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MODELING STREAMBANK EROSION ON COMPOSITE STREAMBANKS ON A WATERSHED SCALE

A. R. Mittelstet
University of Nebraska-Lincoln, amittelstet2@unl.edu

D. E. Storm
Oklahoma State University

G. A. Fox
Oklahoma State University

P. M. Allen
Baylor University

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ABSTRACT. *Streambanks can be a significant source of sediment and phosphorus to aquatic ecosystems. Although the streambank-erosion routine in the Soil and Water Assessment Tool (SWAT) has improved in recent versions, the recently developed routine in SWAT 2012 has undergone limited testing, and the lack of site or watershed specific streambank data increases the uncertainty in the streambank-erosion predictions. There were two primary objectives of this research: (1) modify and test the 2012 SWAT streambank-erosion routine on composite streambanks, and (2) compare SWAT default and field-measured channel parameters and assess their influence on predicted streambank erosion. Three modifications were made to the SWAT 2012 streambank-erosion routine: (1) replacing the empirical effective shear stress equation with a process-based equation, (2) replacing bankfull width and depth measurements with top width and streambank height, and (3) incorporating an area-adjustment factor to account for non-trapezoidal cross-sections. The proposed streambank-erosion routine was tested on gravel-dominated streambanks on the Barren Fork Creek in northeastern Oklahoma. The study used data from 28 cross-sectional surveys, including streambank height and top width, side slope, thickness and texture of streambank layers, and an area-adjustment factor. Gravel d_{50} and k_d-τ_c relationships were used to estimate the critical shear stress (τ_c) and the erodibility coefficient (k_d), respectively. Incorporating the process-based shear stress equation, area-adjustment factor, or the top width and streambank height increased predicted streambank erosion by 85%, 31%, and -30%, respectively. Incorporating the process-based effective shear stress equation, sinuosity, radius of curvature, and measured bed slope improved the predicted versus observed streambank erosion Nash-Sutcliffe efficiency from -0.33 to 0.49 and the coefficient of determination (R^2) from 0.02 to 0.65 at the ten study sites. Although the process-based effective shear stress equation was the most influential modification, incorporating the top width, streambank height, and area-adjustment factor more accurately represented the measured irregular cross-sections.*

Keywords. *Composite streambanks, Fluvial erosion, Streambank erosion, SWAT.*

Sediment is a primary pollutant to surface waters and the fifth leading cause of water quality impairment in the U.S. (USEPA, 2015). Although erosion is a natural process, the rate of erosion has been accelerating due to anthropogenic activities, such as farming and urbanization. Although surface erosion from agricultural fields, deforestation, and construction sites is often the dominant source, streambank erosion can be the largest contributor of sediment in some watersheds (Simon and Darby, 1999; Simon et al., 2002; Wilson et al., 2008). Streambank erosion has been observed to increase 10 to 15 times with the advent of European settlement. The percentage of erosion in a watershed derived from streambanks ranges from 37% to 92% (Simon et al., 1996; Walling et al., 1999). Excess sediment in streams and reservoirs reduces water clarity (Neupane et al., 2015), diminishes aesthetic quality (Pfluger et al., 2010), increases water treatment costs (Dearmont et al., 1998), and has an overall negative impact on aquatic ecosystems (Lloyd, 1987).

Although streambank erosion can contribute a significant quantity of sediment and phosphorus to stream systems (Kronvang et al., 2012; Miller et al., 2014a), most watershed-scale models are limited in their ability to predict streambank erosion accurately (Merritt et al., 2003). The two primary model types used to predict streambank erosion are empirical and process-based (Lai et al., 2012). Empirical models, those that predict erosion based on data alone, are limited to the conditions where the data were measured (Narasimhan et al., 2017). Process-based models simulate the streambank erosion processes, i.e., fluvial erosion and mass wasting. While process-based models, such as the Bank Stability and Toe Erosion Model (BSTEM; Gibson, 2013; Daly et al., 2015b) and Conservation Channel Evolution and Pollutant Transport System (CONCEPTS; USDA-ARS, 2000), estimate erosion on a single cross-section or reach (Staley et al., 2006), data requirements at the watershed scale are vast and often not available. In order to estimate streambank erosion for an entire watershed with relatively simple inputs, the Soil and Water Assessment Tool

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The authors are **Aaron R. Mittelstet, ASABE Member,** Assistant Professor, Department of Biological Systems Engineering, University of Nebraska, Lincoln, Nebraska; **Daniel E. Storm, ASABE Member,** Professor, and **Garey A. Fox, ASABE Member,** Professor and Buchanan Chair, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma; **Peter M. Allen, ASABE Member,** Professor, Department of Geology, Baylor University, Waco, Texas. **Corresponding author:** Aaron R. Mittelstet, 245 L.W. Chase Hall, University of Nebraska, Lincoln, NE 68586; phone: 402-472-1427; e-mail: aaron.mittelstet10@okstate.edu.

(SWAT; Arnold et al., 1998) uses both process-based and empirical equations. Thus, SWAT provides a semi-empirical approach to model the physical processes involved in streambank erosion that may be more practical for use on large watersheds also requiring the simulation of upland processes.

BACKGROUND

SWAT 2009 STREAMBANK-EROSION ROUTINE AND PARAMETER ESTIMATION

The current streambank-erosion routine in SWAT 2009 (Neitsch et al., 2011) only permits streambank erosion if there is sufficient transport capacity and after the deposited sediment from the previous time step is removed (table 1). The routine uses an excess shear stress equation (Partheniades, 1965; Neitsch et al., 2011) to calculate streambank erosion rate (ε, m s^{-1}), given as:

$$\varepsilon = k_d(\tau_e - \tau_c) \quad (1)$$

where k_d is an erodibility coefficient (cm^3 N-s^{-1}), τ_e is an effective shear stress (N m^{-2}), and τ_c is the soil's critical shear stress (N m^{-2}). The k_d and τ_c coefficients are functions of numerous soil properties. SWAT estimates τ_c based on silt and clay content (Julian and Torres, 2006) using the following equation:

