Natural springs' protection and probabilistic risk assessment under uncertain conditions

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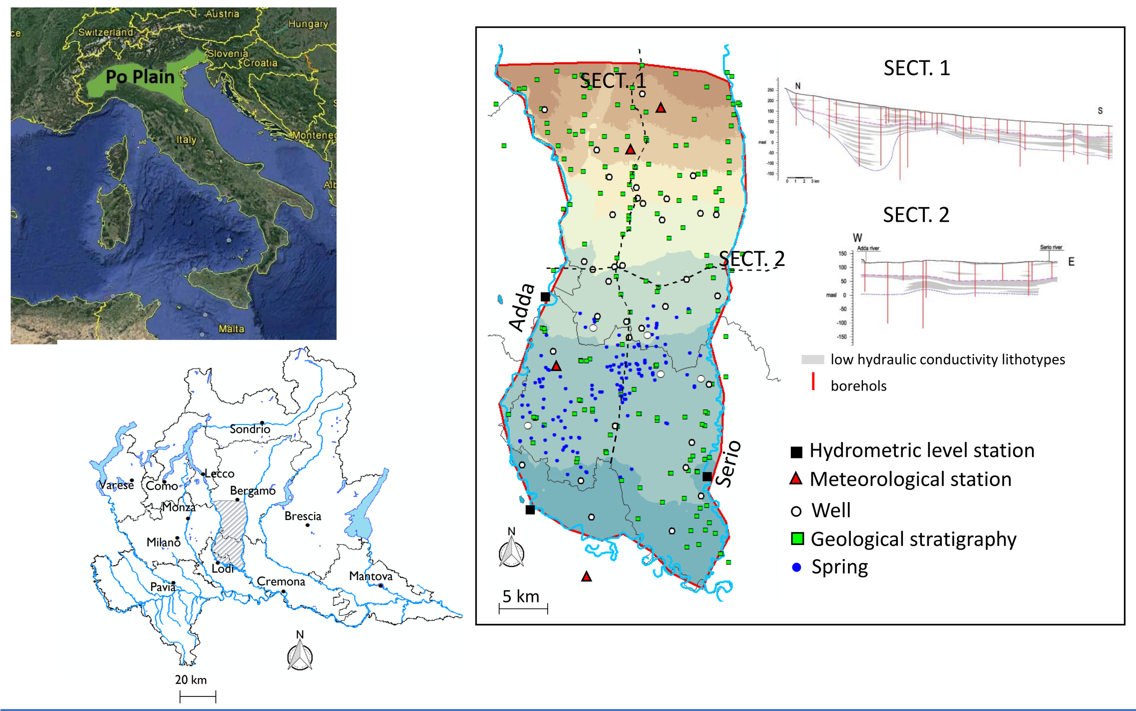
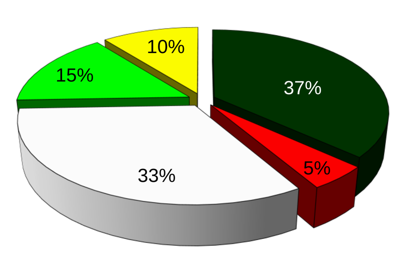
1. Pilot site characterization



CREMONA aquifer is a heavily exploited site in the alluvial Po plain (Northern Italy), its natural high-quality water springs are the main supply to agriculture and a key environmental driver.

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

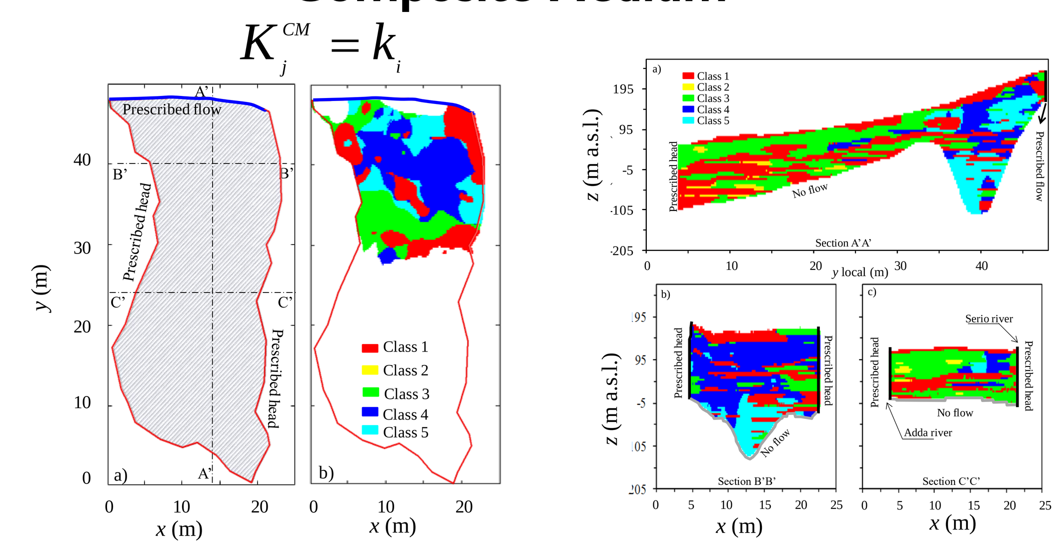


2. Conceptual models

We parameterize the conductivity field following two different conceptual schemes:

