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Development of a grid-based version of the SWAT landscape model

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Abstract:

Integrated river basin models should provide a spatially distributed representation of basin hydrology and transport processes to allow for spatially implementing specific management and conservation measures. To accomplish this, the Soil and Water Assessment Tool (SWAT) was modified by integrating a landscape routing model to simulate water flow across discretized routing units. This paper presents a grid-based version of the SWAT landscape model that has been developed to enhance the spatial representation of hydrology and transport processes. The modified model uses a new flow separation index that considers topographic features and soil properties to capture channel and landscape flow processes related to specific landscape positions. The resulting model is spatially fully distributed and includes surface, lateral and groundwater fluxes in each grid cell of the watershed. Furthermore, it more closely represents the spatially heterogeneous distributed flow and transport processes in a watershed. The model was calibrated and validated for the Little River Watershed (LRW) near Tifton, Georgia (USA). Water balance simulations as well as the spatial distribution of surface runoff, subsurface flow and evapotranspiration are examined. Model results indicate that groundwater flow is the dominant landscape process in the LRW. Results are promising, and satisfactory output was obtained with the presented grid-based SWAT landscape model. Nash–Sutcliffe model efficiencies for daily stream flow were 0.59 and 0.63 for calibration and validation periods, and the model reasonably simulates the impact of the landscape position on surface runoff, subsurface flow and evapotranspiration. Additional revision of the model will likely be necessary to adequately represent temporal variations of transport and flow processes in a watershed. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS raster-based simulation; watershed modeling; discretization scheme; SWATgrid; landscape routing

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INTRODUCTION

River basin models are valuable tools for examining the impact of land use and management on landscape hydrology, sediment transport and water quality. The Soil and Water Assessment Tool (SWAT) has proven to be a suitable tool under many landscape conditions, and in most applications the prediction accuracy was satisfactory for obtaining knowledge of the hydrologic system and the watershed processes (Arnold and Fohrer, 2005; Gassman *et al.*, 2007). However, previous studies showed that the assessment of the effects of conservation practices on watershed-scale water quality relies strongly on the flow and transport models used (e.g. Mausbach and Dedrick, 2004). The SWAT model typically utilizes a hydrologic response unit (HRU) approach. The watershed is divided into sub-watersheds which are further subdivided into HRUs. However, the SWAT routing command language enables the model to use an HRU, a representative hillslope or a grid cell configuration, alone or in combination, to model a watershed (Arnold *et al.*, 1994, 2013). Nevertheless, SWAT uses the HRU configuration as the primary discretization scheme (Gassman *et al.*, 2007; Arnold *et al.*, 2013), and all geographic information system (GIS) input interfaces use the computationally efficient HRU discretization. Thus, there are only few SWAT applications and studies which actually have used a different discretization approach (e.g. Manguerra and Engel, 1998; White *et al.*, 2009; Arnold *et al.*, 2010; Rathjens and Oppelt, 2012a,b).

Within the HRU approach, all areas in a sub-watershed with the same combination of soil, topography and land use are lumped to form an HRU. The HRUs represent percentages of the sub-watershed area and are not spatially related. Water, sediment and agricultural chemical yields

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generated in the HRUs are currently routed directly into the stream channel, and SWAT is not able to model flow and transport from one landscape position to another prior to entry into the stream. The non-spatial character of the HRUs and the inability to model transport processes in the land-phase of the hydrologic cycle (Neitsch *et al*., 2011) have been identified as key weaknesses of the model (Gassman *et al*., 2007; Arnold *et al*., 2010; Bosch *et al*., 2010). To fulfill the requirements of river basin management, integrated models should provide a spatially distributed representation of basin hydrology and transport processes (Arnold *et al*., 2010; Bosch *et al*., 2010). The incorporation of greater spatial detail into SWAT has therefore been investigated with the focus on (1) developing routing capabilities between landscape units (Volk *et al*., 2007; Arnold *et al*., 2010) and (2) developing a grid-based SWAT model setup (Rathjens and Oppelt, 2012b).

The newly developed SWAT landscape model is able to capture the hydrologically different channel and landscape flow and transport processes related to specific landscape positions (Arnold *et al*., 2010). The model links watershed processes from the hillslope to the watershed scale using the concept of hydrologic landscape units (divides, hillslopes, floodplains; see Volk *et al*., 2007) and route surface runoff, lateral subsurface flow and shallow groundwater flow between these landscape routing units. The model was tested by Arnold *et al*. (2010) and Bosch *et al*. (2010); both studies concluded that additional development and testing of the SWAT landscape model are necessary to confirm model operation. In particular, the landscape model may require additional detail to properly describe interactions between soil surface, vadose zone and groundwater to accurately represent the hydrology in landscapes where subsurface processes dominate (Bosch *et al*., 2010). The results are, however, 'encouraging' (Bosch *et al*., 2010) and show a realistic representation of landscape flow and transport processes in a watershed. A detailed description of the landscape routing model is given by Arnold *et al*. (2010).

Understanding the two mechanisms of landscape and channel network transport is crucial for obtaining knowledge of the hydrologic system of a watershed (e.g. Robinson *et al*., 1995; Rigon, 2003; Drewry *et al*., 2006). Many studies have focused on analyzing the effects of landscape processes on the hydrologic response in a watershed by examining differences between landscape and channel flow travel times (van der Tak and Bras, 1990; Rinaldo *et al*., 1995; Rigon, 2003). They concluded that in small to medium size watersheds the share of landscape and channel processes is essential to estimate streamflow at the outlet, whereas in larger river basins landscape processes are less significant than channel and floodplain processes. Studies examining the spatial variability of landscape and channel processes within watersheds (e.g. Rinaldo *et al*., 1991; Saco and Kumar, 2002) suggest that it is more realistic to use spatially varying parameters to represent the different flow processes. Therefore, hydrologic models require a spatially detailed description of landscape and channel flow processes controlling runoff generation and routing that can be provided by a grid-based approach.

There are, however, advantages and disadvantages for both, the grid and the commonly used HRU method. The HRU approach inherent in the current landscape model provides a fast and numerically efficient model, but leads to a loss of spatial information during modelling and does not account for landscape position. This might be important for existing applications, for example when studying diffuse matter transport in agricultural areas. The grid configuration enables the model to simulate the impact of landscape position on management, such as conservation measures, plant growth, crop yields and runoff in spatial detail (Arnold *et al*., 2010). The appropriate spatial resolution and discretization method depends on the purpose of modelling and the availability of data sources. If the modeler's aim is the replication of aggregated events (e.g. monthly values at the watershed outlet) in a data scarce area, the HRU approach may be adequate. But if the modeler's scope is a spatial description of a hydrologic system (e.g. detection of critical source areas), a spatially distributed model is recommended, because spatial patterns of topography and subsurface characteristics often exert significant control over hydrological processes within a watershed (Schulz *et al*., 2006).

Furthermore, the process of calibrating a model at stream gages does not necessarily improve the spatial accuracy of the model (e.g. Arabi *et al*., 2006; White *et al*., 2009). Data collected at discrete locations contain no information concerning the source, only that it must have originated somewhere upstream. Therefore, spatial model results can be used to refine the model and help to detect disregarded processes, when spatial patterns of model output indicate that the model is not representing the system's behaviour adequately (Bennett *et al*., 2013).

The purpose of this study was to develop a grid-based, spatially distributed hydrologic model that represents channel and landscape transport mechanisms and includes surface, lateral and groundwater fluxes in each grid cell of the watershed. Prior grid applications (e.g. White *et al*., 2009; Rathjens and Oppelt, 2012b) are characterized by the lack of landscape flow routing between grid cells (i.e. interaction between grid cells was part of in-stream processes in the routing phase) or used a constant coefficient for each landscape unit for partitioning landscape and channel flow (Arnold *et al*., 2010). Therefore, an index of hydrologic similarity used by TOPMODEL (Beven and Freer, 2001) was modified to differentiate channel and landscape processes. Stepwise testing in experimental watersheds at various scales and under different hydrologic, climatic and topographic conditions will be developed to evaluate the model. The testing will include (1) evaluation of model output at discrete locations (i.e. stream gages), (2) qualitative and (3) quantitative analysis of hydrologic model output at the grid scale, (4) examination of water quality at stream gages and (5) at the grid scale, and (6) testing of in-stream processes.