$$\tau_c = 0.1 + 0.1779SC + 0.0028SC^2 - 0.0000235SC^3 \quad (2)$$

where SC is the percent silt and clay content. SWAT predicts k_d using the relationship proposed by Hanson and Simon (2001) based on 83 *in situ* jet erosion tests:

$$k_d = 0.2\tau_c^{-0.5} \quad (3)$$

Effective shear stress is calculated using the following empirical equations (Eaton and Millar, 2004):

$$\frac{\tau_e}{\gamma ds} = \frac{SF_{bank}}{100}\left(\frac{(W + P_{bed})\sin\theta}{4d}\right) \quad (4)$$

$$\log(SF_{bank}) = -1.40\log\left(\frac{P_{bed}}{P_{bank}} + 1.25 + 2.25\right) \quad (5)$$

where SF_{bank} is the proportion of shear force acting on the bank (N m^{-2}), γ is the specific weight of water (9800 N m^{-3}), d is the depth of water in the channel (m), W is the top width of the channel (m), P_{bed} is the wetted perimeter of the bed (m), P_{bank} is the wetted perimeter of the channel bank (m), θ is the angle of the channel bank from horizontal, and s is the slope of the channel (m m^{-1}).

SWAT uses a digital elevation model (DEM) to define the stream network and estimate bed slope and drainage area. The model uses a default channel side slope of 2:1 (26.6°) and regression equations to estimate bankfull parameters (Neitsch et al., 2011). Currently, the following global equations are used worldwide to estimate bankfull width (BW) and bankfull depth (BD):

$$BW = 1.278DA^{0.6004} \quad (6)$$

$$BD = 0.1291DA^{0.4004} \quad (7)$$

where BW and BD are in meters, and DA is the drainage area (km^2). BW and BD are the average width and depth measured at bankfull discharge, which is defined as the dominant channel-forming flow.

The current streambank-erosion routine has several limitations. Although streambanks on the outside of a meander experience more shear stress (Sin et al., 2012) and erosion (Purvis and Fox, 2016; Fox et al., 2016), the current routine does not account for the sinuosity of the stream system. In addition, the routine that redefines channel dimensions after streambank erosion occurs needs further work. Therefore, most users assume a balance between erosion and deposition at a cross-section, and thus channel dimensions remain constant. Unlike BSTEM and CONCEPTS, which simulate multiple bank layers and mass wasting, SWAT assumes a uniform bank and only considers fluvial erosion. Modeling only one layer can be inaccurate if the τ_c and k_d values of a multilayer streambank are different. In addition, ignoring mass wasting of a cohesive layer may lead to underpredicting streambank erosion, especially during rainfall events when the top cohesive layer becomes saturated and unstable (Fox and Wilson, 2010). Large-scale hydrological models require many assumptions and simplifications since data are often unavailable. Some assumptions in SWAT include average shear stress on the bank, BW and BD accurately represent the channel dimensions, defined channel parameters represent the entire reach, and the channel is homogeneous and symmetrical.

SWAT 2012 STREAMBANK-EROSION ROUTINE

The SWAT 2012 routine (Narasimhan et al., 2017), not yet available to the public, uses an excess shear stress equation to predict streambank and bed erosion. To simplify the channel erosion processes and calculations, the model assumes excess transport capacity (table 1). The effective shear stress is adjusted based on the radius of curvature and sinuosity of the reach. The maximum effective shear stress occurs on the outside of the meander and increases with increasing sinuosity. Sin et al. (2012) developed a dimensionless multiplication bend factor to adjust the effective shear stress on the meander, which was the ratio of the maximum shear stress experienced at the bends divided by the average

Table 1. Streambank and bed erosion processes and equations for SWAT 2009, SWAT 2012, and the proposed SWAT 2012 routines.

Process	SWAT 2009	SWAT 2012	Proposed SWAT 2012
Channel erosion	Excess shear stress	Excess shear stress	Excess shear stress
Transport capacity	Yes	None	None
Effective shear stress	Empirical equations 4 and 5	Empirical equations 4 and 5	Process-based equations 11 and 12
Sinuosity	None	Yes	Yes
Channel dimensions	Bankfull width/depth	Bankfull width/depth	Top width/bank height
Cross-section heterogeneity	None	None	Area-adjustment factor

channel shear. The dimensionless bend factor (K_b) is estimated using (Sin et al., 2012; Narasimhan et al., 2017):

$$K_b = 2.5\left(\frac{R_c}{W}\right)^{-0.32} \quad (8)$$

where R_c is the radius of curvature (m), and W is the top width of the channel (m). The R_c is estimated using the empirical relationship based on several studies and has a wide range of applicability over widths ranging from 1.5 to 2,000 m (Williams, 1986), given as:

$$R_c = 1.5W^{1.12} \quad (9)$$

The maximum effective shear stress on the outside of the meander (τ_e^*) is calculated using:

$$\tau_e^* = K_b \tau_e \quad (10)$$

To calculate the total mass of sediment eroded from streambanks, the channel is divided into straight and meandering reaches. The length of the reach affected by meandering is calculated using the inverse of the sinuosity, i.e., ratio of channel length to the straight-line length, which is then multiplied by K_b, while the straight section uses a K_b equal to one. For the meandering section of a reach, erosion is only calculated for the critical bank, while both banks are eroded for the straight section.

Objectives

The SWAT 2012 channel erosion routine has only been tested on cohesive soils in the Cedar Creek watershed in north-central Texas with lateral bank erosion rates ranging from 0.025 to 0.37 m year^{-1} (Narasimhan et al., 2017). Although this routine addresses some of the SWAT 2009 model limitations, several additional limitations and assumptions remain. Therefore, this study aims to propose modifications and test the SWAT 2012 routine before it is incorporated into the official SWAT release and used by watershed modelers worldwide. Three modifications to the SWAT 2012 channel erosion routine were proposed and tested on the Barren Fork Creek watershed in eastern Oklahoma.

At watershed scale, site-specific streambank data are typically limited, both spatially and temporally. While stream reaches range in length from a few hundred meters to several kilometers, only one value for each parameter is used to characterize the reach in SWAT. Gathering data for channel parameters by reach is a daunting task and is not feasible for most projects; therefore, the most critical parameters need to be identified to focus data collection efforts. Although there is considerable uncertainty in stream channel parameters (Chaubey et al., 2005; Wechsler, 2007; Bieger et al., 2015), no study has compared field-measured to SWAT-derived parameters and their influence on streambank erosion predictions.

