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Simulating hydrological and nonpoint source pollution processes in a karst watershed: A variable source area hydrology model evaluation

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ABSTRACT

An ecohydrological watershed model can be used to develop an efficient watershed management plan for improving water quality. However, karst geology poses unique challenges in accurately simulating management impacts to both surface and groundwater hydrology. Two versions of the Soil and Water Assessment Tool (SWAT), Regular-SWAT and Topo-SWAT (which incorporates variable source area hydrology), were assessed for their robustness in simulating hydrology of the karstic Spring Creek watershed of Centre County, Pennsylvania, USA. Appropriate representations of surface water – groundwater interactions and of spring recharge – discharge areas were critical for simulating this karst watershed. Both Regular-SWAT and Topo-SWAT described the watershed discharge adequately with daily Nash-Sutcliffe efficiencies (NSE) ranging from 0.77 to 0.79 for calibration and 0.68–0.73 for validation, respectively. Because Topo-SWAT more accurately represented measured daily streamflow, with statistically significant improvement of NSE over Regular-SWAT during validation (p-value = 0.05) and, unlike Regular-SWAT, had the capability of spatially mapping recharge/infiltration and runoff generation areas within the watershed, Topo-SWAT was selected to predict nutrient and sediment loads. Total watershed load estimates (518 t nitrogen/year, 45 t phosphorus/year, and 13600 t sediment/year) were within 10% of observed values (−9.2% percent bias for nitrogen, 6.6% for phosphorous, and 5.4% for sediment). Nutrient distributions among transport pathways, such as leaching and overland flow, corresponded with observed values. This study demonstrates that Topo-SWAT can be a valuable tool in future studies of agricultural land management change in karst regions.

1. Introduction

Hydrologic and pollution transport processes in watersheds with karst hydrology are complicated by underground networks of bedrock fractures and solution cavities. The subsurface heterogeneity and presence of preferential flow paths enhance groundwater recharge (Hartmann et al., 2015). Resulting high infiltration capacities limit surface runoff and reduce actual evapotranspiration during wet conditions (Malard et al., 2016). Sub-surface channels within karst aquifers accelerate groundwater flow (Parizek, 1984; Fulton et al., 2005) as compared to water movement through non-karst aquifers. Moreover, springs recharged outside the topographic watershed boundary can discharge inside the basin and vice versa. However, the high storage capacities of karst aquifers tend to sustain stream channel baseflow and decrease hydrograph peaks as compared to the hydrology of similar non-karst watersheds (Fulton et al., 2005; Baffaut and Benson, 2009; Amatya et al., 2013). Additionally, the karst geology of northeastern USA promotes rapid infiltration in areas with karst features like sink holes and solution cavities along with saturation excess surface runoff in topographic lows like near-stream areas, where soils tend to be poorly drained and regional groundwater systems are most likely to intersect the land surface (Fulton et al., 2005; O'Driscoll and DeWalle, 2006; Buda and DeWalle, 2009). This non-uniform spatial arrangement of runoff generation processes, or variable source area (VSA) hydrology, becomes a primary driver of surface runoff generation and nutrient loss throughout the region (Srinivasan et al., 2002; Easton et al., 2008).

Hydrologic and water quality models of karst watersheds must incorporate increased complexity in the simulation of hydrolog-

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Table 1
Summary of relevant modeling studies in karst watersheds.