Here we cover the first two points; in particular, it is the aim of this paper (1) to present a grid-based version of the SWAT landscape model, (2) to test the hydrologic components of the SWAT landscape model at a stream gage and at the grid-scale and, in addition, (3) to analyse the impact of a new parameter that controls the proportions of channel and landscape flow in the watershed. The model is evaluated by comparing observed and simulated daily discharge at the catchment outlet and analyzing the spatial distribution of simulated surface runoff, subsurface flow and evapotranspiration. The study area is the Little River Watershed (LRW), a coastal plain watershed near Tifton (Georgia, USA).

MATERIALS AND METHODS

Study area

The LRW is located near Tifton in Central South Georgia (see Figure 1). It covers an area of 334 km^2 and is characterized by a relatively flat topography and a dense stream network (1.54 km km^{-2}). The streams are surrounded by broad, flat alluvial floodplains, river terraces and gently sloping uplands with gradients of less than 5% and channel slopes ranging between 0.1 and 0.5% (Sheridan, 1997).

Figure 1 gives an overview of the LRW stream network, topography, land use and soil type distributions. Land use types occurring in the LRW are row crop agriculture, pasture and forage, upland forest, riparian forest, urban land and water areas. Riparian forest wetlands dominate the landscape close to the stream channels, while upland areas are mostly characterized by agricultural use (Bosch *et al.*, 2004). The most common soil types are sands and sandy loams with high infiltration rates, which are underlain by the shallow, relatively impermeable Hawthorne formation. This formation restricts downward movement of water and promotes lateral movement of shallow groundwater from uplands to the stream channels (Sheridan, 1997; Cho *et al.*, 2013).

The climate is classified as humid subtropical with mean annual precipitation of 1208 mm (1922–1988) and a mean annual temperature of 19.1 °C (Sheridan, 1997). Rainfall often occurs as short-duration, high-intensity convective thunderstorms during midsummer and winter months (Bosch *et al.*, 1999).

Hydrology and water quality of the LRW have been monitored since 1967 (Sheridan, 1997). Additionally, many research projects including several SWAT-related studies

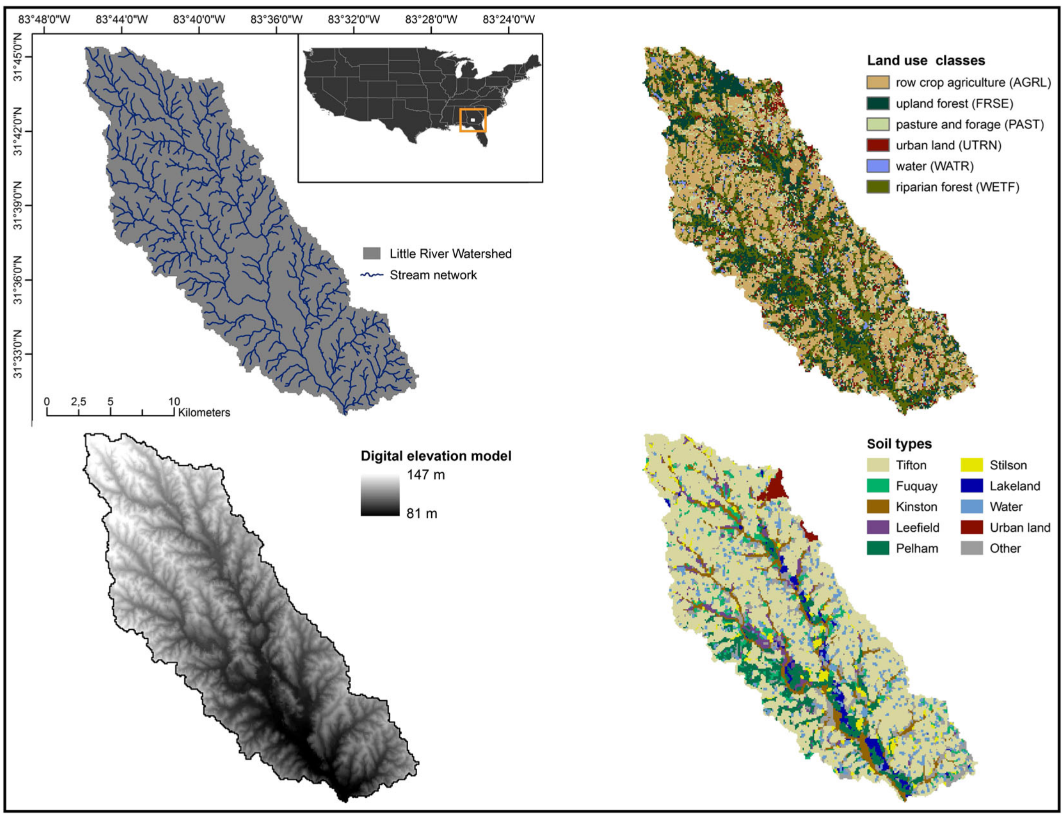

Figure 1. Overview of the Little River watershed near Tifton in Georgia (USA), its stream network, digital elevation model, and land use and soil maps

(Bosch *et al.*, 2004; Feyereisen *et al.*, 2007; Cho *et al.*, 2009, 2013) have investigated water quantity and quality aspects during the past decades (see Bosch *et al.*, 2010). Bosch *et al.* (2010) tested the SWAT landscape model in a sub-basin of the LRW. A frequently reported difficulty when modelling the LRW is the saturation condition of the alluvial aquifer (e.g. Shirmohammadi *et al.*, 1986; Bosch *et al.*, 2004). Runoff processes in the LRW are mainly characterized by infiltration excess overland flow, but saturation excess flow dominates when the shallow aquifer and the vadose zone are near saturation, which is a normal condition from December to April. SWAT considers primarily infiltration excess runoff mechanisms (White *et al.*, 2009), and thus previous studies underpredicted the observed data during saturated conditions and overpredicted discharge during dry conditions, while further calibration of the models would likely yield mixed results (Bosch *et al.*, 2004).

SWAT and the SWAT landscape model

SWAT (Arnold *et al.*, 1998) is a catchment-scale model developed to simulate hydrology and water quality under varying land use and management conditions. The simulated hydrologic processes include surface runoff, percolation, lateral and shallow groundwater flow, evapotranspiration, snow melt, transmission losses from streams, channel routing and water storage in and losses from ponds. A detailed description of all components can be found in Arnold *et al.* (1998) and Neitsch *et al.* (2011).

SWAT divides the hydrology of a watershed into two major phases: (1) the land phase of the hydrologic cycle controls the amount of water entering the channel; (2) the routing phase determines the movement of water through the channel network to the watershed outlet (Neitsch *et al.*, 2011). The current SWAT version does not distinguish individual routing units in the land phase of the hydrologic cycle. Accordingly, the model is not able to simulate runoff and infiltration processes that typically occur in a landscape. Volk *et al.* (2007) and Arnold *et al.* (2010) developed a landscape routing method that enables surface, lateral and groundwater flow interaction across the landscape between divides, hillslopes and floodplains. The model uses a coefficient for each landscape unit to partition the amount of flow into landscape and channel flow.

The grid-based version of the SWAT landscape model refines the concept of the three discrete landscape units and uses a modified version of a topographic index that ranges between 0 and 1 to spatially describe the landscape position of each grid cell. Valley and floodplain grid cells have values close to 1, while grid cells near the divide have values close to 0. The grid landscape routing model computes surface runoff, lateral and shallow groundwater flow for each grid cell individually. While Arnold *et al.* (2010) used a constant flow separation ratio, the new grid-based model estimates spatially distributed proportions of channel and landscape flow with the modified topographic index.

