POLITECNICO DI MILANO

WE-NEED
WatEr NEEDs, Availability, Quality and Sustainability

Natural spring' protection and groundwater management under uncertainty conditions: the Cremona Aquifer

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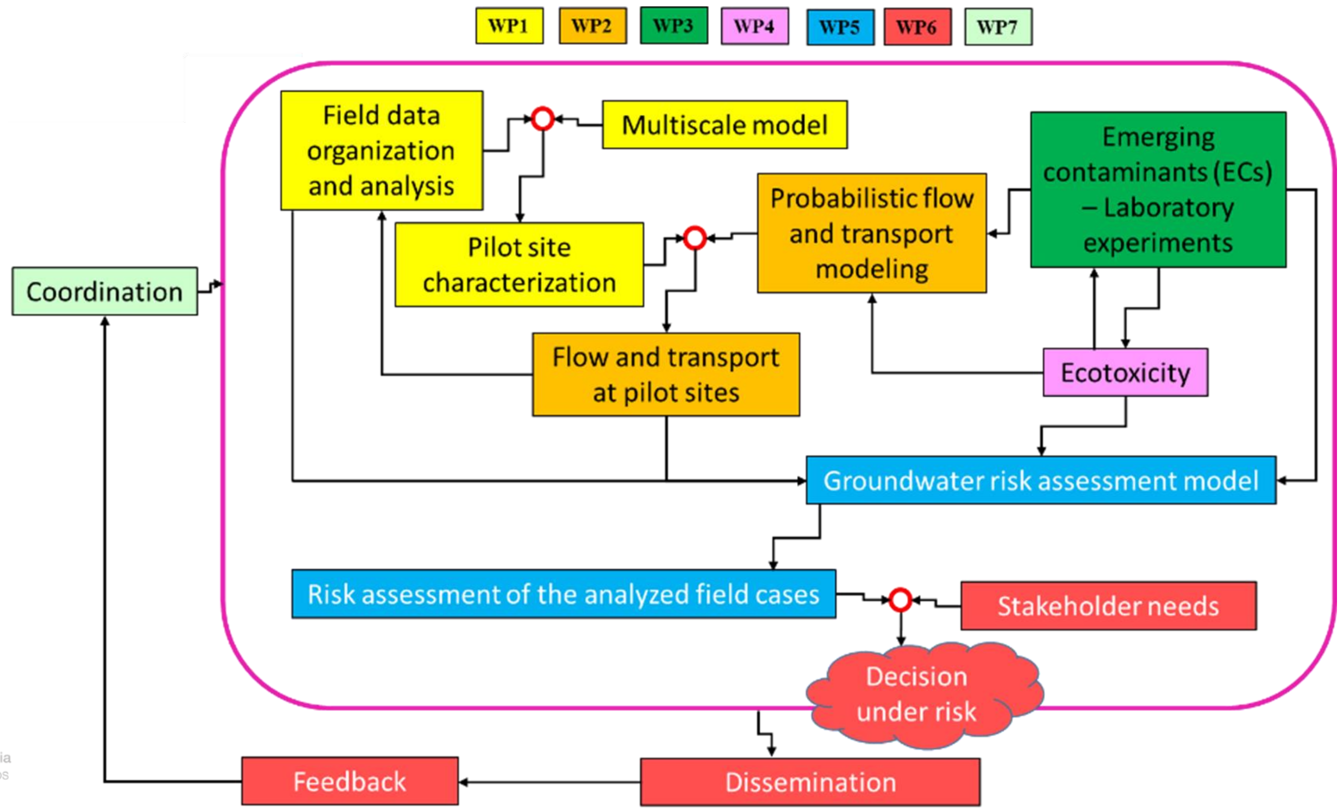
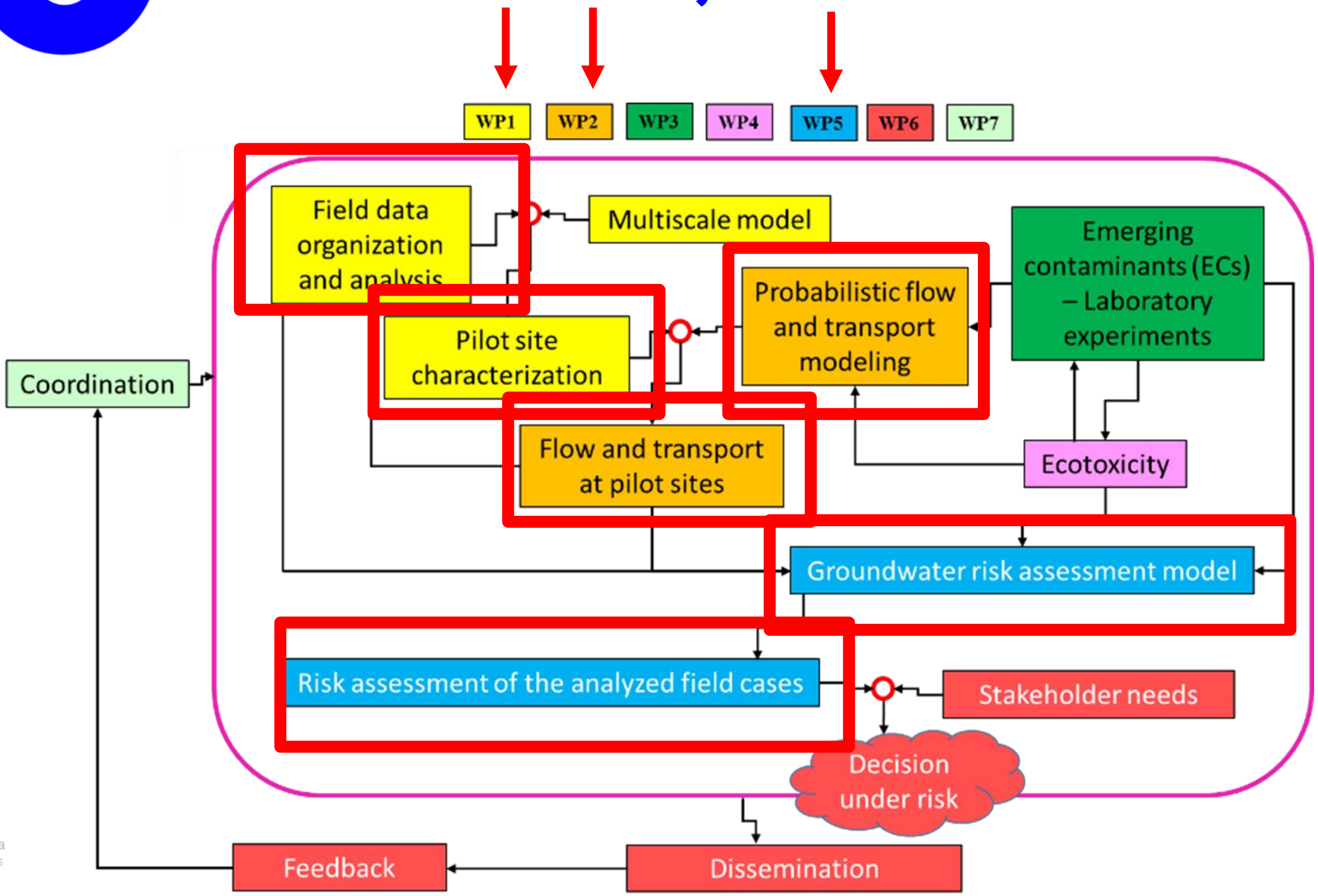
WE-NEED Project Structure



WE-NEED Project Structure



Outline

Test case description and model conceptualizations

- Study area and available data set
- Spatial distribution of geomaterials
- Hydraulic conductivity fields

WP1

Global sensitivity and model calibration approaches

- Derivative-based, Variance-based, Moment-based sensitivity indices
- Model calibration

WP1

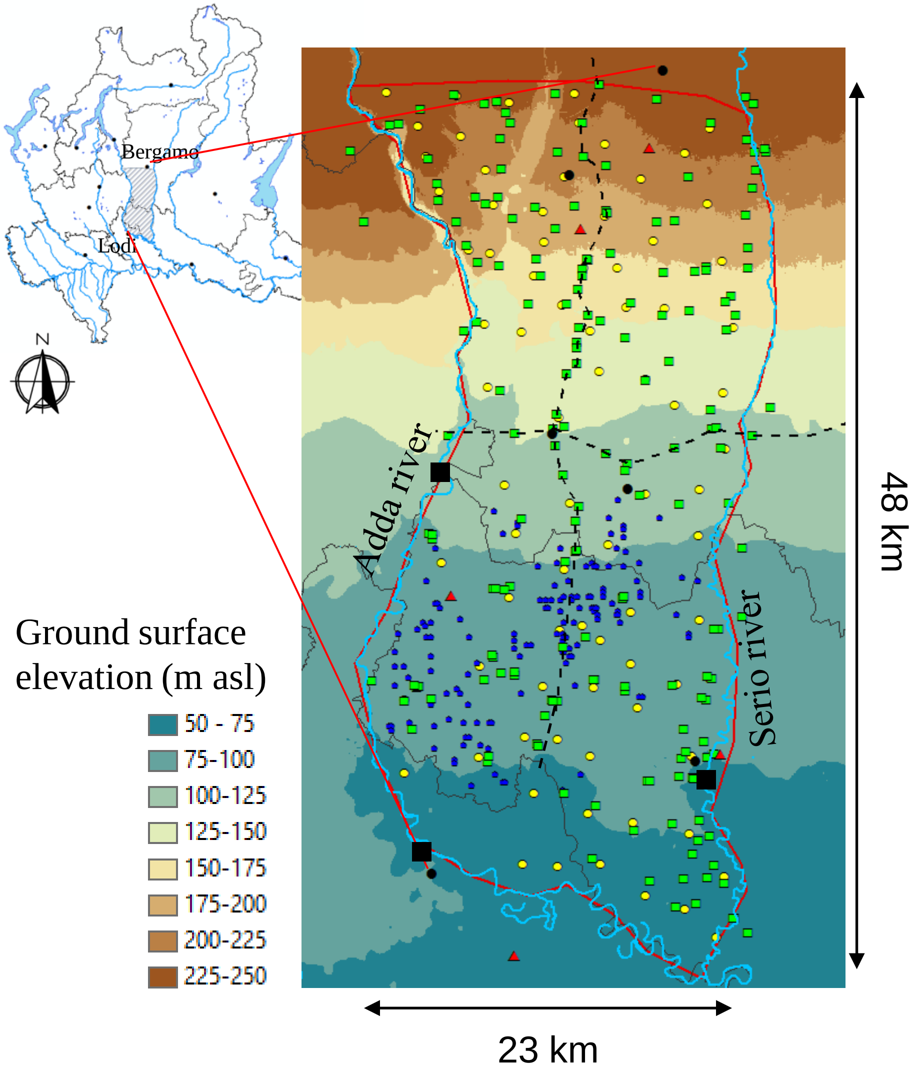
WP2

Groundwater management model

- Spring depletion problem
- Fault tree analysis and evaluation of probability of system failure

WP5

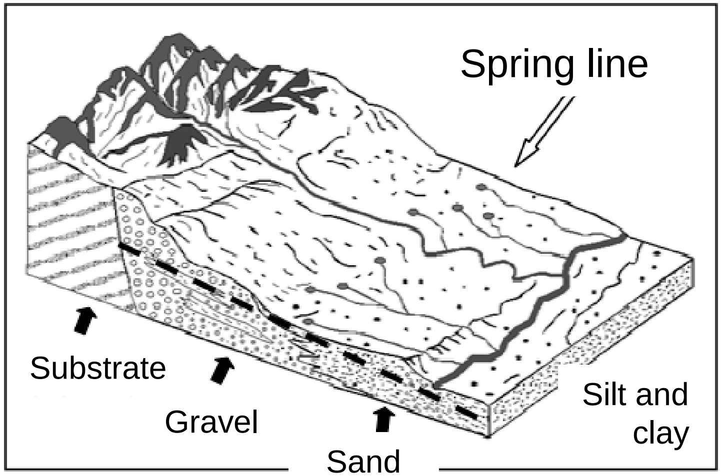
Test case: Cremona Aquifer



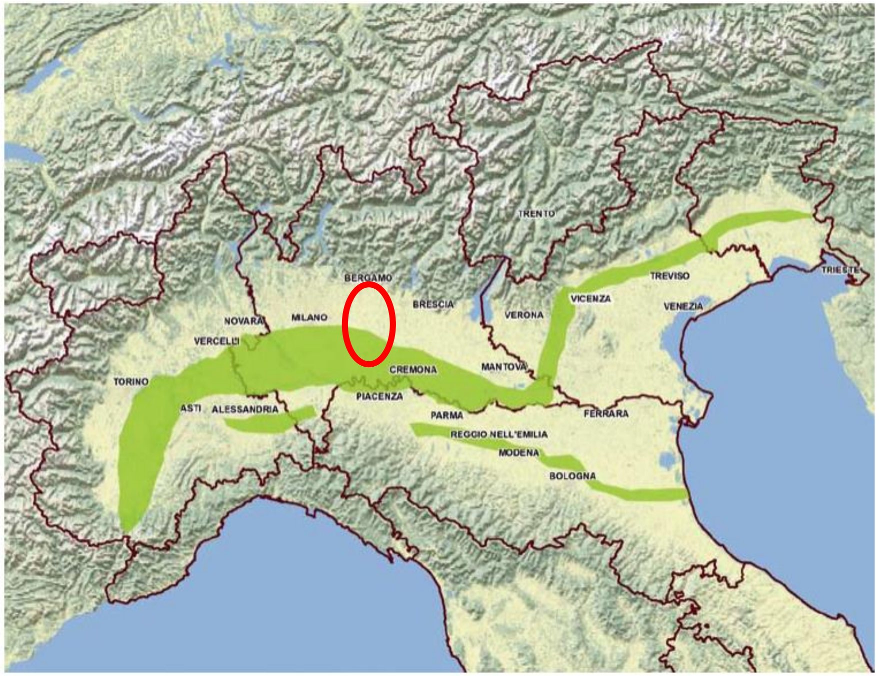
- The study area lies in the Lombardia region (Northern Italy)
- Adda and Serio rivers bound the aquifer on eastern, southern and western sides
- Surface Area: 785 km^2 (84% agricultural)
- A key feature of the study area is the occurrence of natural high-quality water springs

