DEVELOPMENT OF SUB-DAILY EROSION AND SEDIMENT TRANSPORT ALGORITHMS FOR SWAT

J. Jeong, N. Kannan, J. G. Arnold, R. Glick, L. Gosselink, R. Srinivasan, R. D. Harmel

ABSTRACT. *New Soil and Water Assessment Tool (SWAT) algorithms for simulation of stormwater best management practices (BMPs) such as detention basins, wet ponds, sedimentation filtration ponds, and retention irrigation systems are under development for modeling small/urban watersheds. Modeling stormwater BMPs often requires time steps as small as minutes to realistically capture the instantaneous flow and sediment load coming from upland areas. SWAT2005 uses the Modified Universal Soil Loss Equation (MUSLE) for modeling upland erosion and sediment load. The MUSLE model is an empirical soil loss equation, which was formulated based on field observations rather than theoretically derived relationships to predict long-term average soil loss. This article presents modified physically based erosion models in SWAT for seamless modeling of erosion processes with the recently developed sub-hourly flow models. In the new algorithms, splash erosion is calculated based on the kinetic energy delivered by raindrops, adapted from the European Soil Erosion Model, and overland flow erosion is estimated using a physically based equation adapted from the Areal Nonpoint-Source Watershed Environment Response Simulation (ANSWERS) model. The Yang model and the Brownlie model were also modified for in-stream sediment routing. The SWAT model with the modified sub-daily sediment algorithms was calibrated and validated each for a one-year period at 15 min intervals with measured data from the USDA-ARS Riesel watersheds in Texas. Results show that SWAT with the sub-daily algorithms performed as well or better in terms of sediment yield prediction than SWAT with the current daily output structure. In addition, SWAT (sub-daily) was able to adequately represent the timing, peak, and duration of sediment transport events. Thus, this initial evaluation indicates that the new sub-daily flow and sediment structure in SWAT is a promising tool for water quality assessment studies in small watersheds or urban watersheds where sub-daily process are so important to quantify.*

Keywords. *Sediment, Soil erosion, Sub-daily, SWAT, Watershed modeling.*

In collaboration with the city of Austin, Texas, Texas AgriLife research scientists are developing algorithms within SWAT for simulation of stormwater BMPs such as detention basins, wet ponds, sedimentation filtration ponds, and retention irrigation systems. Modeling small/urban watersheds often requires time steps as small as minutes to realistically capture the instantaneous flow and sediment load coming from upland areas. In a previous study, SWAT routines for sub-hourly flow simulation were developed to improve hydrologic modeling capabilities on small watersheds and urban/urbanizing watersheds (Jeong et al., 2010). A unit hydrograph model using the gamma distribution was added to SWAT to smoothly route surface runoff, especially for those storms with short durations and high peaks. The sub-daily flow model estimates the surface runoff lag with a first-order equation, which is a function of the simulation time interval, the time of concentration, and the surface runoff lag parameter. Ponds, reservoirs, and stream flows are also estimated at sub-hourly operational time interval.

Watershed models may be characterized as continuous or event-based depending on their time scale of simulation. Continuous models, which typically simulate long time periods up to several decades with sub-daily, daily, or larger time intervals, are efficient tools for predicting long-term catchment responses to land cover changes or soil management practices. Examples of such models include SWAT, the Annualized Agricultural Non-Point Source (AnnAGNPS) model by Bingner and Theurer (2001), the Large-Scale Catchment Model (LASCAM) by Sivapalan et al. (2002), the Simulator for Water Resources in Rural Basins (SWRRB) model by Arnold et al. (1990), and the Water Erosion Prediction Project (WEPP) model by Laflen et al. (1991).

Event-based models simulate finer time periods with intervals as small as several seconds. These models are generally formulated with physically based flow and sediment equations, and the solutions are numerically approximated. A generally recognized drawback of event-based models is the high computational cost. As a result, they are typically used

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only for small catchments. Examples of event-based models include ANSWERS (Park et al., 1982) and the European Soil Erosion Model (EUROSEM) by Morgan et al. (1998).

In SWAT, upstream erosion and sediment yield are estimated for each hydrologic response unit (HRU) with the MUSLE equation (Williams, 1975). The MUSLE equation has a number of benefits, such as good prediction accuracy, no need for a delivery ratio, and the capability of estimating sediment yield from a single storm (Neitsch et al., 2005). However, MUSLE is an empirically developed method that is typically applied for estimating long-term average erosion processes in rural watersheds and is generally not appropriate for continuous simulations with short (hourly or sub-hourly) time steps.

