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Joint data assimilation and parameter calibration in real-time groundwater modelling using nested particle filters

Maximilian Ramgraber (1,2) and Mario Schirmer (1,2)

(1) Department of Water Resources and Drinking Water, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Switzerland, (2) Centre d'hydrogéologie et de géothermie (CHYM), University of Neuchâtel, Switzerland

The surge in data availability sparked by wireless sensor technologies harbours great potential to investigate environmental systems in real time. This development paved the way for autonomous data interpretation algorithms, often using numerical models to predict future trends based on measured data. This data assimilation is typically used to correct the model drift, a result of the model's imperfection. More complex algorithms may not only assimilate data, but also calibrate the underlying model parameters in order to reduce future model drift. In hydrogeology, the most prominent example of these techniques is the ensemble Kalman filter, a highly efficient tool for data assimilation and real-time calibration as long as all probability density functions (pdfs) are Gaussian and the model dynamics are linear. However, these assumptions are restrictive and rarely met in reality. Thus, significant effort has been devoted to the development of variations capable of circumventing the necessary assumptions to some degree.
In the broader statistical context, however, there exists another promising technique in form of the particle filter. This algorithm represents the underlying analytic pdf by an ensemble of discrete Monte Carlo samples thereof (the eponymous particles). In principle, this filter places no restriction on the structure of the pdf or the model dynamics, but its flexibility comes at the price of the so-called curse of dimensionality: the amount of particles required to adequately represent the pdf grows exponentially with the number of model variables, rendering the basic particle filter computationally infeasible for conventional groundwater modelling exercises. Recent advances in stochastics, however, have yielded promising tools to navigate even extremely high-dimensional parameter space with only few particles. Though some of the error and uncertainty information of the analytic solution is inevitably lost to the curse of dimensionality, the particle filter offers a greater degree of freedom for the exploration of parameter space. This is of particular interest in parameter calibration, as the regions of parameter space representing realistic geology rarely coincide with the modes of the analytic pdfs employed in the ensemble Kalman filter.
Here, we present our recent developments for real-time data assimilation and parameter calibration based on nested particle filters. The freedom of choice of the calibration pattern, and the resulting ability of the algorithm to generate highly complex subsurface parameter fields, is demonstrated using several generated synthetic MODFLOW examples.