Watershed Configuration and Simulation of Landscape Processes with the SWAT Model

Volk, M. [1], J.G. Arnold [2], D.D. Bosch [3], P.M. Allen [4] and C.H. Green [2]

[1] Department of Computational Landscape Ecology, UFZ Helmholtz Centre for Environmental Research, Leipzig, Germany
[2] USDA-ARS, Grassland, Soil and Water Research Laboratory, Temple, Texas, USA
[3] USDA-ARS, Southeast Watershed Research Laboratory, Tifton, Georgia, USA
[4] Department of Geology, Baylor University, Waco, Texas, USA
Email: martin.volk@ufz.de

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EXTENDED ABSTRACT

Recent and future river basin management requires a more spatially distributed description of basin hydrology and nutrient transport processes to enable land use management as a process controlling factor to realize sound river basin management. The spatial description of these processes in the Soil and Water Assessment Tool (SWAT) watershed model is presently realized by aggregating the flows from overlaid soil and land use patches in subbasins with averaged slope angles. Many concepts with different degrees of complexity have been developed in river basin modelling to aggregate units with similar hydrologic behavior (Hydrological Response Units). Watershed configuration for SWAT currently consists of: 1) subbasins defined by surface topography and 2) hydrologic response units in each subbasin to account for heterogeneity in soils and land use. The hydrologic response units do not account for landscape position within the subbasin. Until recently, many existing watershed models did not implicitly account for landscape processes within a subbasin. Other smaller scale models do account for hillslope transfer (e.g. WEPP, REMM, APEX, HYDRUS-2D).

In an attempt to account for landscape position and processes, SWAT was modified to simulate landscape units within subbasins. Surface, lateral vadose zone, and groundwater flows are routed between landscape units (while allowing for hydrologic response units within each landscape unit). Surface runoff can be overland or channelized when routed from one landscape unit to the next. The model is being tested on the USDA-ARS experimental Y-watershed at Riesel, Texas, USA, using soil moisture and groundwater data. Using GIS techniques, the watershed was divided into three landscape units - valley bottom, hillslope, and upland. Further development will include landscape unit routing of sediment and nutrients and stream interaction with the valley bottom (i.e.; riparian/flood plain landscape unit). Simulated daily stream flow at the watershed outlet after routing across the landscape units, compared well to measured flow ($R^2 = 0.7$). Mean annual lateral flows across landscape units were also realistically simulated. Soil moisture (upper 1 m) was compared to measured soil moisture at one monitoring site in each landscape unit with the model predicting drying early in the summer but following general wetting/drying cycles. The revised version of the model is also tested using data collected from a low-gradient watershed near Tifton, Georgia, USA which contains heavily vegetated riparian buffers. The modified model provided reasonable simulations of surface and subsurface flow across the landscape positions without calibration. The application demonstrates the applicability of the model to simulate filtering of surface runoff, enhanced infiltration, and water quality buffering typically associated with riparian buffer systems. Future validation will include comparison with: 1) the Riparian Ecosystem Management Model (REMM) and riparian data sets; 2) with data from larger basins with defined floodplains; and 3) watersheds having well defined variable source contributing areas. The concept assumes the controlling factors for hydrological processes and functions must be adequately described at different spatio-temporal scales to accurately delineate such response units. This requires a sound description of the characteristics by using physically based parameters and indicators, but also simplified solutions at larger scales. Presentation of the new model concept and first results of testing simulations of different aspects of catchment-related control of landscape processes, pattern hydrology, and spatially distributed modelling are discussed.

1. INTRODUCTION

Watershed models are valuable tools for examining the impact of land use on hydrology and water quality. While extensive research has been done to describe the impact of agricultural management practices on small scales (field and farm level, hillslopes or headwaters), less is known about how these changes are reflected at the watershed scale. While linkages are being developed between the micro- and meso-scale (Shaman *et al.* 2004), the lack of reliable field data limits testing to a few specific linkages such as stream chemistry or groundwater flow, but not the many other features which actually occur. However, the success of programs such as the Total Maximum Daily Load (TDML) in the United States and the European Water Framework Directive (WFD) will be based on water quality improvements that result at the watershed scale.

