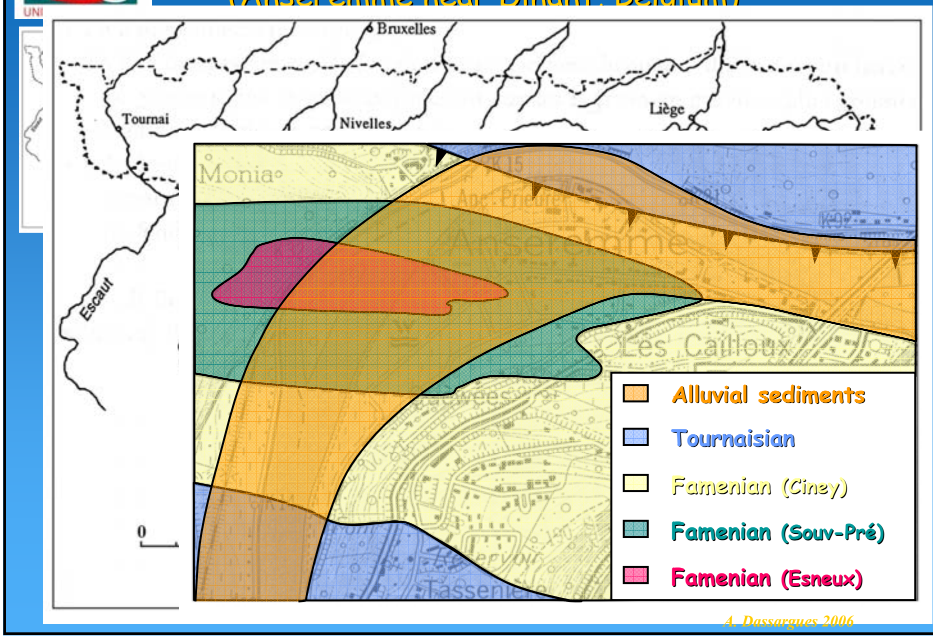
Application to a real case
(Anseremme near Dinant, Belgium)



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Application to a real case
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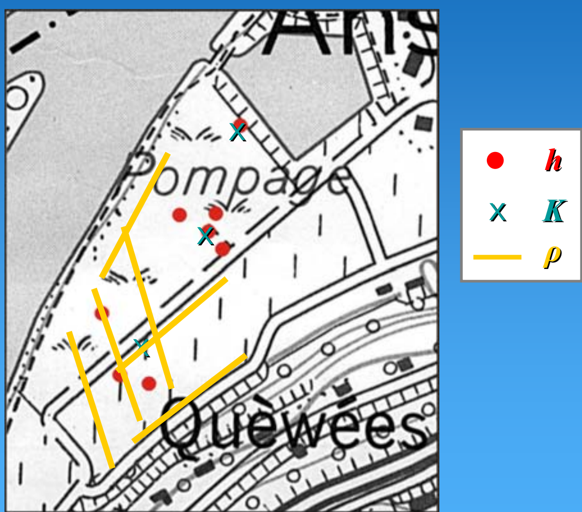

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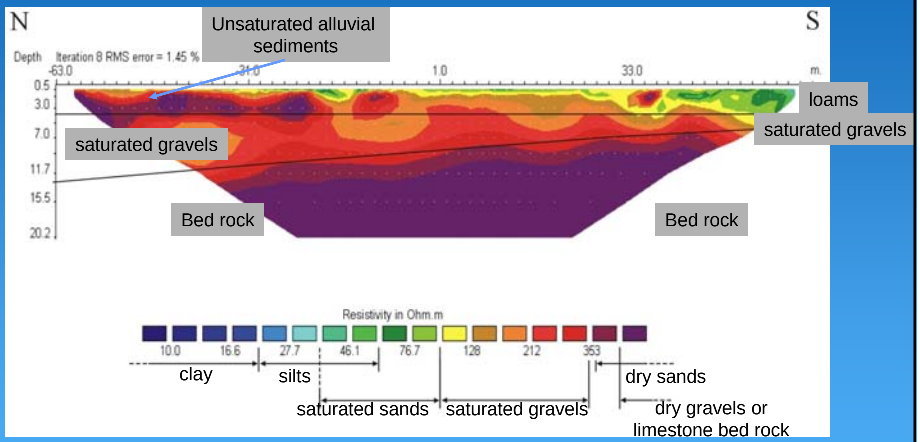

Equivalent value of ρ obtained in the gravel layer (alluvial sediment) → $$\frac{e_{tot}}{\rho} = \sum_{i=1}^{n} \frac{e_i}{\rho_i}$$

