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Assessing the effects of spatial discretization on large-scale flow model performance and prediction uncertainty

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SUMMARY

Large-scale physically-based and spatially-distributed models (>100 km^2) constitute useful tools for water management since they take explicitly into account the heterogeneity and the physical processes occurring in the subsurface for predicting the evolution of discharge and hydraulic heads for several predictive scenarios. However, such models are characterized by lengthy execution times. Therefore, modelers often coarsen spatial discretization of large-scale physically-based and spatially-distributed models for reducing the number of unknowns and the execution times. This study investigates the influence of such a coarsening of model grid on model performance and prediction uncertainty. The improvement of model performance obtained with an automatic calibration process is also investigated. The results obtained show that coarsening spatial discretization mainly influences the simulation of discharge due to a poor representation of surface water network and a smoothing of surface slopes that prevents from simulating properly surface water-groundwater interactions and runoff processes. Parameter sensitivities are not significantly influenced by grid coarsening and calibration can compensate, to some extent, for model errors induced by grid coarsening. The results also show that coarsening spatial discretization mainly influences the uncertainty on discharge predictions. However, model prediction uncertainties on discharge only increase significantly for very coarse spatial discretizations.

1. Introduction

Large-scale physically-based and spatially-distributed models (>100 km^2) are increasingly used in water management for their unique capacity of gathering every piece of information obtained on a hydrological system to simulate its quantitative and qualitative evolution for several predictive scenarios. These models are intended to provide predictions on both the integrated response (discharge) and the distributed response (hydraulic heads) of the catchment.

Physically-based and spatially-distributed models take explicitly into account the heterogeneity and the physical processes occurring in the surface and the subsurface. Therefore, they are expected to provide predictions with higher level of confidence than black-box models (e.g. Ebel and Loague, 2006; Li et al.; 2008; Goderniaux et al., 2009). Additionally, they are also used for improving the understanding of the physics of hydrological processes (e.g. Frei et al., 2009; Meyerhoff and Maxwell, 2011; Irvine et al., 2012). However, physically-based and spatially-distributed models are characterized by lengthy execution times, especially for integrated surface and subsurface transient flow simulations at large-scale. Consequently, choices and simplifications are made for obtaining tractable execution times. The most common simplification consists in coarsening the spatial discretization for reducing the number of unknowns of the problem and the execution time. The effects of such a coarsening of model grid are worthy being studied since they can limit the accuracy of model results and increase model prediction uncertainties.

A series of studies have already been performed on the effects of spatial discretization on physically-based and spatially-distributed model performance. Refsgaard (1997) calibrated and validated a 3D model with a 500 m grid i.e. with a constant element size of 500 m (no refinement) for the Karup catchment in Denmark (440 km^2). Three other models with 1000 m, 2000 m, and 4000 m grids were then generated using the same parameter values than those obtained by calibration for the initial model (no recalibration, no upscaling). The models were compared in terms of both discharge and hydraulic heads. The results from this study indicated that runoff was poorly simulated by the models coarser than 1000 m due to a poor representation of the surface water network which prevents from simulating properly surface water–groundwater interaction. However, the author suggested that a significant recalibration of models with a coarse grid could improve their performance. This is supported by the study of Vázquez et al. (2002). They calibrated a 3D model with a 600 m grid i.e. with a constant

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element size of 600 m (no refinement) for the Gete catchment in Belgium (586 km^2). They also generated a second model with a finer grid (300 m) and a third model with a coarser grid (1200 m) using the same parameters than those obtained by calibration for the initial model (no recalibration, no upscaling). These 300 m and 1200 m grid models were then recalibrated individually using a trial-and-error calibration process. As for the study of Refsgaard (1997), the models were compared in terms of both discharge and hydraulic heads. Although, in general, model results remained worse for the 1200 m grid model than for the 300 m and the 600 m grid models, this study proved that a recalibration is required for obtaining effective parameter values and improving model performance when the grid resolution is changed. Sciuto and Diekkrüger (2010) developed a 3D model with a 25 m grid refined in the river zone for the Wüstebach catchment in Germany (0.27 km^2). They also developed a second model with a 100 m grid using the mean averaging method for upscaling parameter values and a third model with the same model grid than the initial model and the same soil configuration than the second model. They compared the results obtained in terms of discharge and spatial pattern of soil moisture. The influence of upscaling was investigated by comparing the first and the second models and the effects of spatial discretization were studied by comparing the second and the third models. They showed that a coarse grid leads to higher discharge and less actual evapotranspiration than a fine grid due to the smoothing of soil surface which induces a loss of topographic information. They also showed that the upscaling technique they selected was efficient for simulating discharge and spatial pattern of soil moisture. They suggested that the nonlinear relationship between soil moisture and evapotranspiration could explain the deterioration of model results when the grid is coarsened without parameter upscaling. However, none of their models were calibrated. Downer and Ogden (2004) performed a spatial convergence study for the Hortonian Godwin Creek Experimental catchment (21.2 km^2) and the non-Hortonian Muddy Brook catchment (3.64 km^2) in the US. They developed a series of 2D vadose zone model of increasing vertical cell size for each of these catchments. The models were calibrated with an automated calibration process using the shuffled complex evolution method. The calibrated models were compared in terms of infiltration, runoff, and evapotranspiration fluxes to evaluate the appropriate vertical discretization required for accurately solving the Richards' equation. The results from this study showed that small vertical cell size (on the order of centimetres) is required in the unsaturated zone to accurately simulate hydrological fluxes. However, providing that effective parameters obtained by calibration are used, the results of this study also shows that it is possible to slightly increase vertical cell size in the unsaturated zone without significantly deteriorating the simulation of hydrological fluxes. These results about the vertical cell size required in the unsaturated zone for accurately solving the Richards' equation are consistent with those obtained by Vogel and Ippisch (2008).