Recently, Wolock *et al.* (2004) have proposed a linkage between basin scales that is based on a fundamental hydrologic landscape unit. According to the authors, this unit is defined as an upland and lowland separated by a valley side slope. They assert that hydrological landscapes can be conceived as variations and multiples of this fundamental unit. Bogaart and Troch (2006) investigations into the flow processes follow a similar approach in that they indicate that an ideal catchment would be characterized into a fixed drainage network and a fixed hillslope that folds around the channel network.

The Soil and Water Assessment Tool (SWAT) has been applied to watersheds throughout the world (Arnold and Fohrer, 2005). In most cases, the prediction accuracy was satisfactory to obtain working knowledge of the hydrologic system and the processes occurring in the watersheds. One of the shortcomings of SWAT has been an inability to model flow and transport from one position in the landscape to a lower position prior to entry into the stream. The model utilizes a Hydrologic Response Unit (HRU) concept which combines a unique combination of land use and soil type within a defined subbasin. Transported water, sediment, and chemicals from the HRUs are routed directly into the stream channel. Due to the importance of the different hydrological processes and transport mechanisms related to specific landscape positions, the purpose of this study is to document a new modelling approach which links these watershed processes from the hillslope to the watershed scale using the concept of hydrological landscape units. The modification divides the catchment into three units, the upland divide, the hillslope, and the floodplain. The modified model routes surface runoff, lateral subsurface flow, and shallow ground water flow from the divide, through the hillslope, through the floodplain, and eventually to the stream. By linking these units within watersheds, processes at the micro scale can be more appropriately summed for assessment of impacts and flow regimes at the watershed scale within a reasonable programming architecture for rapid assessment of land use and management scenarios. The specific objectives of this study are: 1) to develop a simple yet realistic model for landscape processes that can be generally applied at the river basin scale, 2) incorporate the landscape model into SWAT, and 3) test it at the USDA-ARS experimental watersheds at Riesel, Texas. The revised model is also tested using data collected from a low-gradient watershed near Tifton, Georgia, USA, which contains heavily vegetated riparian buffers (Bosch *et al.* 2007).

2. CURRENT LANDSCAPE APPROACHES IN MODELS

There have been numerous attempts to simulate landscape processes at various scales with varying complexity. Merrit *et al.* (2003) and Drewry *et al.* (2006) provide excellent reviews of and references for the following and numerous other models with details on how they spatially represent the processes in a watershed. The WEPP model simulates flow and sediment transport across a hill slope using multiple overland flow elements. HYDRUS-2D uses a numerical model to route surface and subsurface flow across a hill slope. Riparian zones near a stream are simulated in REMM, which needs inputs from upland models such as GLEAMS or EPIC or observed data.

There are also several different approaches to simulating landscape processes when scaling up to watersheds. One common approach, used in TOPMODEL, AGNPS, ANSWERS, and several numerical models like MIKE SHE, is to divide the watershed into cells. This accommodates significant spatial detail but for larger watersheds does not preserve channel reaches. Another approach is to divide a watershed into subwatersheds defined by topography (typically using a DEM), ensuring all surface water within the subwatershed flows to the outlet and each subwatershed contains a channel reach for routing. Models differ on accounting for heterogeneity within each subwatershed. The WEPP watershed model assumes a representative hill slope within each subwatershed, while models like DWSM, PRMS and KINEROS use overland flow planes or segments. HSPF allows pervious and impervious areas within a subwatershed. The HRU approach of SWAT is described in sections 1 and 3.1.

3. METHODS

3.1. SWAT Model Background

SWAT (Arnold *et al.* 1998) is continuous time and operates on a daily time step. The objective in model development was to predict the impact of management on water, sediment and agricultural chemical yields of long periods in large ungaged basins. A command structure is used for routing runoff and chemicals through a watershed. Using the routing command language, the model can simulate a basin sub-divided into grid cells or subwatersheds. Additional commands have been developed to allow measured and point source data to be input and routed with simulated flows.

In SWAT, a watershed is divided into subwatersheds with unique soil/landuse characteristics called hydrologic response units (HRUs). The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile (0-2m), shallow aquifer (typically 2-20m), and deep aquifer (>20m). Flow, sediment, nutrient, and pesticide loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

3.2. Methods for Landscape Delineation

Existing methods to delineate landscape units range from simple soil considerations to complex methods using multivariate statistics and iterative segmentation algorithms to interpolate the continuous character of the landscape (MacMillan 2004). Gallant and Dowling (2003) point out, that "there are no published methods for mapping valley bottoms by automated algorithms although a number of methods exist that are designed to map floodplains". We searched for an effective but simplified solution for large-scale application and for potential integration into the SWAT. After an intensive method evaluation we selected the slope position method (USDA Forest Service 1999) as a useful method to delineate the landscape units.

