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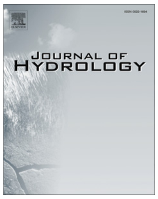

On the implementation of the surface conductance approach using a block-centred surface–subsurface hydrology model

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S U M M A R Y

In physically based catchment hydrology models, dynamic surface–subsurface interactions are often represented using the surface conductance (SC) coupling approach. Guidance on SC parameterisation within block-centred codes is limited, and common practice is to express the SC coefficient as the quotient of the vertical saturated hydraulic conductivity and the half-cell thickness of the uppermost layer. This study evaluates the implementation of the SC approach utilising a popular block-centred, surface–subsurface hydrology model (MODHMS) to simulate one-dimensional infiltration experiments under Hortonian conditions. Results show that defining the SC coefficient based on a half-cell thickness of the uppermost subsurface cell inhibits accurate prediction of infiltration rates (q_e) and the time to initiate surface runoff (t_{ro}) for the adopted rainfall–runoff scenario. Increasing the SC coefficient independently of the grid allows for accurate simulation of q_e, but not t_{ro}. The addition of a thin layer at the surface is shown to improve model accuracy substantially, such that q_e and t_{ro} approach those obtained using an equivalent mesh-centred model (i.e. where the surface and upper subsurface nodes are coincident). Whilst the addition of a single thin layer in block-centred codes allows improved prediction of surface–subsurface interaction, it does not provide a surrogate for fine discretisation throughout the subsurface that is necessary for accurate simulation of unsaturated zone flow. This study offers guidance on the implementation of the SC approach in a block-centred code and demonstrates the importance of systematic testing of parameters (that are otherwise calibrated) in physically based surface–subsurface hydrology models.

1. Introduction

Over the last two decades, considerable progress in hydrologic modelling techniques has led to the development of physically based, spatially distributed codes that are capable of simulating integrated surface–subsurface hydrological processes at the catchment-scale. Popular fully integrated codes (i.e. in which surface and subsurface governing equations are solved simultaneously; Furman, 2008) include Integrated Hydrology Model (InHM; VanderKwaak, 1999), MODHMS (HydroGeoLogic Inc., 2006), HydroGeoSphere (HGS; Therrien et al., 2009) and ParFlow (e.g. Kollet and Maxwell, 2006). The coupling of the surface and subsurface domains in these models is critical in the simulation of catchment-scale hydrology, given its control on dynamic surface–subsurface processes (e.g. rainfall partitioning into infiltration and surface runoff) (Ebel et al., 2009; Liggett et al., 2012).

Surface–subsurface coupling in fully integrated codes is achieved typically using one of two conceptual approaches: (1) the surface conductance (SC) approach (e.g. as applied in MODHMS), which is the focus of this study; and (2) the continuity of pressure and flux (COP) approach (e.g. as applied in HGS and ParFlow) (Ebel et al., 2009). The SC approach involves a distinct exchange interface between the surface and subsurface nodes, over which hydraulic head gradients between these nodes drive surface–subsurface exchange fluxes. However, the presence of a distinct exchange interface may not be justifiable, in a physical sense, unless a known discontinuity between the surface and subsurface domains exists (e.g. due to surface sealing from raindrop impact, fire effects, cultivation, etc.) (Ebel et al., 2009). Moreover, parameters involved in the formulation of the SC approach are not easily measured or estimated (Kollet and Zlotnik, 2003). The COP approach arguably yields a more physical representation of surface–subsurface systems because it avoids the assignment of the SC coefficient (α_e) (Kollet and Maxwell, 2006). Nevertheless, the SC approach is easier to apply and less computationally intensive in comparison to the more physically based COP method

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(Huang and Yeh, 2009; Kollet and Maxwell, 2006), and as such, its application in catchment hydrology modelling is common.

The formulation of the SC approach for simulating surface–subsurface interactions depends on the nodal arrangement in the model grid (i.e. block-centred or mesh-centred). In mesh-centred codes (e.g. HGS), the surface and uppermost subsurface nodes are coincident at the land surface (i.e. there is no physical separation between the respective nodes). Previous studies have characterised the influence of the SC approach on catchment flow processes using mesh-centred codes (e.g. Ebel et al., 2009; Delfs et al., 2009; Huang and Yeh, 2009; Liggett et al., 2012). However, the application of the SC approach in block-centred codes in the context of runoff generation processes has received little attention to date. For block-centred codes (e.g. MODHMS), an inherent vertical separation between the surface and the uppermost subsurface nodes exists, which is expected to affect the simulation of surface–subsurface interactions. As such, the implementation of the SC approach needs to account for the uppermost grid cell thickness. Few block-centred codes are capable of simulating fully integrated surface–subsurface flow, although there are some (e.g. MODHMS) that are used widely in catchment modelling (e.g. Werner et al., 2006; Barr and Barron, 2009; Donn et al., 2012). It is important that the use of the SC approach in block-centred codes is assessed given that fully integrated codes are increasingly being used in catchment modelling (Sebben et al., 2013).