The objectives of this research were to (1) modify and test the SWAT 2012 streambank-erosion routine on gravel-dominated streambanks and (2) compare SWAT default to field-measured channel parameters and assess their influence on streambank-erosion predictions. Results of this study will improve the SWAT 2012 streambank-erosion routine, provide recommendations to optimize data collection and parameter estimation efforts on the most critical streambank-erosion parameters, and improve the accuracy of model predictions of streambank erosion.

Methods

SWAT Streambank Erosion Modifications

Three proposed modifications were made to the SWAT 2012 streambank-erosion routine to address some of the model's current limitations. First, the empirical effective shear stress equations (eqs. 4 and 5) were replaced with the process-based equations (eqs. 11 and 12) given below. The second modification replaced *BW* and *BD* with *W* and *SBH*. Finally, the third modification added an area-adjustment factor to account for heterogeneous stream channel cross-sections (table 1). In addition to these three modifications to the streambank-erosion routine, alternative methods were used to calculate τ_c based on the d_{50} of the gravelly streambank layer, and bankfull parameters.

To accurately predict streambank erosion, an accurate estimate of the effective shear stress is essential. Currently, SWAT uses empirical equations derived from laboratory studies using symmetrical trapezoidal channels (Eaton and Millar, 2004), which may not be applicable to *in situ* conditions that differ from the conditions for which the equations were developed. The proposed equation is process-based and used by CONCEPTS (USDA-ARS, 2000):

$$\tau = \gamma R S_f \quad (11)$$

where R is the hydraulic radius (m), and S_f is the friction slope (m m^{-1}). The S_f is computed using the following equation:

$$S_f = \frac{n^2 Q^2}{A^2 R^{\frac{4}{3}}} \quad (12)$$

where Q is the average flow rate (m^3 s^{-1}), n is Manning's roughness coefficient, and A is the channel cross-sectional area (m^2).

SWAT currently assumes a symmetrical trapezoidal channel cross-section with dimensions derived from *BW* and *BD*. There are two primary reasons to replace these bankfull parameters with *W* and *SBH*. First, identifying and measuring *BW* is subjective and thus carries considerable uncertainty (Johnson and Heil, 1996). Second, bankfull estimates are often less than the top width and streambank height, thus resulting in inaccurate streamflow depth predictions (fig. 1). In summary, replacing bankfull parameters with *W* and *SBH* defines the simulated flow conditions more accurately.

To accurately model streambank erosion, channel dimensions must represent the studied stream system. Although the current SWAT model is constrained by its symmetrical trapezoidal channel cross-section, a simple area-adjustment factor to account for a heterogeneous channel cross-section is proposed (fig. 2). No natural channel is symmetrical with a

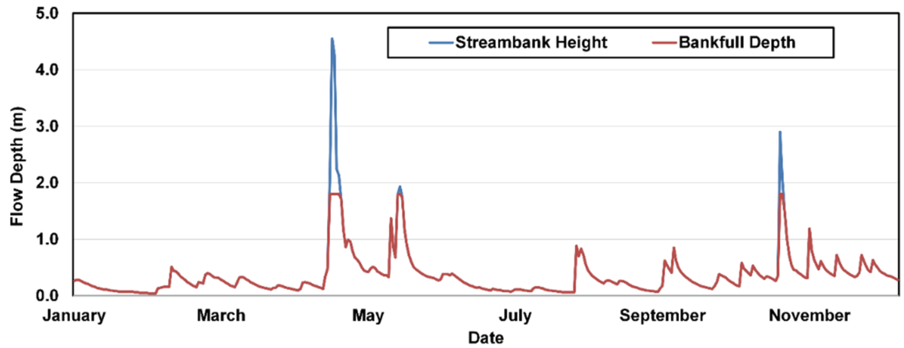


Figure 1. SWAT-simulated flow depth using both bankfull depth and streambank height to define the channel cross-section on the Barren Fork Creek for 2011.

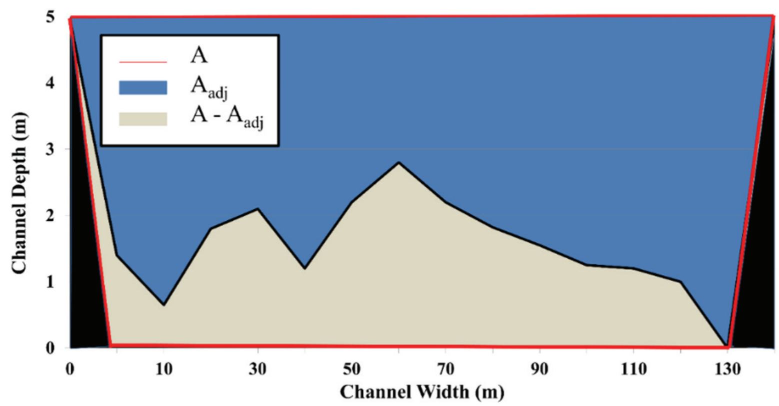


Figure 2. Example SWAT trapezoidal (*A*) and measured (*A_{adj}*) stream cross-section at the USGS gauge station near Eldon, Oklahoma (07197000) used to adjust cross-sectional area and calibrate flow depth. *A_{adj}* is the measured cross-sectional area of the natural irregular channel, *A* is the cross-sectional area of an assumed trapezoidal channel, and *$A - A_{adj}$* is the difference between the two cross-sections.

flat and level streambed; thus, assuming a trapezoidal channel will result in errors in predicting flow depth. The proposed area-adjustment equation is:

$$A_{adj} = aA \tag{13}$$

where A_{adj} is the adjusted channel cross-sectional area (m^2), A is the trapezoidal cross-sectional area (m^2), and a is a dimensionless area-adjustment factor ($a \leq 1.0$). Given a surveyed channel transect, the value of a is calculated by dividing the measured irregular cross-sectional area by the trapezoidal area. The trapezoidal area is calculated using the SWAT input for top width of the channel (W), streambank height (SBH), and side slope.