Therefore, our specific objective was to develop and test physically based erosion and sediment algorithms incorporated into SWAT to run with the recently developed sub-daily flow algorithms (Jeong et al., 2010) in an effort to improve SWAT simulations of small watersheds or urban watersheds. In this article, we present integration of a splash erosion algorithm, an overland flow erosion and sediment transport algorithm, and two in-stream sediment routing methods to create a new sub-daily SWAT structure. Sensitivity of newly added parameters was investigated using a global sensitivity method. Performance of the sub-daily erosion and sediment algorithms was tested on a small rural watershed in Texas by comparing estimated flow and sediment to observed values. The sub-daily output was also compared to the SWAT daily output for a relative evaluation.

Methods

To accomplish this objective, we evaluated the theory, data demands, modeling mechanism, and applicability of the currently available routines to determine which ones were best suited for SWAT. Selected models were modified and inserted as algorithms, which resulted in a new structure for sub-daily erosion and sediment processes in SWAT. In the new structure, surface runoff is calculated separately for pervious and impervious areas in each HRU. The urban buildup/washoff routine is applied to urban runoff from impervious areas, while soil erosion processes such as splash erosion apply to pervious areas. Overland flow erosion is estimated only in runoff from pervious areas. Then, the combined runoff and sediment load is routed based on the subbasin geometry (fig. 1). The erosion and sediment transport algorithms as well as in-stream sediment routing methods adapted in the sub-daily SWAT structure are described in detail below.

Erosion by Rainfall (Splash Erosion)

Splash erosion can be a significant upland erosion mechanism in short-duration, high-intensity storms. Raindrops of such flashy storms often deliver high kinetic energy to the soil surface, which detaches a large amount of soil in a short time; therefore, sub-daily simulation models need to adequately represent these processes. A splash erosion model proposed by Brandt (1990) has been widely used in rainfall-runoff simulation models such as EUROSEM. Unlike other popularly used erosion models, such as WEPP, that estimate splash erosion as a part of interrill erosion by parameterization, only EUROSEM estimates soil detachment by raindrop impact as a function of kinetic energy available to detach soil particles from the soil surface:

$$D_R = k \cdot KE \cdot e^{-\varphi h} \qquad (1)$$

where D_R is the soil detachment by raindrop impact (g m^{-2} s^{-1}), k is an index of the detachability of the soil (g J^{-1}), KE is the total kinetic energy of the rain (J m^{-2}), φ is an exponent varying from 0.9 to 3.1 with a representative value of 2.0 for a wide range of soil conditions (Torri et al., 1987), and h is surface runoff depth (mm).

Leaf drainage is a part of canopy interception that falls on the soil as water drops directly from leaf surfaces. The intercepted rainfall evaporates or becomes stem drainage and is subtracted from the total rainfall to estimate the effective rainfall. Rainfall kinetic energy is partitioned into direct through-fall and leaf drainage. The kinetic energy of leaf drainage is estimated by Brandt (1990):

$$KE_{leaf} = 15.8 H_p^{0.5} - 5.87 \qquad (2)$$

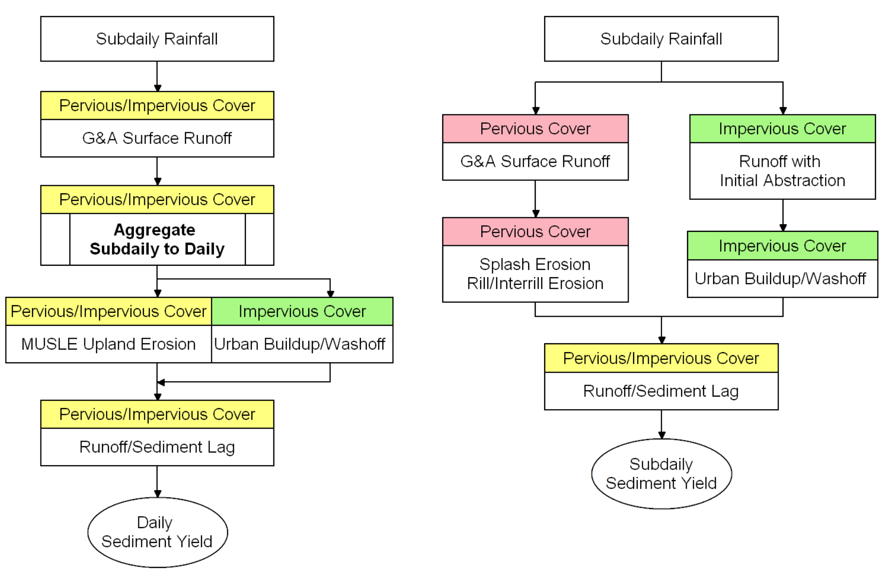

Figure 1. Schematic of sub-daily erosion processes (right) compared to daily erosion processes in SWAT2005 (left).

where KE_{leaf} is the kinetic energy of leaf drainage (J m^{-2} mm^{-1}), which is always equal to or larger than zero, and H_p is effective height of the plant canopy (m).