- ■ Hydrometric level station
- ▲ Meteorological station
- ○ Well
- □ Geological stratigraphy
- • Spring

"*Fontanili*" a particular kind of spring in the Po Plain



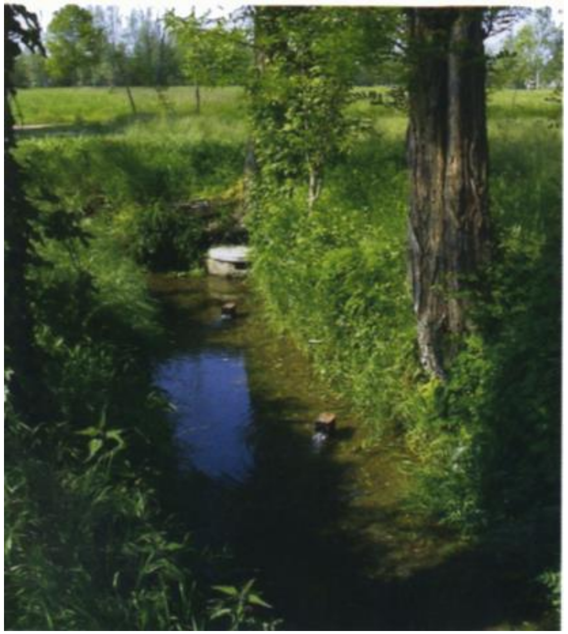
Illustrative draft of the Po Plain and types of prevalent deposits (Giornale di Geologia Applicata 2 (2005) 377–382)



"*Fontanili* Line" (QdR n. 144, 2012 Regione Lombardia)

- "*Fontanili* Line" is characterized by spring subsurface water emergence, produced by a sediment permeability decrease.
- A great number of "*Fontanili*" consists of an excavation that reaches the unconfined aquifer.

“*Fontanili*” within the study area

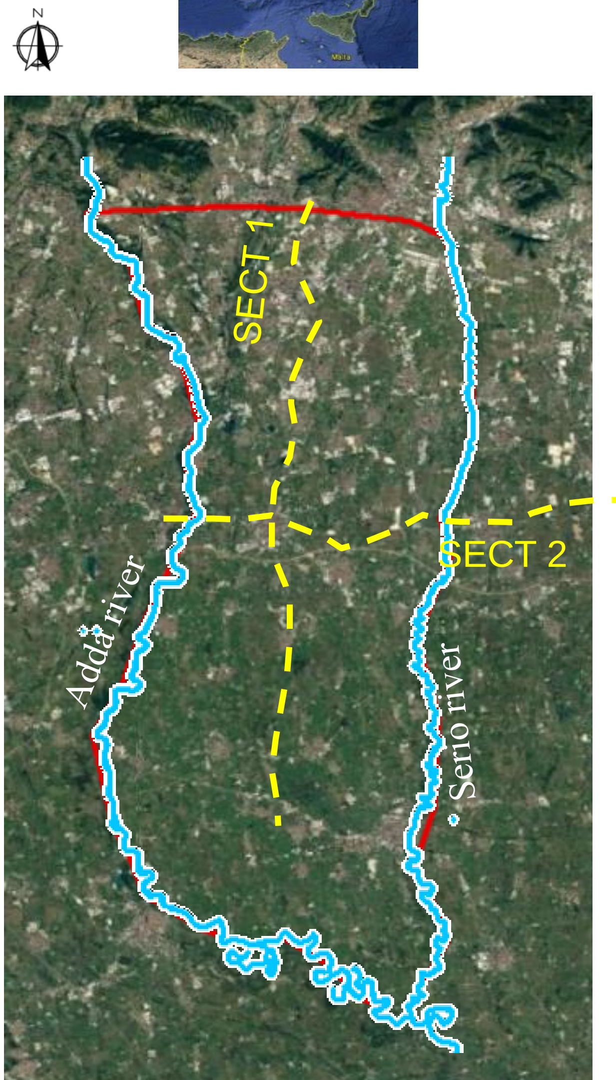


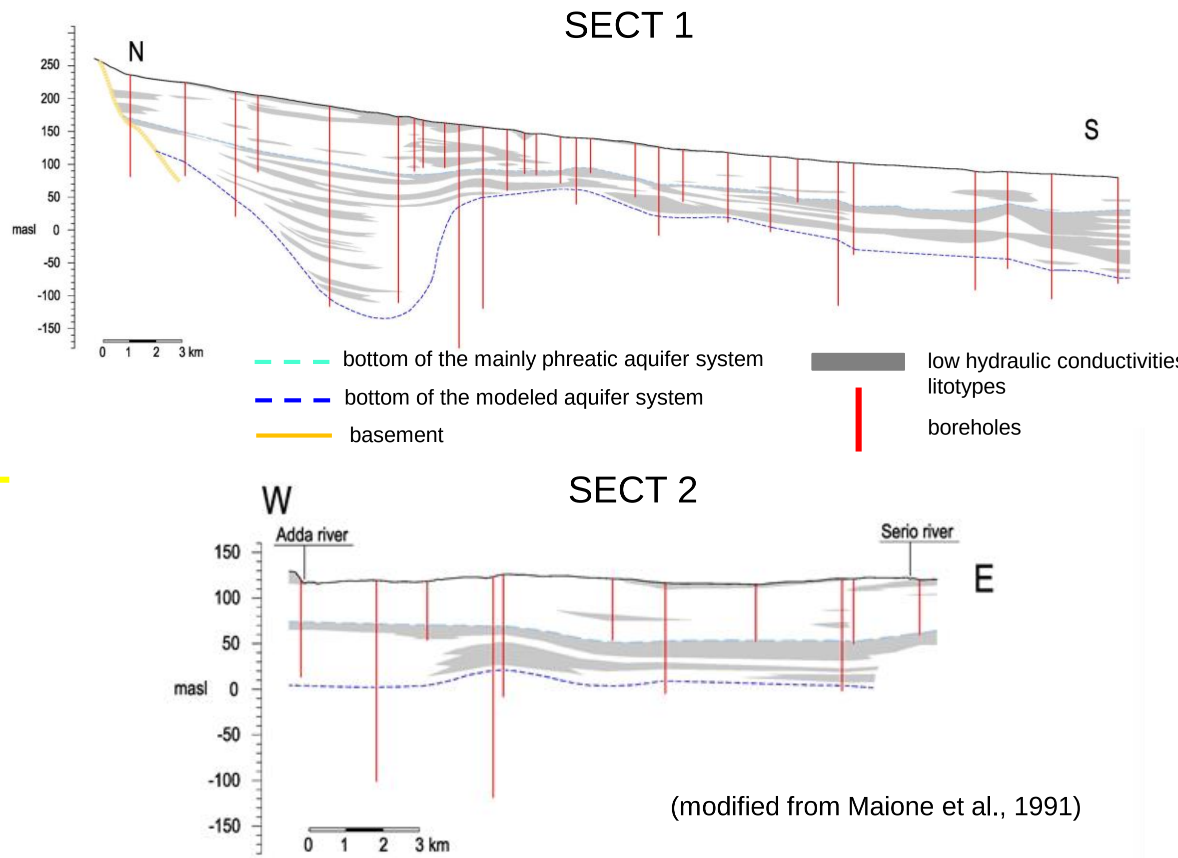
Brunascani (CR)

Cremosano Est (CR)

Cascinetto (CR)

Geological cross-sections



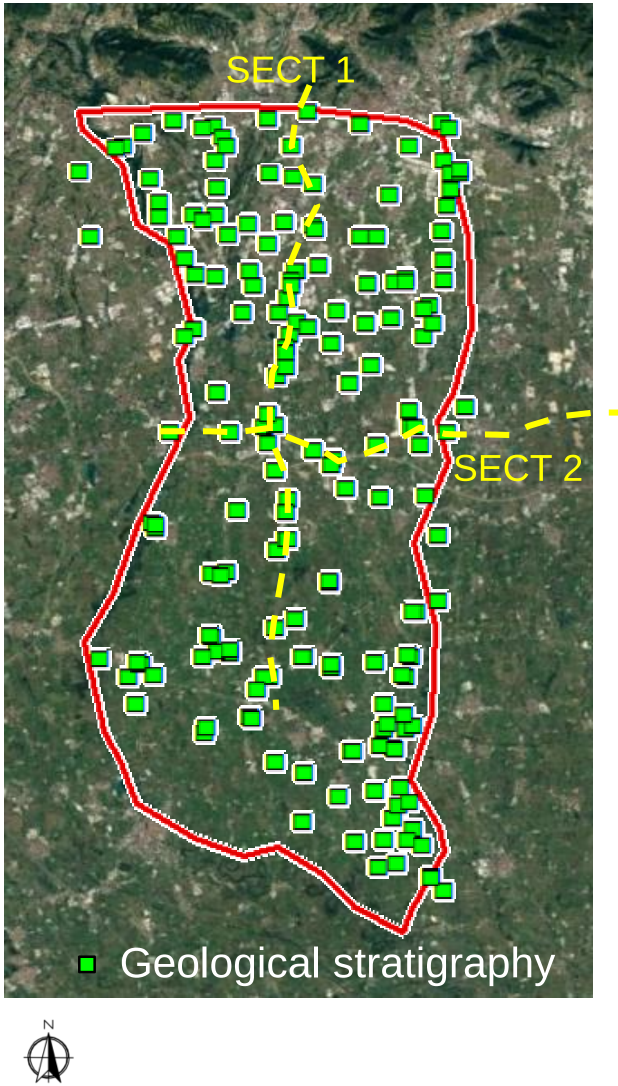


(modified from Maione et al., 1991)

The aquifer system has an average thickness of about 120 m and comprises:

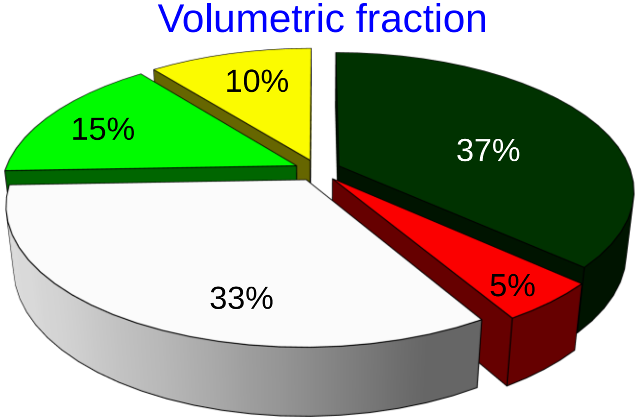
- a surface, locally semiconfined, aquifer
- a deeper, semiconfined/confined portion

Geological stratigraphies



- The analysis of available sedimentological information allows identifying a set of $n_f = 5$ main geomaterials (facies/classes) which constitute the geological makeup of the system.

FACIES	GEOLOGICAL MATERIAL
1	Clay and silty deposits
2	Fine Sands, Clay Sands, Silty Sands
3	Gravel, Gravel and Sand, Medium Sand
4	Compact Conglomerates
5	Fractured Conglomerates



Conceptual models

- We discretize the aquifer system of extent 23 km (East-West direction) × 48 km (North-south direction) × 475 m (depth) through blocks of uniform size 100 m × 200 m × 5 m. Total of $N_c = 5.2 \times 10^6$ voxels

- Numerical code MODFLOW-2005 (Harbaugh, 2005) is employed to simulate steady-state groundwater flow within the domain

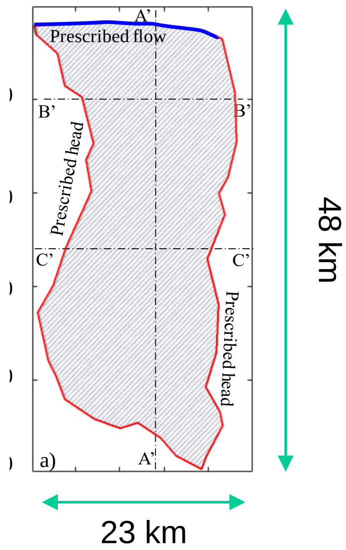
GEOLOGICAL AQUIFER ARCHITECTURE

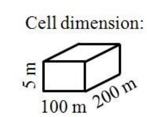
HYDRAULIC CONDUCTIVITY FIELDS

1. COMPOSITE MEDIUM (*CM*) → a. Composite Medium (*CM*)

2. OVERLAPPING CONTINUA (*OC*) → b. Arithmetic mean (*OC_A*)

   → c. Geometric mean (*OC_G*)