Measured d_{50} coupled with an alternative τ_c equation (Millar, 2005) was used to estimate τ_c for the streambank gravel layer using the following algorithm developed specifically for non-cohesive gravel particles (Millar, 2005):

$$\tau_c = 0.05\tan(\varphi)\rho g(SG-1)d_{50}\sqrt{1-\frac{\sin^2\theta}{\sin^2\phi}} \tag{14}$$

where ρ is the density of water (1000 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), SG is the specific gravity of the bank soil (assumed to be 2.65 for all soils), d_{50} is the median particle diameter of the soil (m), ϕ is the angle of repose (degrees), and θ is the bank angle (Daly et al., 2015a, 2015b). The average measured bank angles for the 28 cross-sections were used as input to this equation. Although equation 3 was derived from cohesive soils, SWAT uses this equation to calculate k_d for both cohesive and gravel-dominated streambanks. Furthermore, the equation was successfully used for gravel layers at similar sites by Midgley et al. (2012) and Daly et al. (2015b). Research is needed to derive k_d for gravel-dominated soils.

Only two equations are used by SWAT 2012 to estimate BW and BD, although studies have shown that the use of regional curves can improve bankfull predictions considerably (Bieger et al., 2015). Therefore, bankfull parameters were estimated using the results of Bieger et al. (2015), which were developed using compiled BW and BD data from 51 studies across the U.S., one equation for the entire U.S., and eight regional equations based on physiographic divisions. The equations for the entire U.S. (BW_{us} and BD_{us}, m) are (Bieger et al., 2015):

$$BW_{US} = 2.70DA^{0.352} \tag{15}$$

$$BD_{US} = 0.30DA^{0.213} \tag{16}$$

where DA is drainage area (km^2).

Dutnell (2000) developed regional equations for the Internal Highland Region (IHR), which includes the Barren Fork Creek (BW_{IHR} and BD_{IHR}, m), as:

$$BW_{IHR} = 23.23DA^{0.121} \tag{17}$$

$$BD_{IHR} = 0.27DA^{0.267} \tag{18}$$

Study Site

The streambank-erosion routine was tested on ten composite streambanks in the Barren Fork Creek watershed, located in the Ozark Highland Ecoregion in northeast Oklahoma and northwest Arkansas (fig. 3). The watershed has a drainage area of 890 km^2 and is composed of 55% forest, 30% pasture, and 13% hay meadow (Mittelstet et al., 2016). The Barren Fork Creek, a fourth-order stream, is approximately 73 km in length. The headwaters begin in Washington County, Arkansas, and flow through Adair County, Oklahoma, before discharging into the Illinois River in Cherokee County, Oklahoma, just north of Tenkiller Ferry Lake. Barren Fork Creek is a State of Oklahoma designated Scenic River and is on the Oklahoma 303(d) list for nutrient and sediment impairments (USEPA, 2015). Typical of the Ozark Highland Ecoregion, the watershed is characterized by cherty soils and gravel-bed streams (Mittelstet et al., 2011). Due to land cover changes and deforestation, gravel has eroded from the upland areas throughout the Barren Fork Creek watershed. Much of this gravel has reached the Barren Fork Creek, resulting in changes in the channel dimensions and flow dynamics. The streambanks consist of a fining upward sequence of basal gravels and overlying silts and clays derived from overbank deposition (fig. 4). The gravel layer makes up 44% to 79% of the total bank (Miller et al., 2014b). Miller et al. (2014a) found that streambank erosion was a significant P source in the Barren Fork Creek, and 36% of the streambanks in the watershed were unstable and eroding. Reported lateral streambank erosion rates range from 0.5 to 8.7 m year^{-1} (Heeren et al., 2012; Midgley et al., 2012; Daly et al., 2015b). In a study by Heeren et al. (2012), lateral streambank erosion on 23 reaches on the Barren Fork Creek and Spavinaw Creek, located approximately 50 km north, averaged more than 7 m from 2003 to 2008, with one reach retreating 55 m.

Parameter Measurement

Channel geometry characterization was divided into two categories: digitally available data and field data collection. Digitally available data included existing online digital data and derivatives, such as bed slope, radius of curvature, and sinuosity. Field data included measured stream and streambank information, i.e., *BW*, *BD*, *W*, *SBH*, side slope, and τ_c. Critical shear stress (τ_c) data for the ten study sites were obtained from Miller et al. (2014a). For each parameter, an analysis of covariance (ANCOVA), conducted at 95% confidence level, was used to test differences in the slopes and slope intercepts of the regression lines between the measured and SWAT default parameters.

Digitally Available Data

Kocian (2012) reported that bed slopes derived from aerial images and topographic maps were highly correlated with measured data. Therefore, bed slope for each study site reach was calculated using 1:24,000 USGS topographic maps and USDA National Aerial Imagery Program (NAIP) images to estimate elevation change and stream length, respectively. The radius of curvature was calculated for each of the meandering reaches by visually overlaying and fitting a circle to each bend and then comparing estimates obtained from equation 9 using BW and *W*. The average sinuosity and radius of curvature were estimated using NAIP images from 2003, 2008, and 2013.

Field Data

A total of 28 stream cross-sections, including the ten study sites, were used to characterize the Barren Fork Creek geometric channel parameters. Starting from the Oklahoma-Arkansas state line to the confluence of the Barren Fork Creek and the Illinois River (fig. 5), the sites were surveyed using a laser level, measuring tape, and survey rod. Eight sites were cross-over points, nine at meanders and eleven at straight cross-sections, with the cross-section locations based on available access. Cross-over points were defined as river reaches where the thalweg crossed from one side of the channel centerline to the other, straight reaches were defined as reaches with a sinuosity less than 1.1 (Dey, 2014), and