The kinetic energy of direct through-fall is estimated by Wischmeier and Smith (1978), which is used for rating erosivity in the Universal Soil Loss Equation (USLE):

$$KE_{direct} = 11.87 + 8.73 \log_{10} R_i \tag{3}$$

where KE_{direct} is the kinetic energy of direct through-fall (J m^{-2} mm^{-1}), and R_i is rainfall intensity (mm h^{-1}). The total kinetic energy of effective rainfall is the summation of equation 2 multiplied by the rainfall depth of leaf drainage and equation 3 multiplied by the rainfall depth of direct through-fall.

Erosion by Surface Runoff

Coupled with the splash erosion model, an overland flow erosion model in ANSWERS was adapted for the sub-hourly SWAT model to estimate rill/interrill erosion. In ANSWERS, the overland flow erosion rate is associated with the cross-sectional average bed shear stress, crop management, and soil erodibility:

$$D_F = 11.02 \alpha K_f C_f \tau^{\beta} \tag{4a}$$

where D_F is the flow erosion rate (kg m^{-2} h^{-1}), K_f is the flow erodibility factor, C_f is the crop factor (Wischmeier, 1975), α and β are calibration parameters (α may vary from 0.5 to 2.0 depending on the susceptibility of rill erosion, and β is 1.5 by default but can be as large as 3.0), and τ is the reach-average bed shear stress (N m^{-2}) defined in equation 4b:

$$\tau = \gamma \cdot h \cdot S_f \tag{4b}$$

where γ is the specific weight of water, h is the depth of overland flow, and S_f is the energy slope.

Sediment Yield from Urban Pavements

Dust, dirt, and other solids build up on urban paved surfaces during dry periods preceding a storm. The built-up solids are then washed off during storm events. Buildup is a function of time, traffic flow, dry fallout, and street sweeping (Neitsch et al., 2005). The existing buildup/washoff algorithm in SWAT, which uses the Michaelis-Menton buildup equation (Ammon, 1978) and a first-order washoff equation (Huber et al., 1988), was modified for the sub-daily algorithm. Treatment of runoff and sediment from urban pavement by urban stormwater BMPs before draining to creeks can also be simulated in SWAT.

In-Stream Sediment Routing

The SWAT model uses Bagnold's (1977) stream power function for sediment routing. The transport of sediment in the channel is controlled by deposition and degradation that occur simultaneously. The net amount of sediment re-entrained is estimated based on a channel erodibility factor, the volume of water in the channel segment, and a channel cover factor. Richardson et al. (2001) suggests that the Bagnold model works well on large rivers (width > 50 m), but the performance was less reliable on intermediate (width = 10 to 50 m) to small rivers (width < 10 m) in which stream bed materials are larger than 2 mm. Therefore, two new sediment routing models were added to SWAT for modeling intermediate to small rivers: Yang's (1996) total load equations for sand and gravel, and Brownlie's (1982) model. According to Richardson et al. (2001), Yang's model works the best on small rivers that have gravel or sandy bed materials, while Brownlie's model performs well on intermediate to small rivers. With the addition of the Yang model and the Brownlie model, estimation of potential sediment concentrations can be more accurately simulated over a wide spectrum of particle sizes.

The Brownlie Model

The Brownlie model (1982) is a numerical model for unsteady flows in channel with sediment transport that was developed based on dimensional analysis and the best fit of a set of alluvial channel observations. The general equation for the net sediment concentration in the stream is estimated by:

$$C_{ppm} = 7115\, c_F \left(F_g - F_{go}\right)^{1.978} S^{0.6601} \left(\frac{R_h}{D_{50}}\right)^{-0.3301} \tag{5a}$$

where C_{ppm} is sediment concentration (parts per million, equivalent to mg L^{-1}), S is bed slope, R_h is hydraulic radius, D_{50} is the median particle size, and c_F is a coefficient (1.268 for field data). The grain Froude number (F_g) is defined as:

$$F_g = \frac{v}{\sqrt{\left(S_g - 1\right) \cdot g \cdot D_{50}}} \tag{5b}$$

where v is flow velocity, S_g is particle specific gravity (default = 2.65 tons m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), and F_{go} is the critical grain Froude number, defined as:

$$F_{go} = 4.596\, \tau_{*o}^{\;0.5293} S^{-0.1405} \sigma_g^{\;-0.1606} \tag{5c}$$