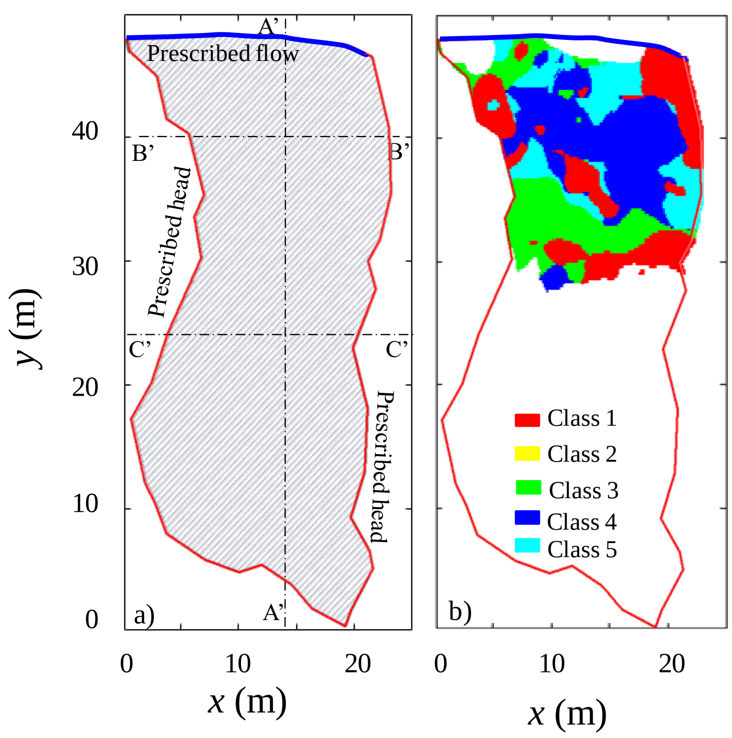


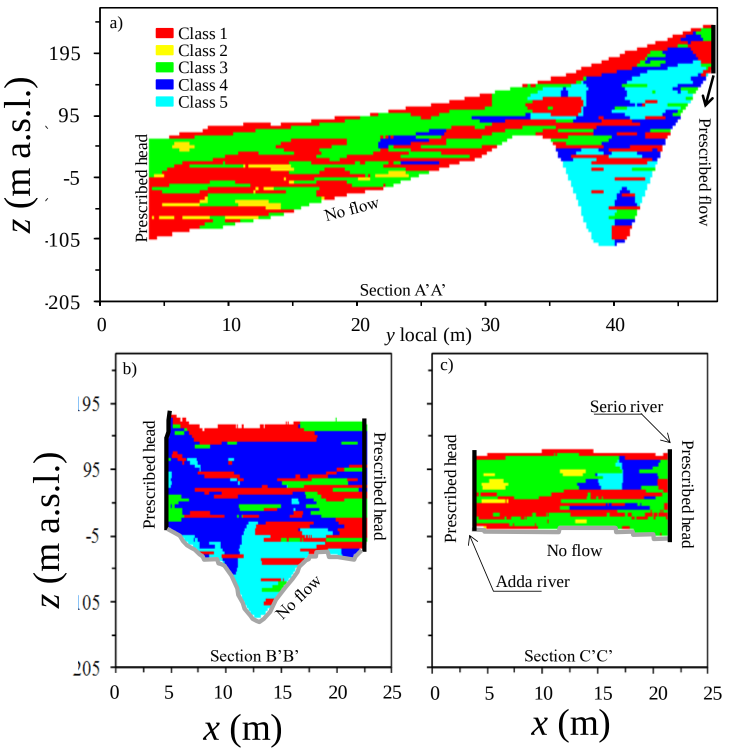
-230 columns
-240 rows
-95 layers

Composite medium (*CM*) approach

- Each block of the numerical model is formed by a single geomaterials (e.g., Guadagnini et al., 2004).
- The conductivity value assigned to each cell of the model domain consists in one (constant) value for each facies.

$$K_j^{CM} = k_i$$



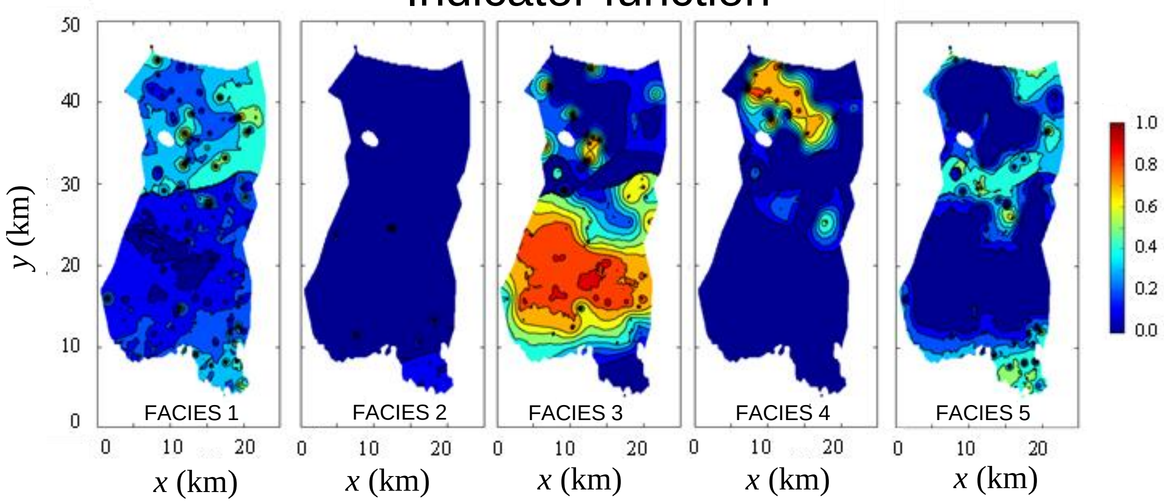


Overlapping continua (*OC*) approach

- Each voxel *j* of the numerical grid represents a finite volume in which all geomaterials (or hydro-facies) can coexist, each associated with a given volumetric fraction

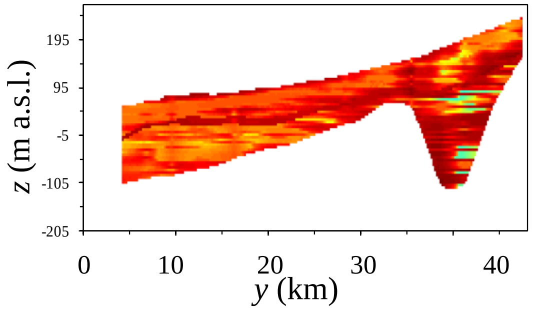
- Conditional Indicator Kriging yields $n_f \times N_c$ values of the Indicator function corresponding to the estimated probabilitity that a given geomaterials (class M_i) resides within block *j*

Indicator function



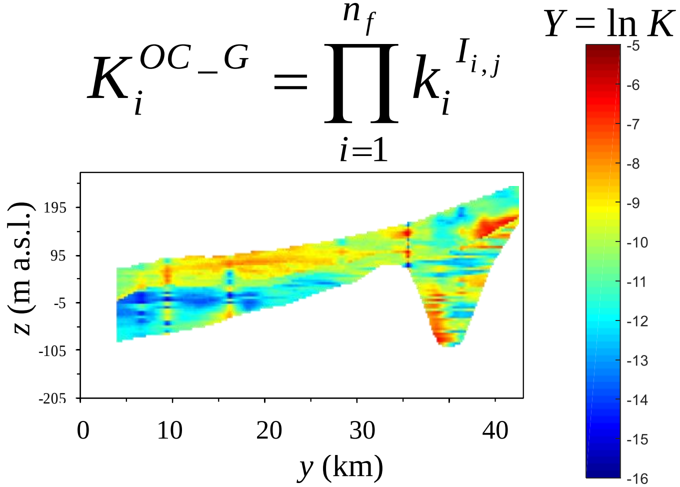
Arithmetic mean (*OC_A*)

$$K_j^{OC\_A} = \sum_{i=1}^{n_f} I_{i,j}\, k_i$$



Geometric mean (*OC_G*)

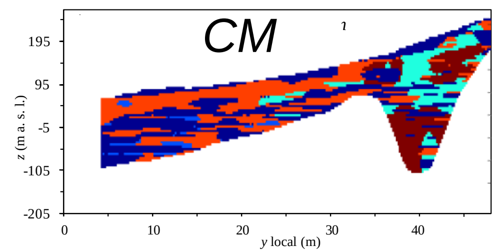
$$K_i^{OC\_G} = \prod_{i=1}^{n_f} k_i^{\,I_{i,j}}$$



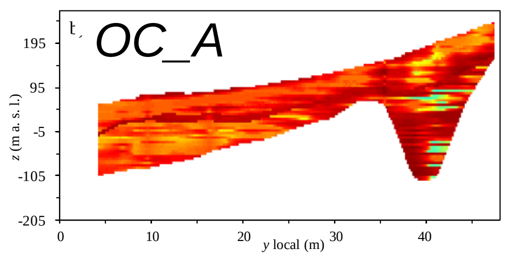
GEOLOGICAL AQUIFER ARCHITECTURE

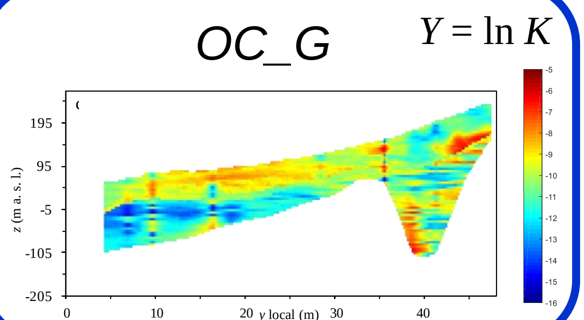
HYDRAULIC LOG-CONDUCTIVITY FIELDS

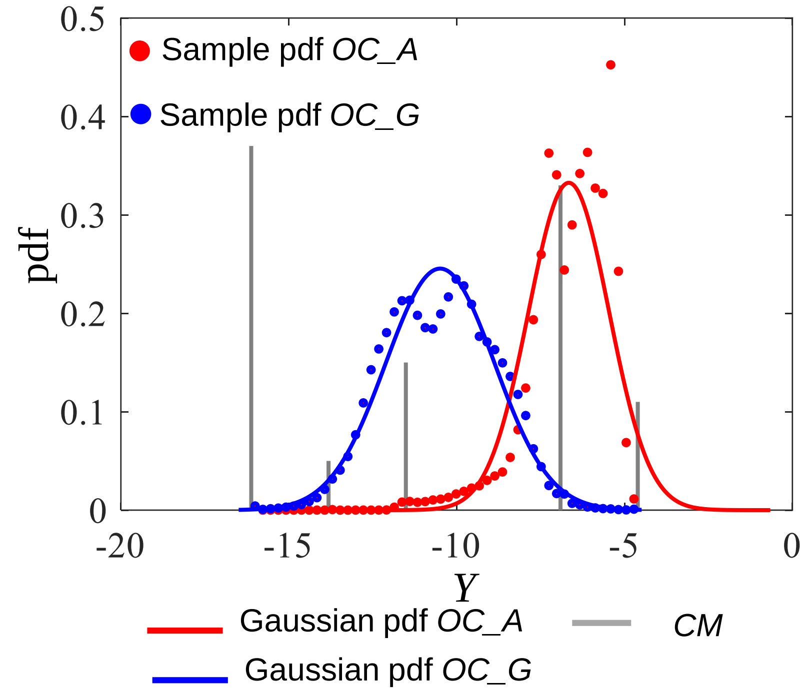
COMPOSITE MEDIUM (CM)

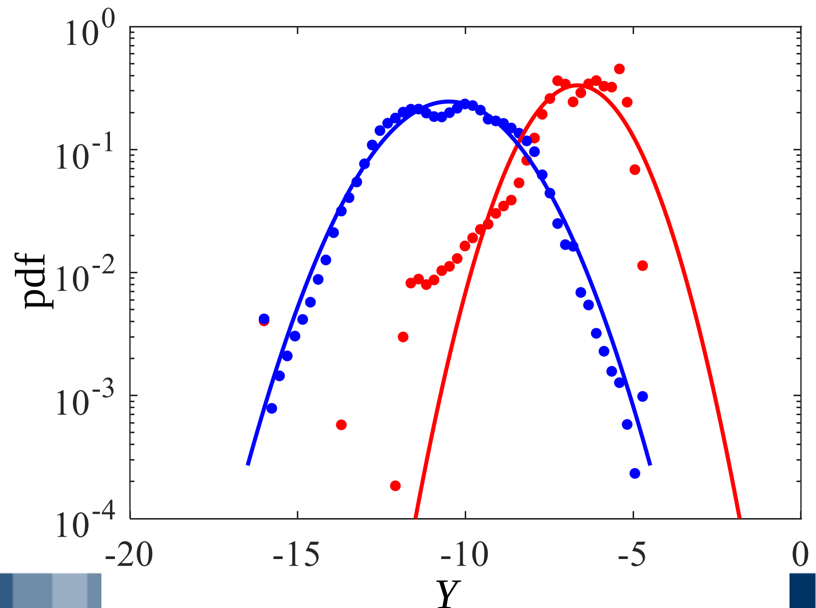


OVERLAPPING CONTINUA (OC)



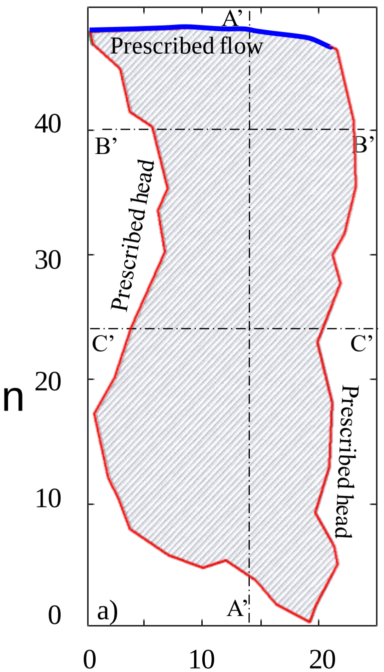






Global sensitivity analysis

- We analyse the impact on the groundwater system response of the uncertainty in
  - conceptual model (OC_A, OC_G, CM)
  - boundary conditions
  - hydraulic parameters (hydraulic conductivities of the 5 facies)
- Width of the intervals associated with parameter variability is based on geological features