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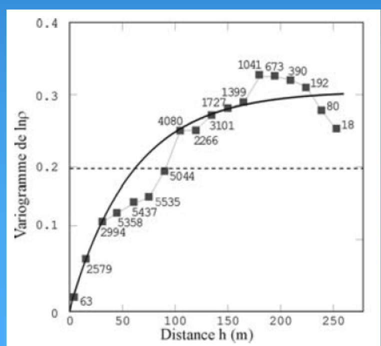
Application to a real case
(Anseremme near Dinant, Belgium)

- conditioning on lnρ (293 data points)
- inverse modelling on ***h*** (8 data points)
- verifiying the coherence of the obtained ***K*** fields with regards to the 3 data points of measured ***K***



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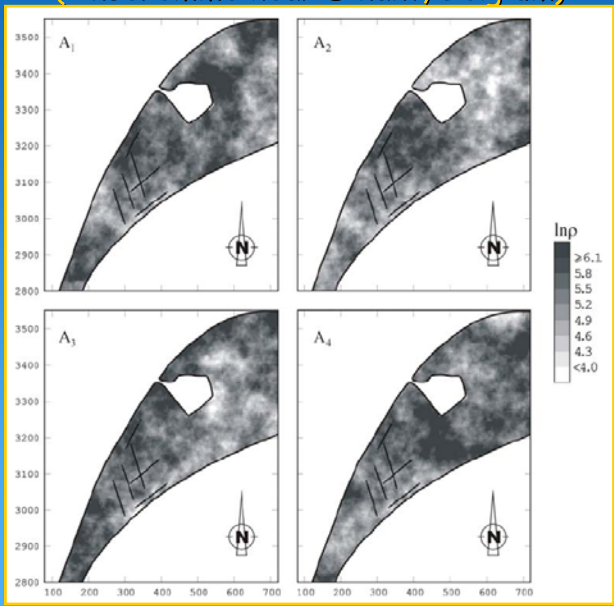
Application to a real case
(Anseremme near Dinant, Belgium)



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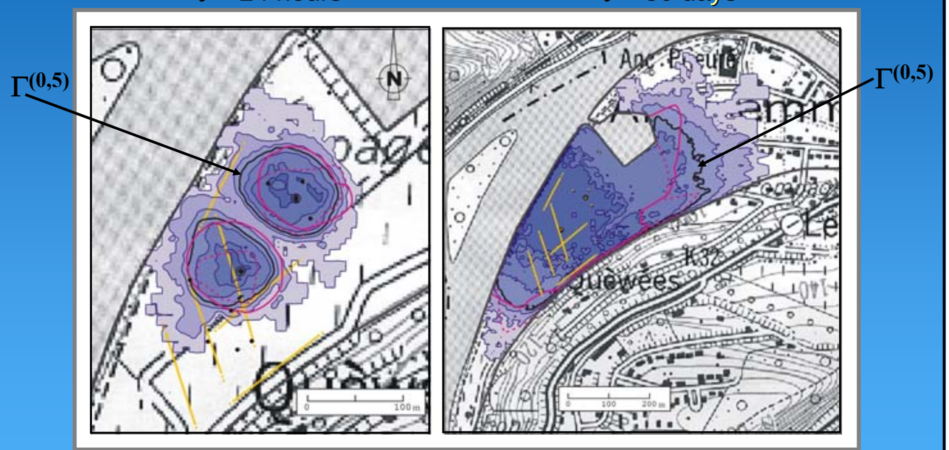
Application to a real case
(Anseremme near Dinant, Belgium)

t = 24 hours — *t* = 50 days



τ *of a previous 3D deterministic model*

τ *of a previuous 2D deterministic model*

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Lessons

- stochastic co-conditional approaches bring improvements
- it does not spare us the acquisition of measured data
- selection of ‘best’ locations for geophysical measurements can be crucial
- if piezometric heads are used for inverse modelling
  - ➡ parameterisation / zonation in ‘facies’
  - ➡ thresholds values / selection criterion
  - ➡ statistics on remaining realisations
  - ➡ if selection criterion not too bad

    geostatistical structure seems to be preserved
- the ‘facies’ zones can be disjoint … possible links to be found with more ‘genetic’ based geological analysis

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Conclusions

- advantages of fusioning available geological / geophysical / hydrogeological data
- optimizing soft data measurements is required …
- assumption that geology generates ‘sediment facies’
- genetic/genesis models modelling rock formation processes should help more and more ?
- when zones corresponding to ‘facies’ are defined, … how to deal with a calibration ?
  - * keeping the geometry of the facies: changes in parameters values and find criteria for selection
  - * adjustment of the geometry: ‘gradual deformation’ (Hu et al., 2001)
- future combination with multiple point geostatistical techniques ?

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Effect of the zonation in facies and selection on the spatial structure ?