where σ_g is the geometric standard deviation of particle sizes directly taken from field samples, and τ_{*o} is the critical dimensionless shear stress for initiation of motion estimated by the transformed Shields curve:

$$\tau_{*o} = 0.22Y + 0.06 \cdot 10^{-7.7Y} \tag{5d}$$

where $Y = \left(\sqrt{S_g - 1} \cdot R_g\right)^{-0.6}$, and R_g is the grain Reynolds number:

$$R_g = \frac{\sqrt{g D_{50}^{\;3}}}{v} \tag{5e}$$

The Yang Model

Yang's total load equations are widely accepted in sediment routing models. There are two equations to estimate sediment concentrations for sand and gravel bed materials. The sand equation is used for median particle sizes less than 2.0 mm:

$$\log C_{ppm} = 5.435 - 0.286 \log \frac{\omega D_{50}}{v} - 0.457 \log \frac{V_*}{\omega} + \left(1.799 - 0.409 \log \frac{\omega D_{50}}{v} - 0.314 \log \frac{V_*}{\omega}\right) \log\left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega}\right) \tag{6}$$

The gravel equation is used for median particle sizes between 2.0 and 10.0 mm:

$$\log C_{ppm} = 6.681 - 0.633 \log \frac{\omega D_{50}}{v} - 4.816 \log \frac{V_*}{\omega}$$

$$+\left(2.874 - 0.305 \log \frac{\omega D_{50}}{v} - 0.282 \log \frac{V_*}{\omega}\right)$$

$$\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (7)$$

In equations 6 and 7, C_{ppm} is sediment concentration in parts per million (ppm) by weight, ω is the fall velocity of sediments (m s^{-1}), D_{50} is the median particle size, ν is the kinematic viscosity of water (m^2 s^{-1}), V_* is the shear velocity (m s^{-1}), V is the stream velocity (m s^{-1}), V_{cr} is the critical velocity (m s^{-1}) to initiate erosion, and S is bed slope. In Yang's equations, the dimensionless critical velocity is given as follows:

$$\frac{V_{cr}}{\omega} = \frac{2.5}{\log \frac{V_* D_{50}}{v} - 0.06} + 0.66 \text{ for } 1.2 < \frac{V_* D_{50}}{v} < 70 \quad (8a)$$

$$\frac{V_{cr}}{\omega} = 2.05 \text{ for } \frac{V_* D_{50}}{v} \geq 70 \quad (8b)$$

Particle fall velocity is estimated by the settling velocity based on Stokes' law:

$$\omega = \frac{9.81 D_{50}{}^2 (S_g - 1)}{18 v} \quad (8c)$$

Evaluation of SWAT Sub-Daily Erosion and Sediment Transport Algorithms

The SWAT sub-daily algorithms for erosion and sediment transport were evaluated with data from watershed Y-2 at the Agricultural Research Service (USDA-ARS) Grassland, Soil and Water Research Laboratory near Riesel, Texas. The Riesel watersheds, as they are commonly called, lie within the Brushy Creek watershed in the Texas Blackland Prairie (Harmel et al., 2007). The Blackland Prairie is a stretch of fertile agricultural lands extending from San Antonio in the south to the Red River in the north. There are four subwatersheds that comprise Y-2 (fig. 2). The dominant soils are Houston Black soils, which exhibit a strong potential for shrinking and swelling, and thus have a dramatic effect on rainfall-runoff relationships (Allen et al., 2005; Harmel et al., 2006). Dominant land use in the watershed is cropping and pasture systems (Arnold et al., 2005); therefore, this research focused on evaluating erosion and sediment transport algorithms on pervious areas.

The surface runoff and erosion at the Riesel watersheds have been monitored by USDA-ARS for more than 70 years (Harmel et al., 2007). Sub-daily breakpoint data for rainfall, runoff, and sediment data were downloaded from the USDA website (www.ars.usda.gov/spa/hydro-data), and 15 min interval data were prepared based on the breakpoint values.

Flow and sediment loading at the outlet of the Y-2 watershed were calibrated to the 15 min field data for a one-year

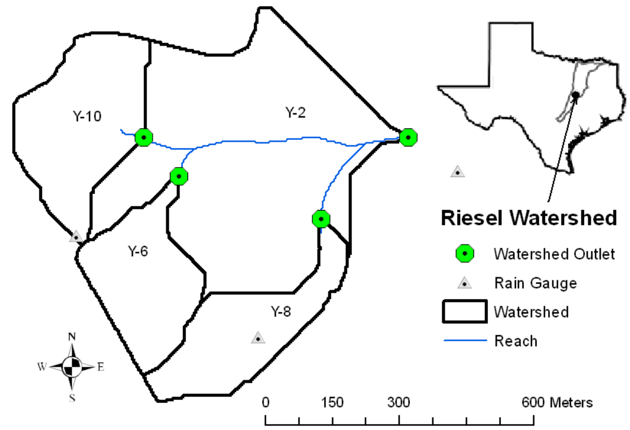

Figure 2. Experimental watersheds and rain gauges at the USDA-ARS Grassland, Soil and Water Research Laboratory near Riesel, Texas.

