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Simulating the spatio-temporal dynamics of soil erosion, deposition, and yield using a coupled sediment dynamics and 3D distributed hydrologic model

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ABSTRACT

Since soil erosion is driven by overland flow, it is fair to expect heterogeneity in erosion and deposition in both space and time. In this study, we develop and evaluate an open-source, spatially-explicit, sediment erosion, deposition and transport module for the distributed hydrological model, GEOtop. The model was applied in Dripsey catchment in Ireland, where it captured the total discharge volume and suspended sediment yield (*SSY*) with a relative bias of −1.2% and −22.4%, respectively. Simulation results suggest that daily *SSY* per unit rainfall amount was larger when the top soil was near saturation. Simulated erosion and deposition areas, which varied markedly between events, were also found to be directly influenced by spatial patterns of soil saturation. The distinct influence of soil saturation on erosion, deposition and *SSY* underscores the role of coupled surface-subsurface hydrologic interactions and a need to represent them in models for capturing fine resolution sediment dynamics.

Software availability

Software Name: GEOtopSed
Developers: Tan Zi
Contact Address: Department of Civil and Environmental Engineering, Duke University, Durham, North Carolina, 27708, US
Email: tan.zi@duke.edu
Year First Available: 2015
Hardware Required: Desktop/Laptop with 2 GHz CPU, 2 GB RAM or more
Operating System Required: Macintosh OSX 10.4 or newer; Windows XP or newer; Linux
Libraries Required: ASCII, FLUIDTURTLES, GEOMORPHOLOGYLIB, KeyPalette, MATH
Cost: Free
Source Code: https://sourceforge.net/projects/geotopero/
Program Language: C

1. Introduction

Soil erosion by rainfall and overland flow is a widespread threat to soil fertility and water quality. Accurate estimation of soil loss and its spatial distribution is often needed for pollutant risk analyses, reservoir management, agriculture productivity forecasts, and soil and water conservation. In this regard, several distributed models have been developed to obtain erosion estimates (DeRoo et al., 1996; Wicks and Bathurst, 1996; Morgan et al., 1998; Hessell, 2005; Jain et al., 2005; de Vente et al., 2008). Notably, majority of distributed erosion-deposition models e.g., WEPP, EUROSEM etc., consider simplistic representations of vertical and lateral subsurface water flow, and often do not account for the lateral subsurface water movement, or the coupled dynamic interactions between vadose zone and the groundwater table, or the evolution of soil moisture and groundwater with evapotranspiration. Given that the detachment, transport, and deposition of soil are dominantly influenced by the velocity and volume of overland flow (Julien and Simons, 1985), which in turn may be influenced by antecedent soil moisture conditions (Legates et al., 2011; Penna et al., 2011; Jost et al., 2012; Chen et al., 2014;

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Hueso-González et al., 2015), subsurface heterogeneity (Lewis et al., 2012; Ghimire et al., 2013; Orchard et al., 2013; Zimmermann et al., 2013; Niu et al., 2014; Tao and Barros, 2014), and groundwater distribution (Kumar et al., 2009; Miguez-Macho and Fan, 2012; Rosenberg et al., 2013; Safeeq et al., 2014; von Freyberg et al., 2015), it is important to consider the coupled impacts of antecedent hydrologic states (soil moisture and groundwater distribution) and subsurface hydrogeologic properties on sediment generation and yield. Failing to do so may limit the applicability of these models to a few events (Hessel et al., 2006; Mati et al., 2006; Ramsankaran et al., 2013) or to regimes where the dynamic role of antecedent conditions and subsurface heterogeneity on erosion are not large enough. Heppner et al. (2006) made significant headway in this direction by coupling sediment processes within an integrated hydrologic model, InHM (VanderKwaak and Loague, 2001). The study specifically evaluated the rainfall splash erosion component of the model on a 6 m by 2.4 m plot. Heppner et al. (2007) used the same model to perform sediment-transport simulations for six events in a 0.1 km^2 rangeland catchment. It is to be noted that InHM solves subsurface flow using the variably saturated 3D-Richards equation, while surface flow is simulated using diffusion wave approximation of St. Venant equation. Equations corresponding to these coupled processes are spatially discretized using a control volume finite element strategy on each unstructured grid. A global implicit solver is used to perform the simulation. Another notable effort in this direction was by Kim et al. (2013), who coupled sediment processes within a hydrologic and hydrodynamic model tRIBS-OFM and validated their model against analytical solutions. Similar to InHM, tRIBS-OFM is also an unstructured grid based model. The model uses a gravity-dominated formulation (Cabral et al., 1992) to simulate vadose zone flow and a quasi-3D Boussinesq's equation under the Dupuit-Forchheimer assumptions to simulate groundwater flow (Ivanov et al., 2004). The model was used to evaluate sediment yield simulations for 10 events in a 0.036 km^2 Lucky Hills watershed located in southeastern Arizona, USA. Development of these physically-based integrated models of hydrology and sediment dynamics has opened new opportunities, especially in regards to understanding the impact of the hydrologic state on spatio-temporal distribution of erosion, deposition and yield. Notably, the aforementioned two models are not open-source.

