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A comparison of two physics-based numerical models for simulating surface water–groundwater interactions

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ABSTRACT

Problems in hydrology and water management that involve both surface water and groundwater are best addressed with simulation models that can represent the interactions between these two flow regimes. In the current generation of coupled models, a variety of approaches is used to resolve surface–subsurface interactions and other key processes such as surface flow propagation. In this study we compare two physics-based numerical models that use a 3D Richards equation representation of subsurface flow. In one model, surface flow is represented by a fully 2D kinematic approximation to the Saint–Venant equations with a sheet flow conceptualization. In the second model, surface routing is performed via a quasi-2D diffusive formulation and surface runoff follows a rill flow conceptualization. The coupling between the land surface and the subsurface is handled via an explicit exchange term resolved by continuity principles in the first model (a fully-coupled approach) and by special treatment of atmospheric boundary conditions in the second (a sequential approach). Despite the significant differences in formulation between the two models, we found them to be in good agreement for the simulation experiments conducted. In these numerical tests, on a sloping plane and a tilted V-catchment, we examined saturation excess and infiltration excess runoff production under homogeneous and heterogeneous conditions, the dynamics of the return flow process, the differences in hydrologic response under rill flow and sheet flow parameterizations, and the effects of factors such as grid discretization, time step size, and slope angle. Low sensitivity to vertical discretization and time step size was found for the two models under saturation excess and homogeneous conditions. Larger sensitivity and differences in response were observed under infiltration excess and heterogeneous conditions, due to the different coupling approaches and spatial discretization schemes used in the two models. For these cases, the sensitivity to vertical and temporal resolution was greatest for processes such as reinfiltration and ponding, although the differences between the hydrographs of the two models decreased as mesh and step size were progressively refined. In return flow behavior, the models are in general agreement, with the largest discrepancies, during the recession phase, attributable to the different parameterizations of diffusion in the surface water propagation schemes. Our results also show that under equivalent parameterizations, the rill and sheet flow conceptualizations used in the two models produce very similar responses in terms of hydrograph shape and flow depth distribution.

1. Introduction

Surface and subsurface waters are not isolated components of the hydrologic cycle, but instead interact in response to topographic, soil, geologic, and climatic factors [8]. The study of these interactions has been addressed at both small (field and hillslope) (e.g. [1,39]) and large (watershed to global) scales (e.g. [23,37]). A number of hydrological models that incorporate some representation of groundwater–surface water interactions have been developed over the past decades, including physically-based, distributed-parameter models. This latter class of models, more rigorous but also more computationally intensive than empirical or semi-empirical approaches, uses the shallow water equations to describe surface flow, i.e., one- or two-dimensional approximations of the Saint–Venant equations for overland and/or channel flow, coupled with a subsurface component that solves the

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three-dimensional equation for variably saturated flow, i.e., Richards' equation (e.g. [41,28,33,18]). A comprehensive description of the types of process representation in distributed models and their inherent assumptions and limitations, together with a discussion of comparison and assessment issues, is provided in Kampf and Burges [19], Clarke [5], Furman [10], Ebel et al. [9], and Maxwell [24].

For physically-based coupled models, which are the focus of this study, various schemes have been proposed for solving the system of surface and subsurface equations and for resolving the interactions across the land surface. The solution approaches can be broadly classified as full coupling, sequential coupling, and loose coupling, whereas the formulations for the exchange fluxes are based on continuity principles, diffusion paradigms, boundary conditions switching, or other schemes. In full coupling (e.g. [41,33,20]), the governing equations are solved simultaneously; in sequential coupling (e.g. [12,28,3]), they are solved separately, with an explicit discretization used for at least one of the equations or with an iterative cycle superposed on the overall system; in loose coupling (e.g. [36,6]), the equations are again solved separately, with the output from one regime (e.g., surface flow) simply passed as input to the other, without iteration or other conditions imposed.

Whereas the accuracy, robustness, and other performance features of surface and subsurface numerical models have been extensively documented (e.g. [35,42] for Saint–Venant approximations; [16,29] for Richards' equation), there have been very few assessments of coupled models based on these equations. The purpose of this study is to provide such an assessment via a comparative analysis of two process-based groundwater–surface water models. One model, ParFlow [20,21], uses a full coupling approach and continuity of pressures and fluxes across the land surface to resolve the surface–subsurface interactions; the other model, CATHY [2,3], is based on sequential coupling with boundary condition switching to partition atmospheric fluxes into infiltration (or exfiltration) and a change in surface water storage. A comparison of these two very different models provides a first opportunity to critically examine some key features of coupled hydrological models. In addition to different schemes for coupling and exchange flux resolution, the two models use different conceptualizations of surface routing: sheet flow representation and a kinematic wave equation in ParFlow; rill flow representation and a diffusion wave equation in CATHY. Although not directly inherent to coupling issues, these additional differences are also worthy of assessment, given the high interest in applying coupled hydrological models at catchment and river basin scales where terrain features (slope, roughness, etc.), and consequently surface flow conditions, can vary greatly. Other differences between the models (e.g., ParFlow uses a finite difference/finite volume discretization whereas CATHY uses finite elements for the subsurface and finite differences for the surface) will also have an effect on the intercomparison tests and will be duly considered.