period (2001) and then validated for another one-year period (2002). Infiltration and runoff were estimated by the Green and Ampt equation (King et al., 1999), and evapotranspiration (ET) was calculated using the Penman-Monteith model (Neitsch et al., 2005). The average annual precipitation during the two-year study period was 1,054 mm, and water balance components as a percentage of precipitation determined based on calibrated model output were 34% surface runoff, 0.2% baseflow, 59% evapotranspiration, and the rest used for plant growth and increasing soil moisture content. In comparison, Allen et al. (2005) estimated that 25% of precipitation left the watershed as direct surface runoff and 11% as surface seepage (lateral subsurface return flow). Thus, a significant part of the water yield was contributed by surface runoff. The high content of expansive clay makes the soil almost impermeable when saturated; thus, only a small amount of baseflow might have been generated even with excess rainfall. The rainfall-runoff relationship in the Y-2 watershed was also affected by the soil such that generated runoff was sensitive to the antecedent moisture condition (Allen et al., 2005; Harmel et al., 2006). As the curve number is updated based on the daily change in soil moisture, the response of the soil to rainfall between storms within 24 h could not be adequately represented by the model.

Due to the high density in data points, model performance was evaluated by comparing sub-daily, daily, and annual predicted and observed sediment yields for two one-year periods and for two event storms from both the calibration and validation periods. Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) (NSE), coefficient of determination (R^2), and percent bias (PBIAS) values were calculated for statistical evaluation of model performance.

Sensitivity Analysis

The erosion and sediment transport models incorporated in SWAT for sub-daily predictions are physically based mechanistic models. Predicted output from these models depends on input parameters that represent local geophysical conditions. Sensitivity analysis was conducted to investigate the impact of input parameters on predicted sediment at 15 min time interval. The sensitivity of ten parameters related to the new erosion and sediment processes as described in table 1 were evaluated using the Latin hypercube sampling method incorporated with the one-factor-at-a-time analysis

Table 1. SWAT parameters used in the sensitivity analysis.

Parameter	Definition	File Name	Range of Values Min.	Range of Values Max.
CFACTOR	Cover and management factor for overland erosion	.bsn	0.001	1
CH_COV	Channel cover factor	.rte	0	1
CH_D50	Median particle diameter of channel bed (mm)	.bsn	0.001	10
CH_EROD	Channel erodibility factor	.rte	0	0.6
EROSEXPO	Exponent in the overland flow erosion equation	.bsn	1.5	3
EROS_SPL	Splash erosion coefficient	.bsn	0.9	3.1
PRF	Peak rate adjustment factor for sediment routing in the main channel	.hru	0.001	2
RILLMLT	Multiplier to USLE_K for soil susceptible to rill erosion	.bsn	0.5	2
SPCON	Linear parameter for calculating the maximum amount of sediment	.bsn	0.0001	0.001
SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	.bsn	1	2

technique (LH-OAT). These parameters are related to splash erosion, overland flow erosion, and in-stream routing erosion and sediment transport. The sub-daily SWAT model was linked to a public domain FORTRAN code developed by van Griensven and Meixner (2003) to perform the sensitivity analysis. In this method, a sensitivity index is estimated to facilitate a direct comparison of parameters by calculating the derivatives of the model output for each parameter (x_i) as a small perturbation (Δx_i) is added while other parameters are fixed:

$$S_{ij} = \frac{\dfrac{\left| M(x_1, ..., x_i + \Delta x_i, ..., x_K) - M(x_1, ..., x_i, ..., x_K) \right|}{M(x_1, ..., x_i + \Delta x_i, ..., x_K) + M(x_1, ..., x_i, ..., x_K)}}{\left| \Delta x_i \right| / x_i} \quad (9)$$

where S_{ij} is the relative partial effect of parameter x_i around LH point j, K is the number of parameters, and M is the model output. The partial sensitivity index values for x_i are averaged to produce the final sensitivity index (S_i).

Results and Discussion

The results of the sensitivity analysis are summarized in table 2. The ten parameters were ranked from 1 to 10 based on sensitivity index values for the three in-stream sediment routing methods (i.e., Bagnold, Brownlie, and Yang methods). PRF and SPCON were the most sensitive parameters when the Bagnold model was used for in-stream sediment routing. These parameters directly influence in-stream sediment calculations. Similarly, CH_D50, which is also an in-stream sediment parameter, was the most influential in the Yang model. On the other hand, CFACTOR, RILLMLT, and EROSEXPO, which are related to overland flow processes, were the most sensitive parameters in the Brownlie model.