Surface runoff. The model simulates surface runoff using the curve number method. To determine velocity (V_s) and ultimately travel time (*trt*), Manning's equation is used assuming a 1-m overland flow strip (see also Volk *et al.*, 2007; Arnold *et al.*, 2010):

$$V_{s,i} = q_{s,i}^{0.4} \cdot tan(\beta_i)^{0.3} \cdot \eta_i^{-0.6}, \quad i = 1, \ldots, n,$$

where n is the number of grids in the watershed and i is the number of a particular grid cell. $q_{s,i}$ is the flow rate, β_i is the slope angle and η_i is Manning's n. Travel time [h] is

$$trt_i = sl_i \cdot \left(3600 \cdot V_{s,i}\right)^{-1},$$

where sl_i is the slope length. Infiltration is calculated by multiplying the travel time by the saturated hydraulic conductivity:

$$I_i = trt_i \cdot K_i + R_{c,i}, \quad i = 1, \ldots, n,$$

where I_i is infiltration, K_i is saturated hydraulic conductivity and $R_{c,i}$ is roughness storage.

Lateral flow. The model calculates lateral flow volumes with a kinematic storage model (Arnold *et al.*, 1998) as a function of saturated hydrologic conductivity, slope, slope length and porosity (see also Volk *et al.*, 2007; Arnold *et al.*, 2010):

$$Q_{lat,i} = 0.048 \cdot SW_i \cdot K_i \cdot tan(\beta_i) \cdot \left(\phi_{d,i} \cdot sl_i\right)^{-1}, \quad i = 1, \ldots, n,$$

where SW_i is soil water, and $\phi_{d,i}$ is porosity. The model also estimates surface seeps during saturated conditions, which is considered as surface run-on to the next landscape unit. Lateral flow (summed from each soil layer) flows to the adjacent downslope grid cell and is distributed to each soil layer. When water enters the adjacent downslope grid cell, it is subject to soil evaporation, plant water uptake, lateral soil flow, percolation and groundwater recharge (Arnold *et al.*, 1998).

Shallow groundwater. Groundwater flow is simulated as routing through a series of linear storage elements (i.e. grid cells) using the classic linear tank storage model (e.g. Brutsaert, 2005). In addition to routing flow to the next grid cell, water may also be lost to groundwater evaporation or to seepage to the deep aquifer.

Landscape routing and channel interaction. Surface runoff and subsurface flow from each grid cell are routed through the landscape or contributes to streamflow. The share of landscape and channel flow is estimated for each grid cell individually with the modified topographic index (see next section).

Spatial distribution of landscape and channel flow

The SWAT landscape model enables the distribution of runoff between grid cells in the land phase of the hydrologic cycle. This raises the question which part of the flow is routed as channelized flow and which part is routed through the landscape. The concepts of hydrologically sensitive areas (HSAs, e.g. Walter *et al*., 2000; Agnew *et al*., 2006), morphological types of channel heads (Montgomery and Dietrich, 1994) and channel head detection by average source areas (Jaeger *et al*., 2007) were selected as useful methods to develop an index for partitioning landscape and channel flow.

HSAs are areas within a watershed where the probability that runoff will occur is high. The importance of runoff generating areas for watershed management is well documented in the literature. These areas have commonly been identified using topographic indices (Beven and Kirkby, 1979; O'Loughlin, 1986; Beven and Freer, 2001; Lyon *et al*., 2004). Agnew *et al*. (2006) used a topographic index (λ) that considers variations in slope and soil properties to detect HSAs. They found that the general patterns of high hydrologic sensitivity are similar to those of high λ values. The topographic index they used takes the form

$$\lambda_i = ln\left(\frac{A_i}{tan(\beta_i)\cdot K_i\cdot Z_i}\right)\in\mathbb{R}_{>0}, \qquad i=1,\ldots,n, \qquad (1)$$

where n is the number of grids in the watershed and i is the number of a particular grid cell. λ_i is the topographic index [ln(d m^{-1})], A_i is the upslope contributing area per unit contour length [m], β_i is the local surface topographic slope angle, K_i is the mean saturated hydraulic conductivity of the soil [m d^{-1}] and Z_i is the soil depth [m]. λ can be easily calculated for each grid cell in a watershed and solely requires a digital elevation model (DEM) and soil data that are necessary for SWAT modelling (see also Agnew *et al*., 2006). Grid cells with high λ_i values are expected to have a high probability to generate runoff and to be dominated by channel flow.

Channel heads represent a boundary between hillslope and channels and can be defined as the initiation of a channel (Montgomery and Dietrich, 1989). They tend to have characteristic morphologic forms and have been classified as either gradual (a swale that gradually changes into a channel) or abrupt (channel initiation caused by seepage water and erosion). Both abrupt and gradual channel heads are likely to occur in a watershed. However, Montgomery and Dietrich (1989) stated that depending on climate, topography and soil properties, one of the channel head types is likely to be dominant in a watershed. To reasonably represent the dominant channel head type, two modifications of λ were developed in this study. First, λ is transformed into two normalized indexes:

$$\lambda^a_{\mathrm{norm},i} = \frac{\lambda_i}{max_{i=1,\ldots,n}\{\lambda_i\}}\in(0,1] \quad \text{and} \qquad (2a)$$

$$\lambda^g_{\mathrm{norm},i} = \frac{\lambda_i - min_{i=1,\ldots,n}\{\lambda_i\}}{max_{i=1,\ldots,n}\{\lambda_i\} - min_{i=1,\ldots,n}\{\lambda_i\}}\in[0,1], \qquad (2b)$$

$$i=1,\ldots,n.$$

where $\lambda^a_{\mathrm{norm}}$ is used for watersheds where abrupt channel heads dominate, and $\lambda^g_{\mathrm{norm}}$ is used for watersheds dominated by gradual channel heads.

Second, $\lambda^a_{\mathrm{norm}}$ and $\lambda^g_{\mathrm{norm}}$ are adjusted to realistically represent the position of channel head locations in the watershed. Channel heads represent the major boundary between landscape and channel flow processes. Thus, the channel head location is a crucial parameter to realistically represent flow and transport processes in a watershed. Jaeger *et al*. (2007) stated that an average source area size based on field surveys may provide the most practical method for identifying channel head locations. Therefore, the drainage density (DD [km^{-1}]) of the watershed is used to adjust $\lambda^a_{\mathrm{norm}}$ and $\lambda^g_{\mathrm{norm}}$ values. The drainage density is defined by the length [km] of all channels in the watershed divided by its total drainage area (DA [km^2]). Therefore, the smallest λ^a_{xnorm} and $\lambda^g_{\mathrm{norm}}$ values are set to zero (i.e. no channel flow) until the sum of all $\lambda^a_{\mathrm{norm},i}$ and $\lambda^g_{\mathrm{norm},i}$ values multiplied with the unit contour length of the current grid cell divided by the total drainage area matches the drainage density of the watershed. The resulting normalized indexes can be stated as $\lambda^a_{DD,i}, \lambda^g_{DD,i}\in[0,1]$, $i=1,\ldots,n$ satisfying

$$DD \approx \frac{\sum_{i=1}^{n}\lambda^a_{DD,i} l_i}{DA} \approx \frac{\sum_{i=1}^{n}\lambda^g_{DD,i} l_i}{DA},$$

where l_i [km] is the unit contour length of the current grid cell.

The indexes solely differ in the method selected for normalization (see Equations 2a and 2b. Equation (2a) leads to discontinuous distribution of channelized flow fractions, whereas Equation (2b) results in a continuous distribution. Hence, $\lambda^a_{DD,i}$ represents the fraction of channelized flow for grid cell i in a watershed dominated by abrupt channel heads, and $1-\lambda^a_{DD,i}$ represents the fraction of landscape flow. The same applies for $\lambda^g_{DD,i}$ in watersheds dominated by gradual channel heads.