7 sources of uncertainty:

Parameter	Short name	Description	Lower bound	Upper bound	Unit
p_1	k_1	Clay and silt conductivity	10^{-8}	10^{-5}	m/s
p_2	k_2	Fine and silty sand conductivity	10^{-7}	10^{-4}	m/s
p_3	k_3	Gravel, sand and gravel conductivity	10^{-4}	10^{-2}	m/s
p_4	k_4	Compact conglomerate conductivity	10^{-6}	10^{-3}	m/s
p_5	k_5	Fractured conglomerate conductivity	10^{-3}	10^{-1}	m/s
p_6	p_6	Total flow rate from northern boundary	4.83	14.47	m^3/s
p_7	p_7	Height of the river	0.0	3.0	m

Facies conductivity values

Boundary conditions

Sensitivity metrics

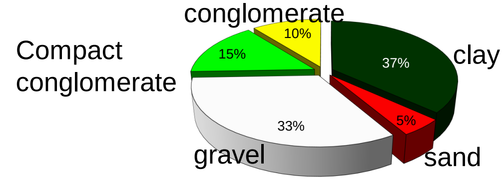
$$y = f(\mathbf{p})$$

Methodology	Sensitivity	Definition
1. Derivative-based Morris Indices	**Local derivatives** of the model output with respect to input parameters	$EE_{p_i}(j) = \frac{f(p_1,\ldots,p_i+\Delta,\ldots,p_N) - f(\mathbf{p})}{\boldsymbol{\Delta}}$ $\mu^*_{p_i} = \frac{1}{r}\sum_{j=1}^{r} \left\lvert EE_i(j)\right\rvert$
2. Variance-based Sobol' indices	Expect **reduction** of the **Variance** of *f* due to the knowledge of p_i	$S_{p_i} = \frac{E\left[V_f - V\left[f \mid p_i\right]\right]}{V_f}$
3. Moment-based AMA*M* Indices	Expected variation of **Mean, Variance** and **Skewness** *of f* to the knowledge of p_i	$\mathrm{AMA}M_{p_i} = \frac{E\left[\left\lvert M_f - M\left[f \mid p_i\right]\right\rvert\right]}{\left\lvert M_f\right\rvert}$

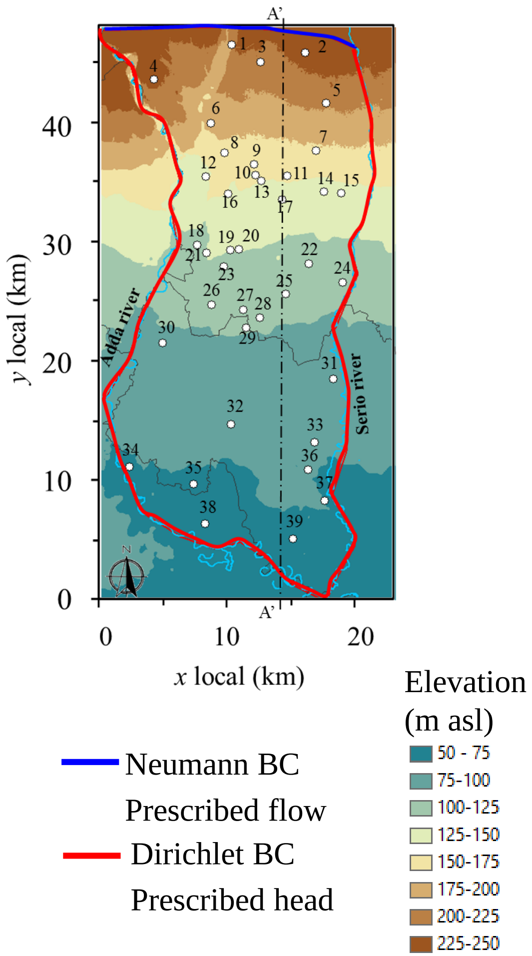
Global sensitivity analysis

$$\mathrm{AMAV}_{p_i} = \frac{E\left[\left|V_f - V\left[f \mid p_i\right]\right|\right]}{\left|V_f\right|}$$

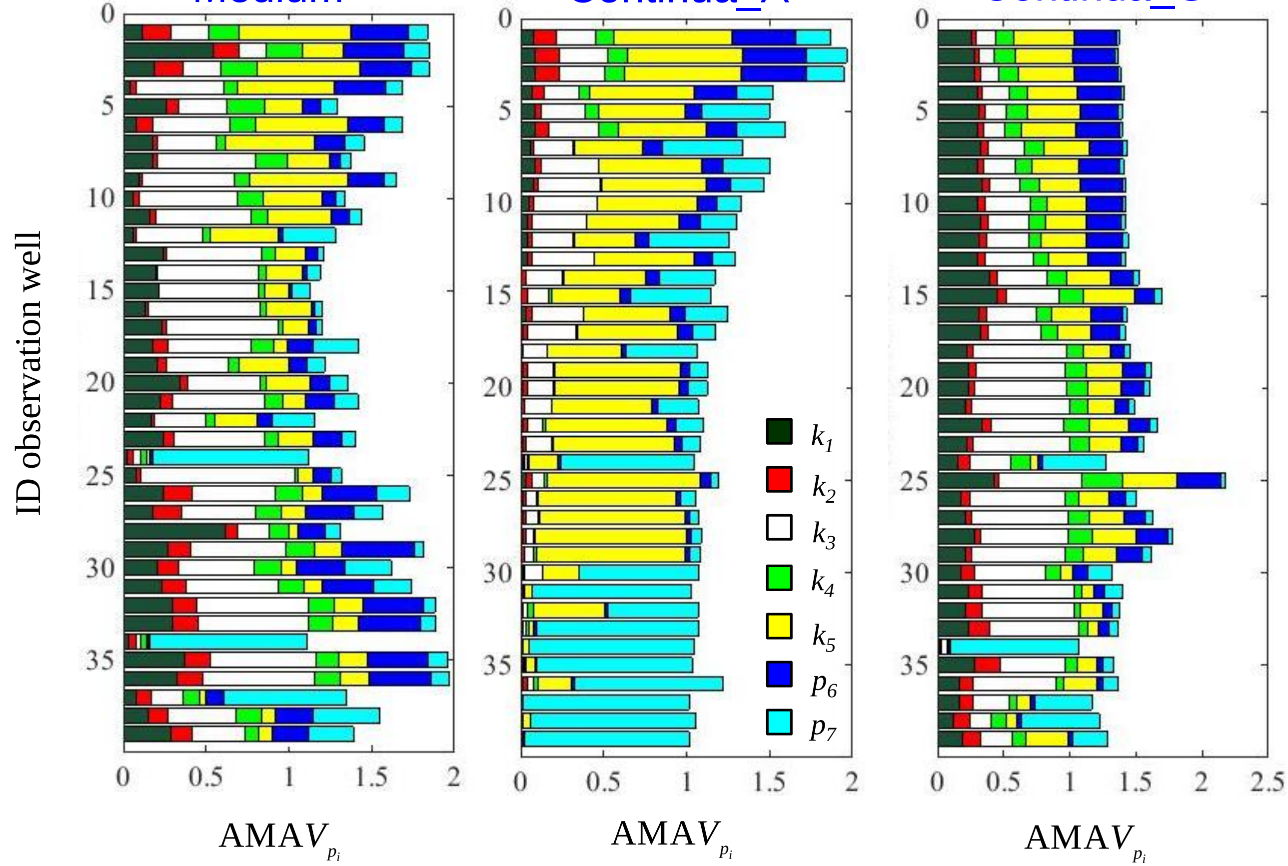
Volumetric fraction



Location of observation wells

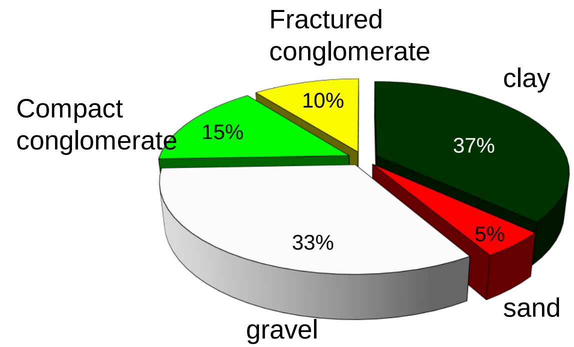


Composite Medium | Overlapping Continua_A | Overlapping Continua_G



Average of sensitivity indices

Volumetric fraction



Facies conductivity values: k_1, k_2, k_3, k_4, k_5

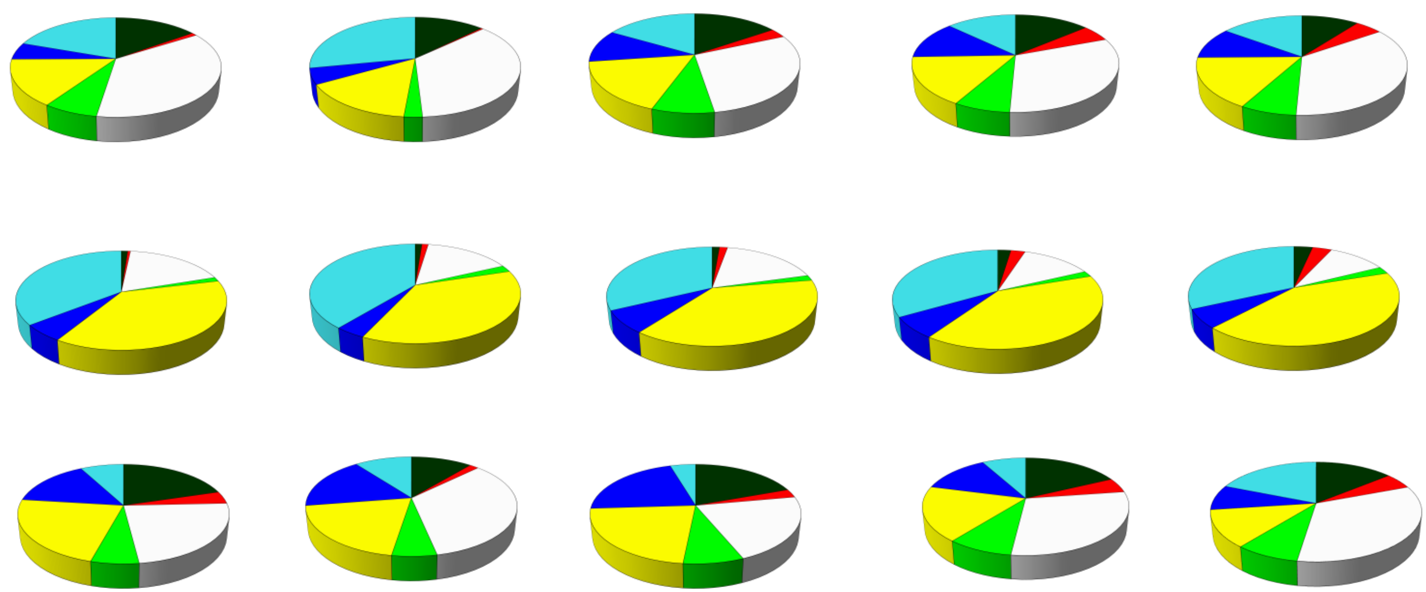
Boundary conditions: p_6, p_7

$\bar{\mu}^*_{p_i}$ | $S^T_{p_i}$ | $AMAE_{p_i}$ | $AMAV_{p_i}$ | $AMA\gamma_{p_i}$