The current study explores the influence of the block-centred implementation of the SC approach on simulated surface–subsurface interactions using MODHMS. The mesh-centred code HGS is used as a basis for comparison against block-centred results. One-dimensional numerical infiltration experiments of Hortonian conditions are used to examine the simulation of infiltration-excess surface runoff. We explore the partitioning of rainfall into infiltration and surface runoff (and the associated surface–subsurface head differences) to assess the influence of SC parameters and the vertical separation of the surface and uppermost subsurface nodes on modelling predictions. The primary objectives are to: (1) characterise the dependence of simulated surface–subsurface interactions on coupling parameters and uppermost cell thickness, and (2) propose ways in which the SC approach can be applied in a block-centred code to accurately and efficiently predict rainfall partitioning. We thereby offer guidance for catchment modellers on SC parameterisation in block-centred codes.

2. Background

2.1. SC coupling approach

In fully integrated codes that utilise the SC approach, the exchange flux q_e [LT^{-1}] (positive for infiltration) across the surface–subsurface exchange interface is given by:

$$q_e = \alpha_e(h_s - h_{ss}) \tag{1}$$

where h_{ss} [L] is the hydraulic head at the uppermost node of the subsurface system, h_s [L] is the hydraulic head at the surface node, and α_e [T^{-1}] is the SC coefficient, which is otherwise known as the "conductance" or "first-order exchange coefficient" (e.g. Mehl and Hill, 2010; Ebel et al., 2009).

Conceptually, the SC approach in surface–subsurface coupling takes a similar form to conductance-based techniques that have a long history in other hydrogeologic applications (VanderKwaak, 1999). For example, conductance-based approaches have been used to represent fracture-matrix and macropore-matrix exchange (e.g. Barenblatt et al., 1960; Gerke and van Genuchten, 1993), and stream–aquifer interaction in the application of analytical solutions (e.g. Hantush, 1965; Hunt, 1999) and numerical models (e.g. the RIV package of MODFLOW; McDonald and Harbaugh, 1988). The conductance parameter has been described as either a function of the exchange interface geometry (e.g. Warren and Root, 1963; Hantush, 1965; Prickett and Lonnquist, 1971; Hunt, 1999) or as a lumped calibration parameter that holds no physical meaning (e.g. Bencala, 1984; Kollet and Maxwell, 2006; Doppler et al., 2007; Mehl and Hill, 2010). The conceptualisation and numerical implementation of each of these conductance approaches vary slightly as a result of the unique assumptions associated with each application. For example, the conductance approach adopted in the MODFLOW RIV package is designed to represent flow across a lower conductivity streambed. It is assumed that water infiltrating through the streambed is added to the saturated groundwater system instantaneously. This package is not designed to consider dynamic surface–subsurface interactions such as the initiation of surface runoff. Mehl and Hill (2010) demonstrated the differences in simulated stream-aquifer exchange using three different conductance formulations based on the block-centred grid structure in MODFLOW. They found that stream–aquifer exchange was highly dependent on the formulation of the conductance parameter, combined with the horizontal and vertical grid discretisation. It is therefore expected that the implementation of the SC approach in a block-centred code will impact the simulation of infiltration and surface runoff in a variably saturated soil, given Mehl and Hill's (2010) findings for stream–aquifer exchange.

In applying the SC approach to surface–subsurface interactions in fully integrated codes, α_e is represented commonly as:

$$\alpha_e = \frac{K_{sat}}{l_e} \tag{2}$$

where K_{sat} [LT^{-1}] is the vertical saturated hydraulic conductivity and l_e [L] is the thickness of the exchange interface. Additional parameters (e.g. degree of land surface saturation or inundation) may also be included in the parameterisation of α_e (e.g. VanderKwaak, 1999; HydroGeoLogic Inc., 2006; Therrien et al., 2009). Codes that employ the SC approach require the user to specify either α_e as a whole (e.g. MODHMS), or l_e (e.g. the "coupling length" in HGS) is specified and K_{sat} is taken from the properties of the uppermost subsurface layer. It has been shown that non-physical hydrologic behaviour may occur in response to inappropriate parameterisation of α_e (e.g. Ebel et al., 2009; Gaukroger and Werner, 2011; Liggett et al., 2012). Previous studies using mesh-centred codes conclude that informed selection of α_e allows the model user to optimise the trade-off between model accuracy and computational efficiency, while preserving near continuity of surface and subsurface heads (Ebel et al., 2009; Liggett et al., 2012).

The nodal arrangement within the model grid (i.e. block-centred or mesh-centred) influences the conceptualisation of the SC approach. In a mesh-centred code, the SC approach represents flow through an artificial layer of thickness l_e, given that the surface and uppermost subsurface nodes are coincident at the land surface (Fig. 1a). In this case, l_e (and therefore α_e) is not related to the model grid structure. Surface runoff generation (which requires the saturation of the uppermost soil profile; Horton, 1933) is therefore generated as a result of saturation of the uppermost subsurface node (i.e. when h_{ss} reaches its nodal elevation, z_{ss}) and h_{ss} intersecting the land surface concurrently. However, in a block-centred code, there is a vertical separation between the surface and uppermost subsurface nodes that is equal to the half-cell thickness ($\Delta z/2$) (Fig. 1b). In this case, the SC approach represents flow through the top half of the uppermost subsurface cell (Fig. 1c). However, saturation of the uppermost node (i.e. when h_{ss} reaches z_{ss}) is not coincident with h_{ss} reaching the land surface (Fig. 1b and c). This combination of effects caused by the vertical separation of the surface and upper subsurface nodes is expected to affect the simulation of surface runoff generation. To the best of the