All these studies provide valuable information on the effects of spatial discretization on model performance. However, most of them neglect the calibration or use a simple trial-and-error calibration process which is, by nature, subjective (Poeter and Hill, 1997). An automatic calibration process is essential for properly evaluating the capacity of calibration to improve the performance of models with a coarse grid. The present study includes such an automatic calibration process. Additionally, the present study includes for the first time an evaluation of the influence of spatial discretization on model prediction uncertainties by comparing the linear confidence intervals on predictions calculated for each model.

The objective of the present study is to evaluate the effects of horizontal spatial discretization on discharge and hydraulic heads simulated by a large-scale physically-based and spatially-distributed model. This evaluation is performed using graphs of model fit and performance criteria. The improvement of model performance obtained with an automatic calibration process is also investigated and linear confidence intervals on predictions are calculated for each model. The results of this study can help modelers defining the horizontal spatial discretization for their models by better perceiving its influence on model performance and model prediction uncertainties.

2. Methodology

The effects of horizontal spatial discretization on model performance and model prediction uncertainties are investigated using a synthetic catchment. The hydrological processes in this synthetic catchment are simulated with HydroGeoSphere (Therrien et al., 2012). HydroGeoSphere is a fully-integrated physically-based hydrological model capable of solving very complex problems such as integrated flow in large-scale catchments (for example, see Goderniaux et al., 2009, 2011). Two-dimensional surface water flow is represented using the two-dimensional diffusion-wave approximation to the Saint-Venant equation. Three-dimensional subsurface water flow in both the saturated and the vadose zones is represented using the Richards' equation. The processes of interception and evapotranspiration are modeled following the conceptualization of Kristensen and Jensen (1975). The coupling of the surface to the subsurface is either performed with the common node approach (continuity of hydraulic head between the two domains) or the dual node approach (exchange of water between the two domains via a first-order exchange coefficient). A complete description of HydroGeoSphere is available in Therrien et al. (2012). A short summary is provided in the paper of Li et al. (2008) and in the software spotlight of Brunner and Simmons (2012).

The choice of working with a synthetic catchment instead of a real catchment is motivated by the wish of focusing only on the effects of horizontal spatial discretization on model performance. When working with a synthetic catchment, the model geometry, the parameter values, and the boundary conditions are exactly known. Furthermore, there is no measurement error on the observations produced. Therefore, it is possible to test specific model features such as the influence of grid resolution on discharge and hydraulic head simulation without unintentionally taking into account other sources of errors related to a lack of knowledge of the hydrological system. The concept of synthetic catchment is quite usual in hydrogeology (for example, see Poeter and McKenna, 1995; Hill et al., 1998; Schäfer et al., 2004; Bauer et al., 2006; Beyer et al., 2006). The synthetic catchment generated for this study is complex in that the flow system is fully-integrated and physically-based with consistent physical state parameters. However, the synthetic catchment is simplified with respect to the heterogeneity of land use and geology in reality. Yet, this study focuses on the effects of spatial discretization on model performance and not on the influence of heterogeneity representation. The way grid size influences model results would have been similar for a synthetic catchment with a higher level of heterogeneity, provided that the heterogeneity is correctly represented. Therefore, despite this simplification, the synthetic catchment is judged complex enough to serve the objective of this study.

The methodology involves three main steps:

Step 1 – Generation of the reference model/generation of models with a coarse grid. A 5-year simulation is run with the reference model for producing reference discharge and hydraulic head observations. The reference model is characterized by a fine spatial discretization. The same 5-year simulation is then run with models