Composite Medium

Overlapping Continua_A

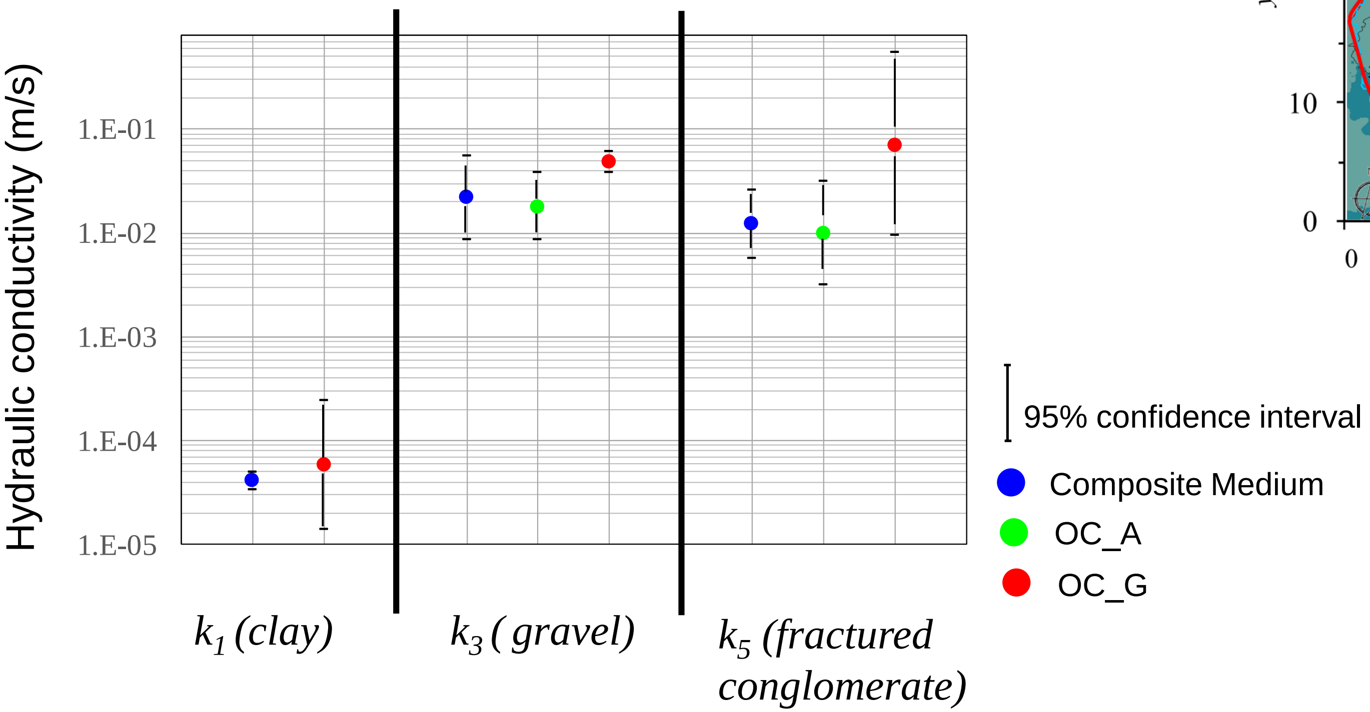
Overlapping Continua_G

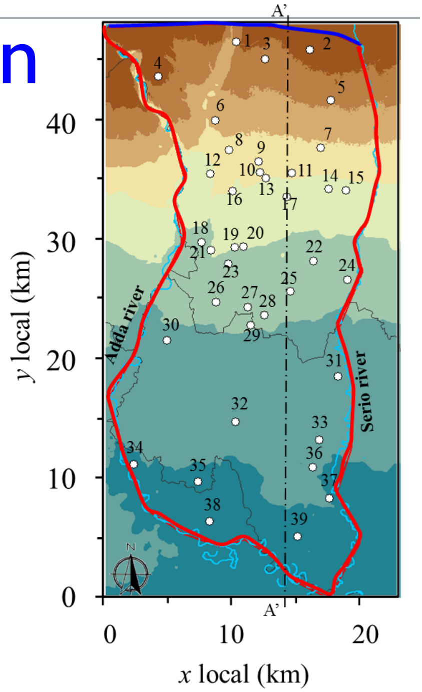


Hydraulic conductivity calibration

- Each selected model have been calibrated within a Maximum Likelihood approach

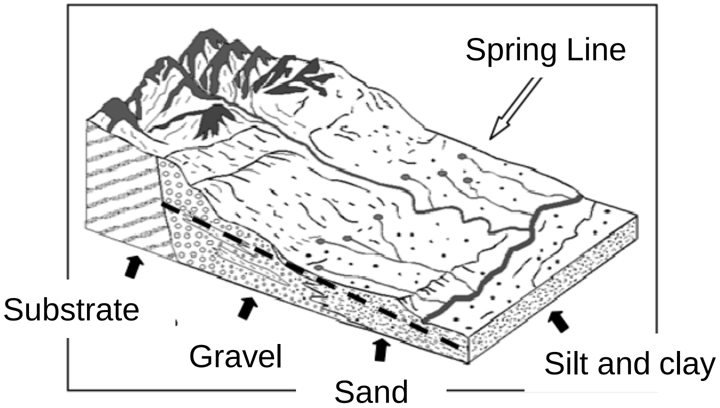
$$NLL = \sum_{i}^{N_h} \frac{J_i}{\sigma_h^2} + \ln|\mathbf{C}_h| + N_h \ln(2\pi) \qquad J_i = \left(h_i^* - h_i\right)^2$$



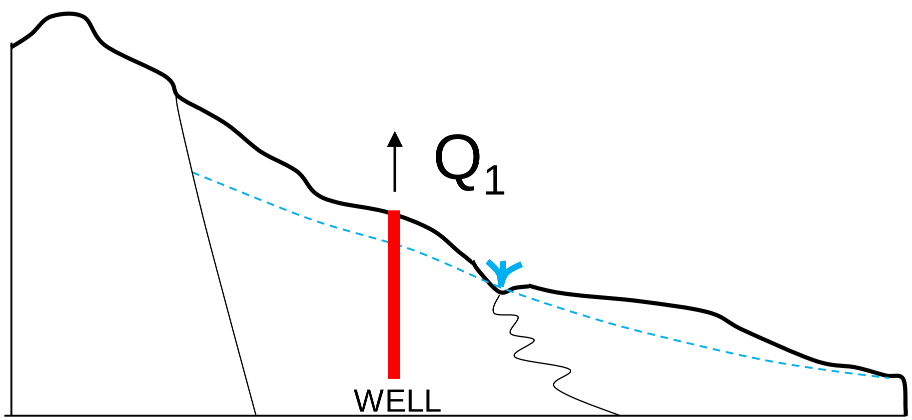


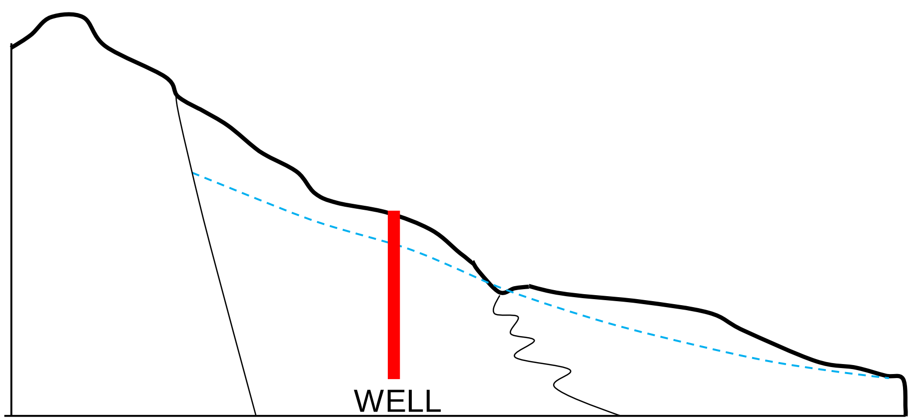
- The estimated values are consistent with the geological features of the classes
- The estimated values are consistent with the selected modeling approach

Spring depletion problem

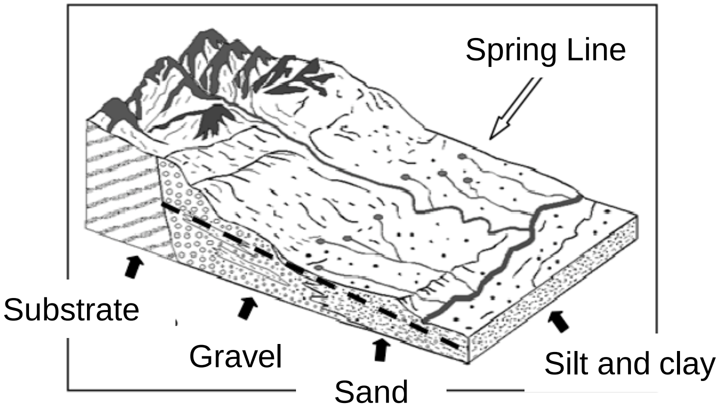


- ➢ What is the probability of spring depletion due to increasing exploitation of the aquifer?





Spring depletion problem



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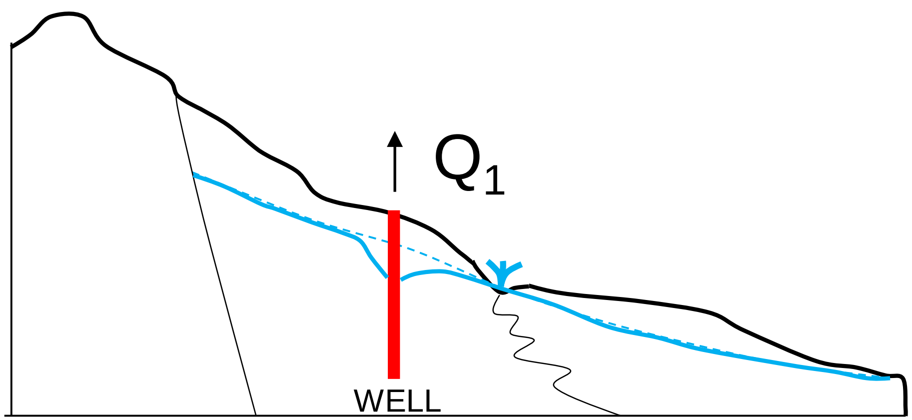
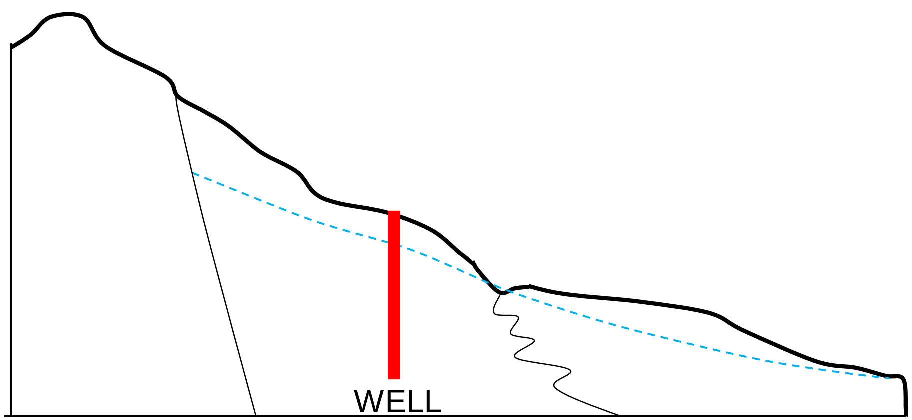
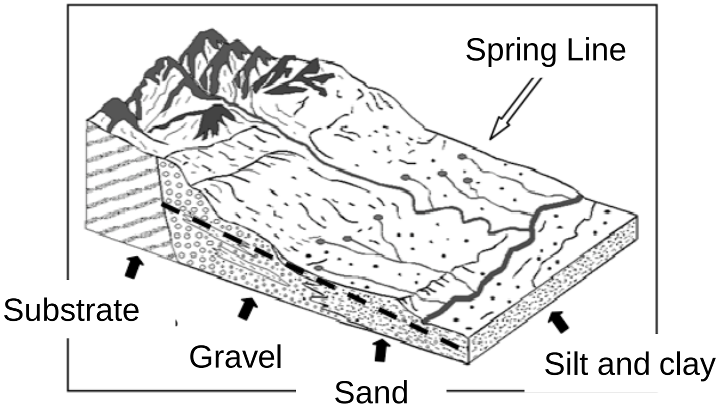
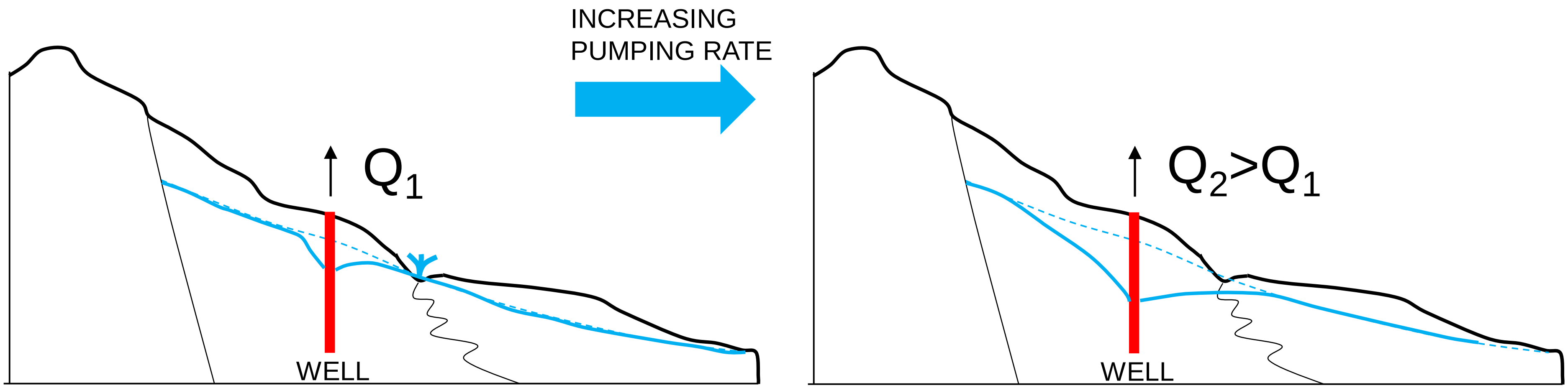




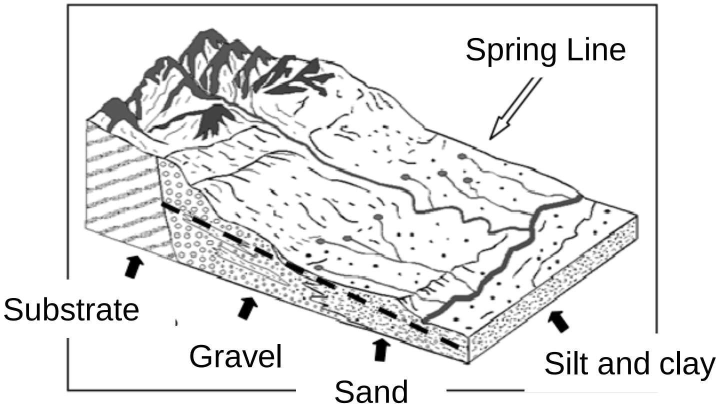
Spring depletion problem



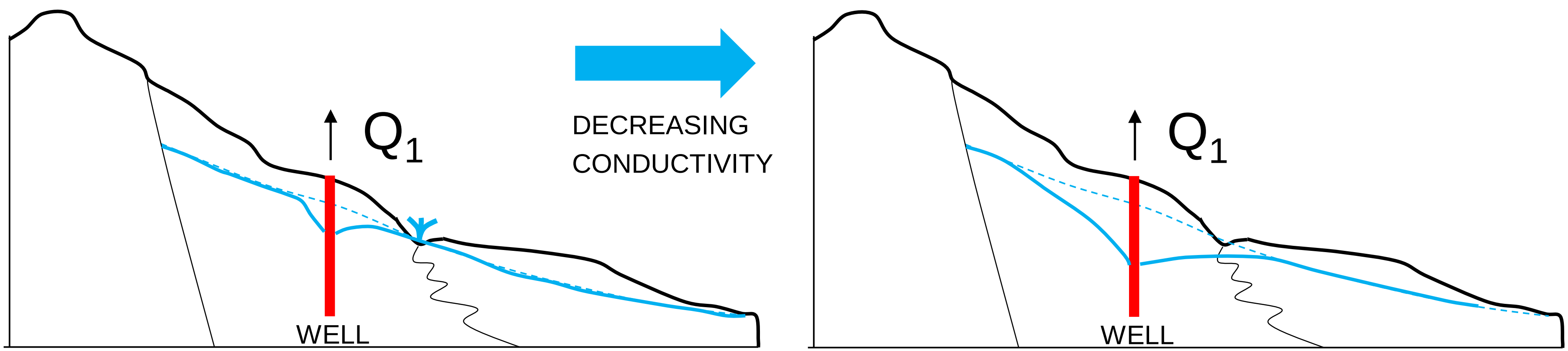
- What is the probability of spring depletion due to increasing exploitation of the aquifer?