Modelling framework

The interface SWATgrid (Rathjens and Oppelt, 2012b) was used for developing grid-based SWAT model input using weather data and spatially distributed geographic datasets (DEM, soil and land use data). An overview of the essential input data sources is given in Table I. Differences between the weather stations can dominate the spatial model output. To spatially analyse the output of the SWAT landscape model, values of all weather stations were aggregated to one data set and integrated in the simulation.

SWATgrid divides the watershed into linked grid cells. Flow paths are determined from the DEM using the digital landscape analysis tool TOPAZ (Garbrecht and Martz, 2000), and runoff from a grid flows to one of the eight adjacent grid cells. A small grid size is necessary to ensure an accurate representation of the flat topography in the LRW. A small grid size, however, leads to an increase of computation time and memory requirements of the model. As a compromise between an accurate spatial representation of landscape patterns and a manageable model, DEM, soil and land use data were resampled to a resolution of 100 m (1 ha).

Grid-based simulations with the SWAT landscape model were conducted for a 5-year period from 2004 to 2008, plus a 2-year warm-up period from 2002 to 2003. The accuracy of simulated streamflow, water budgets and spatial patterns of model output was examined for this period. Three model setups were developed to evaluate the grid-based landscape model and to analyse the sensitivity of the flow separation ratio. The primary setup (*Model 1.0DD*) is used for the evaluation of the grid-based landscape model, and the additional setups (*Model 1.5DD* and *Model 0.5DD*) are used for analyzing the impact, sensitivity and uncertainty of the flow separation ratio on model output.

Model 1.0DD uses the original drainage density *DD* and λ_{DD}^{a} to represent the share of channelized and landscape flow in the watershed as realistic as possible. *Model 1.0DD* was calibrated manually to fit simulated to observed daily discharge. The grid discretization requires more computation time than the commonly used HRU approach; the LRW model takes approximately 1 h per simulated year on a single 2.67-GHz processor. As a consequence, manual calibration was performed by comparing simulated and observed discharge at the watershed outlet for the year 2004 only. The calibrated parameter set was validated using the time period from 2005 to 2008. A sensitivity analysis for SWAT LRW simulations was previously conducted by Bosch *et al.* (2004) and Cho *et al.* (2013). Their results showed a strong influence of groundwater parameters. Based on these studies and a manual sensitivity analysis, five parameters were chosen for model calibration: soil evaporation compensation factor (ESCO), groundwater parameters (groundwater delay time (GW_DELAY), baseflow alpha factor (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN)) and surface runoff lag coefficient (SURLAG). Table II shows the parameters selected for calibration, their ranges and their calibrated values. A detailed description of each parameter is provided by Arnold *et al.* (2013). Standard test statistics recommended by Moriasi *et al.* (2007) (i.e. the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE, see Nash and Sutcliffe, 1970) and percent bias (PBIAS, see Gupta *et al.*, 1999)) as

Table II. SWAT input parameters chosen for hydrologic calibration and final calibrated values

Parameters	Default	Lower limit	Upper limit	Value
ESCO.bsn	0.95	0	1	1.00
SURLAG.bsn	4	0.05	24	0.15
GW_DELAY.gw	31	0	500	0.75
ALPHA_BF.gw	0.048	0	1	0.96
GWQMN.gw	0	0	5 000	50.0

Table I. Data sources for the LRW (downloadable at ftp://www.tiftonars.org/)

Data type	Scale/Resolution	Source	Data description and usage
Topography	30 m	Georgia GIS Data Clearinghouse	Digital Elevation Model (DEM), model input
Land use	30 m	(Sullivan *et al.*, 2007)	Land use classification based on Landsat 7 imagery (20 Jul 2003), model input
Soils	1: 12 000	Soil Survey Geographic Database (SSURGO)	Soil physical properties, model input
Weather	25 stations (rainfall), 2 stations (temperature, wind speed, relative humidity, solar radiation)	(Bosch *et al.*, 2007)	Daily weather data (1 Jan 2004 to 31 Dec 2008), model input
Streams	7.5-minute quadrangle	(Sullivan *et al.*, 2007)	Mapped stream network, model validation
Discharge	1 Station	(Bosch and Sheridan, 2007)	Daily discharge data, model calibration and validation

well as visual comparisons of observed and simulated data were used to evaluate daily, monthly and yearly streamflow simulations. At this stage, it was not possible to perform a spatially distributed calibration of the model. Thus, spatial distributions of model output were evaluated qualitatively. It was examined whether spatial patterns of model output reasonably reflect hydrologic processes that are expected to occur in the landscape.

In *Model 1.5DD* and *Model 0.5DD*, the drainage density of the watershed, which determines the proportions of channel and landscape flow, was modified to analyse the sensitivity and uncertainty of the flow separation ratio. The drainage density in *Model 1.5DD* is 1.5 times larger than in *Model 1.0DD*, whereas in *Model 0.5DD* it is half as large; all remaining parameters were set to the same values as in *Model 1.0DD*. The factors 0.5 and 1.5 correspond to previously observed variations in drainage density (e.g. Gregory and Walling, 1968; Moglen *et al.*, 1998). Thus, *Model 0.5DD* and *Model 1.5DD* results indicate the range of uncertainty of the proposed approach. A comparison was made between simulated results obtained using *Model 1.0DD*, *Model 1.5DD* and *Model 0.5DD*. Time series of daily simulated streamflow at the watershed outlet as well as spatial patterns of model output were compared.

RESULTS AND DISCUSSION

Spatial analysis and differences of the partitioning ratios

The development of a grid-based SWAT landscape model requires the spatial partitioning of landscape and channel flow to realistically represent flow and transport processes in a watershed. In this paper, the topographic index λ (Equation 1) that has been commonly used to identify runoff generating areas was modified to obtain estimates of partitioning ratios (see Equations 2a and 2b). Figure 2 shows the spatial and frequency distributions of λ, λ_{DD}^{a} and λ_{DD}^{g} values in the LRW. The histograms (Figure 2d–f) visualize the effects of normalization and adjustment to the drainage density. The overall share of channel and landscape flow is determined by the drainage density of the watershed and is the same for λ_{DD}^{a} and λ_{DD}^{g}, but the ratios differ in their frequency distributions. While calculations using the index λ_{DD}^{g} result in few cells with no channel flow, λ_{DD}^{a} calculations results in a large proportion of grid cells with no channel flow (i.e. $\lambda_{DD,i}^{a} = 0$) and in compensation a small number of grid cells with a high share of channel flow (≥ 0.3). Both indexes realistically represent the share of channel and landscape flow determined by the drainage density of the watershed. Their spatial patterns suggest a stream network (Figure 2a–c) similar to the mapped network (see Figure 1).

Channel heads represent the boundary between landscape and channel flow and are thus considered as a crucial parameter to realistically represent flow and transport processes in a watershed. The methods selected for normalization result in a continuous (λ_{DD}^{g}) and discontinuous distribution (λ_{DD}^{a}) of channelized flow fractions (see Figure 2e and f), causing abrupt and gradual channel heads in the corresponding maps (see Figure 2b and c). Previous channel initiation studies by Montgomery and Dietrich (1988, 1989) found that in basins with gentle slopes and infiltration excess overland flow, which applies for the LRW, channel heads caused seepage erosion to occur more frequently than gradual channel heads.