Here, we develop an open-source, spatially-explicit, structured-grid based, sediment erosion/deposition module for a 3D surface-subsurface hydrologic model, GEOtop (Rigon et al., 2006; Endrizzi et al., 2014), and evaluate its applicability in explaining the sediment yield dynamics. Similar to InHM (Heppner et al., 2007), the GEOtop model also solves subsurface flow using the variably saturated 3D-Richards equation, while surface flow is simulated using kinematic wave approximation of St. Venant equation. The sediment dynamics model developed here takes advantage of the GEOtop simulated distributed hydrological states such as moisture content, surface flow depth, and flow velocity. The model accounts for the influence of spatial heterogeneities in land surface characteristics, subsurface hydrogeology, and antecedent conditions in the generation of overland flow, and hence on the erosion and deposition of sediment in the catchment. The model developed here was applied on a much larger catchment (area = 15 km^2) and for a longer period (simulation duration = 2 years) than in Heppner et al. (2007) and Kim et al. (2013), allowing validation of the coupled model for extended wet and dry periods. The coupled model is then used synergistically with the observed data to answer four pointed questions: a) Is the performance of the GEOtopSed model for simulating *SSY*, dependent on the flow regime and the model's ability to capture streamflow response? b) Does the daily suspended sediment yield (*SSY*) from the watershed vary monotonically with precipitation amount and energy? If not, does the hydrologic response of the watershed has a role to play in the departure from monotonic relation? c) Does the simulated source/sink area of sediments vary spatially from one event to other? If yes, is the variation driven by hydrologic state, specifically the surface soil saturation state? and d) To what extent does the linear relation between erosion and the slope-length factor (product of specific catchment area and slope), which is often used in USLE-based model representations (e.g. USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1991), RUSLE2 (Foster et al., 2005)), hold for GEOtopSed simulated states and fluxes?

2. Process formulation, model implementation, and verification

2.1. The GEOtop model: a short review

The open-source GEOtop model (Rigon et al., 2006) is process based and simulates core hydrological processes such as unsaturated flow, saturated flow, overland flow, stream flow generation/routing, and surface energy balances. Overland flow modeling is performed using the kinematic wave approximation of St. Venant equation while subsurface flow and soil moisture simulations are performed by solving a variably-saturated representation of 3D Richards equation. By solving the Richards equation, GEOtop model can simulate the surface runoff generation processes due to both infiltration excess and saturation excess, and can also redistribute the sub-surface water both laterally and vertically, as determined by the head gradient. The model has been extensively tested and validated in Bertoldi (2004). The water and energy balance calculations in GEOtop were recently refined to account for soil freezing and thawing effects (Endrizzi et al., 2014). In summary, with detailed water and energy balance modules, GEOtop can provide accurate simulations of evapotranspiration and soil moisture dynamics (Bertoldi et al., 2014; Della Chiesa et al., 2014), given adequate watershed data. By simulating coupled hydrologic states (e.g. surface flow depth, soil moisture and groundwater) on each grid of the model domain, the model is well suited to study the influence of watershed properties and subsurface states on spatially-distributed runoff, an important control on erosion, at multiple scales. Furthermore, as an open source software (http://www.geotop.org/wordpress/), the GEOtop model provides a complete hydrological model framework with ease for extensions. One such example is the incorporation of landslide occurrence prediction within the GEOtop framework by Simoni et al. (2008).

2.2. Process formulation of the sediment dynamics model

The sediment dynamics model developed here takes advantage of the GEOtop simulated distributed hydrological states such as moisture content, surface flow depth, and flow velocity. Here we only highlight the aspects of the model that are most relevant to the sediment erosion, deposition and transport modeling. Readers may refer to GEOtop model papers (Rigon et al., 2006; Endrizzi et al., 2014) to learn more about the individual process representations.

GEOtop simulates soil moisture in each subsurface layer by solving the 3D Richards equation:

$$(C(H)\phi + S_W S_s)\frac{\partial H}{\partial t} + \nabla\cdot(-\mathrm{K}\nabla \mathrm{H}) + S_w = 0 \qquad (1)$$

where K [m s^{-1}] is the hydraulic conductivity, H [m] is the sum of pressure and potential head, and S_w is the source/sink mass flux [s^{-1}], S_s is the specific storage coefficient [m^{-1}], ϕ is porosity [$-$], and $C(H)$ is the specific moisture capacity function.