A tool to estimate the location of high conductivity channels in heterogeneous porous media

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Abstract

Solute transport in groundwater is characterized by a high level of uncertainty since it is impossible to completely measure the spatial distribution of key soil properties, such as the hydraulic conductivity. Several studies have shown how an heterogeneous hydraulic conductivity field may lead to the formation of preferential channels (or high conductivity channels) in which the solute flows. Given a realization of the hydraulic conductivity field, it is possible to estimate the location of preferential channels using a graph-theory based method. The minimum hydraulic resistance (MHR) and least resistance path (LRP) are efficiently computed, so that these metrics can be effectively employed to assess the uncertainty of preferential flows using computationally intensive stochastic methods, such as Monte-Carlo simulations. For example, these metrics can be used for site characterization, choosing locations where to sample the hydraulic conductivity in order to reduce the uncertainty of high conductivity channels. As a consequence, our preliminary studies displayed more than 40% reduction on first arrival time uncertainty, when compared to a regular grid sampling protocol with the same number of sampling locations. The iterative sampling strategy can be reproduced using LazyMole, an open-source tool implementing the algorithms to compute the minimum hydraulic resistance and least resistance path for a given hydraulic conductivity field.

Iterative Strategy

Let S and T be two set of points (e.g., a point, surface, or volume) representing the starting points and target points respectively. We define the MHR between S and T as:

$$\mathrm{R_S(T)} = \min_{\Gamma \in \mathrm{P_S^T}} \int_\Gamma \frac{1}{\mathrm{K}} \mathrm{d}\gamma$$

where $\mathrm{P_S}^\mathrm{T}$ are all the possible paths connecting one point of S to one point of T. The path that minimizes the hydraulic resistance between S and T is the LRP. For a given K field, we follow an iterative sampling strategy to identify the LRP and its uncertainty:

I. Select the initial $\mathbf{x}^{(j)} = (x_1^{(j)}, x_2^{(j)}, x_3^{(j)})$ sampling locations where $j=1,\dots,N_0$ and N_0 is the initial number of measurements.

II. In each new location $\mathbf{x}^{(j)}$, sample the hydraulic log-conductivity, and create a new measurement data vector:
$$\boldsymbol{\theta}^* = (Y(\mathbf{x}^{(1)}), Y(\mathbf{x}^{(2)}), Y(\mathbf{x}^{(3)}), \dots)$$