Spring depletion problem



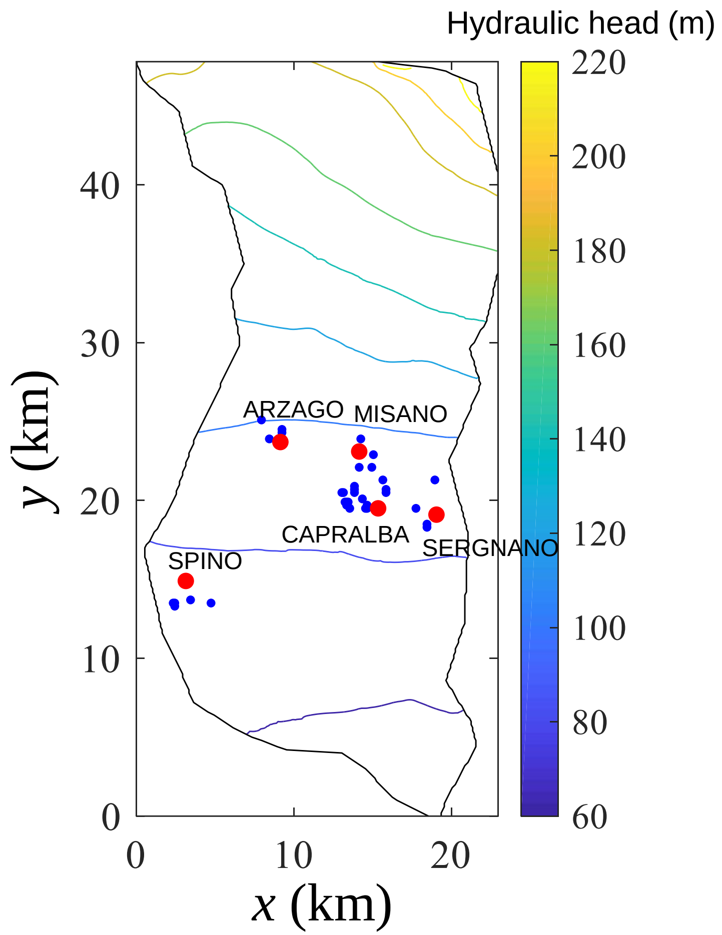
- What is the probability of spring depletion due to increasing exploitation of the aquifer?
- How does the uncertainty associated with the hydraulic conductivity affect the solution?



$K_1 > K_2$

Problem variables

- Springs (N_s = 34)
- Pumping wells with variable rates (N_w=5)



Design variables: pumping well rates at a subset of 5 selected pumping wells

$$\mathbf{Q} = \left[Q_1; Q_2; Q_3; Q_4; Q_5\right] \qquad Q_i^{\min} - Q_i^{\max}$$

$$\Phi = \sum_{i=1}^{N_W} Q_i$$

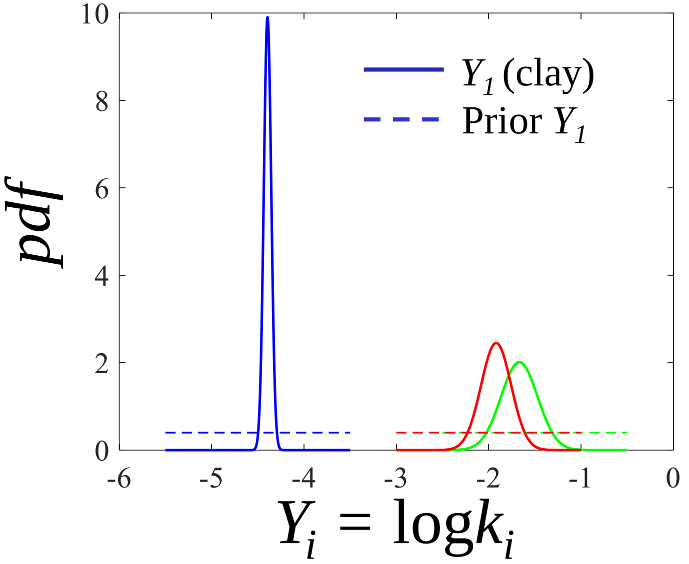
Function to be maximized: total sum of well rates

Failure event (constrain): the hydraulic head at the spring cells is beyond a specific threshold

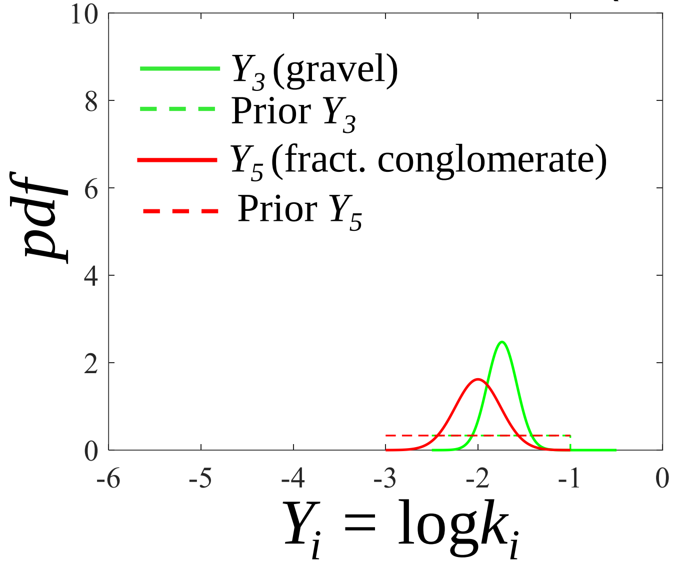
$$h_i\left(\mathbf{Q}, \mathbf{Y}\right) - h_i^{\min} \leq 0 \qquad i = 1, N_s$$

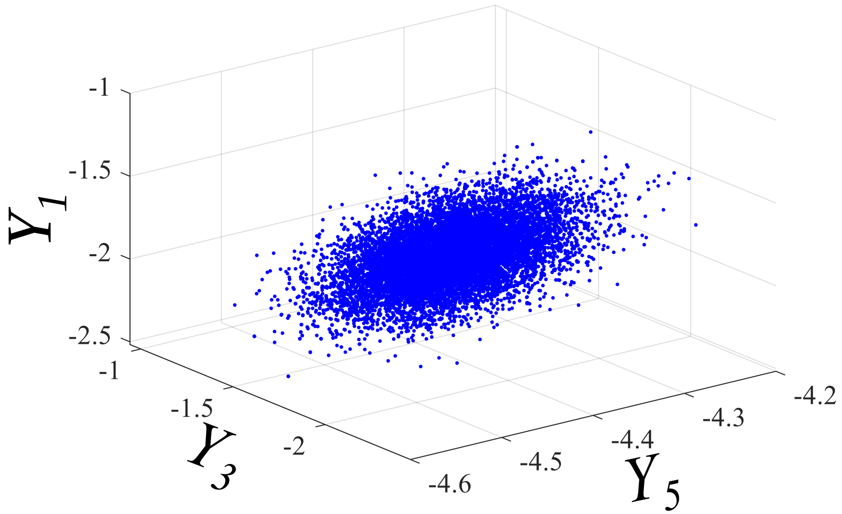
Uncertainty in log-conductivities

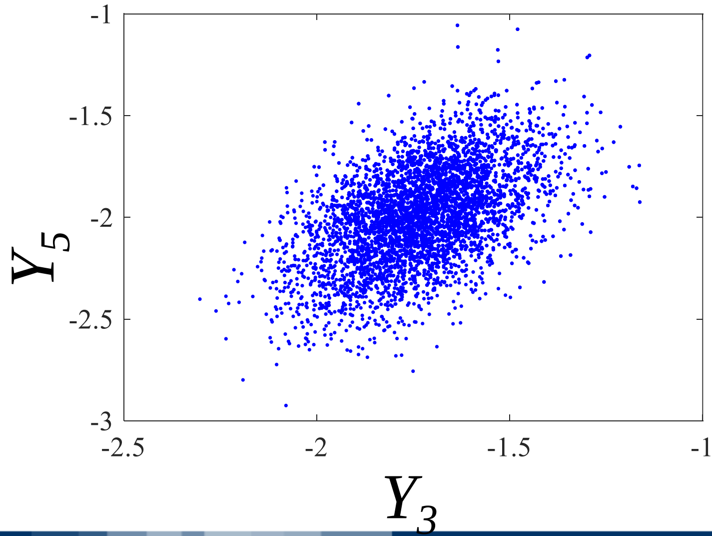
COMPOSITE MEDIUM



OVERLAPPING CONTINUA (arithmetic)

