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Multi-criteria optimization of a regional spatially-distributed subsurface water flow model

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Abstract

This paper presents the multi-criteria calibration of a regional distributed subsurface water flow model for a 1400 km^2 irrigated agricultural area in the western San Joaquin Valley of California. Two global optimization algorithms were used to identify model parameters using data on spatially distributed local water table depth measurements, district-average groundwater pumping and district-average subsurface drainage data. Model parameters that were subjected to calibration included irrigation efficiency, effective drain depth and conductance, crop evapotranspiration correction coefficient, saturated hydraulic conductivity and specific yield values of coarse and fine fractions, and saturated hydraulic conductivity values defining water fluxes across domain boundaries. Using the single-objective function approach, the three measurement types were weighted into a single-objective function for global optimization purposes. Additionally, a three-objective multi-criteria optimization problem was formulated in which no prior weighting of the individual objectives was specified. The single-objective optimization approach resulted in identifiable parameters with relatively small uncertainties, however, most likely values for various optimized parameter approached the outer bounds of their physical-realistic ranges. The normalized weighting of the single-objective function approach emphasized the pumping and drainage data more than the water table depth data. In the multi-objective approach, the objective function of each measurement type was treated independently, so that no subjective preferences were assigned a priori. Within a single optimization run, a Pareto set of solutions was generated, which included the optimal results for each end-member of each of the three objective functions. The results showed a moderate trade-off between pumping and water table predictions, and a slight independence of drainage predictions from the other two measurements. The estimated Pareto set exhibited large parameter uncertainty, indicating possible model structural inadequacies. We further show that the magnitude of prediction uncertainties associated with the Pareto parameter uncertainty is large for making water table predictions, but much smaller for drainage and pumping predictions. Trade-offs between fitting shallow and deep water tables were revealed by considering additional performance criteria for model evaluation, namely BIAS

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and RMSE values for six water table depth groups. These results point to possible model improvements by spatially distributing some of the model parameters.

Keywords: Vadose zone hydrology; Salinity; Drainage; Irrigation efficiency; Measurement error

1. Introduction

Two fundamental problems complicate large-scale (field to regional) modeling of variably-saturated subsurface flow and transport. First, no fundamental 'laws' are available that describe flow and transport at the field or regional scale. Although Darcy's law, the Richards equation (RE) and the advection–dispersion equation (ADE) are valid at the local scale, their application at the field-scale is questionable, for example, in the presence of preferential flow and transport (Šimůnek et al., 2003). Second, parameterization of large-scale models is hampered by the tremendous spatial heterogeneity of the subsurface, as well as the spatial and temporal variations in boundary conditions. Consequently, methodologies are needed that quantify the propagation of model structure and model input uncertainties in model output. Essentially, two broad approaches may be distinguished to achieve this.

The first approach consists of upscaling the small-scale physics, as represented by the RE and ADE, to the larger scale of interest using statistical averaging procedures. Model parameters and boundary and initial conditions are treated as stochastic variables with prescribed probability density functions (pdf's), which are estimated from a large number of local-scale measurements. The propagation of parameter uncertainty in the simulation results is accomplished by Monte Carlo (MC) analysis by solving the large-scale hydrological model for many realizations with each realization generated from the pdf's of parameter and boundary condition values. An example of this approach is the GLUE methodology of Beven and Freer (2001). Their methodology recognizes that often many parameter sets may describe the available data, resulting in equifinality of the parameters (Beven, 1993). Although MC analysis is conceptually straightforward, it can become computationally very intensive. Stochastic methods based on first-order perturbation (Zhang, 2002) and cumulant expansion (Wood and Kavvas, 1999) approximations have been developed that achieve similar upscaling results as MC analysis, but at a much lower computational costs. Though, the problems of estimating the parameter pdf's from local-scale measurements still remains.

The second approach to large-scale modeling is to directly apply the hydrologic model at the scale of interest using single-valued effective parameters. These effective parameters are defined such that the model results using the uniform parameter field and the heterogeneous parameter field are identical (Blöschl and Sivapalan, 1995). Effective parameters are usually estimated from inverse modeling, whereby the model parameters are adjusted by minimizing differences between observed and predicted output variables (residuals). Due to the inherent nonlinear nature of variably-saturated flow in porous media, however, no effective parameters exist in general that are a function of the porous media only (Beven, 2001). Nevertheless, effective parameter values may still produce very good results for specific situations (e.g. Wildenschild and Jensen, 1999) or for a range of flow conditions. Whereas traditional inverse modeling has focused on estimating the optimal parameter sets, recent studies have developed algorithms that also provide estimates of parameter and model structure uncertainties, especially with applications in watershed scale rainfall-runoff modeling (Gupta et al., 1998).

An example of this approach is the Shuffled Complex Evolution Metropolis global optimization algorithm, SCEM-UA, recently developed at the University of Amsterdam (Vrugt et al., 2003a). The SCEM-UA algorithm is a general purpose global optimization algorithm that provides an efficient estimate of the most likely parameter set and its underlying posterior probability distribution, defining parameter uncertainty within a single optimization run. The algorithm is an extension of the SCE-UA population evolution method developed by Duan et al. (1992). In this single-objective function approach,