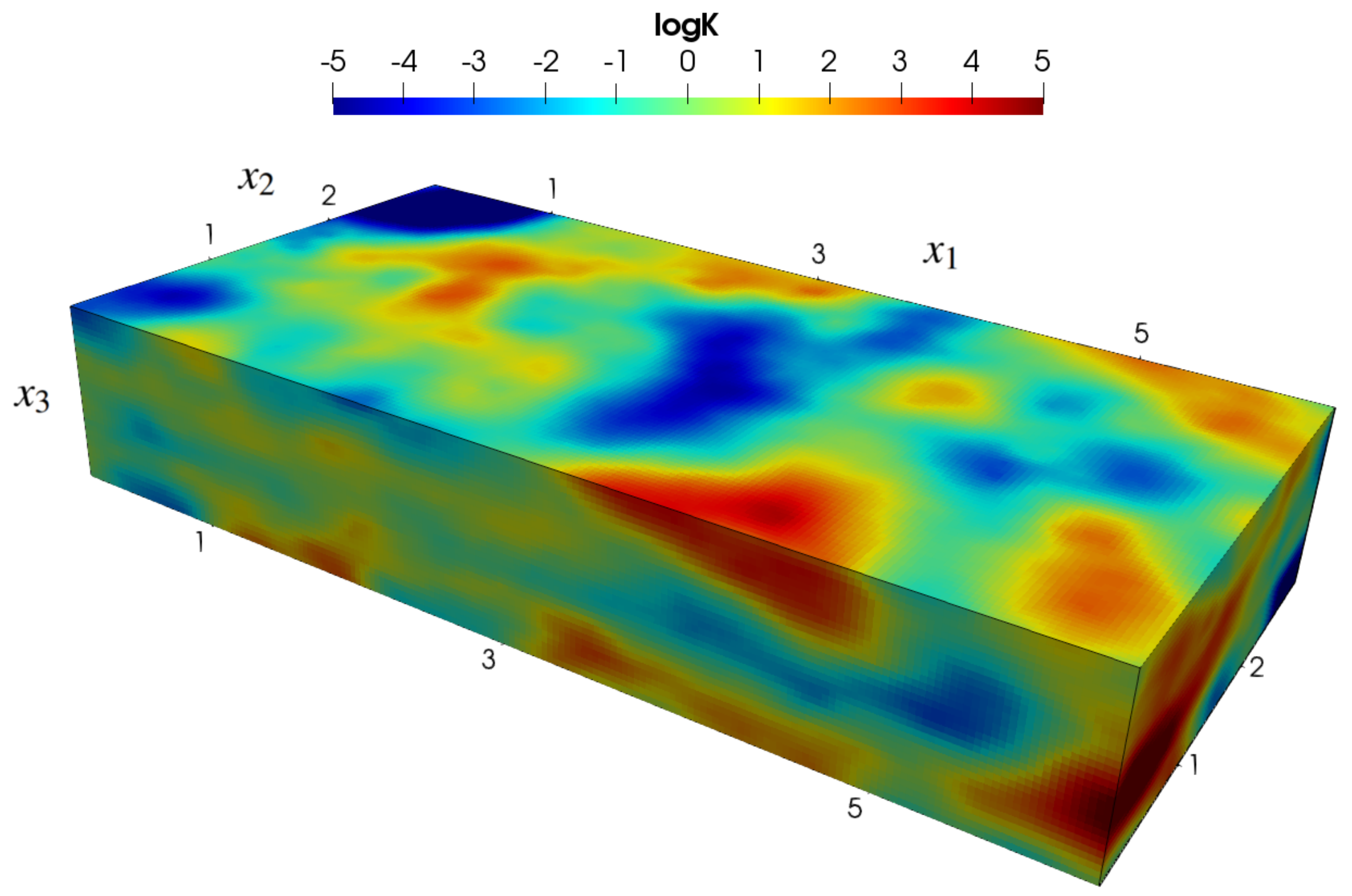
III. Using the new measurement data $\boldsymbol{\theta}^*$ together with previously sampled data, generate N_f conditional realizations of the K-field.

IV. For each realization, employ the graph theory algorithm to compute the LRP. From all these realizations, compute the probability map of the LRP.

