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A coupled stream flow and depth-integrated subsurface flow model for catchment hydrology

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SUMMARY

Few hydrological models that couple stream flow and subsurface flow in shallow aquifers are based on a compromise between simple and complex depiction of the system, although this compromise could result in tractable tools for various applications. We present a depth-integrated approach in which flows in the vadose and saturated zones are assumed to be parallel to the bottom of the aquifer and thus are integrated in the direction normal to the bottom of the aquifer. The hydrodynamic parameters are also integrated in this direction, and gravity effects are preserved. Stream flow is handled by a diffusive-wave equation that is calculated over a network of one-dimensional bonds. The first-order coupling between the stream and subsurface flows exchanges water fluxes between the stream network and the subsurface compartment according to the hydraulic head differences between the systems. Three synthetic test cases, one including a comparison with a three-dimensional code, are used to evaluate the general behavior of the coupled model. It is shown that the approach reproduces the main hydrological features at the catchment scale, including the generation of runoff, infiltration–exfiltration into (from) the vadose zone, and smooth transient head variations in the aquifer.

1. Introduction

Stream flow and subsurface flow are linked components of the continental hydrological cycle whose interactions strongly impact the response of hydrologic systems to atmospheric forcing (Winter et al., 1998; Sophocleous, 2002). The interactions between stream and subsurface flows are complex because of the controls exerted by topographic, geologic, and pedologic features (e.g., Anderson and Burt, 1978; Dunne et al., 1991; Torres et al., 1998; Freer et al., 2002; van Meerveld et al., 2007; Penna et al., 2011). These interactions have been investigated through experimental and numerical studies over wide ranges of time and spatial scales and for many hydrological systems (e.g., Harvey and Bencala, 1993; Cloke et al., 2006; Fiori et al., 2007; Storey et al., 2003; Partington et al., 2013). Nonetheless, how the coupling between stream and subsurface flows impacts the hydrodynamics of natural underground reservoirs, runoff and river dynamics is not yet fully understood (e.g. McDonnell et al., 2010). Therefore, it is critical to better understand the interplay between surface and subsurface processes for ongoing hydrologic research and applications to water resources management and water quality (Fleckenstein et al., 2010).

Although the development of new techniques and the reliability of data have improved field studies in recent years, experimental investigations are still insufficient to fully describe the generation of stream flow mechanisms. Integrated hydrologic modeling (with the meaning of including both surface and subsurface compartments in the same modeling tool) is a valuable complement to field and laboratory experiments due to its ability to provide insights into flow and transport mechanisms at different scales (e.g., Goderniaux et al., 2009; Frei et al., 2010; Weill et al., 2013; Hunt et al., 2013). Implementing the interactions between stream and subsurface flows in hydrologic models is often complicated because of the non-linear nature and the different time scales of the mechanisms involved in the flow process (Spanoudaki et al., 2009). Thus, stream and subsurface flows were either oversimplified or loosely coupled (i.e., relying upon a single relationship) in hydrological models until the late 1990s, when the so-called integrated hydrological models were developed. These models were braking from previous approaches in being spatially distributed, in solving the physics of flow–transport processes, and in coupling surface and subsurface compartments of a watershed (Furman, 2008).

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Integrated hydrological models are intended to describe the relationships within the hydrological cycle using mechanisms that are represented in a physically relevant way. For example, the models solve the partial differential equations of mass and momentum conservation to simulate water flow and transport in the different compartments of the hydrologic system, such as the land surface, vadose zone and saturated zone. The equations, their dimensionality and the numerical techniques used to solve the equations result in different types of models (Kampf and Burges, 2007). The most detailed models rely on the solution to the three-dimensional Richard's equation for subsurface flow and on approximations of the Saint Venant equations – a kinematic or a diffusive wave equation – for stream flow (e.g., VanderKwaak, 1999; Panday and Huyakorn, 2004; Camporese et al., 2010). The first tests carried out with these detailed models appear promising (e.g., Ebel et al., 2008; Frei et al., 2010) and demonstrate the utility of these models for improving our understanding of flow and transport processes in hydrologic systems. Despite their appealing characteristics, the application of these detailed models to natural systems faces significant challenges with time and space discretization issues, computational cost, the scarcity of available data for calibration and validation, and parameterization issues (e.g., Ebel and Loague, 2006; Mirus et al., 2011; Sulis et al., 2011). These difficulties raise the question of the optimal complexity of the equations and their dimensionality that are needed for reliable and efficient simulations of hydrological catchments (Gunduz and Aral, 2005).

