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Sequential parameter optimisation with nested particle filters for geologically-consistent identification of subsurface connectivity patterns

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The increasing availability of wireless sensor networks encourages the development of self-optimising groundwater models. Based on a sequential Bayesian framework, such approaches may not only assimilate data to correct their own predictive shortcomings, but also optimise model parameters.
In hydrogeology, this optimization is particularly challenging: numerical models generally involve vast numbers of unknown variables, while seeking compliance with a prescribed geological patterns limits the realm of viable solutions. As a consequence, the resulting probability distribution is both high-dimensional and complex, precluding an analytic solution. Instead, it is common practice to employ ensemble-based approaches. The Ensemble Kalman Filter (EnKF) has proven relatively robust in high-dimensional problems, but its simplifying assumptions are ill-suited for the pursuit of complex and non-Gaussian geological patterns. Particle filters could support the necessary complexity, but are generally disregarded in high-dimensional systems due to their intrinsic 'curse of dimensionality'.
However, a self-imposed restriction to a subset of parameter space – for example the subset corresponding to all parameter fields featuring the desired geology – can reduce the effective dimensionality substantially. Such an approach may render a particle filter implementation viable, but requires a way to draw random samples from (and efficiently navigate within) the chosen subset. This may be achieved through multiple-point statistics (MPS), a versatile tool capable of generating random realizations of parameter fields based on a training image.
Here, we present an implementation of a nested particle filter for sequential data assimilation and parameter optimization, using MPS to ensure conformance with a prescribed geology during optimization. We demonstrate the algorithm in an experimental site near Settolo (Italy), characterized by a complex hydrogeological connectivity pattern due to the presence of paleo-riverbeds.