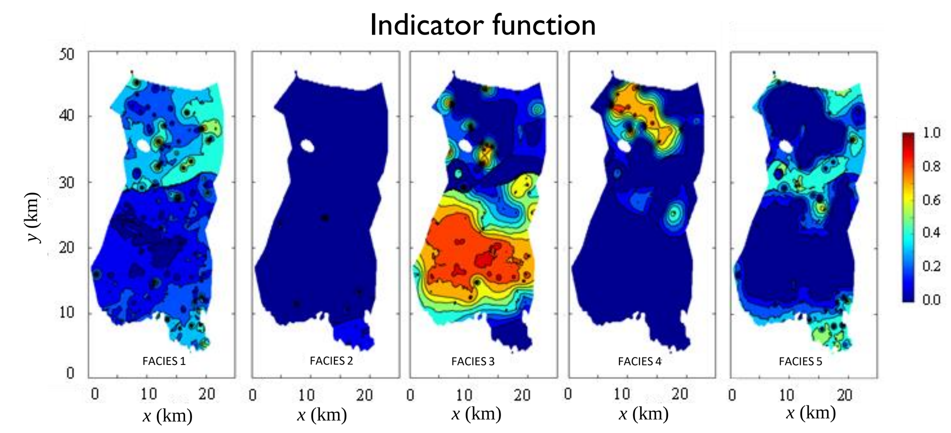
Composite Medium

$$K_j^{CM} = k_i$$

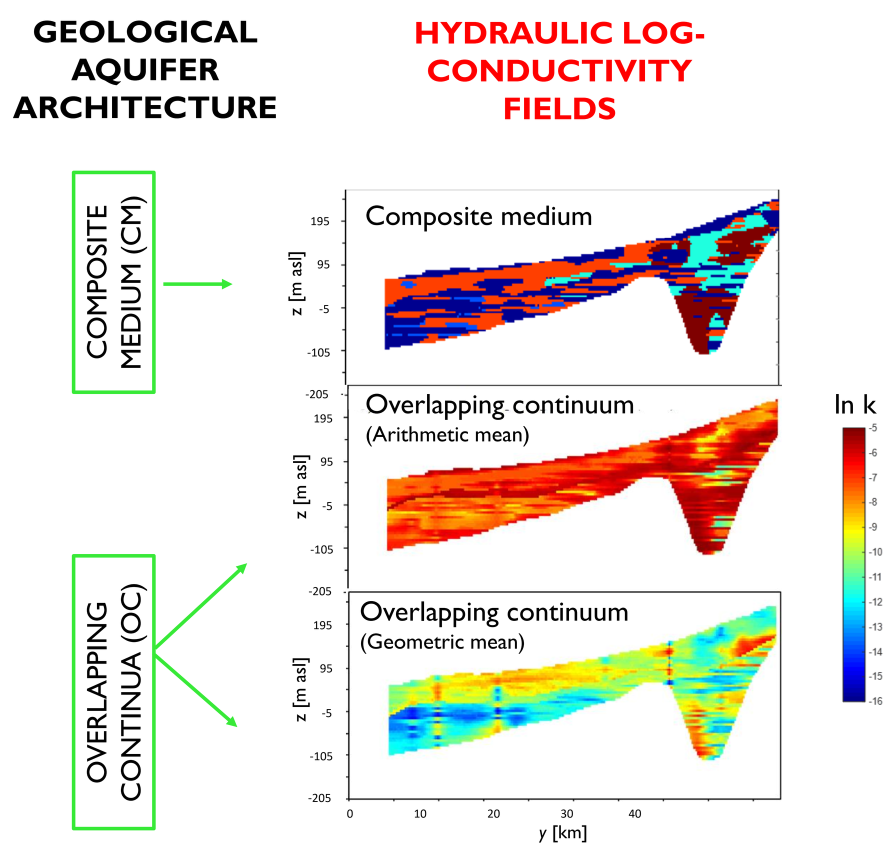


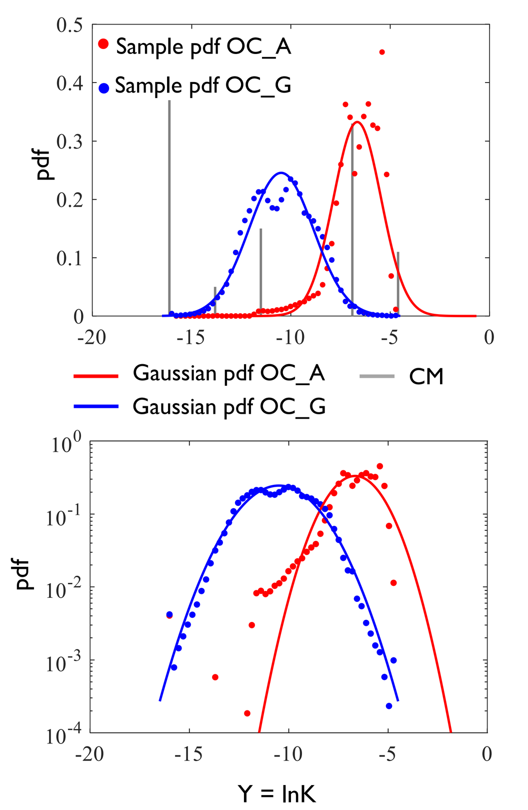
Overlapping Continuum

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



3. Groundwater flow modeling





Three-dimensional groundwater flow model under steady state regime.

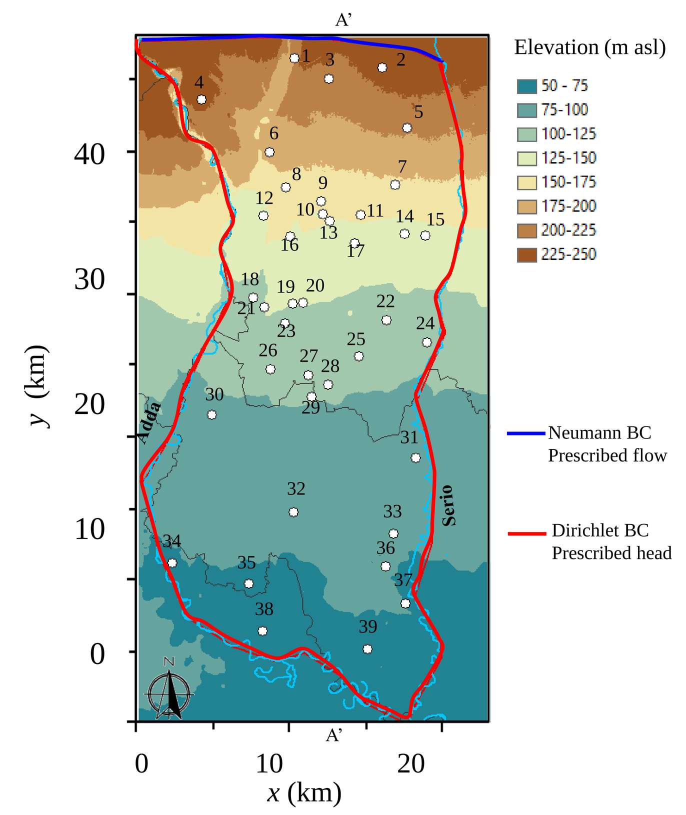
The flow domain size is 23 km (E-W direction) × 48 km (N-S direction) × 475 m (depth). Each cell has dimension 100 m × 200 m × 5 m.

