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A model integration framework for linking SWAT and MODFLOW

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ABSTRACT

Assessment of long-term anthropogenic impacts on agro-ecosystems requires comprehensive modelling capabilities to simulate water interactions between the surface and groundwater domains. To address this need, a modelling framework, called "SWATmf", was developed to link and integrate the Soil Water Assessment Tool (SWAT), a widely used surface watershed model with the MODFLOW, a groundwater model. The SWATmf is designed to serve as a project manager, builder, and model performance evaluator, and to facilitate dynamic interactions between surface and groundwater domains at the watershed scale, thus providing a platform for simulating surface and groundwater interactions. Using datasets from the Fort Cobb Reservoir experimental watershed (located in Oklahoma, USA), the SWATmf to facilitate linkage and dynamic simulation of SWAT and MODFLOW models. Simulated streamflow and groundwater levels generally agreed with observations trends showing that the SWATmf can be used for simulating surface and groundwater interactions.

1. Introduction

Assessing the long-term impacts of natural and anthropogenic drivers in watershed dynamics (i.e., hydrological response, transport of contaminants, and ecosystems services) requires integration of knowledge and modelling capacities across biophysical responses, environmental problems, policies, economics, datasets, and computer capabilities (Laniak et al., 2013). The primary goal of model integration is to bridge fragmented cross-disciplinary knowledge to strengthen the quantitative capacity to rigorously evaluate hypotheses and system response under dynamic scenarios (Arnold, 2013).

The Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) and the Modular Three-Dimensional Finite-Difference Groundwater Flow (MODFLOW; McDonald and Harbaugh, 1988) models are well-tested and widely-used surface and groundwater models, respectively. However, these models represent the physical world (i.e., model spatial discretization and process simulation) differently and each is limited to its simulation domain, each having advantages and disadvantages when simulating biophysical processes and using computational resources.

The SWAT model only simulates shallow groundwater dynamics above a restricted layer (SWAT model lower boundary domain). Percolation below the impervious layer, which is set at a maximum value of six m below the ground surface (Neitsch et al., 2011), is flow assumed lost out of the system (Fig. 1). SWAT simulates surface and shallow aquifer processes (Fig. 1) based on hydrological response units (HRUs), which are conceptual units of homogeneous land use, management, slope, and soil characteristics that extend below the surface to a soil profile depth (Arnold et al., 1998). HRUs are modelled as non-geo-located, spatially disconnected representations of spatially derived geolocated polygons belonging to a given sub-basin in the surface domain. Thus, the SWAT model uses a quasi-two dimensional step-by-step budgetary approach at the HRU level to account for changes in the hydrological response. This configuration has both advantages and constraints (Garen and Moore, 2005; Walter and Shaw, 2005). The lumping of spatially geolocated polygons into HRUs speeds up simulation of processes that takes into account land use and land management. However, individual one-dimensional computations at the HRU level are summed up within a sub-basin and routed to the corresponding sub-basin outlet without considering HRU-to-HRU spatial

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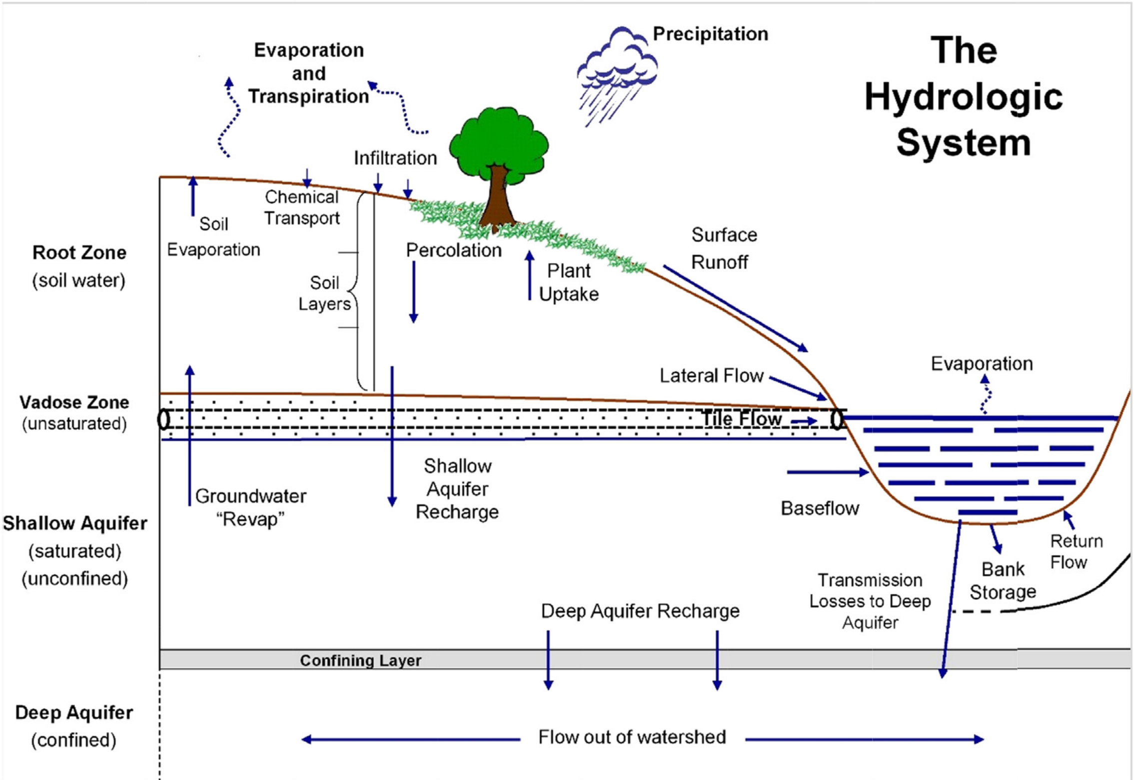