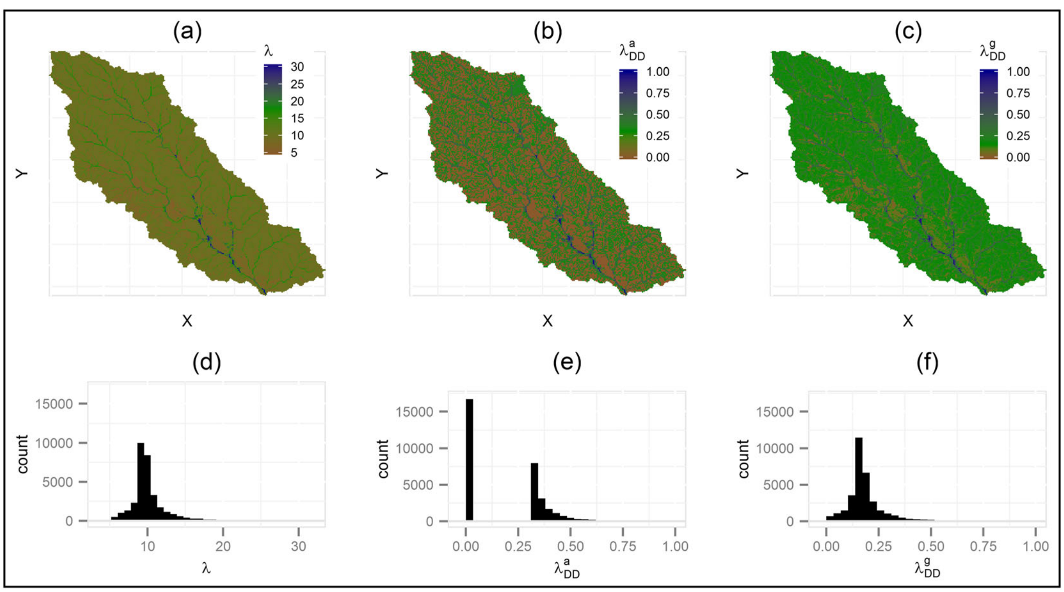

Figure 2. Spatial and frequency distributions of the topographic indexes λ, λ_{DD}^{a} and λ_{DD}^{g} used for channel and landscape flow separation in the LRW

Therefore, the λ^a_{DD} map is used to evaluate the grid-based SWAT landscape model.

Both landscape and channel processes are related to heterogeneously distributed parameters within the watershed (such as soil properties, land use, topography, stream roughness and other physical properties). The newly developed separation index considers this spatial variability within watersheds and shows the capability to realistically represent spatial distributions of flow and transport processes in the LRW. There is, however, a remaining uncertainty inherent to the analysis of flow and transport processes in watersheds. The results should be considered as a rough estimate of landscape and channel flow separation; future studies should focus on the identification of channel head locations in different landscapes and the validation of the proposed flow separation methodology.

Model evaluation at the watershed outlet

Calibration and validation results. One aim of this research was to assess how well the new grid-based landscape configuration performs. For this purpose, simulations were conducted for the period from 2004 to 2008 using λ^a_{DD} for estimating the share of landscape and channelized flow (*Model 1.0DD*). Precipitation in the LRW is variable from year to year with a long term (1922–1988) annual mean of 1208 mm. During the simulation period, precipitation varies between 884 and 1204 mm (2004: 1204 mm, 2005: 1197 mm, 2006: 884 mm, 2007: 896 mm, 2008: 1116 mm). Distribution within the year is also highly variable, although the fall months are typically dry (Sheridan, 1997).

Measures of model performance including PBIAS, R^2 and NSE values are listed in Table III. They indicate satisfactory to good model performance during both calibration and validation periods. Monthly NSE and R^2 values are better than daily values, a result that is often observed in model applications (Moriasi *et al*., 2007).

The hydrograph of daily streamflow for the 5-year period (see Figure 3a) indicates that the grid-based SWAT model simulated daily streamflow satisfactorily in both low and high flow conditions. The model, however, tends to underpredict discharge peaks during the entire period. Confirming the high variability of precipitation from year to year, streamflow also varies significantly between the individual years of the simulation period. In 2004 and 2005, observed streamflow is comparatively high (297 and 433 mm), while from 2006 to 2008 values are lower (139 mm on average). During the drier years, zero-flow conditions were observed repeatedly. The model generally predicts the trends in observed data well and a tendency of over-predicting streamflow during zero-flow conditions that was reported by Bosch *et al.* (2004) and Feyereisen *et al.* (2007) does not occur. There are, however, differences in magnitude and duration of observed and simulated daily streamflow. In dry years, the model generally overpredicts streamflow during wetting-up periods and simulates flow events in periods where none were observed. The observed baseflow component increases slowly, while the simulated baseflow rises too rapidly. The opposite is happening during drying periods, where observed streamflow decreases slowly while the simulated streamflow falls too rapidly. The simulated hydrograph during wetting-up and drying periods indicates an underestimation of the available groundwater storage. Greater groundwater storage would lead to slower filling in the wetting-up period and a longer hydrograph on the falling side. The underestimation of available groundwater storage could be related to the comparatively high precipitation in the calibration year (2004). Saturation occurred throughout this year, and groundwater storage capacity is insignificant for model performance.

Comparing the simulated and observed daily hydrographs further indicates an overestimation at the beginning of wetting-up periods. In its current status, the model seems to be unable to represent temporal variations of flow processes related to the saturation condition of the watershed. Among other reasons, this can be attributed to the curve number method implemented in SWAT, because it is mainly related to infiltration excess runoff (e.g. White *et al*., 2009), while saturation excess runoff is also important (see also Garen and Moore, 2005). Thus, the prediction of discharge during wetting-up periods is particularly challenging when using the curve number method. This means that extending the calibration period will lead to a better estimation of the available groundwater storage but not improve the model.

Table III. Summary of performance measures of grid-based *Model 1.0DD* SWAT simulations for the LRW for 2004 (calibration period) and from 2005 to 2008 (validation period)

	Streamflow [mm/a]			NSE		R^2	
Periods	Observed	Simulated	PBIAS [%]	Daily	Monthly	Daily	Monthly
Calibration	297	275	7.18	0.60	0.92	0.59	0.92
Validation	212	193	8.96	0.63	0.79	0.65	0.82
Entire period	229	210	8.50	0.62	0.81	0.63	0.83

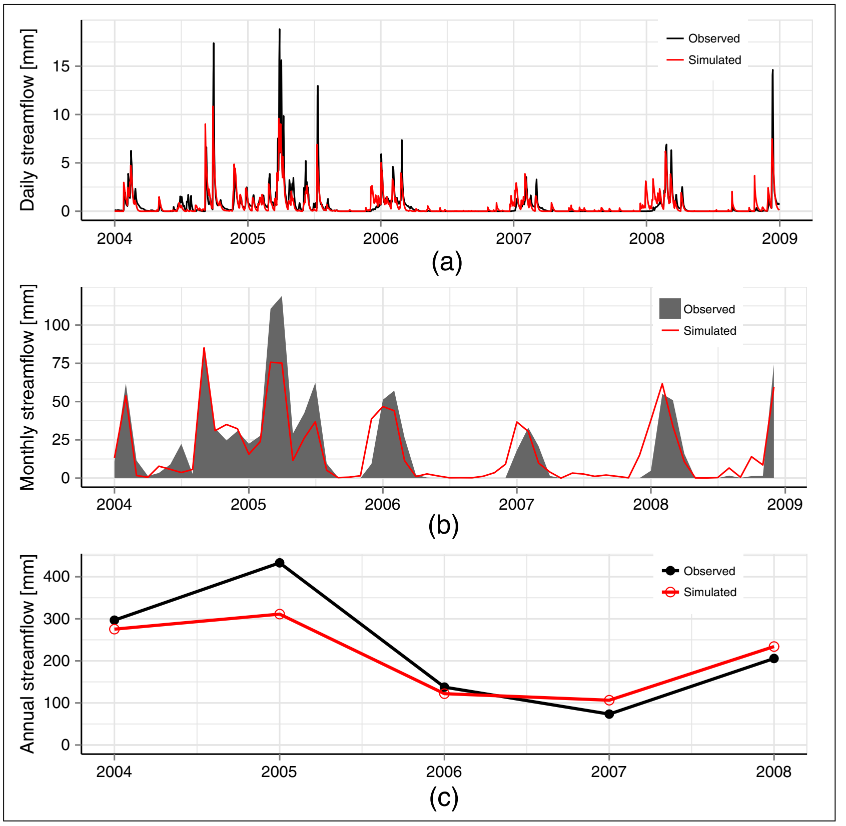

Figure 3. Observed and simulated (*Model 1.0DD*) (a) daily, (b) monthly and (c) annual total streamflow for the LRW from 2004 to 2008

The model underpredicted the observed data during parts of the year and overpredicted the observed data during other parts of the year. Thus, further calibration of the model yielded mixed results.