The diverse averaging strategies significantly affect the spatial distribution of *Y*. The domain is (on average) more permeable and less heterogeneous when the arithmetic rather than the geometric mean operator is employed.

4. Uncertain parameters

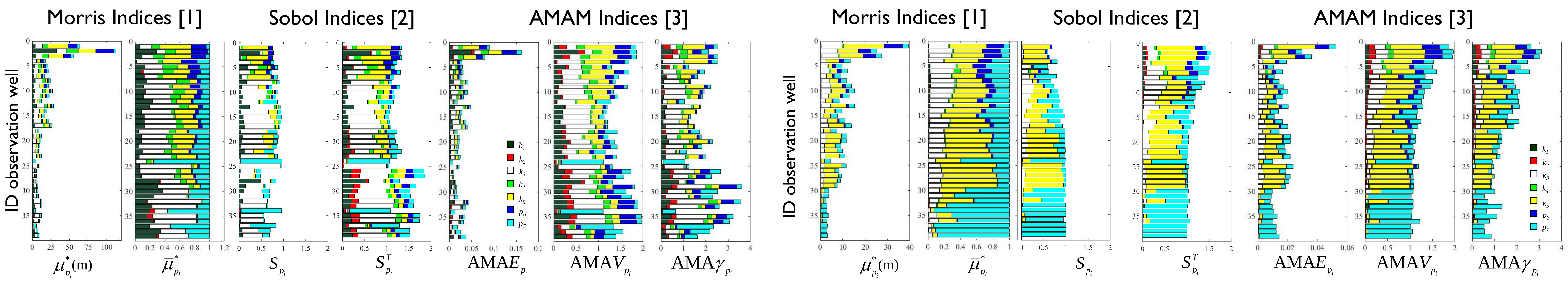
Uncertain parameters are associated with (i) 5 hydraulic conductivities and (ii) 2 selected boundary conditions