The slope position of a cell is its relative position between the valley floor and the ridge top. Filling sinks and leveling peaks is the first step of the method and important to make the valleys and ridges fairly continuous. Downhill and "uphill" flow accumulation values greater than user specified limits are used to identify valleys and ridges, respectively. When large limits are used only large valleys and ridges will be identified as such, and small valleys and ridges will be considered somewhere mid-slope. Slope position is calculated for the cells in the output grid as the elevation of each cell relative to the elevation of the valley the cell flows down to and the ridge it flows up to. This is presented as a ratio, ranging from 0 (valley floor) to 100 (ridge top). Hill slope areas are represented by the values between these two ranges. Delineations in several watersheds have been validated by calculated relief amplitudes (moving window method) and soil maps of different scales.

3.3. Data

The test study site is located within the USDA-ARS Grassland, Soil and Water Research Laboratory watershed network near Riesel, TX, USA. The selected study watershed, Y2, drains 53.4 ha and includes three smaller upland subwatersheds of varying sizes between 6.6 and 8.4 ha. Convective thunderstorms during the warmer months contribute intense, short duration rainfall events. Long-term records collected at the site indicate an annual mean rainfall of 890 mm with relatively wet spring and fall seasons and drier summer and winter seasons.

Clay soils (Vertisol) dominate the site. The soil series consists of deep, moderately well-drained soils formed from weakly consolidated calcareous clays and marls and generally occurs on 1-3% slopes in upland areas. This soil is very slowly permeable when wet (saturated hydraulic conductivity = 1.52 mm/hr). However, when dry, preferential flow associated with soil cracks contributes to rapid infiltration rates. A shallow groundwater system follows local topography at an average depth of 3 meters. Recharge occurs through aerial infiltration at the outcrop.

4. DEVELOPMENT OF THE LANDSCAPE MODEL

To simulate water flow across the landscape, we propose a conceptual model similar to WEPP using a representative hill slope with landscape units within each subwatershed (Figure 1). We used the slope position method to delineate landscape units from a DEM. An example landscape unit delineation at the USDA-ARS experimental watershed in Riesel, Texas, USA, is shown in Figure 2. In this example, three landscape units were delineated: the divide, hill slope and floodplain (Figure 3). In a small watershed like Riesel, the floodplain unit would behave similar to a small stream riparian zone. The model still allows multiple hydrologic response units based on soil and land use within each landscape unit.

Surface Runoff/Run-on:
Surface runoff for each landscape unit is computed with the curve number method or the Green and Ampt infiltration equation. Run-on to an adjacent down slope landscape unit is estimated using a coefficient to partition the amount of flow that is channelized before leaving the landscape unit and the amount that is direct surface run-on. The amount of surface run-on that infiltrates is determined by multiplying the travel time by the saturated conductivity of the soil. To determine velocity and ultimately travel time, Manning's equation is used assuming a one-meter overland flow strip:

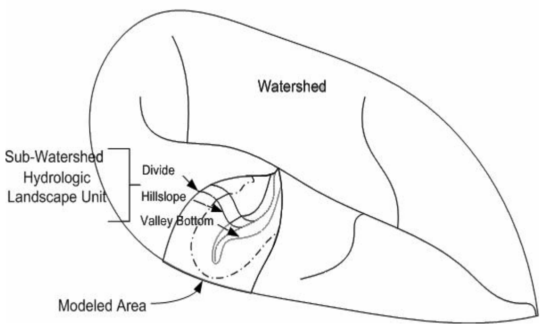

Figure 1. Subwatershed landscape delineation within a watershed.