Another factor contributing to the error in simulated daily streamflow was the hydrograph timing, which was observed by Bosch *et al*. (2004). The simulated hydrograph peaks occur approximately 1 day prior to the observed peaks; shifting the simulated daily streamflow values 1 day forward during the entire simulation period increases NSE values from 0.62 to 0.71 and R^2 values from 0.63 to 0.73.

Figure 3b displays monthly observed and simulated discharge values. The graphs confirm the differences between simulated and observed streamflow volume during wetting-up and drying periods. The underestimation of streamflow peaks leads to an underestimation of flow volumes in wet months; the model, however, performs well in average conditions, which is confirmed by monthly NSE and R^2 values (see Table III).

The annual time series of observed and simulated streamflow for the simulation period is shown in Figure 3c. Visual comparison confirms the calculated PBIAS values. In general, the model tends to underpredict annual discharge, which is mainly caused by the underestimation of discharge peaks during wet periods.

Sensitivity of the partitioning ratio. The separation ratio of landscape and channel flow turned out to be a crucial parameter to realistically represent flow and transport processes in a watershed. The impact of the partitioning ratio on streamflow at the watershed outlet is analysed by comparing the results of *Model 1.0DD*, *Model 1.5DD* and *Model 0.5DD*. Figure 4 shows observed and daily streamflow of the three models from 1 Nov 2005 to 30 Apr 2006, a time period including wetting-up, drying, average and peak flow conditions (see also Figure 3).

Model 1.5DD has a higher share of channel flow than *Model 1.0DD*, and the hydrograph responds quickly to precipitation events. As a consequence, *Model 1.5DD* performs worse during wetting-up and drying periods but simulates streamflow peaks more accurately than *Model 1.0DD*. However, the simulated hydrograph timing is too early. *Model 0.5DD* has the lowest share of channel flow. As a consequence, water remains longer in the watershed, and streamflow rises and falls more slowly than *Model 1.0DD*. Accordingly, *Model 0.5DD* simulates discharge during wetting-up and drying periods more accurately than *Model 1.0DD* but clearly underestimates peak events.

In summary, the simulated hydrographs displayed in Figure 4 indicate that the models perform differently depending on the saturation of the watershed. *Model 0.5DD* predicts streamflow most realistically during wetting-up and

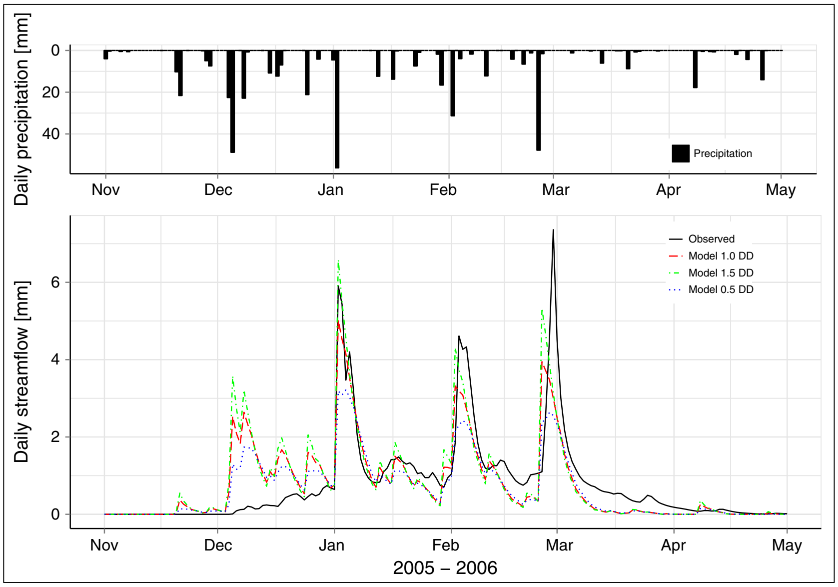

Figure 4. Precipitation and observed and simulated daily stream flows of *Model 1.0DD*, *Model 1.5DD* and *Model 0.5DD* in the LRW from 1 Nov 2005 to 30 Apr 2006

drying periods; *Model 1.5DD* realistically simulates discharge peaks when the watershed is saturated and *Model 1.0DD* shows good performance during average streamflow. These results suggest that landscape and channel flow processes in a watershed vary depending on watershed saturation on temporal scales ranging from a single storm to seasonal fluctuations. Therefore, the prediction of discharge during wetting-up periods still remains a challenge in hydrologic modelling (Piñol *et al.*, 1997; Beven and Freer, 2001).

The grid-based SWAT landscape model uses an index for flow separation that is based on the topographic index λ (Equation 1) and the drainage density (*DD*) of the watershed. Implicit in this index is the assumption of a constant upslope area (A_i) at every location in the watershed. This means the model expects downslope flow in the entire landscape, which is clearly not the case when the landscape is dry. During such periods, large amounts of rainfall may produce little or no streamflow response at the gauging stations.

Table IV shows the LRW streamflow–precipitation ratio for the first ten precipitation events after a dry period; there is almost no response to the first three events. As the wetting-up progresses, the streamflow–precipitation ratio increases before it levels off at a ratio of 0.5. The wetting-up of the watershed leads to saturation and downslope flow of water in the shallow aquifer. Further wetting will start to link unsaturated areas within the watershed. As the wetting-up period continues, the landscape becomes more saturated, the upslope areas that contribute surface and subsurface flow increase and the water yield per unit of rainfall increases in a non-linear way (see Table IV). Therefore, it is expected that the effective contributing area varies over time (see also Barling *et al.*, 1994; Piñol *et al.*, 1997; Beven and Freer, 2001) and is not ideally represented by a constant upslope area derived from the DEM. Studies from Dunne and Black (1970), Hewlett and Nutter (1970) and Dunne *et al.* (1975) confirm these results. They stated that the size of runoff generating areas varies over time with watershed saturation on temporal scales ranging from a single storm to seasonal fluctuations.

Table IV. Precipitation (P [mm]) events ≥5 mm, accumulated runoff (Q [mm]) in the 5 days following the end of the precipitation event and the ratio of Q to P for the first ten precipitation events between Nov 2005 and Mar 2006

Event no.	Date	P [mm]	Q [mm]	Q / P
1	20 Nov 2005–26 Nov 2005	31.86	0.00	0.00
2	28 Nov 2005–3 Dec 2005	12.35	0.00	0.00
3	4 Dec 2005–13 Dec 2005	95.07	1.25	0.01
4	15 Dec 2005–23 Dec 2005	30.01	3.35	0.11
5	25 Dec 2005–7 Jan 2006	86.14	28.37	0.33
6	13 Jan 2006–22 Jan 2006	26.43	12.55	0.47
7	23 Jan 2006–28 Jan 2006	8.37	5.97	0.71
8	29 Jan 2006–6 Feb 2006	53.76	21.71	0.40
9	11 Feb 2006–15 Feb 2006	12.23	6.38	0.52
10	18 Feb 2006–3 Mar 2006	61.37	31.32	0.51

In this context, the assumption of a steady drainage density can also be questioned. Moglen *et al.* (1998) reported that the drainage density is a seasonally variable parameter influenced by the climate, mainly precipitation, in the watershed. They illustrated seasonal changes in drainage density that result from sinusoidal variability in precipitation. The occurrence of zero-flow conditions confirms a seasonal variance of drainage density in the LRW. During dry periods, parts of the watershed do not produce significant downslope flow, and channel head locations are expected to move downslope. Hence, the assumptions of a steady effective upslope area and a steady drainage density limit the model's capability to accurately simulate runoff peaks and discharge during wetting-up periods. A dynamic flow separation ratio could be based on the index used in this study and additionally include a space–time representation of soil or shallow aquifer saturation, the interaction between precipitation and streamflow and dynamics of the effective upslope areas contributing to runoff generation.