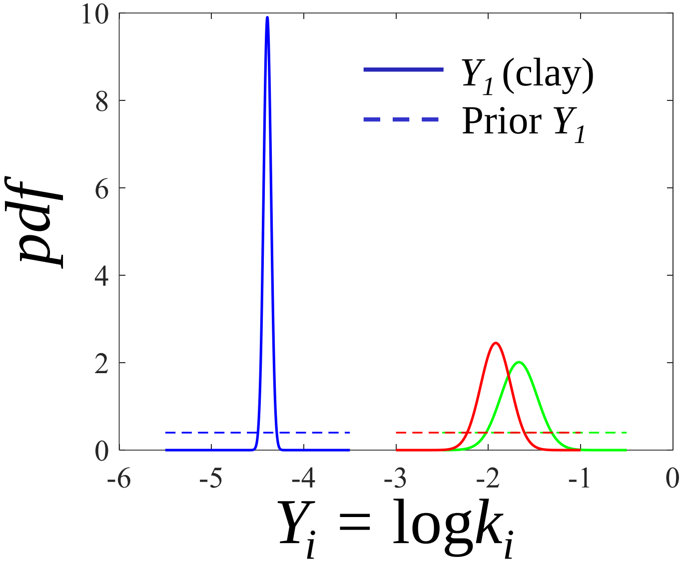




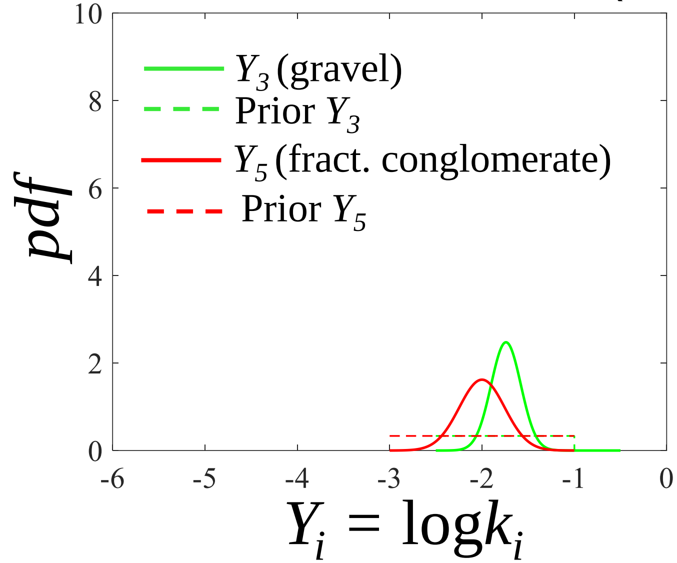


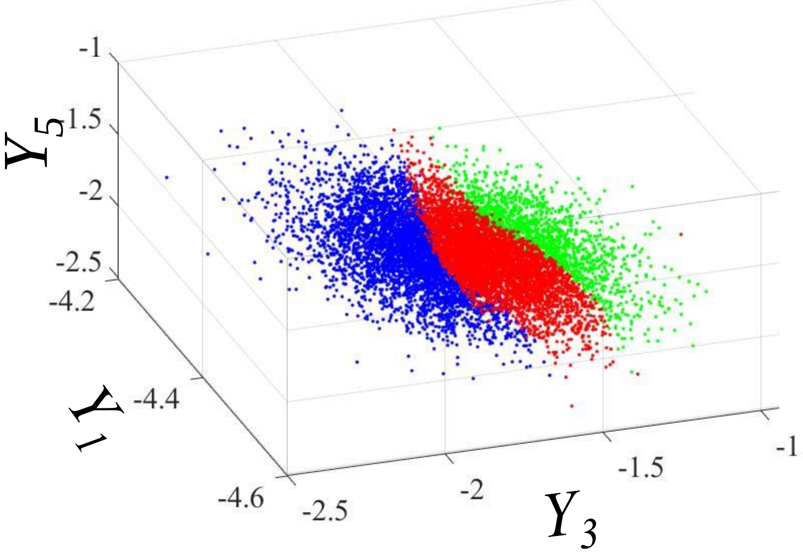
Uncertainty in log-conductivities

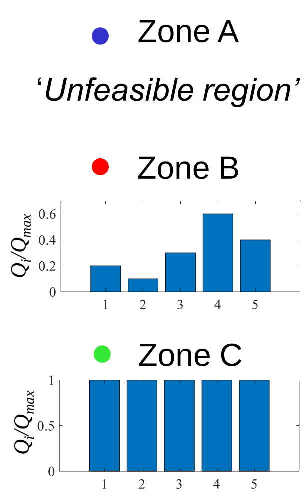
COMPOSITE MEDIUM

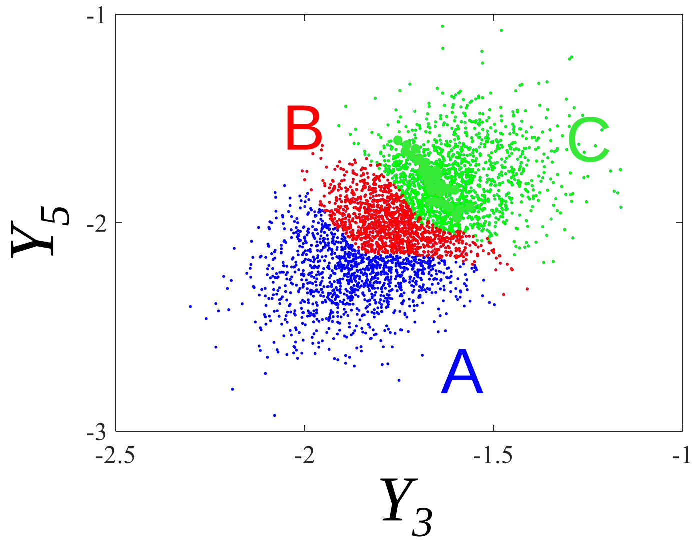


OVERLAPPING CONTINUA (arithmetic)

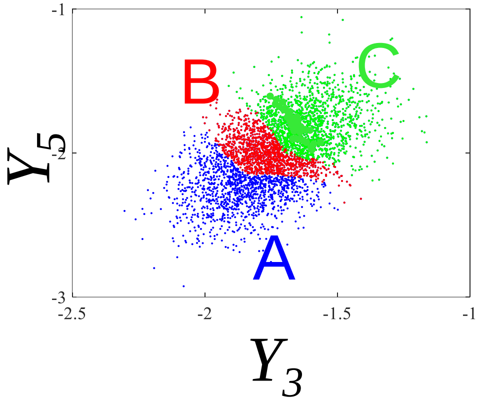


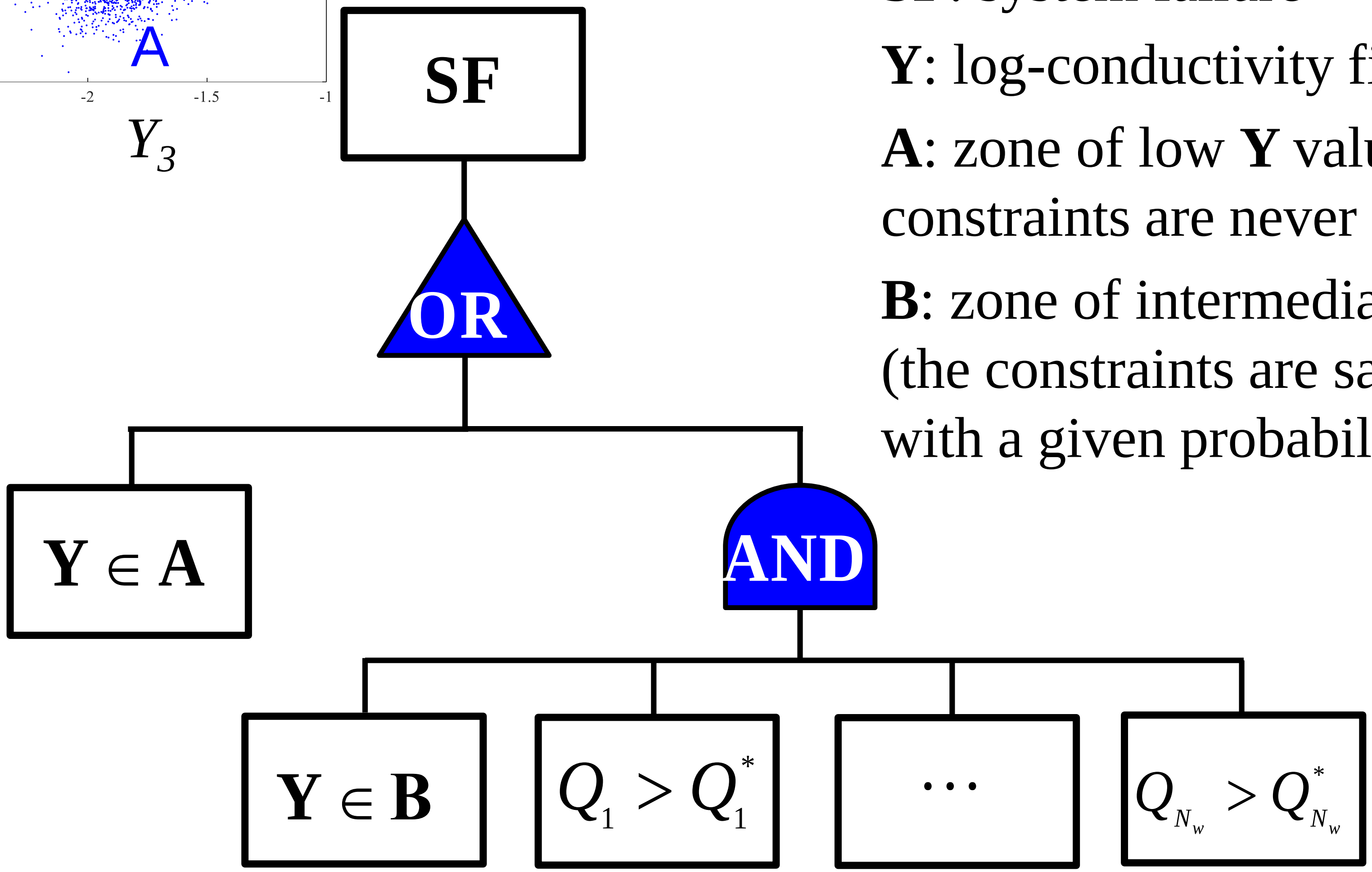






Fault tree analysis





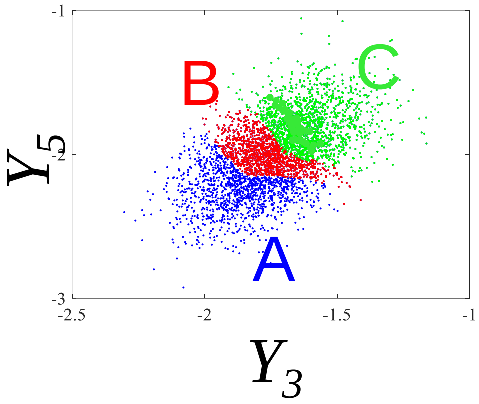
SF: system failure

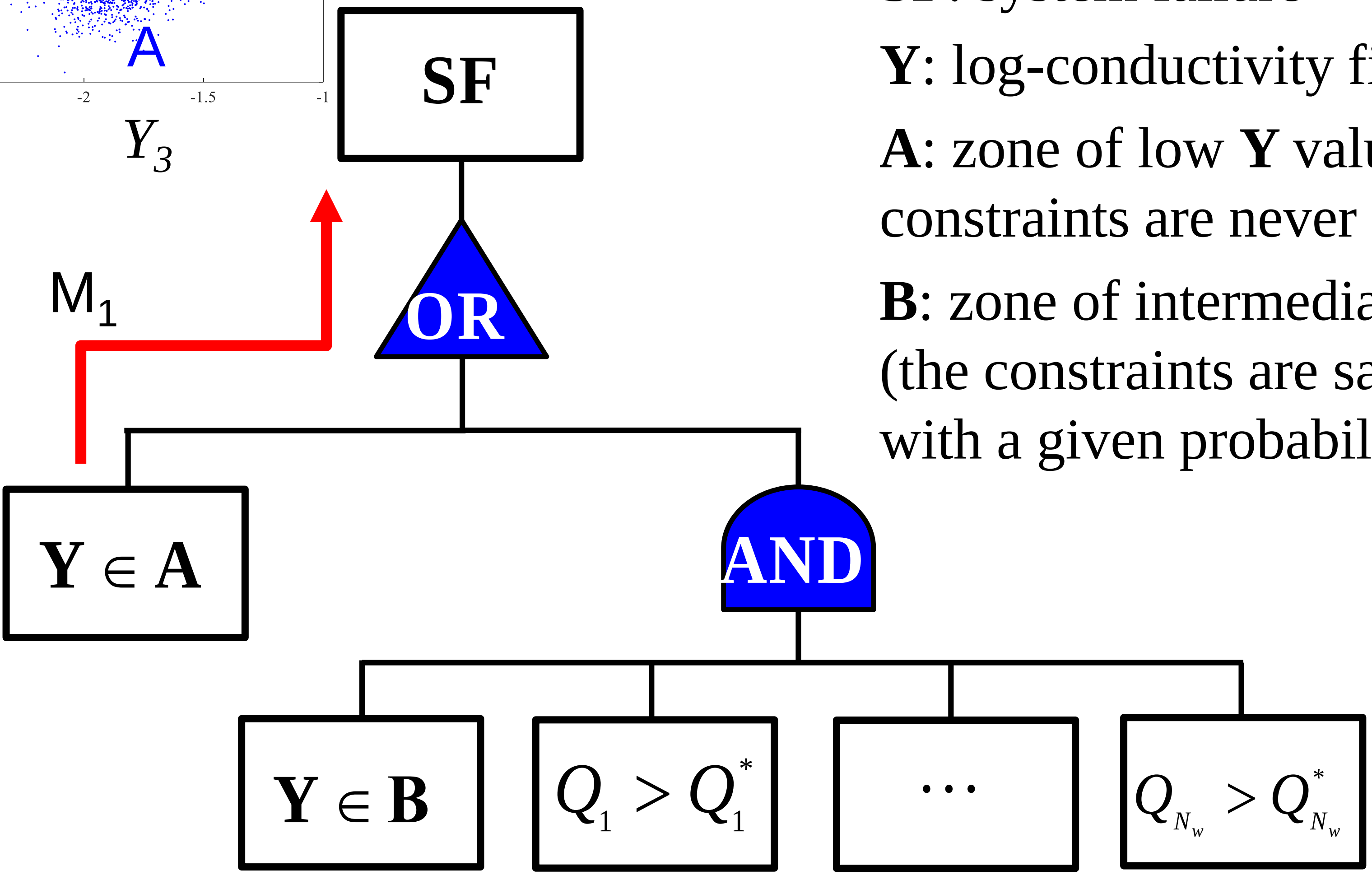
Y: log-conductivity field

A: zone of low **Y** values (the constraints are never satisfied)

B: zone of intermediated **Y** (the constraints are satisfied with a given probability)