V. Select N_m new $x^{(j)}$ locations using the information on the uncertainty of the LRP, and restart from Step II.

Experiment Setup

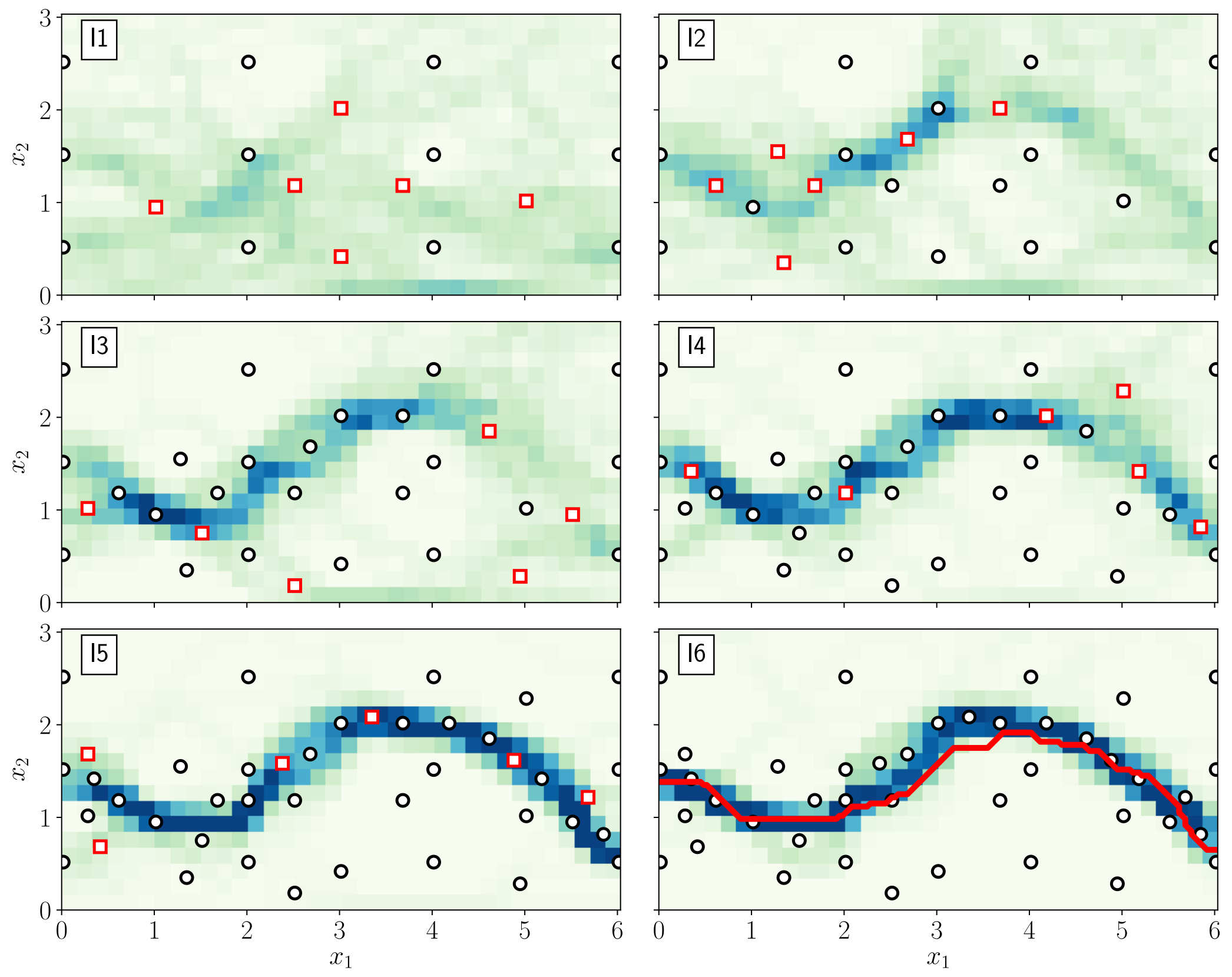
A 3D random field is generated, representing a synthetic true field (right figure). Emulating real site explorations, we assume that the conductivity values are initially unknown. We use the iterative strategy to find the LRP in two cases: in Scenario I, we search for the LRP along the x_1 direction, and in Scenario II, we search for the LRP between two injection/production wells. Using the conductivity extracted at the 42 horizontal sampling locations indicated by the iterative strategy, we run a stochastic flow and transport simulation. Finally, we compare the uncertainty on first time arrival with a regular sampling strategy, where the horizontal locations are located on a regular 7x6 grid.