Spatial analysis

A major advantage of the grid-based model is the availability of spatially distributed model output. This section evaluates spatial model output at the grid scale and analyses the impact of the flow separation ratio on the spatial distribution of model output.

Spatial model evaluation. The spatial distribution of *Model 1.0DD* output parameters shows the impact of topography, landscape position, land use classes and soil types on model output. To evaluate the grid-based SWAT landscape model, spatial distributions of surface runoff (SURQ, see Figure 5a), lateral flow (LATQ, see Figure 5b), groundwater flow (GWQ, see Figure 5c) and evapotranspiration (ET, see Figure 5d) were analysed. At this stage, the model is not spatially calibrated, so the spatial output cannot be evaluated quantitatively and was analysed qualitatively instead.

As expected, the highest SURQ values occur on the urban areas. The model simulates more surface runoff in the upland areas than in the floodplain areas adjacent to the channel network. This can be explained by the comparatively steep, mostly agricultural upland areas.

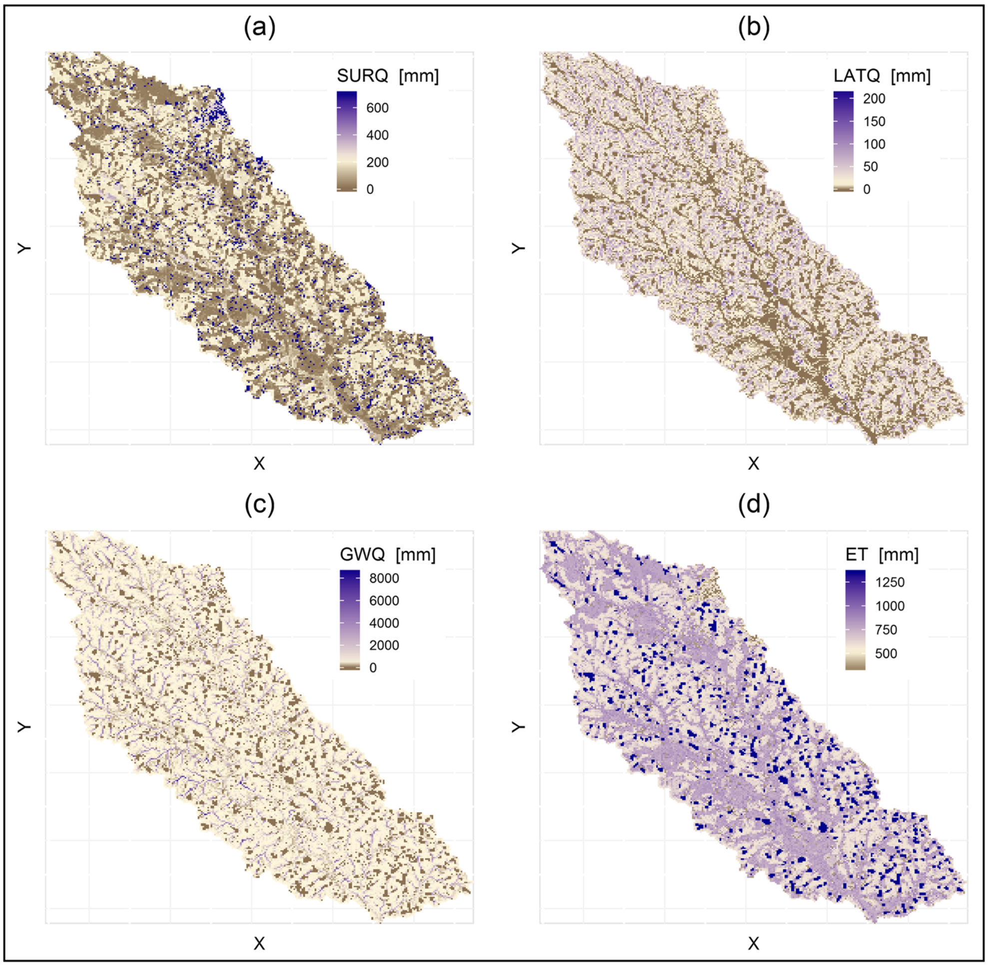

Figure 5. *Model 1.0DD* simulated average annual (a) surface runoff [mm], (b) lateral flow [mm], (c) groundwater flow [mm] and (d) evapotranspiration [mm] in the LRW from 2004 to 2008

However, sands and sandy loams with high infiltration rates dominate in these parts of the watershed, and thus, most of the water infiltrates and is not routed through the landscape as surface runoff.

The spatial patterns of LATQ and slope values are similar, and the spatial distribution of LATQ values is reasonable. The highest LATQ values occur on the steepest slopes, while almost no lateral flow occurs in the valley bottoms. In the steeper areas, the model routes the lateral flow through the landscape, whereas in the flat parts the water percolates to the shallow groundwater aquifer.

In contrast to SURQ and LATQ, GWQ patterns indicate a routing scheme. This means that the main portion of flow routed through the landscape is groundwater flow, which increases as the water moves across the watershed from the upland areas to the valleys. Groundwater flow of several upslope grid cells concentrates in grid cells located directly upslope of channel heads, before it enters the stream channel. In these grid cells, GWQ values can be extraordinarily high ($\geq$ 5000 mm) and exceed the amount of rainfall, although this only affects 55 of 330 055 grid cells in the LRW. The amount of groundwater decreases considerably as soon as the water enters a stream channel. As the topographic index λ^{a}_{DD} determines the position in the landscape where the water is passed from the land phase to the routing phase, GWQ and λ^{a}_{DD} (see Figure 5c and 2d) patterns look similar.

Considering inflow from higher landscape positions, the model produces more ET in the valley bottoms than in the upland areas. Highest ET values occur in the water and forested wetland areas around the channel network, while the urban land and agricultural areas on higher landscape positions produce less ET (see Figure 5d).

The spatial LRW model results indicate that the grid-based landscape model reasonably simulates water balance throughout the landscape. Spatial changes in the water balance are, however, not necessarily related solely to the landscape position, because they might be masked by the physical properties of soil type and land cover. This means that patterns of hydrologic model output are related to both, the landscape position itself and the different hydrological properties of soil type, geology and land cover in the landscape.