Table 2. Sensitive sediment parameters for three routing methods as ranked by the LH-OAT method.[a]

Rank	Bagnold Model	Yang Model	Brownlie Model
1	PRF (100)	CH_D50 (100)	CFACTOR (100)
2	SPCON (46.1)	CH_EROD (8.8)	RILLMLT (82.4)
3	SPEXP (13.3)	CH_COV (4.7)	EROSEXPO (62.2)
4	EROSEXPO (0.5)	EROSEXPO (0.7)	EROS_SPL (0.04)
5	CFACTOR(0.4)	CFACTOR (0.6)	PRF (-)
6	CH_EROD (0.4)	RILLMLT (0.4)	SPCON (-)
7	CH_COV (0.3)	PRF (-)	SPEXP (-)
8	RILLMLT (0.1)	SPCON (-)	CH_COV(-)
9	EROS_SPL (-)	SPEXP (-)	CH_EROD (-)
10	CH_D50 (-)	EROS_SPL (-)	CH_D50 (-)

[a] Sensitivity indices (in parentheses) are rescaled such that the highest sensitivity index value is set to 100.

Typically, model performance is poorer for shorter time steps than for larger time steps (Moriasi et al., 2007). This result also occurred in the present analysis of sub-daily sediment modeling (table 3). Although the sub-daily SWAT predictions were "unsatisfactory" during the calibration period (NSE = 0.49) based on comparison of the 15 min predictions and measured values, it is important to note that the 15 min measured values are often in fact estimates, as many of the breakpoint data were extended to 15 min periods with no attempt to correlate flow and sediment concentration (see the flat portions of the measured sediment yields in fig. 3b). When the predictions were aggregated to a 24 h period (daily), as typically output by SWAT, the model performance improved to "very good" (NSE = 0.92), and the predicted sediment yield (1.46 ton ha^{-1}) was similar to the measured value (1.50 ton ha^{-1}). In fact, the sub-daily results in this case were better than the results produced using daily SWAT output (sediment yield = 2.89 ton ha^{-1}, NSE = 0.75). For the validation period, sub-daily SWAT predictions were

Table 3. Measured and simulated sediment yields for annual periods and storm events.

	Period	Observed Sediment (ton ha^{-1})	SWAT (sub-daily) 15 Min Output: Sediment (ton ha^{-1})	NSE	R^2	PBIAS (%)	SWAT (sub-daily) Aggregated to Daily: Sediment (ton ha^{-1})	NSE	SWAT Daily Output: Sediment (ton ha^{-1})	NSE
Annual	Calibration (2001)	1.50	1.46	0.49	0.37	2	1.46	0.92	2.89	0.75
	Validation (2002)	0.66	1.06	0.21	0.23	-59	1.06	0.16	0.69	0.29
Event	8 March 2001[a]	0.10	0.21	0.28	0.80	-105	0.21	--[b]	0.15	--
	16 December 2001	0.56	0.45	0.59	0.61	19	0.45	--	0.52	--
	21 October 2002	0.04	0.05	0.57	0.70	-16	0.05	--	0.06	--
	30 December 2002	0.12	0.16	0.85	0.89	-36	0.16	--	0.03	--

[a] Parameter values were not calibrated for each event. Instead, parameters derived from the calibration period were used unmodified.
[b] NSE values are not appropriate with only one measured and predicted value for each event.