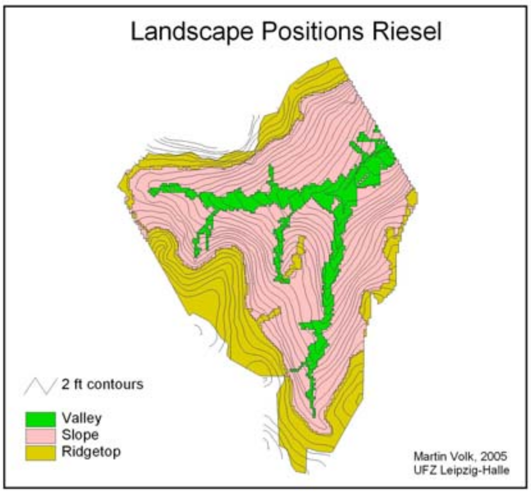

Figure 2. Landscape positions delineated at the Riesel experimental watershed.

$$V_s = (q_s)^{0.4} s^{0.3} / n^{0.6} \quad (1)$$

where q_s is the flow rate, s is slope and n is Manning's n. Then travel time (hours) is:

$$trt = sl / (3{,}600) * V_s \quad (2)$$

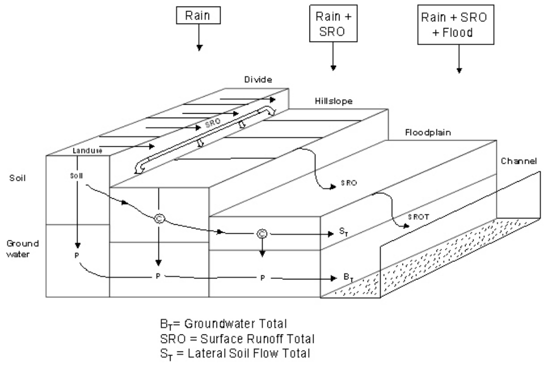

Figure 3. Processes considered in landscape routing units.

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

$$I = trt * sc \quad (3)$$

where I is infiltration and sc is saturated hydraulic conductivity.

Lateral Soil Flow:
The model accommodates multiple soil layers as required to account for vertical heterogeneity and soil horizons typically defined in U.S. soil surveys. Lateral flow volumes are calculated using a kinematic storage model (Arnold *et al.* 1998) as a function of saturated conductivity, slope, slope length, and porosity.

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}} \right) \quad (4)$$

The kinematic model also estimates surface seeps during saturated conditions, which is considered as surface run-on to the next landscape unit. Total lateral flow (summed from each soil layer) flows to the adjacent down slope landscape unit and is distributed to each soil layer weighted by depth of the soil layers. Lateral flow from the flood plain unit enters the channel.

Shallow Groundwater Flow:
Conceptually groundwater flow is simulated as routing through a series of linear storage elements as shown in Figure 4. This is the classic linear tank storage model as summarized by Brutsaert (2005) (5):

$$u(t) = \left(e^{(-t/k)}/k\right) * \left(\alpha_1/2(t/k)^2 + \alpha_2 (t/k) + \alpha_3\right)$$

where u(t) is groundwater flow at time t, k is the recession constant, and α area of each landscape unit. The recession constant, k, can be determined from analysis from daily base flow recession curves.

Interaction with Stream Channel:
Groundwater flow from the flood plain landscape unit contributes flow directly to the stream. During low flow, channel seepage or transmission losses, recharges the shallow aquifer of the floodplain unit. When over bank flow occurs, depression

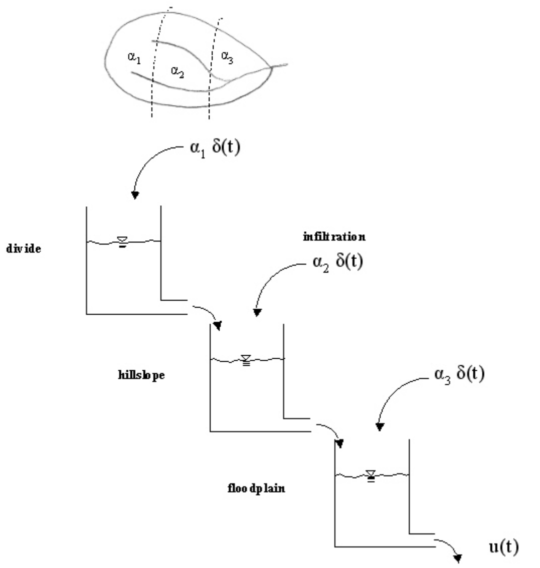

Figure 4. Linear storage elements for routing groundwater flow.

storage in the landscape unit is filled and subsequently allowed to infiltrate into the soil or evaporate.