Parameter	Short name	Description	Lower bound	Upper bound	Unit	
p_1	k_1	Clay and silt conductivity	10^{-8}	10^{-5}	m/s	Facies conductivity
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	B.C.
p_7	p_7	River stage	0.0	3.0	m	



We analyze the impact of the uncertainty in the conceptual model and model parameters on model outputs (hydraulic heads at 39 target wells) by way of three GSA methodologies: (a) derivative-based, (Morris) (b) variance-based (Sobol') (c) moment based (AMAM indices, Dell'Oca et al., 2017).

5. Global Sensitivity Analysis



Our results show that: (i) hydraulic head for all conceptual models are significantly affected by the uncertainty of k_3 and/or k_5,(ii) impact of k_2 and/or k_4 is negligible and (iii) impact of BCs depends on the model.

We find that the sensitivity measures considered convey different yet complementary information. The choice of the conceptual model employed to characterize the lithological reconstruction of the aquifer affects the degree of influence that uncertain parameters can have on modeling results.

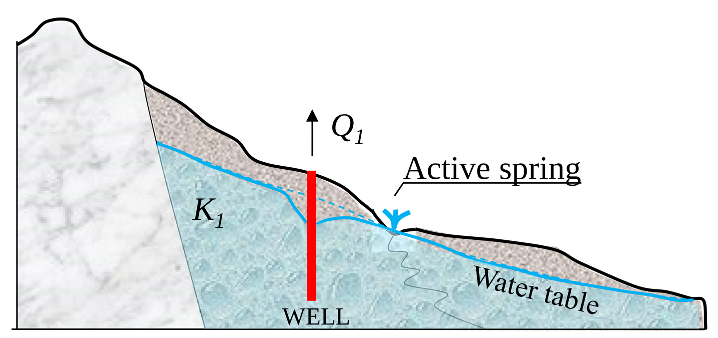
$$S_{p_i,\dots,p_s} = \frac{V_{p_i,\dots,p_s}}{V[f]} \qquad S_{p_i}^T = S_{p_i} + \sum_j S_{p_i,p_j} + \sum_{j,k} S_{p_i,p_j,p_k} + \dots + S_{p_i,\dots,p_N}$$

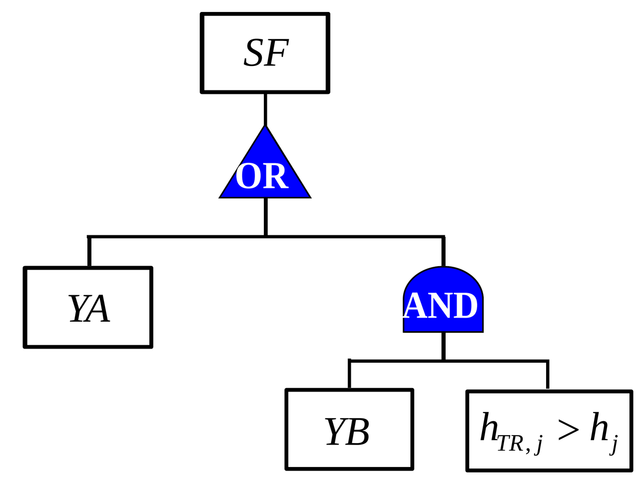
$$\mathrm{AMAM}_{p_i} = \frac{1}{|M[f]|} \int_{\Gamma_{p_i}} |M[f] - M[f \mid p_i]| \, \rho_{\Gamma_{p_i}} \, dp_i$$

6. Probabilistic Risk Assessment

What is the probability of spring discharge reduction due to increasing exploitation of the aquifer?

We evaluate this probability, stemming from the combination of the various sources of uncertainty illustrated above, through a Fault Tree Analyses.





References

[1] Morris, M.D., 1991. Factorial sampling plans for preliminary computational experiments. *Technometrics* 33, 161-174. ; [2] Sobol, I. M., 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Math. Comput. Simulat.* 55(1–3), 271-280. ; [3] Dell'Oca, A., Riva, M., Guadagnini, A., 2017. Moment-based metrics for global sensitivity analysis of hydrological systems. *Hydrol. Earth Syst. Sci.* 21, 6219-6234.; [4] Bianchi Janetti, E., Guadagnini, L., Riva, M., Guadagnini, A., 2019. Global sensitivity analyses of multiple conceptual models with uncertain parameters driving groundwater flow in a regional-scale sedimentary aquifer, *J. Hydrol.*, 574, 544-556.