The intercomparison study is carried out through a series of simple test cases subjected to step functions of rainfall followed by a recession or evaporation period. The test cases involve a sloping plane [11] and a tilted V-catchment [33]. The simulations are designed to clearly expose model differences and similarities under complex and realistic physical conditions. The first tests focus on the different treatments of the exchange fluxes between the subsurface and surface domains and their sensitivity to factors such vertical mesh resolution, time step size, and slope angle. A second set of tests is intended to evaluate the impact of the different conceptualizations for propagation of surface runoff in terms of water depth distribution at the ground surface and timing and shape of the hydrograph.

2. Description of the models

The governing equations for the ParFlow model [20,25] are the three-dimensional (3D) Richards equation for subsurface flow in variably saturated soils and the kinematic wave approximation of the Saint–Venant equation for overland and channel flow:

$$S_s S_w \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = -\nabla \cdot \mathbf{q} + q_s, \tag{1}$$

$$\mathbf{q} = -K_s K_r \nabla(\psi - z), \tag{2}$$

$$\frac{\partial \psi_s}{\partial t} = \nabla \cdot (\psi_s \vec{v}) + q_r(x), \tag{3}$$

$$S_{f,i} = S_{o,i}, \tag{4}$$

where S_s is the specific storage coefficient [1/L], $S_w = S_w(\psi)$ is the relative saturation [–], ψ is the subsurface pressure head [L], t is time [T], ϕ is the porosity [–], ∇ is the gradient operator, q is the Darcy flux [L/T], q_s is a general source/sink term [1/T], K_s is the saturated hydraulic conductivity tensor [L/T], $K_r = K_r(\psi)$ is the relative hydraulic conductivity function [–], z is the vertical coordinate pointing downward [L], ψ_s is the pressure at the ground surface (surface ponding depth) [L], $\vec{v}$ is the depth-averaged velocity vector [L/T], q_r is the rainfall rate [L/T], and $S_{f,i}$ and $S_{o,i}$ are the gravity forcing and friction slope terms, respectively [–], with i indicating the x and y directions.

The governing equations for the CATHY model [2,3] are the 3D Richards equation and the diffusion wave approximation of the Saint–Venant equation:

$$S_s S_w \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = \nabla \cdot [K_s K_r(\psi)(\nabla \psi + \eta_z)] + q_{ss}, \tag{5}$$

$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_s, \tag{6}$$

where $\eta_z = (0,0,1)^T$ (the vertical coordinate is positive upward), q_{ss} represents distributed source (positive) or sink (negative) terms $[L^3/L^3T]$, Q is the discharge along the channel link $[L^3/T]$, c_k is the kinematic wave celerity [L/T], s is the hillslope/channel link coordinate [L], D_h is the hydraulic diffusivity $[L^2/T]$, and q_s is the inflow (positive) or outflow (negative) from the subsurface to the surface $[L^3/LT]$.

2.1. Subsurface flow

The three-dimensional Richards equation is solved in ParFlow using a cell-centered finite difference scheme with harmonic averages of the saturated hydraulic conductivity and a one-point upstream weighting of the relative permeability function. CATHY uses a Galerkin finite element spatial integrator using tetrahedral elements and linear basis function. Both models employ an implicit backward Euler scheme for the discretization in time of Richards' equation. The resulting discrete equation is solved in ParFlow by a Newton–Krylov nonlinear solver [17] and in CATHY by Picard or Newton iteration [34].

2.2. Surface routing

The kinematic wave Eqs. (3) and (4) in ParFlow are discretized in space with an upwind finite volume scheme and in time with an implicit backward Euler method. The surface flow equation is solved by posing two types of boundary conditions: the gradient and critical depth outlet conditions, consisting respectively in a prescribed flux and water depth condition. In CATHY the diffusion wave Eq. (6) is discretized in space and time with a matched artificial dispersivity (MAD) scheme [38].

ParFlow uses a two-dimensional sheet flow conceptualization for surface routing, whereby flow is assumed to be distributed in