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Geostatistical Inversion of Coupled Processes in Heterogeneous Porous Media

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The quasi-linear geostatistical approach is an inversion scheme that can be used to estimate the spatial distribution of a heterogeneous hydraulic conductivity field. The estimated parameter field is considered to be a random variable that varies continuously in space, meets the measurements of dependent quantities (such as the hydraulic head, the concentration of a transported solute or its arrival time) and shows the required spatial correlation (described by certain variogram models). This is a method of conditioning a parameter field to observations. Upon discretization, this results in as many parameters as elements of the computational grid. For a full three dimensional representation of the heterogeneous subsurface it is hardly sufficient to work with resolutions (up to one million parameters) of the model domain that can be achieved on a serial computer.
The software framework DUNE ("Distributed and Unified Numerics Environment") provides a parallel grid interface, parallel linear solvers and a module that greatly facilitates the implementation of partial differential equations on parallel computer architectures. The forward problems to be solved within the inversion procedure consists of the elliptic steady-state groundwater flow equation and the formally elliptic but nearly hyperbolic steady-state advection-dominated solute transport equation in a heterogeneous porous medium. Both equations are discretized by Finite Element Methods (FEM) using fully scalable domain decomposition techniques. Whereas standard conforming FEM is sufficient for the flow equation (even for a strongly varying scalar conductivity field), for the advection dominated transport equation, which rises well known numerical difficulties at sharp fronts or boundary layers, we use the streamline diffusion approach. The arising linear systems are solved using efficient iterative solvers with an AMG (algebraic multigrid) pre-conditioner.
During each iteration step of the inversion scheme one needs to solve a multitude of forward problems in combination with different source terms and boundary conditions in order to calculate the sensitivities of each measurement and the related cross-covariance matrix of the unknown parameters and the observations. As an example, on a parallel computer (AMD Opteron 6000 Series), the chosen implementation solves a forward problem at a resolution of 5,4 million parameters on 32 processors in less than 90 seconds. In contrast, the very same calculation on the same machine using only one processor takes more than 15 minutes. This enhancement in computational speed will enable us to simulate practical problems at even higher resolutions within an acceptable time period.