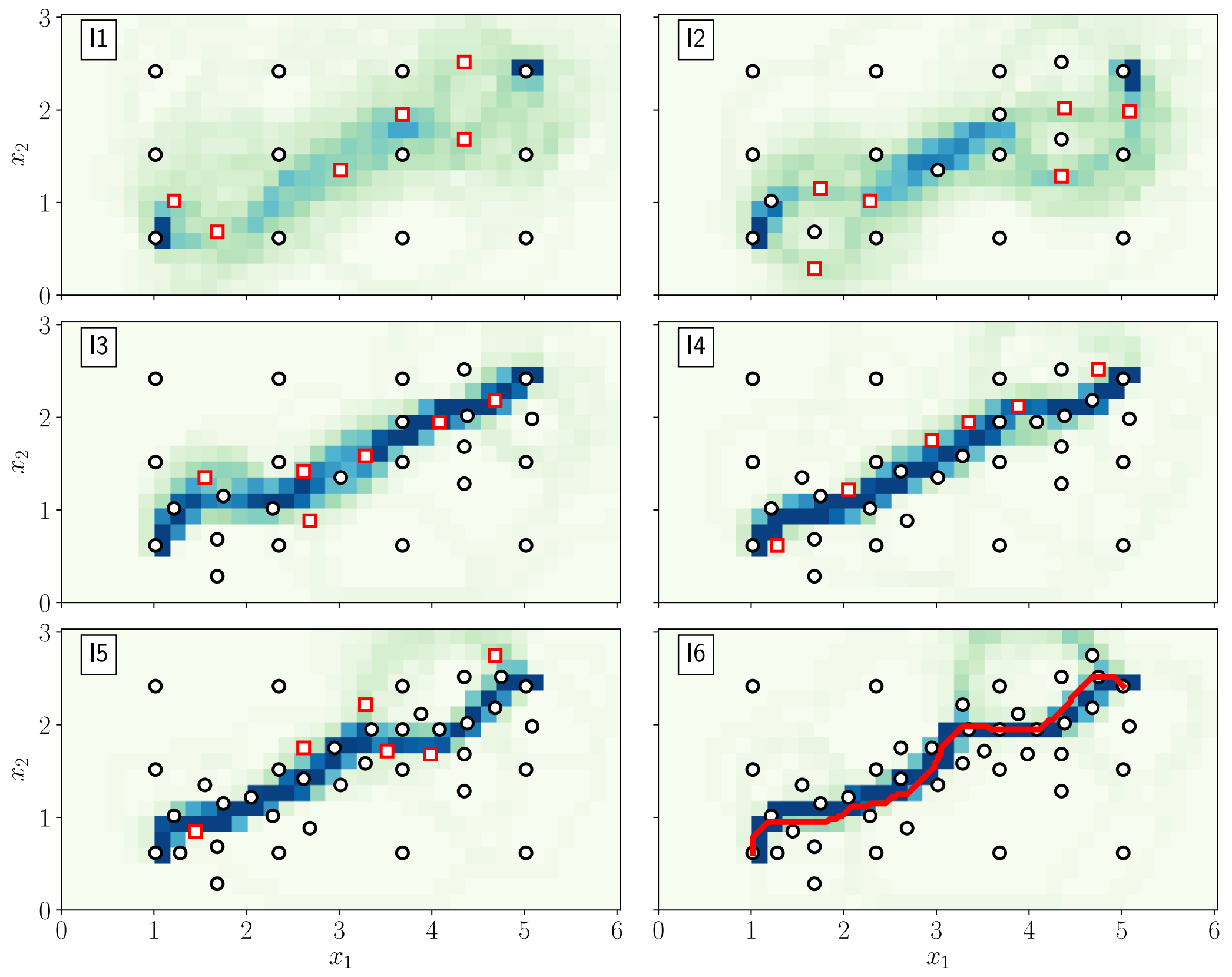


Scenario I

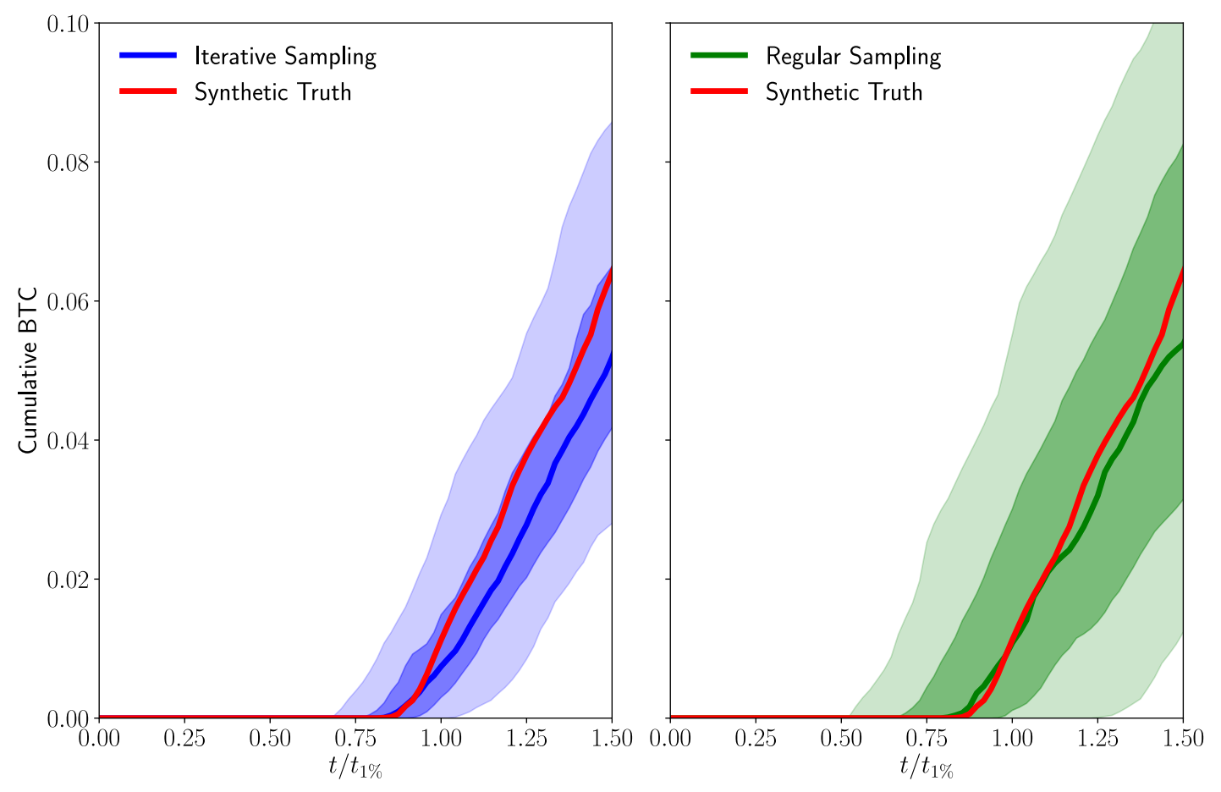
Scenario II

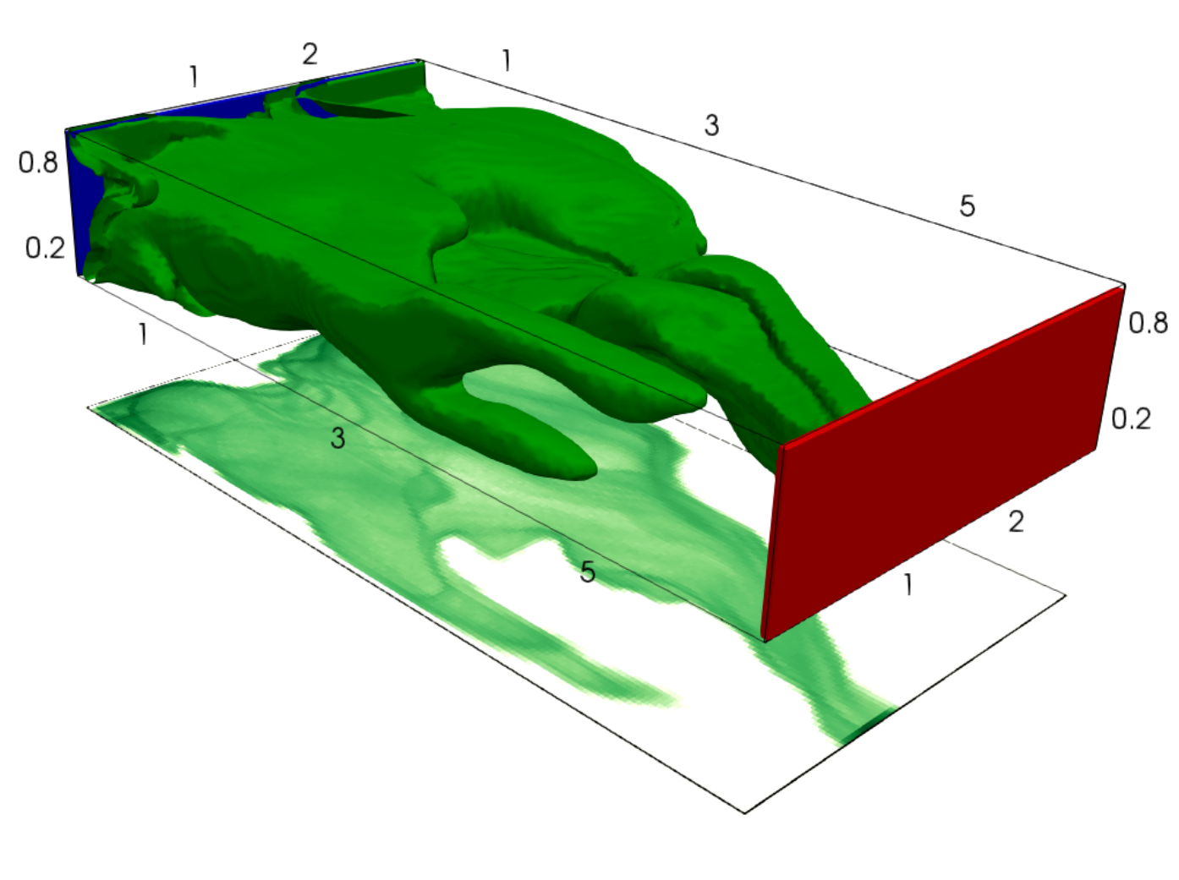
The sampling campaign is divided into six iterations. After each iteration, we use the new available samples to update the LRP probability map. The new sampling locations (red squares) are selected in areas with high LRP probability.