Few models have been developed between the detailed integrated tools, which require efficient numerical methods and heavy computations, and simple approaches, which cannot describe the key factors of stream flow generation because of oversimplified equations and the incorrect dimensionality of the problem. This paper proposes an alternative modeling approach that couples a one-dimensional diffusive wave equation in a ramified stream network to depict the surface flow with a depth-integrated Richard's equation for the subsurface flow. The relationship between these equations is established via the so-called first-order coupling technique. The depth-integrated subsurface model mimics the lateral transfers that are associated with topographic and pressure head variations in both the vadose and saturated zones without needing a full three-dimensional approach. The principle is to map the effects of topographic slopes onto a discretized two-dimensional layer. At the element level of the discretized domain, the vertical component of water movement is assumed to be significantly smaller than the lateral flow. The components of the gravity acceleration vector may also change from element to element to account for variations in the mean slope between elements. Subsurface flow is represented through the computation of vertically averaged conductivity, storage capacity and water content using the characteristics of both the vadose zone and the aquifer.

The governing equations of the modeling approach are described in Section 2, while the details of the numerical implementation are presented in Appendix A. Section 3 reports on a test of the one-dimensional stream network model alone. Then, stream flow and subsurface flow are coupled and compared with the full three-dimensional approach of the CATHY model (Camporese et al., 2010). Section 4 is dedicated to the application of the reduced model (stream network plus subsurface compartment) over an actual hilly catchment with steep topography. This topography is very demanding in terms of space and time discretization for three-dimensional approaches as that in CATHY (or in other fully-dimensioned approaches). This feature justifies that we do not perform any comparison between models on the hilly catchment. Notably, all the tests are designed as synthetic exercises that reproduce simple to complex watershed geometries and hydrological behaviors.

2. Mathematical model

2.1. Stream flow model

The stream flow model is derived from the simplified form of the Saint Venant equations (e.g., Panday and Huyakorn, 2004) that are written as the one-dimensional propagation of a diffusive wave (Govindaraju and Kavvas, 1990). We assume that a mean water velocity $\mathbf{u}_x$ (LT^{-1}) in the direction x normal to the flow section of the river can be defined. The x direction is not fixed in space and follows the main slope of the river bed. Under these conditions, the mass balance (1a) and momentum conservation (1b) equations can be written as

$$\frac{\partial A}{\partial t} + \nabla_x \cdot (A\mathbf{u}_x) = l'q \tag{1a}$$

$$\frac{\partial \mathbf{u}_x}{\partial t} + \mathbf{u}_x \frac{\partial |\mathbf{u}_x|}{\partial x} + |g|\nabla_x h_r = -|g|(\nabla_x z + \mathbf{s}_f) - \frac{q}{h_r}\mathbf{u}_x \tag{1b}$$

A (L^2) is the area of the water section in the river normal to the x direction, h_r (L) is the water level in the river, l' (L) is the width of the water surface in the river, z (L) is the elevation of the river bottom, q (LT^{-1}) is a source term percolating through the banks and the bottom of the river, $|g|$ (LT^{-2}) is the scalar component of the gravity acceleration, and $\mathbf{s}_f$ (–) is the vector of the frictional slope of the river along the x direction.

Assuming slow variations in the flow regime cancels out the term $d/dt = \partial/\partial t + \mathbf{u}\partial/\partial x$ in (1b). With negligible lateral fluxes q compared with the fluxes along the main direction of the river bed, the momentum Eq. (1b) simplifies into

$$\nabla_x(h_r + z) = -\mathbf{s}_f \tag{2}$$

The friction slope $\mathbf{s}_f$ allows reintroducing the velocity $\mathbf{u}_x$ in (2) by means of the Manning formula

$$\mathbf{u}_x = \frac{R_h^{2/3}}{N_{Man}} \mathbf{s}_f^{1/2} \tag{3}$$

where N_{Man} (L$^{-1/3}$T) is the Manning coefficient, and R_h (L) is the hydraulic radius (see below).

The river cross-section (Fig. 1) is assumed to have a trapezoidal shape that may vary along the river profile. The width of the water surface l' and the water surface area A are therefore determined by the local (in x) values of the water level h_r, the bottom width l of the river and the slope α of the river bank

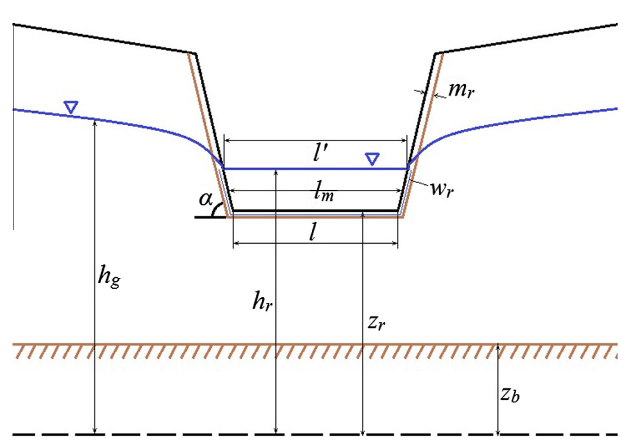

Fig. 1. Stream/ditch geometry and associated parameters; h_r and h_g represent the heads in the river and the aquifer, respectively. z_r is the elevation of the river bottom, z_b is the reference elevation, l' is the width of the water surface, h is the water level, l is the bottom width of the river, α is the slope of the river bank, w_r is the wetted perimeter of the river bed, and m_r is the sediment thickness at the bottom of the river.