Fault tree analysis





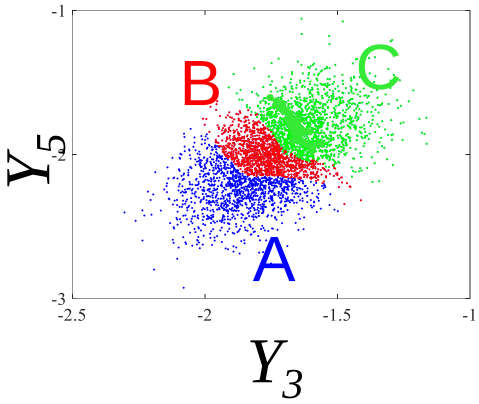
SF: system failure

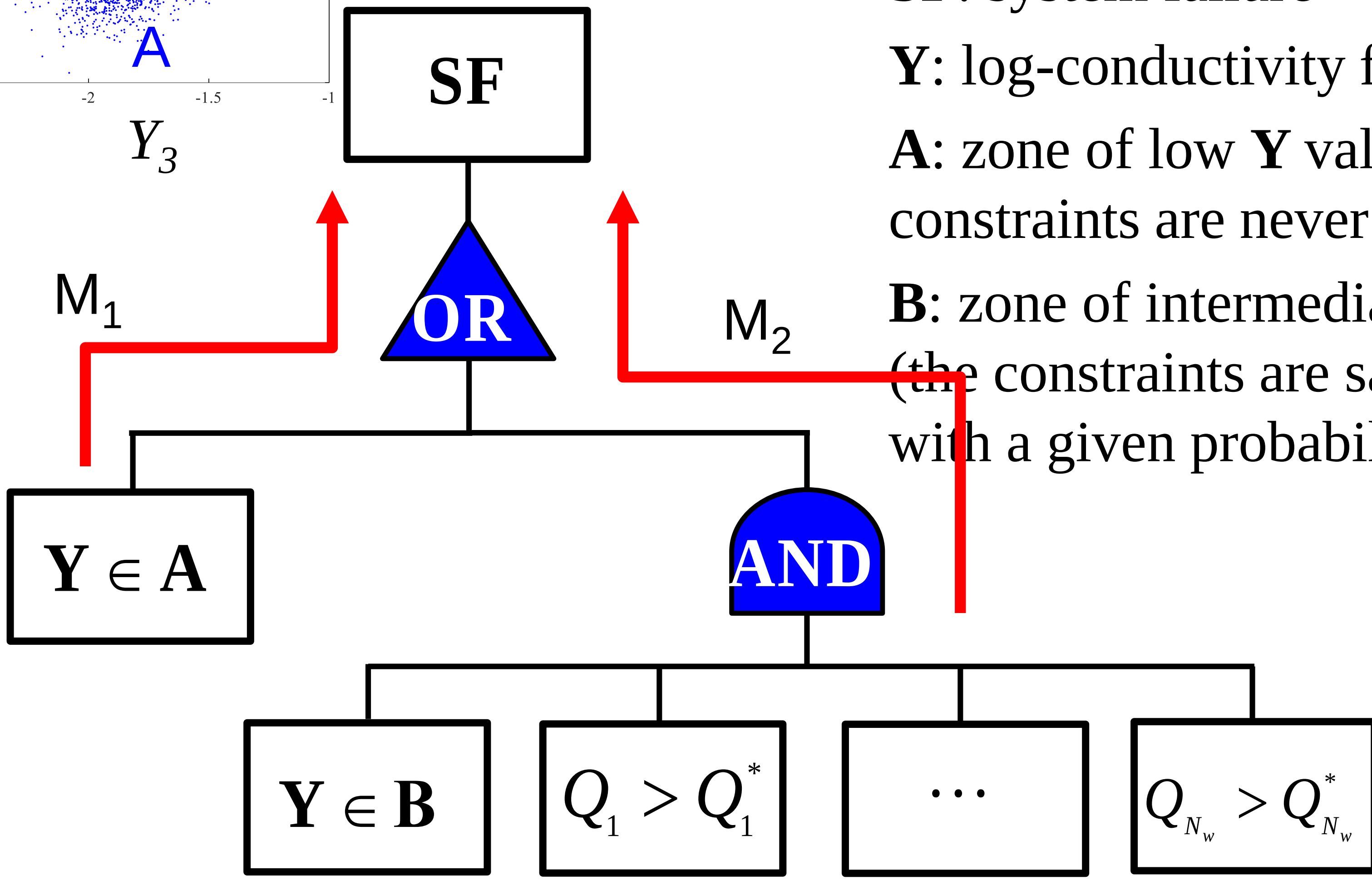
Y: log-conductivity field

A: zone of low **Y** values (the constraints are never satisfied)

B: zone of intermediated **Y** (the constraints are satisfied with a given probability)

Fault tree analysis





SF: system failure

Y: log-conductivity field

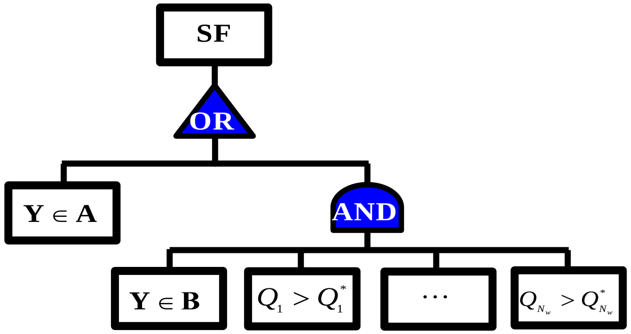
A: zone of low **Y** values (the constraints are never satisfied)

B: zone of intermediated **Y** (the constraints are satisfied with a given probability)

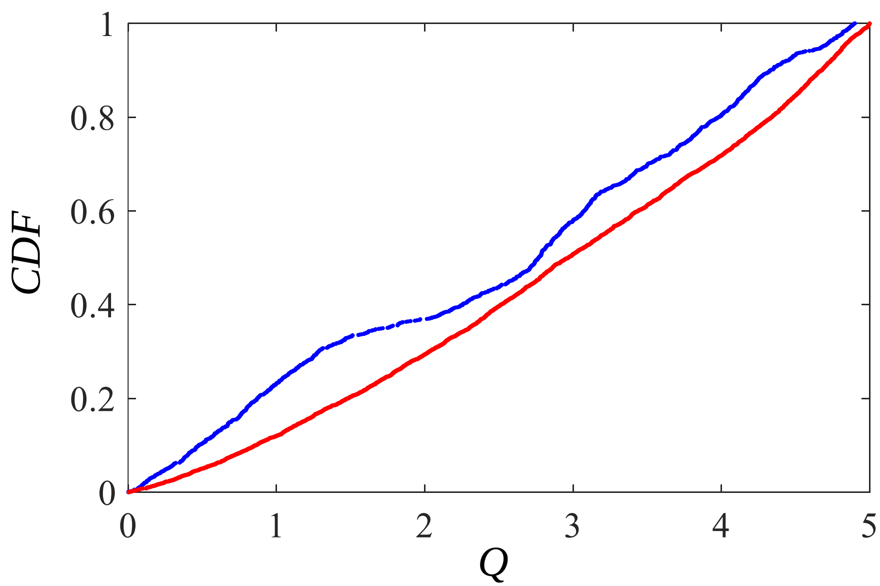
Example of results

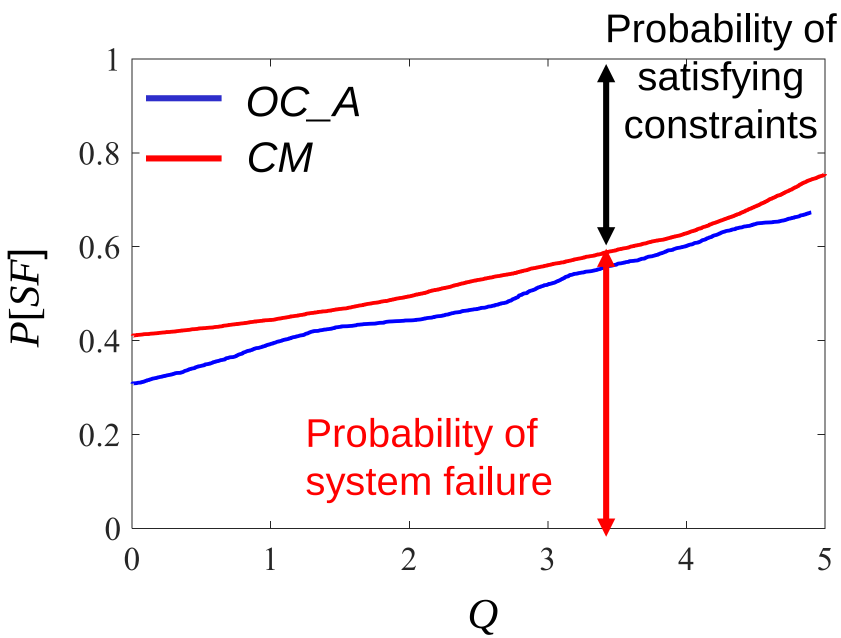
- Considering the sum of the 5 wells flow rates

$$Q = \sum_{i=1}^{5} \left(Q_i / Q_i^{\max} \right)$$



$$P[SF] = \frac{N_A}{N_{tot}} + CDF(Q)\frac{N_B}{N_{tot}}$$





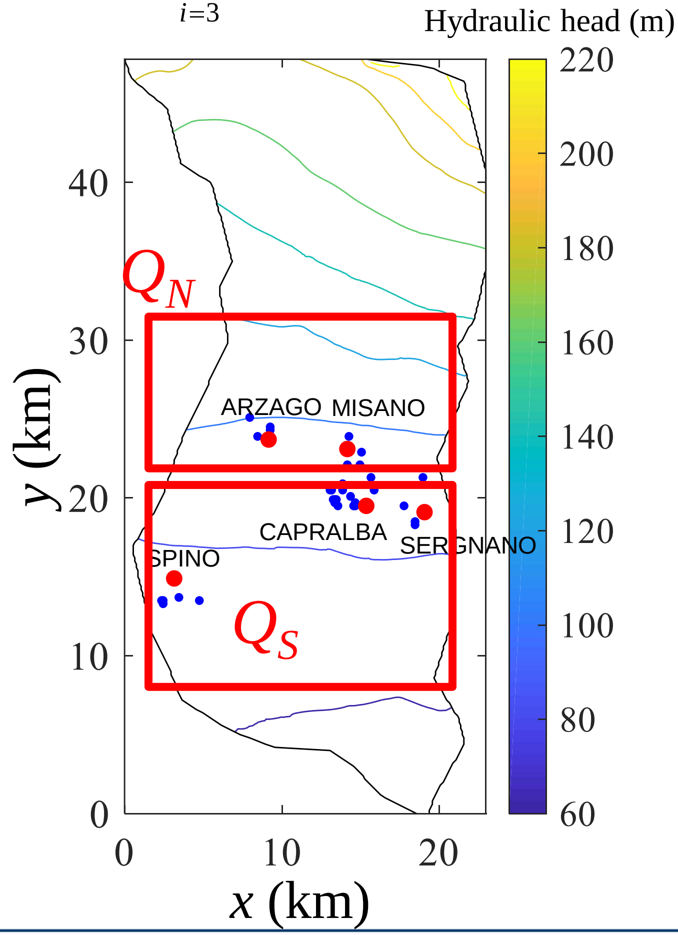
Example of results

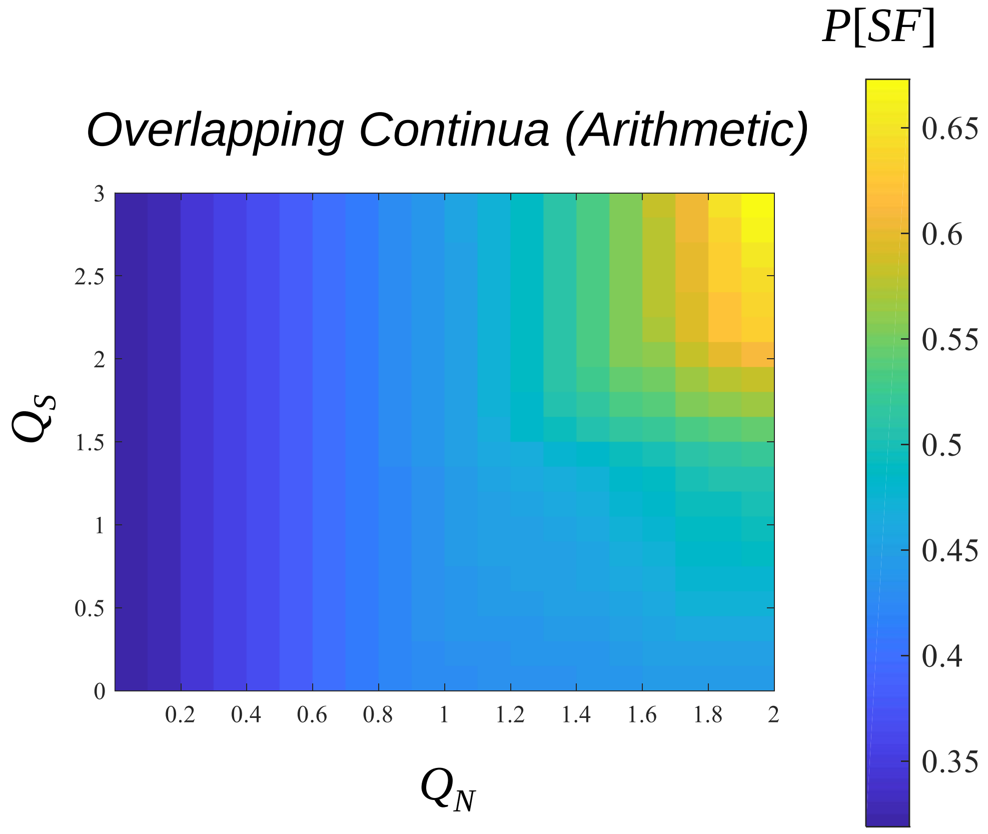
➢ Considering the Northern and Southern wells separately

$$Q_N = \sum_{i=1}^{2} \left(Q_i / Q_i^{\max} \right)$$

$$Q_S = \sum_{i=3}^{5} \left(Q_i / Q_i^{\max} \right)$$

$$P[SF](Q_N, Q_S) = \frac{N_A}{N_{tot}} + CDF_{\text{joint}}(Q_N, Q_S) \frac{N_B}{N_{tot}}$$





Conclusions

- We compares a set of Global Sensitivity Analysis (GSA) approaches in the context of groundwater flow in a three-dimensional large scale groundwater system
- Albeit being based on differing metrics and concepts, the three GSA approaches analyzed lead to similar and consistent rankings of parameters which are influential to the target model outcomes
- GSA results provide insight about model calibration and model parameter reduction
- Risk assessment, based on a Fault Tree analysis, allows to identify optimal pumping rates preserving the springs' activity

POLITECNICO DI MILANO

Natural spring' protection and groundwater management under uncertainty conditions: the Cremona Aquifer

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