Landscape Unit Configuration:
The example given here shows a simple three landscape unit hill slope representation on a small experimental watershed. To keep the model flexible to accommodate more complex watersheds and landscape unit configurations, we developed a command routing structure similar to the subwatershed routing used in SWAT. Four commands are used to route water through landscape units: landscape, route, add, and finish commands. The landscape command initializes the units and hydrologic response units in each, and sets the overland routing fraction. The route and add commands set the interaction between landscape units. In this example, the divide unit is routed through the hill slope unit, which is then routed through the floodplain unit. A more detailed structure can easily be accommodated using this command structure.

5. LANDSCAPE MODEL EVALUATION AT RIESEL WATERSHED

The SWAT landscape model was configured as shown in Figure 1 with one subbasin and three landscape units (divide, hillslope, and flood plain) and one HRU in each landscape unit. Soils are relatively uniform across the landscape and a Houston Black soil series was used. Slopes are relatively flat on the divide (about 1%), fairly steep on the hillslope (4%) and then flatten out in the flood plain (1%). The dominate land use was cropland on the divide, and pasture on the hillslope and flood plain. SWAT datasets were developed for the watershed and landscape units using the landscape unit configuration shown in Figure 3 and one HRU in each landscape unit.

Calibration Procedure:
Watershed Y-2 at Riesel was one of the original validation watersheds for the SWAT model and its predecessors and thus inputs had been developed and calibrated from previous studies. Also, Arnold et al. (2005) evaluated the model for watershed Y-2 and found good agreement with measured flow (R^2=0.87 and regression slope near 1.0). There were 66 measurable runoff events during the 1998-1999 period with measured runoff of 228 mm and simulated runoff of 245 mm. In this study with landscape units included, we started with inputs as they were calibrated in the 1998-1999 study and made adjustments to two inputs. Curve number was lowered by 2 and saturated conductivity of the lower soil layers was set at 30 mm/h to account for the impact of cracking on lateral soil flow.

6. RESULTS

Simulations were performed over a three year period during which soil moisture, lateral flow, and surface runoff data were jointly measured. All measurements were daily with the exception of lateral flow, which was recorded on a 2-3 day cycle. Results are described by routing structure within the model beginning with soil moisture.

Streamflow:
Regression of measured and simulated daily stream flow at gage Y-2 is shown in Figure 4. Stream flow is the sum of surface runoff and lateral soil flow as it leaves the valley bottom (landscape unit 3) and enters the channel – groundwater flow is negligible. We assume that all runoff that is channelized as it leaves the landscape unit does not infiltrate and reaches the subbasin outlet.

Mean measured and simulated daily stream flow is within 10% with a regression slope of 0.85 and R^2 = 0.70 and Nash-Sutcliffe coefficient = 0.67 (Figure 5). This is reasonable compared to other model studies comparing daily flows. In a previous

SWAT study at Riesel, for the period of 1998-1999, total flow at Y-2 was also within 10% with an $R^2 = 0.87$.

Lateral Soil Flow:

Lateral soil flow from landscape unit 2 to landscape unit 3 is compared to the hillslope seepage rates collected in the drainage trench. By adjusting the saturated conductivity of the lower

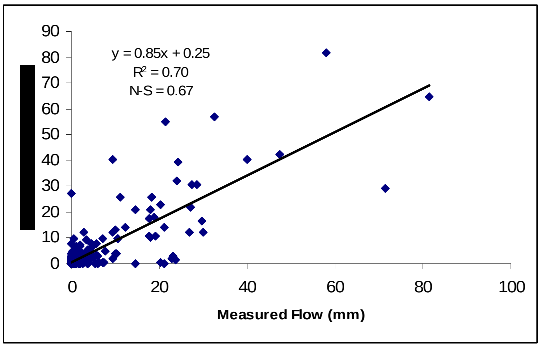

Figure 5. Measured and simulated daily streamflow at gauge Y-2.

layers to 30 mm/hr to account for crack flow, average annual measured and simulated lateral soil flow were 96 and 102 mm, respectively. However, regression of daily lateral soil flow resulted in a relatively low $R^2 = 0.20$. Figure 6 shows that ranges of peaks and recessions are realistic but the model typically overpredicts peaks. It is also important to recognized that flows are low (0-2 mm) which magnified any uncertainty or minor errors. While this needs to be addressed in future simulations, the model is routing water reasonably between the landscape units and does contribute water from divide, through the hillslope to the valley bottom. Another possible cause for the discrepancy between measured and simulated lateral flow during the three large storms was discovered after the data collection efforts. It was found the top over the collection pit had been left open and that rainwater was entering the weir pit. This may have influenced the storm volume on the days with major discrepancies as noted.

