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Can normal-score data transformations improve the Ensemble Kalman Filter? Application and test on a hydraulic tomography example

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Heterogeneity of hydrogeological parameters introduces uncertainty into predictions of groundwater flow and contaminant transport processes. Prediction uncertainty can be reduced by conditioning spatially distributed parameter fields to field measurements. In this work, we use the Ensemble Kalman Filter (EnKF) in order to condition random log-conductivity fields on available measurement data and quantify the remaining uncertainty of model predictions.

The main drawback of EnKFs is their optimality in the sense of Bayesian updating only if all involved variables (parameters and data) are multivariate Gaussian. This is a major limitation when applying EnKFs to subsurface parameter estimation, since flow and transport variables generally do not show multivariate Gaussian dependence on the parameter log-conductivity and among each other, even if log-conductivity is assumed to be multi-Gaussian.

To mitigate the effects of non-Gaussianity on the performance of the EnKF, we propose non-linear, monotonous transformations that render arbitrary marginal distributions of state variables univariate Gaussian. We show that this transformation (Gaussian anamorphosis, GA) leads to an implicit pseudo-linearization of the dependence of the state variable on the parameter field, which can be exploited more efficiently by the filter. The expected usefulness of GA can be evaluated beforehand by applying copula-based multivariate analysis tools. The transformation is followed by the classical updating scheme of the EnKF, thus we denote this procedure as tEnKF.

The performance of the tEnKF is illustrated by an application to parameter estimation from synthetic 3-D and 2-D hydraulic tomography data in multi-Gaussian log-conductivity fields. Additionally, we compare the performance of the tEnKF with a reference solution obtained with a brute-force statistical filter for Bayesian updating. Comparing to the reference solution, we can assess the accuracy of both prediction quality and estimated prediction uncertainty. We prove the statistical significance of our results by analyzing 200 randomized 2-D test cases.

Our results show that the linearized dependence of the transformed drawdown data on log-conductivity enhances the processing quality of the available information and this increases the accuracy of parameter identification and flow and transport prognosis. The tEnKF outperforms the traditional EnKF with regard to prediction quality; also the deviation from the prediction variance of the bootstrap filter is significantly reduced.

Combining EnKFs with GA is found to be a computationally efficient tool for nonlinear inversion of measurement data with improved accuracy. The tEnKF is an attractive alternative to existing linearization-free methods such as particle filters that are computationally extremely demanding and therefore limited in their applicability to high-dimensional problems in subsurface hydrology.