Spatial sensitivity of the partitioning ratio. To spatially analyse the impact of drainage density, channel head location and flow separation ratio on model output, differences in SURQ, LATQ, GWQ and ET between the three models (*Model 1.0DD* – *Model 1.5DD* and *Model 1.0DD* – *Model 0.5DD*) were analysed. Differences in SURQ, LATQ and ET are relatively small and occur in

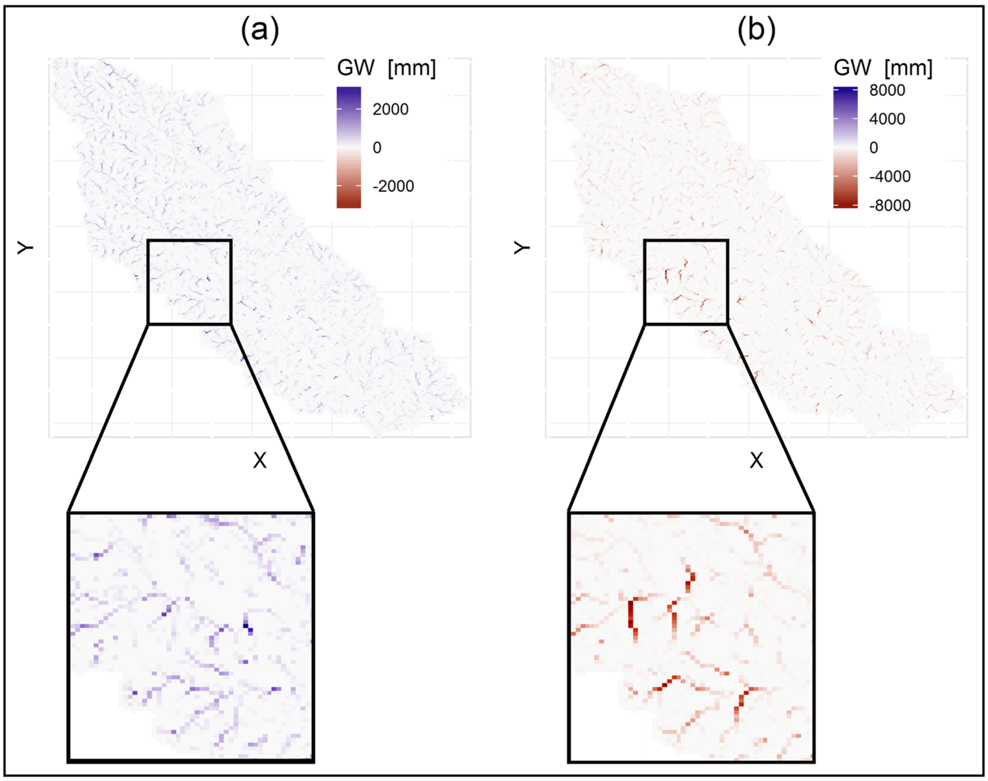

Figure 6. Differences of simulated average annual groundwater flow [mm] ((a) *Model 1.0DD* – *Model 1.5DD* and (b) *Model 1.0DD* – *Model 0.5DD*) in the LRW from 2004 to 2008

small areas. Therefore, spatial differences of SURQ, LATQ and ET are described in the text, and Figure 6 solely shows the GWQ difference maps.

In general, the *Model 1.0DD – Model 1.5DD* distributions are dominated by positive values, while the *Model 1.0DD – Model 0.5DD* patterns mainly contain negative values. The higher drainage density in *Model 1.5DD* compared to *Model 1.0DD* results in a lower share of landscape flow and larger amounts of channel flow. The higher drainage density reduces the impact of landscape processes in the watershed, and SURQ, LATQ, GWQ and ET values in *Model 1.5DD* are generally smaller than in *Model 1.0DD*. For the same reason, the *Model 1.0DD – Model 0.5DD* distributions mainly contain negative values.

The highest differences in SURQ values occur on urban and agricultural land and on steep slopes, and high LATQ differences occur at steep slopes in the upland areas. As surface and lateral flow are relatively low in the LRW, SURQ and LATQ, differences are small ($\leq$10 and 4 mm, respectively). ET differences are in the 40-mm range and mainly occur in the upland areas, where the impact of the flow separation ratio is particularly large. In contrast to the SURQ, LATQ and ET results, GWQ differences are very high (up to 8000 mm). High differences between the scenarios are due to the concentration of groundwater flow on few, relatively small grid cells (1 ha). When the drainage density decreases, channel heads move downslope, and the share of landscape groundwater flow increases (see Figure 6). Thus, differences in GWQ are strongly impacted by differences in channel head locations and indicate a routing scheme that depicts the upslope (*Model 1.0DD – Model 1.5DD*) and downslope (*Model 1.0DD – Model 0.5DD*) movement of channel head locations.

In general, the differences between the model output maps are reasonable, and the results show that the flow separation ratio is a crucial parameter for simulating the spatial distributions of surface runoff, subsurface flow processes and evapotranspiration in a watershed.

CONCLUSION

In this study, a grid-based version of the SWAT landscape model was developed to simulate processes across grid cells in the land phase of the hydrologic cycle. The fully distributed model includes surface, lateral and groundwater fluxes in each grid cell of the watershed. The model was calibrated and validated for the LRW (334 km^2) near Tifton, Georgia. The results suggest that the grid-based landscape model simulated the streamflow hydrograph at the outlet of the LRW satisfactorily which is confirmed by the performance measures. The new model predicts trends in observed data well, and previously reported discrepancies between observed and simulated streamflow, e.g. during zero-flow conditions (Bosch *et al*., 2004; Feyereisen *et al*., 2007), do not occur. However, model calibration can still be improved. Errors in the simulated streamflow can be attributed to an underestimation of streamflow peaks and an overestimation of streamflow during wetting-up periods. An additional challenge is the extensive computation time associated with the grid-based approach, which impedes model calibration.

The new model requires a spatial description of landscape and channel flow processes. For this purpose, a flow separation ratio was selected that proved to be a crucial parameter for a plausible representation of flow and transport processes in a watershed. The estimation of the partitioning ratio is based on a topographic index and considers soil properties, topography, the drainage density of the watershed and the morphology of the channel heads. The resulting index has shown the capability to plausibly represent the spatial distribution of flow and transport processes in a watershed. The proposed separation index assumes a steady drainage density and a steady size of the upslope area contributing to runoff. However, the results of this study suggest that both assumptions can be questioned. Drainage density and effective upslope contributing areas seem to vary over time with landscape saturation on temporal scales ranging from a single storm event to seasonal fluctuations. The selected separation index is able to reasonably depict spatial variations of flow and transport processes in a watershed but fails to represent their temporal variations. Comparisons between the measured and simulated hydrographs confirm that a dynamic partitioning ratio would significantly improve the model.

As the availability of spatially distributed model output is a major advantage of the grid-based model, the spatial distribution of the hydrologic components was analysed qualitatively. The spatial LRW model results indicate that the grid-based landscape model is able to reasonably simulate the impact of the landscape position on surface runoff, subsurface flow and evapotranspiration. To assess the impact of drainage density on model output, a total of three models with different drainage densities that were obtained from literature were constructed. Considerable differences in the resulting spatial distributions of flow components and evapotranspiration suggest a strong influence of drainage density and flow partitioning ratio and indicate the range of uncertainty of the proposed approach. Thus, the results presented should be considered as a rough estimate of the spatial distribution of hydrologic components and the presented methodology should be considered as a first step in the development of the grid-based SWAT model. In general, the grid-based SWAT landscape model is able to provide a plausible basis for water quantity and quality simulations when a detailed spatial analysis is required.

However, results presented in this paper are only valid for the LRW. To reduce the range of model uncertainty, additional development, calibration and testing of the grid-based SWAT landscape model at various scales with different hydrologic and landscape characteristics are necessary. Future studies will follow the stepwise testing of the model and focus on the quantitative evaluation of hydrologic components and on the validation of the proposed flow separation methodology in small scale basins. In addition, future research will include the development of a dynamic flow separation ratio and spatial model validation using remote sensing data (e.g. evapotranspiration (see Glenn *et al*., 2010; Vinukollu *et al*., 2011) or soil moisture (e.g. Cashion *et al*., 2005; Pierdicca *et al*., 2010)). As testing and development of the model are expanded, the full utility of the model will be realized.

Due to the large number of spatial units in large watersheds, computation time of the grid-based model is very long, and thus grid-based model development and application seem to be most efficient for small-scale watersheds. Furthermore, the spatial resolution of input data (climate, topography, land use, soil) is often too coarse for detailed grid-based modelling. However, GISs and remote sensing techniques develop rapidly, and an increasing amount of spatially and temporally detailed data becomes available. The integration of these data into the SWAT landscape model seems to be very promising for enhanced spatial analysis of environmental issues within a watershed.

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