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Geostatistical Inverse Modeling: Success Stories and Remaining Challenges

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In geostatistical inverse modeling, we estimate spatially and/or temporally distributed parameter fields without enforcing a particular structure of the solution. Discretizing a multi-dimensional field and attributing a single parameter (set) to each element or grid cell, we have to determine tens of thousands to millions of parameters from the most hundreds of measurements of dependent quantities. This ill-posed problem is regularized by assuming that the parameter field is auto-correlated in space or time. In this framework, inverse modeling becomes a Bayesian inference problem. Provided that enough independent measurements exist, it is possible to infer the geostatistical parameters (variance and correlation lengths) from the data as well.

In the determination of saturated-zone hydraulic parameters from hydraulic measurements, both flow and transport related, we are now able to estimate about one million parameters of a 3-D domain and its conditional uncertainty on a standard PC within two days. This progress has been made possible by: (1) efficient solvers in the forward problem, (2) adjoint-state methods to compute sensitivities, (3) exploitation of matrix identities, (4) use of spectral methods in the computation of large matrix-matrix products, and (5) stabilization techniques in the inversion procedure. Transient data may be characterized by their temporal moments for which generating partial differential equations can be formulated. The latter not only reduces the computational effort, but also leads to better posed problems.

Despite these achievements, the hydrogeological inverse problem remains challenging in practical applications. (1) Steady-state concentration data are difficult to account for. The major information often reduces to whether a point is within or outside of the plume. Such pseudo-binary information is not well suited for gradient-based inversion techniques. (2) In order to identify the spatial structure of the fields, about one measurement per correlation length is required, implying tremendeous costs, when only traditional hydraulic measurements are considered. The proper integration of geophysical surveying data into groundwater inverse modelling is still in its infancy. (3) In engineering practice, the uncertainty of the hydraulic parameters themselves is not of primary interest. The question is how this uncertainty affects the uncertainty in predicting hydraulic performance. For the latter, efficient uncertainty propagation techniques need to be explored.