Study	Model used	Key issue	Techniques	Key results
1 – Afinowicz et al. (2005)	SWAT	Brush management on water budget	Modification of baseflow code for rapid groundwater movement	NSE = 0.09–0.4
2 – Amatya et al. (2011)	SWAT	Streamflow and embayment	Addition of subsurface point source (spring) and modification of baseflow estimation method	NSE = 0.29–0.91
3 – Amatya et al. (2013)	SWAT	Phosphorous loading	Addition of subsurface point source and modification of baseflow estimation method	PBIAS = 13
4 – Baffaut and Benson (2009)	SWAT	Flow and pollutant transport	Splitting groundwater recharge and using high hydraulic conductivity values	NSE = 0.24–0.56
5 – Fleury et al. (2007)	2-Reservoir	Rainfall-discharge relationship	Transfer function consisting of two reservoirs: a slow discharge reservoir for low flow and a rapid discharge reservoir for high flow	NSE = 0.92
6 – Jourde et al. (2007)	Rainfall-runoff	Groundwater contribution to surface flow	Hydrodynamic analysis of groundwater flow into a standard rainfall-runoff model	Partly good fit
7 – Kourgialas et al. (2010)	Integrated karstic	Hydrology of complex geomorphology	A 2-reservoir model: water flow through the karst network was determined as a function of karstic area and as a fraction of inflow	Good agreement
8 – Martinez-Santos and Andreu (2010)	Lumped & distributed	Natural recharge in semiarid climate	Lumped model approach and distributed model approach with application of a standard finite-difference code	Reproduced recharge accurately
9 – Nikolaidis et al. (2013)	SWAT	Hydrological and geochemical processes	A modified karst flow model: upper reservoir and lower reservoir system	NSE = 0.62 PBIAS = –22.3
10 – Palanisamy and Workman (2015)	SWAT	Flow through sinkholes located in streambeds	Application of orifice flow method incorporated into SWAT model for sinkhole modeling	NSE = 0.57–0.87
11 – Rozos and Koutsoyiannis (2006)	Multicell/MODFLOW	Groundwater level	Application of conduit flow approach using Manning's equation	Improved model performance
12 – Salerno and Tartari (2009)	Wavelet analysis	Baseflow component	Application of the statistical method of Wavelet analysis	NSE = 0.56–0.66
13 – Spruhill et al. (2000)	SWAT	Stream discharge	Regular SWAT model parameterization	NSE = –0.04–0.19
14 – Yactayo (2009)	SWAT	Hydrological process	Allowing overland flow and lateral flow from upstream areas to recharge the sinkholes	NSE = –34.8–0.37
15 – Zhang et al. (2011)	Distributed	Hydrological process	Integrating mathematical routings of porous Darcy flow, fissure flow, and underground channel flow	$R^2 > 0.75$

ical processes, as compared to those of non-karst watersheds, in order to accurately capture the influence of karst groundwater flow on surface water flow and quality (Jourde et al., 2007; Salerno and Tartari, 2009). In particular, many topographically-driven hydrologic models tend to overestimate actual evapotranspiration and surface runoff and thereby underestimate karst recharge (Hartmann et al., 2015). Moreover, a fully distributed model cannot be used if the complete network of the subsurface conduit system is unknown. A summary of relevant simulation studies in karst watersheds (Table 1) illustrates five distinct modeling approaches: (a) conduit flow via Manning's equation, (b) distributed groundwater pools, (c) groundwater storage represented as a reservoir, (d) distributed hydrologic models coupled with conduit routing, and (e) semi-distributed hydrologic response units that interact independently. Some of these studies focused mainly on prediction of flow through sinkholes (Palanisamy and Workman, 2015) and some were unable to incorporate the impacts of land use changes on hydrology and water quality at the watershed scale (Fleury et al., 2007; Jourde et al., 2007).

The semi-distributed Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2011; Arnold et al., 2012; Winchell et al., 2013) is capable of simulating stream discharges and nonpoint source pollution in a watershed using long-term climate and land use data (Kaini et al., 2012; Jeong et al., 2013). Different versions of SWAT have been used for watersheds with karst features in a limited number of cases with a wide range of daily Nash–Sutcliffe efficiencies (NSE) (Table 1). A modified version of SWAT, initially termed SWAT-VSA by Easton et al. (2008) but hereafter called Topo-SWAT, incorporates the topographic wetness index (Beven and Kirkby, 1979) and has been used satisfactorily in a number of cases for simulating hydrology and phosphorus (P) transport (White et al., 2011; Pradhanang et al., 2013; Woodbury et al., 2014; Collick et al., 2015; Winchell et al., 2015) for watersheds with VSA hydrology. However, to our knowledge, Topo-SWAT has not yet been applied in a watershed with substantial karst geology. In the current study, we hypothesized that the surface runoff and baseflow processes in a karst watershed with VSA hydrology would be better simulated by Topo-SWAT than standard SWAT (hereafter Regular-SWAT) due to TopoSWAT's ability to capture spatial differences in recharge/infiltration and runoff generation throughout the basin. Approaches taken in this SWAT modeling study could be adopted in karst regions of the northeastern US and elsewhere.

The overall goal of the study was to develop a simulation tool for a karst watershed with VSA hydrology that dynamically links surface water, groundwater, and field-level land use changes to

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