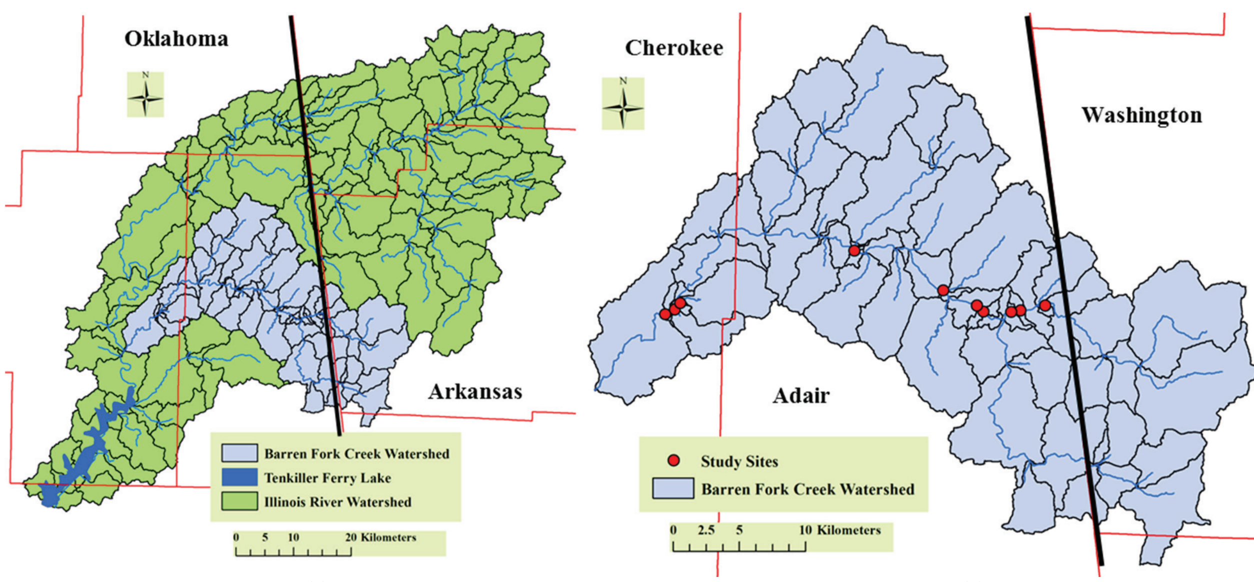


Figure 3. (a) Illinois River and Barren Fork Creek watersheds in Oklahoma and Arkansas and (b) enlarged map of Barren Fork Creek watershed showing the ten study sites.

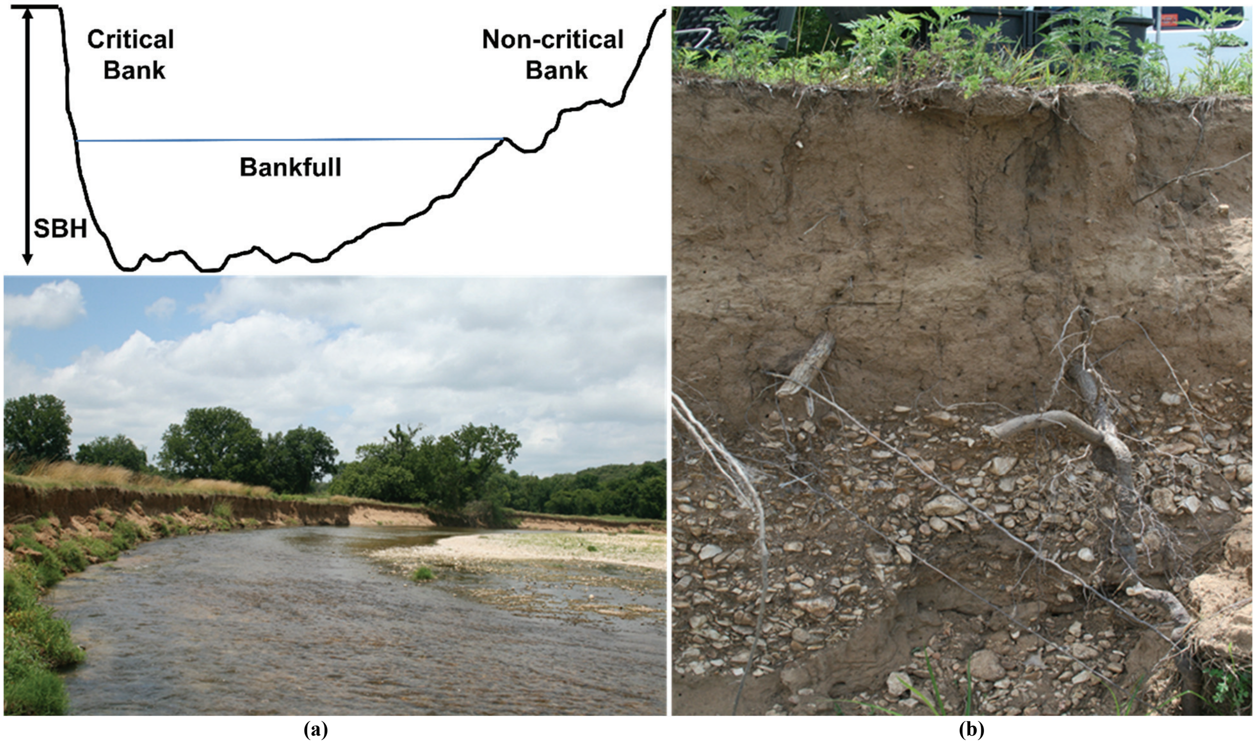


Figure 4. (a) Typical stream channel profile in the Barren Fork Creek with one critical bank and one non-critical bank (SBH = streambank height) and (b) underlying gravel layer and silty loam topsoil for the critical bank (Heeren et al., 2012).