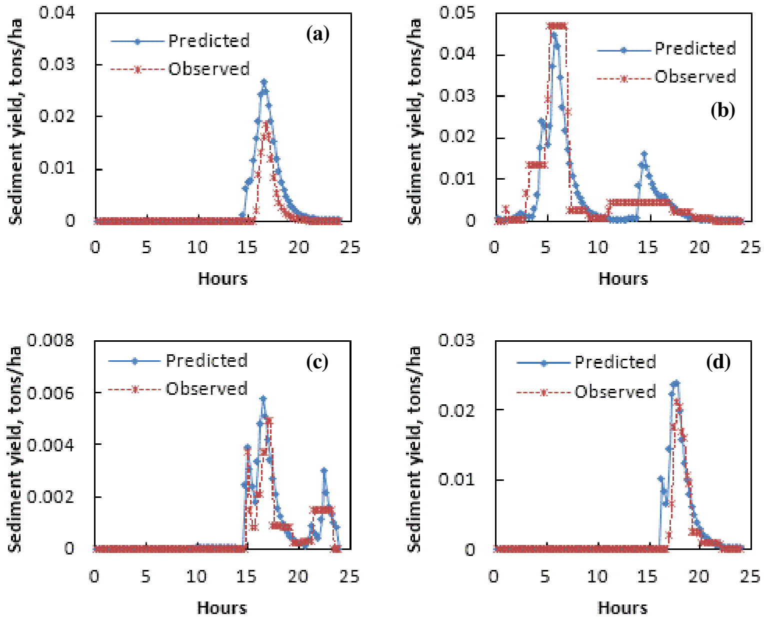

Figure 3. Calibrated sediment yield at the Y-2 outlet for events on (a) 8 March 2001, (b) 16 December 2001, (c) 21 October 2002, and (d) 30 December 2002.

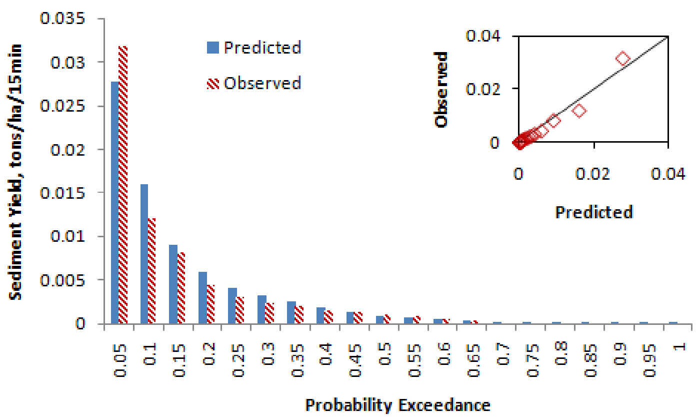

Figure 4. Exceedance probabilities for measured sediment yield data from watershed Y-2 and SWAT sub-daily predictions.

"unsatisfactory" at 15 min intervals (NSE = 0.21) and when aggregated to daily values (NSE = 0.16). However, daily SWAT output also produced "unsatisfactory" predictions (NSE = 0.29) for this period.

For the selected storm events, the 15 min predictions from the sub-daily SWAT model ranged from "unsatisfactory" to "very good" based on NSE values; however, the timing, peak, and duration of sediment production and transport seem to have been accurately simulated (fig. 3). Even for the 8 March 2001 event, which had an "unsatisfactory" model performance rating due to a small but consistent underprediction, sediment yield was very well represented by the sub-daily routines. In comparison, both the sub-daily SWAT results aggregated to daily and the daily SWAT predictions were reasonable in terms of the daily sediment yield, but these predictions offer no insight into the sub-daily processes that are so important in small/urban watersheds. On the other hand, as shown in figure 4, the simulated sediment yields for days with substantial sediment production in the two-year study were well predicted based on the probability of exceedance. This is important because the capability of reproducing sediment yield accurately for various storm events over a long-term period is crucial for a watershed-scale model. Although it was not clear in the present analysis, the differences in sediment yield for high flows may indicate a need for improvement in the sub-hourly sediment and flow routines at low flow conditions.

Summary and Conclusion

Algorithms for representing sub-daily erosion and sediment transport processes were developed and integrated into the SWAT model. The new algorithms were modified from other watershed-scale models, which means they were tested and validated in part before being modified for SWAT. In this new sub-daily SWAT structure, splash erosion is modeled based on the kinetic energy delivered by raindrops, and overland flow erosion is estimated by a physically based algorithm that considers rill and interrill erosion. Options for simulating in-stream sediment were also added to the model specifically for simulating intermediate to small river basins. With these modified algorithms, SWAT performed well in predicting sediment loads in individual events during a long-term simulation without specific storm-by-storm calibration. Based on the results on the Riesel watershed at Y-2, it can be concluded that: (1) the new physically based sub-daily erosion and sediment transport algorithms in SWAT may represent an important enhancement for simulations conducted at sub-daily time intervals, which are often important in projects on small/urban watersheds; (2) in-stream parameters influence sediment output more than overland flow erosion and sediment parameters in both the Bagnold model and the Yang model, but the opposite is true in the Brownlie model; and (3) more evaluation is needed to better assess SWAT's sub-daily erosion and sediment transport predictions at various spatial and temporal scales and under other watershed conditions.

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References

Allen, P., R. D. Harmel, J. Arnold, B. Plant, J. Yelderman, and K. King. 2005. Field data and flow system response in clay (vertisol) shale terrain, north central Texas, USA. *Hydrol. Proc.* 19(14): 2719-2736.

Ammon, D. C. 1978. Urban stormwater pollutant buildup and washoff relationships. MS thesis. Gainesville, Fla.: University of Florida.

