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Coupling Ensemble Kalman filter and groundwater flow moment equations for real time data assimilation

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We consider data assimilation through ensemble Kalman filter (EnKF) in the context of groundwater flow through complex geologic media. EnKF enables one to efficiently assimilate diverse data types to characterize earth system models. The approach allows real-time Bayesian updating of system states and parameters as new data are collected. Modeling hydraulic conductivity as a correlated random field conditioned on measured conductivity and/or hydraulic head values renders the corresponding (conditional) groundwater flow equations stochastic. Solving these equations and coupling them with EnKF is typically performed within a numerical Monte Carlo (MC) simulation framework. We circumvent the need for MC through a direct solution of approximate nonlocal (integrodifferential) moment equations (MEs) that govern the space-time evolution of conditional ensemble means (statistical expectations) and covariances of hydraulic heads and fluxes. Embedding the solution of MEs in EnKF provides sequential updates of conductivity and head estimates throughout the space-time domain of interest. This is well suited for cases where real-time measurements can be used immediately to obtain a constantly up-to-date estimate of the aquifer parameters and avoids the need of assimilating all the available data in batch, where the process has to be repeated for all (previous and recent) data when new measurements become available. The methodology is illustrated through a hypothetical two-dimensional example in which a well pumps water from a randomly heterogeneous aquifer of finite extent. We analyze different scenarios, investigating the impact on the parameters estimates of (a) the number of head measurements assimilated, (b) the error variance associated with log conductivity measurements and (c) the initial hydraulic head field. We demonstrate the computational feasibility and accuracy of our methodology and show that hydraulic conductivity estimates are more sensitive to early than to later head values and improve with increasing assimilation frequency at early time. Increasing the variance of log hydraulic conductivity measurement errors by one order of magnitude brought about only a minor deterioration in the quality of corresponding parameter estimates. We test the influence of variogram model and parameters adopted to obtain the initial distributions of log hydraulic conductivity (Y) mean and covariance on the resulting estimates of (a) hydraulic conductivity and (b) head. Our results show that assuming initial variogram sill and integral scale values different from the true ones has (in general) no adverse effect on the final estimate of Y. In contrast, adopting an incorrect variogram model caused the quality of the parameter estimates to deteriorate during the assimilation of head measurements.