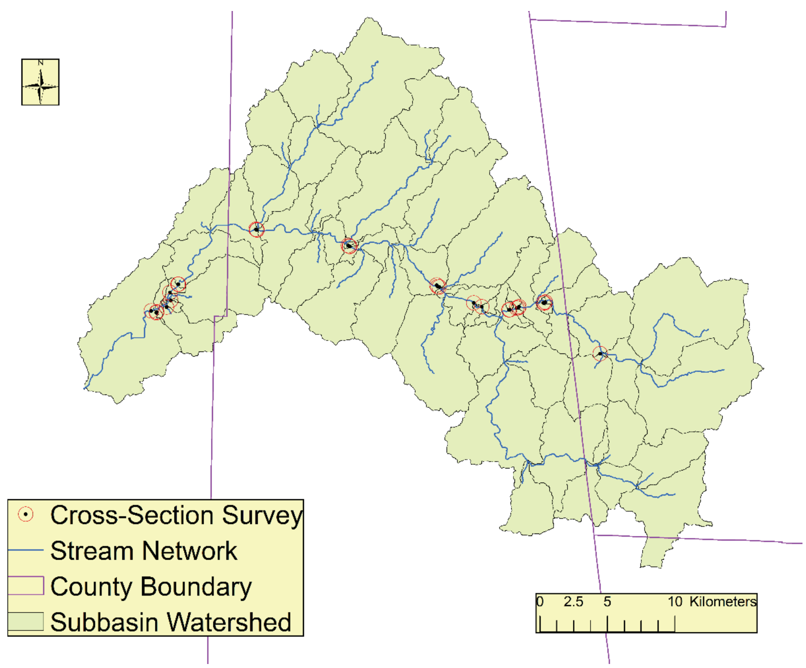


Figure 5. Location of 28 surveyed cross-sections surveyed on the Barren Fork Creek in 2015.

meanders were the remaining reaches with a sinuosity greater than 1.1. Two of the straight reaches included surveys completed at the USGS gauge stations near Eldon, Oklahoma (07197000) and Dutch Mills, Arkansas (07196900). At each of the 28 sites, the following data were collected: *BW*, *BD*, *W*, *SBH*, side slope, bank composition, and irregular cross-sectional area. Streambank height was measured from the top of the critical bank to the bottom of the thalweg, and the *W* was measured from the top of the critical bank to the point on the non-critical bank located at the same elevation. All parameters except streambank thickness, and streambank texture, and *BW* were calculated using the cross-sectional surveys. The thickness of the cohesive and gravel layers was measured using a survey rod. *BW* was identified by physical stream indicators, such as change in elevation, deposited sediment, and vegetation (USGS, 2004). The bankfull area, calculated using the cross-sectional survey, was divided by *BW* to obtain the average *BD*.

Validation of Area-Adjustment Factor

Area-adjustment factors were calculated using a measured irregular-channel cross-section for each of the straight and meandering cross-sections divided by the trapezoidal cross-section, which was calculated from measured W and side slope. FlowMaster V8 (Bentley, 2015) was used to predict and compare water depths for the irregular and trapezoidal cross-sections with and without the area-adjustment factor. Three representative cross-sections were chosen: meander, heterogeneous straight reach, and homogenous straight reach. Flow depths were calculated using uniform flow and Manning's formula.

Protected vs. Unprotected Streambanks

Seven of the ten study sites were protected with riparian vegetation, while three sites (F, E, and A) were unprotected (Miller et al., 2014a). Although quantifying the impact of riparian vegetation on streambank erosion at the watershed scale is challenging, vegetation has an impact on streambank erosion (Daly et al., 2015b; Harmel et al., 1999). While vegetation does not reduce the erodibility of the gravel layer, the stability of the cohesive top layer increases with root density. Micheli and Kirchner (2002) studied similar banks in California and found that the protected sedge banks only failed after the streambank was significantly undercut. After the geotechnical streambank failure, the overbank soil remained partially attached, providing temporary armoring against further erosion. The unprotected meadow banks failed more frequently and detached completely from the bank, thus preventing temporary armoring. Therefore, due to the current limitations of the SWAT model, the τ_c was increased for the seven banks with riparian protection using the following equation (Julian and Torres, 2006):

$$\tau_c^* = CH_{cov}\tau_c \tag{19}$$

where τ_c^* is the effective critical shear stress (N m^{-2}) adjusted for vegetative cover, and CH_{cov} is a channel cover factor. A CH_{cov} value of 2 was selected for forest (Narasimhan et al., 2017), which increased τ_c^* for the seven protected vegetation sites from 5.6 to 11.2 N m^{-2}. The τ_c^* was then used to update k_d using equation 3, which decreased from 0.08 to 0.06 cm^3 N^{-1} s^{-1}.

SWAT Model Setup

A SWAT model for the Barren Fork Creek watershed was created similar to the SWAT model for the Illinois River watershed developed by Mittelstet et al. (2016), which used a land cover dataset developed from 2010 and 2011 Landsat images, a 10 m USGS DEM, and SSURGO soil data. An initial Manning's n of 0.025 was selected (Daly et al., 2015b). The watershed had minor point sources at Westville, Oklahoma, and Lincoln, Arkansas; two USGS stream gauges located near Eldon, Oklahoma, and Dutch Mills, Arkansas; and three weather stations (fig. 6). Outlets were added to the model upstream and downstream of the ten study sites (Miller et al., 2014a) to create SWAT-predicted streamflow and streambank erosion output files for each study reach. We used the same numbering scheme for the sites as Miller et al. (2014a). Management practices, poultry litter application rates, and soil test phosphorus for each subbasin were obtained from Mittelstet et al. (2016). The final SWAT model consisted of 73 subbasins, 2,991 HRUs, and eight land covers.

SWAT Model Evaluation

Calibration of Flow and Flow Depth

The SWAT model was manually calibrated to observed daily and monthly baseflow, peak flow, and total flow at USGS gauge stations near Eldon, Oklahoma, and Dutch Mills, Arkansas. Because Oklahoma's Mesonet began in November 1994, streamflow was calibrated and validated