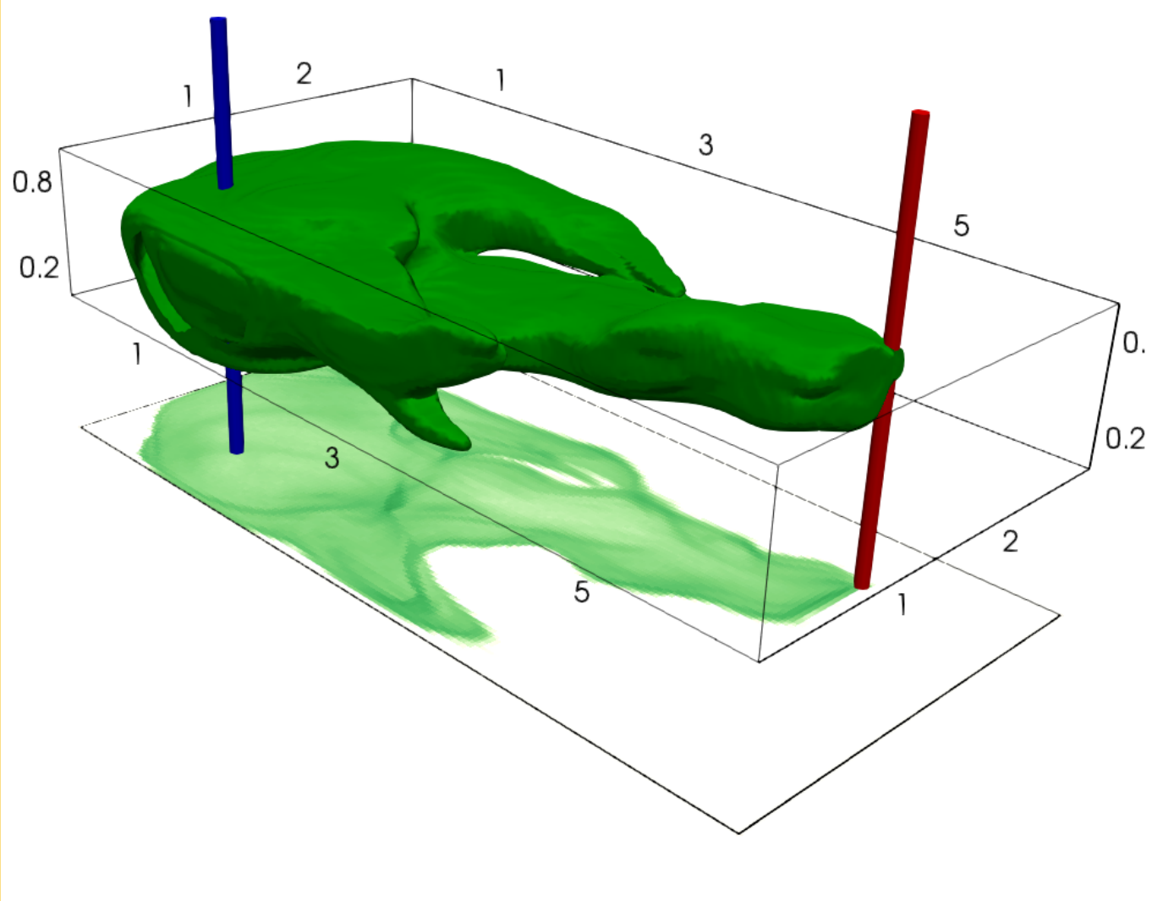


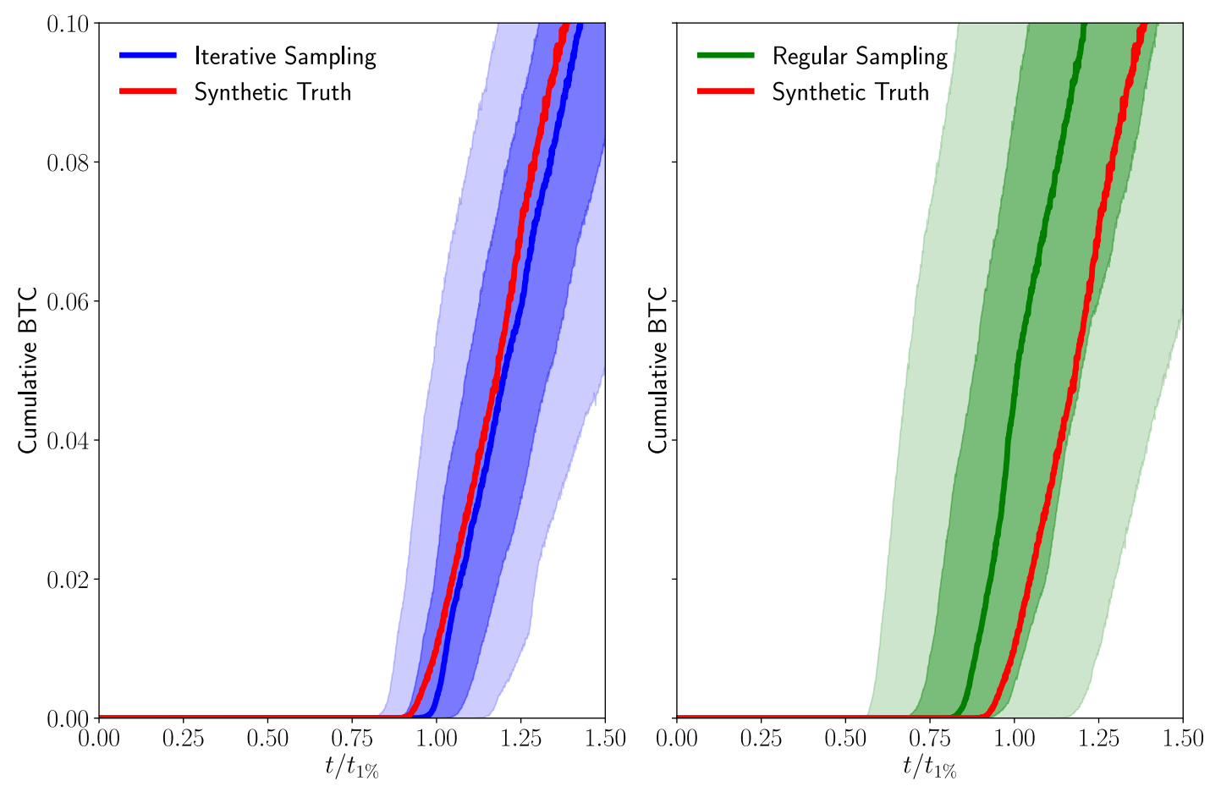


The red line in the last iteration is the true LRP. Using the iterative strategy, we were able to correctly estimate the LRP location after only six iterations. Moreover, since the LRP is linked to the front of the plume trajectory, the uncertainty on first time arrival is reduced when compared to a regular sampling strategy ($t_{1\%}$ std-dev decreased by 47% in Scenario I and 42% in Scenario II).









Lazy Mole

The iterative sampling strategy is just an example of how MHR and LRP can be used in practical scenarios. To simplify future applications, we released LazyMole, a fast implementation of the graph theory algorithm used to compute MHR and LRP in our previous studies. The executable can be downloaded from GitHub and no programming experience is needed for its usage.

Find LazyMole on GitHub:
https://github.com/GerryR/lazymole

References

[1] *Minimum Hydraulic Resistance Uncertainty and the Development of a Connectivity-Based Iterative Sampling Strategy. Rizzo, C. B., & de Barros, F. P. J. (2019). Water Resources Research 55(7), 5593-5611.*

[2] *PAR^2: Parallel Random Walk Particle Tracking Method for Solute Transport in Porous Media. Rizzo, C. B., Nakano, A., & de Barros, F. P. J. (2019). Computer Physics Communications 239, 265-271.*

[3] *Minimum Hydraulic Resistance and Least Resistance Path in Heterogeneous Porous Media. Rizzo, C. B., & de Barros, F. P. J. (2017). Water Resources Research 53 (10), 8596-8613.*

Find PAR^2 on GitHub:
https://github.com/GerryR/par2