Fig. 1. Schematic of the hydrologic cycle and SWAT simulation processes (Neitsch et al., 2011).

interaction. With this configuration, it is not possible to spatially integrate SWAT with gridded groundwater models at the HRU level.

MODFLOW simulates flow processes occurring at the continuum volume in the saturated zone defined by three-dimensional cells (groundwater domain) and hydrogeological properties. MODFLOW simultaneously solves the groundwater flow differential equation using the finite difference approach, and integrates groundwater systems with other hydrological sub-system components (e.g. vadose zone, surface drainage, transport phenomena, etc.) through incorporation of "packages" using a gridded spatial discretization. However, it does not directly account for hydrologic processes that occur on the surface or in the root zone. Consequently, a common practice is to assume lumped percolation fluxes as a percentage of precipitation, and then optimize the value during the calibration process. Whereas the groundwater model calibrated for recharge can provide reasonably good groundwater level predictions, it is possible that the user may get the right answer for the wrong reasons (Kirchner, 2006) because this approach fails to account for spatial variability in recharge rates as a result of varying land use, irrigation and agronomic practices implemented on the surface domain. In addition, this approach may misrepresent transport of nutrients moving to the groundwater domain for the same reasons.

Therefore, an integrated SWAT and MODFLOW is essential to better spatially represent feedback fluxes within the surface and groundwater domains. This will improve simulation of impacts of long-term stressors, such as climate variability and change (Brown and Funk, 2008; Wheeler and von Braun, 2013), irrigation technology and management (Playan and Mateos, 2006), land use change (Scanlon et al., 2005; Chu et al., 2013a), disturbances (e.g., wildfire; Beeson et al., 2001), transport of nutrients to aquifers in agricultural production systems, and water resources assessment. SWAT has been integrated with other models to improve simulations of riparian buffer zones (SWAT-REMM; Ryu et al., 2011), sediment and hydrodynamic flow simulation (SWAT-SOBEK; Betrie et al., 2011), storm water management (SWAT-SWMM; Kim et al., 2011) using dedicated approaches or within the OpenMI model integration framework (Gregersen et al., 2007), and surface and groundwater processes (SWAT-MODFLOW; Sophocleous et al., 1999, 2000; Conan et al., 2002; Kim et al., 2008). Although SWAT and MODFLOW have been integrated for specific purposes and applications, no comprehensive modelling framework is available for application in different locations.

Model integration is challenging and limited by specific model code, model internal logic, cross-model data formats, and data interchange. To address these issues, model integration frameworks such as OpenMI (Gregersen et al., 2007) and PCRaster (2008) have been developed. The OpenMI standard allows integration of model components that comply with this standard to be configured to exchange data during simulations (computation at run-time). Additional code is necessary at the core of the model logic to allow data synchronization at time step simulations in coupling models where feedback fluxes are important. The OpenMI architecture was designed to be cost-effective, and to enable model migration while providing model developers freedom to adopt it whenever necessary. The PCRaster is a collection of operational and logical tools integrating the temporal dimension targeted at the development and deployment of cell described environmental models (structured grids) in two or three dimensions. For example, Schmitz et al. (2009) coupled MODFLOW and PCRaster to build an integrated model of the "Utrechtse Heuvelrug" watershed to demonstrate model integration without low-level programing knowledge. In this investigation, neither the OpenMI nor the PCRaster modelling frameworks were adopted due to the specific model features (differences in models spatial discretization approaches), constraints associated with model maintenance cycle and development roadmap, and the need for integration/development with other important model components (e.g., river model) in