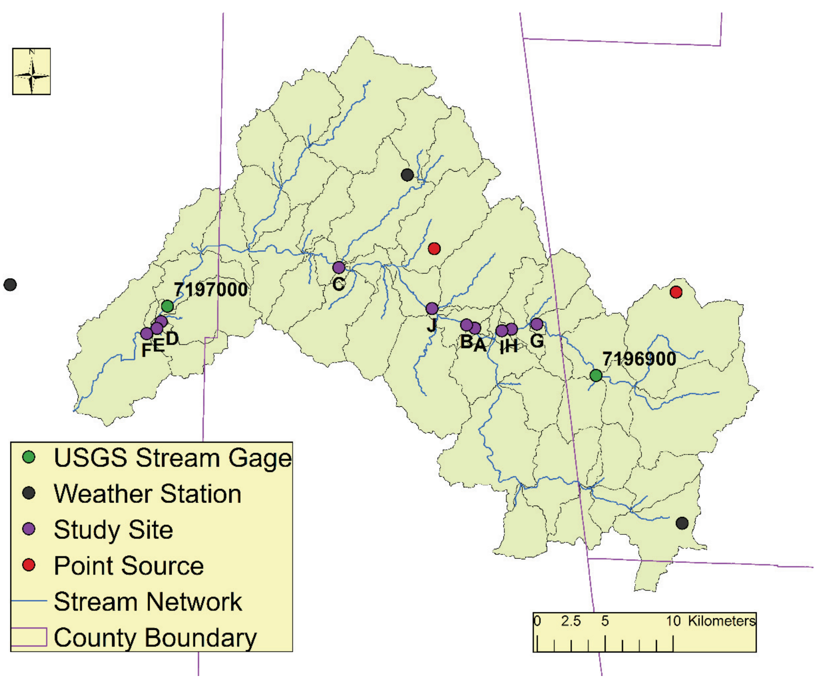


Figure 6. USGS gauge station, National Weather Service stations, and stream reach study sites for the Barren Fork Creek watershed.

from 2004 to 2013 and from 1995 to 2003, respectively. The USGS Hydrograph Separation Program (HYSEP) was used to estimate baseflow (Sloto and Crouse, 1996). The coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) were used to evaluate the model's performance (Moriasi et al., 2007).

Streambank Erosion

NAIP images from 2003 to 2013 were used to estimate lateral streambank retreat (fig. 7) (Heeren et al., 2012; Miller et al., 2014a). The measured eroded widths and lengths were used to calculate the eroded surface area (*EA*, m^2). *SBH* (m) was based on Miller et al. (2014a) and the 28 surveys and was used to estimate the ten-year total sediment loading (*TS*, kg) from each reach using:

$$TS = EA \times SBH \times \rho_b \tag{20}$$

where ρ_b is the soil bulk density (Mg m^{-3}). A weighted ρ_b based on the streambank composition (Miller et al., 2014a, 2014b) was used to estimate the average ρ_b for each bank.

SWAT Scenarios

Several scenarios were simulated using the SWAT 2012 streambank-erosion routine and were chosen based on the data collection method and number of measured parameters. These included a baseline scenario (scenario 1) and scenarios with increasing numbers of measured parameters that were digitally based (scenarios 2 to 6) and field-measured (scenarios 7 to 12). The changes in streambank-erosion predictions as a function of model complexity were evaluated. Table 2 summarizes the scenarios using both the empirical and process-based effective shear stress equation. Because SWAT-modeled fluvial erosion was limited to one streambank layer and the bank toes were predominantly gravel, one gravel layer was selected to represent the streambanks, thereby assuming a fluvial-dominated system.

Table 2. Scenarios simulated with the SWAT 2012 streambank-erosion routine with both the empirical and effective shear stress equations: *BS* = bed slope, *BW* = bankfull width, *BD* = bankfull depth, *SS* = side slope, *CSS* = critical shear stress, R_c = radius of curvature, *W* = top width, *SBH* = streambank height, *A* = area-adjustment factor, and *CF* = cover factor.

Scenario	SWAT Default Parameters	Measurement-Based Parameters
1	*BS*, *BW*, *BD*, *SS*, *CSS*	None
2	*BW*, *BD*, *SS*, *CSS*	*BS*
3	*BW*, *BD*, *SS*, *CSS*	*BS*, R_c
4	*BS*, *SS*, *CSS*	*BW*, *BD*
5	*BS*, BW_{US}, BD_{US}, *SS*, *CSS*	None
6	*BS*, BW_{IHR}, BD_{IHR}, *SS*, *CSS*	None
7	*BS*, *BW*, *BD*, *SS*	*CSS*
8	*BS*, *BW*, *BD*, *SS*, *CSS*	*SS*
9	*BS*, *SS*, *CSS*	*W*, *SBH*
10	None	*BS*, *W*, *SBH*, *SS*, *CSS*, R_c
11	None	*BS*, *W*, *SBH*, *SS*, *CSS*, R_c, *A*
12	None	*BS*, *W*, *SBH*, *SS*, *CSS*, R_c, *A*, *CF*

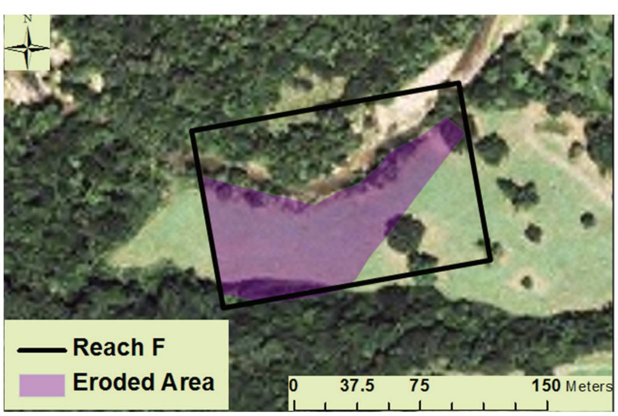
Results and Discussion

Validation of Area-Adjustment Factor

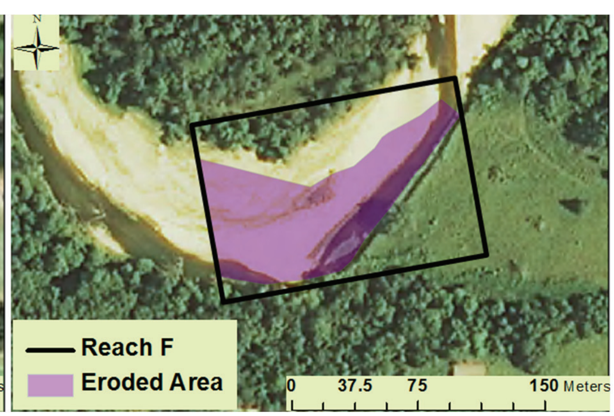
Figure 8 illustrates differences in the area-adjustment factor and flow depth for three cross-sectional reaches: meander (a = 0.72), heterogeneous straight reach (a = 0.77), and homogenous straight reach (a = 0.93). The highly irregular cross-sections (graphs A and B in fig. 8) were more representative of the cross-sections on the Barren Fork Creek. The more irregular the measured channel cross-section, the more important the area-adjustment factor becomes in accurately estimating the flow depth. For all three cross-sections, the predicted irregular cross-section flow depth compared more favorably with the predicted trapezoidal cross-section flow depth when using the area-adjustment factor.