Arnold, J. G., J. Williams, A. Nicks, and N. Sammons. 1990. SWRRB: A Basin-Scale Simulation Model for Soil and Water Resources Management. College Station, Tex.: Texas A&M University Press.

Arnold, J., K. Potter, K. King, and P. Allen. 2005. Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. *Hydrol. Proc.* 19(3): 589-603.

Bagnold, R. 1977. Bed load transport by natural rivers. *Water Resources Res.* 13(2): 303-312.

Bingner, R. L., and F. D. Theurer. 2001. AnnAGNPS technical processes: Documentation version 2. Unpublished report. Oxford, Miss.: USDA-ARS National Sedimentation Laboratory.

Brandt, C. J. 1990. Simulation of the size distribution and erosivity of raindrops and throughfall drops. *Earth Surface Proc. and Landforms* 15(8): 687-698.

Brownlie, W. 1982. Prediction of flow depth and sediment discharge in open channels. PhD diss. Pasadena, Cal.: California Institute of Technology.

Harmel, R. D., C. W. Richardson, K. W. King, and P. M. Allen. 2006. Runoff and soil loss relationships for the Texas Blackland Prairie ecoregion. *J. Hydrol.* 331(3-4): 471-483.

Harmel, R. D, J. Bonta, and C. Richardson. 2007. The original USDA-ARS experimental watersheds in Texas and Ohio: Contributions from the past and visions for the future. *Trans. ASABE* 50(5): 1669-1675.

Huber, W. C., R. E. Dickinson, and T. O. Barnwell Jr. 1988. Storm water management model. Version 4. Washington, D.C.: U.S. Environmental Protection Agency.

Jeong, J., N. Kannan, J. Arnold, R. Glick, L. Gosselink, and R. Srinivasan. 2010. Development and integration of sub-hourly rainfall-runoff modeling capability within a watershed model. *Water Resources Mgmt.* 24(15): 4505-4527.

King, K. W., J. G. Arnold, and R. L. Bingner. 1999. Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT. *Trans.* ASAE 42(4): 919-925.

Laflen, J. M., L. J. Lane, and G. R. Foster. 1991. WEPP: A new generation of erosion prediction technology. *J. Soil and Water Cons.* 46(1): 34-38.

Morgan, R. P. C., J. N. Quinton, R. E. Smith, G. Govers, J. W. A. Poesen, K. Auerswald, G. Chisci, D. Torri, and M. E. Styczen. 1998. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Proc. and Landforms* 23(6): 527-544.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrol.* 10(3): 282-290.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2005. *Soil and Water Assessment Tool Theoretical Documentation*. Temple, Tex.: Grassland, Soil and Water Research Laboratory.

Park, S. W., J. K. Mitchell, and J. N. Scarborough. 1982. Soil erosion simulation on small watersheds: A modified ANSWERS model. *Trans. ASAE* 25(6): 1581-1588.

Richardson, E., D. Simons, and P. Lagasse. 2001. *River Engineering for Highway Encroachments: Highways in the River Environment*. Publication No. FHWA NHI 01-004. Washington, D.C.: U.S. Department of Transportation, Federal Highway Administration.

Sivapalan, M., N. Viney, C. Zammit, V. Singh, and D. Frevert. 2002. LASCAM: Large-scale catchment model. In *Mathematical Models of Large Watershed Hydrology*, 579-648. Highlands Ranch, Colo.: Water Resources Publications.

Torri, D., M. Sfalanga, and M. Del Sette. 1987. Splash detachment: Runoff depth and soil cohesion. *Catena* 14(1-3): 149-155.

van Griensven, A., and T. Meixner. 2003. LH-OAT Sensitivity Analysis Tool. Tucson, Ariz.: University of Arizona, Department of Hydrology and Water Resources. Available at: http://sahra.arizona.edu/cgi-bin/hydroware/hydroware.pl?mode=displayCat&CAT1=4&CAT2=4.

Williams, J. 1975. Sediment-yield prediction with universal equation using runoff energy factor. In *Proc. Sediment Yield Workshop: Present and Prospective Technology for Predicting Sediment Yields and Sources*, 244-252. Washington, D.C.: USDA-ARS.

Wischmeier, W. 1975. Estimating the soil loss equation's cover and management factor for undisturbed areas. In *Proc. Sediment Yield Workshop: Present and Prospective Technology for Predicting Sediment Yield and Sources*, 118-124. Washington, D.C.: USDA-ARS.

Wischmeier, W., and D. Smith. 1978. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*. Washington, D.C.: USDA Science and Education Administration.

Yang, C. 1996. *Sediment Transport: Theory and Practice*. New York, N.Y.: McGraw-Hill.