Soil Moisture:

Simulated soil moisture (total moisture for the upper 1 m) is compared against measured soil moisture at locations in each landscape unit. SWAT simulated soil moisture is printed on a daily time step while measurements were taken every 2 weeks. Results are reasonable for the divide landscape unit except in the summer of 2004 when the model predicts a significant drying while measurements suggest continued wetness into mid summer.

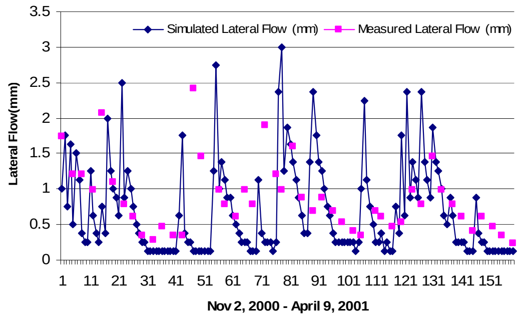

Figure 6. Measured and simulated daily lateral soil flow

The comparison for the hillslope landscape unit shows an over prediction in the winter of 2003 and under prediction of soil moisture in the early summer of 2004. The soil profile stays much dryer on the hillslope due to increased runoff and lateral soil flow caused by the steep slope; the soil is draining appropriately downslope. Similar to the divide, for the flood plain the model predicts low soil moisture in the early summer of 2004 and then overpredicts in the fall/winter. This could be caused by an overestimation of evapotranspiration in the summer growing season or by underestimating the surface runoff and lateral flow from the hillslope landscape unit. It should be noted that the soil moisture is averaged for the 1.0 meter profile and some of the discrepancies may be associated with this effect. Recent work on moisture regimes in vertisol soils at Riesel suggest that moisture levels are staying wetter at about 50 cm depth for the entire year and that the majority of flux is within the top 60 cm. Averaging values then over the whole profile will not accurately reflect these conditions.

7. CONCLUSIONS AND OUTLOOK

A landscape model was developed for simulating surface runoff, lateral soil flow, and shallow aquifer flow between landscape units. The landscape model was integrated into the SWAT watershed model and tested on the USDA-ARS Y2 experimental watershed (53.4 ha) near Riesel, Texas. In addition, a GIS based technique was developed and applied to delineate landscape units. Simulated daily stream flow at the watershed outlet after routing across the landscape units, compared well to measured flow ($R^2 = 0.7$) while mean annual lateral flows across landscape units were also realistically simulated. Soil moisture (upper 1 m) was compared to measured soil moisture at one monitoring site in each landscape unit with the model predicting drying early in the summer but following wetting/drying cycles.

The revision was developed to address variable source areas within watersheds and stream-side buffer systems which exist alongside many streams. The enhanced model will allow for more accurate simulation of natural transport processes within a hillslope. The revision was also tested using data collected from a low-gradient watershed near Tifton, Georgia, USA which contains heavily vegetated riparian buffers (Bosch *et al.* 2007). The modified model provided here reasonable simulations of surface and subsurface flow across the landscape positions without calibration. The application demonstrates the applicability of the model to simulate filtering of surface runoff, enhanced infiltration, and water quality buffering typically associated with riparian buffer systems.

Future planned development includes: 1) additional testing groundwater heights, and lateral soil flow at the Riesel Y2 watershed, 2) additional calibration and testing of the model for the USDA-ARS Gibb's Farm experimental watershed at Tifton, Georgia with "classic' riparian zones, 3) using the kinematic wave equation for overland and channel routing between landscape units, 4) incorporation of sediment and nutrient routing across the landscape. Presently, the plans are here to route firstly sediment with an overland flow and channel component across each landscape unit. Organic N and P will be routed with the sediment, and nitrates and phosphates will be assumed soluble and allowed to infiltrate as the water is routed across the units. Nitrates and phosphates will also be routed through the subsurface (soil and shallow aquifer) and denitrification will be simulated in riparian zones. Finally, 5) includes model testing on larger watersheds with defined flood plains.

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