Calibration of Flow and Flow Depth

Streamflow and flow depth were manually calibrated using seven parameters (table 3). The calibrated Manning's *n* of 0.05 was in the range for other gravel bed streams (Chow, 1959) based on the procedure developed by Cowan (1956). Table 4 presents the daily and monthly SWAT calibration and validation results, which were "good" to "very good" (Moriasi et al., 2007). Figure 9 shows the observed versus predicted daily flow depth for the calibration period at the USGS gauge station Near Eldon, Oklahoma. Although the model underestimated a few major peak flow events, the overall performance was acceptable (table 4). Possible reasons for missing the major peak events include the lack of sufficient spatial precipitation coverage and rainfall intensity. Isolated thunderstorms are particularly common in the spring and summer months.



(a)



(b)

Figure 7. USDA National Agricultural Imagery Program aerial images with polygons (purple) illustrating the streambank retreat from (a) 2003 to (b) 2013 for study site F on the Barren Fork Creek.

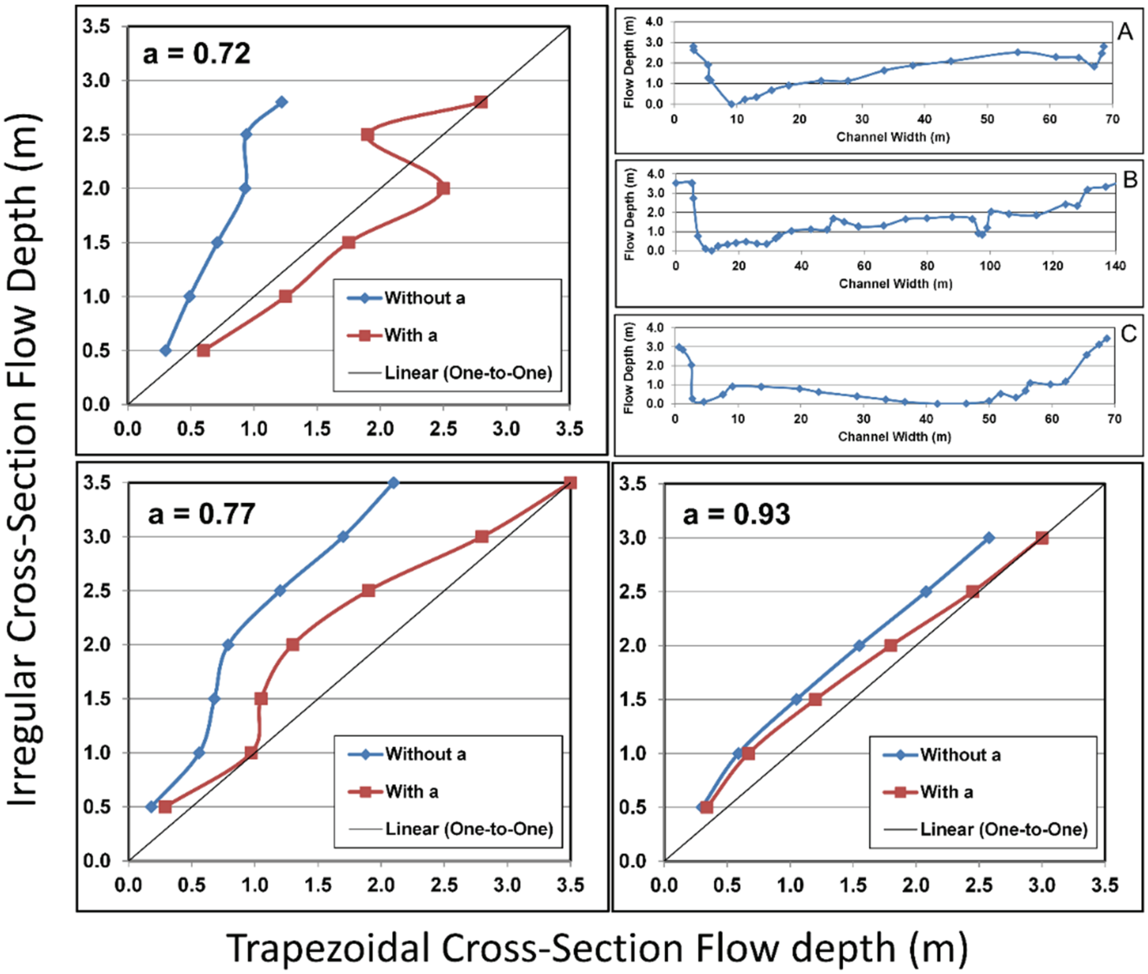


Figure 8. FlowMaster-calculated flow depth for the measured irregular versus trapezoidal cross-sections with and without an area-adjustment factor (*a*). Cross-section A is a meander, B is a heterogeneous straight reach, and C is a homogenous straight reach.

Table 3. SWAT default and calibrated parameter estimates used to calibrate streamflow and flow depth for the Barren Fork Creek watershed SWAT model.

Original Value	Calibrated Value	Parameter	Description
0.95	0.85	ESCO	Soil evaporation compensation coefficient
0.05	0.25	RCHRG_DP	Aquifer percolation coefficient
0.048	0.75	ALPHA_BF	Baseflow alpha factor (days)
39 to 94	-4	CN2	SCS curve number adjustment
0	10	CH_K2	Effective hydraulic conductivity in main channel alluvium (mm h^{-1})
0.5	105	CH_K1	Effective hydraulic conductivity in tributary channel alluvium (mm h^{-1})
0.014	0.05	*n*	Manning's *n* in main channel

Table 4. SWAT calibrated and validation results for monthly flow and daily flow depth for 2004 to 2013 and 1995 to 2003, respectively, for the Barren Fork Creek watershed.

USGS Gauge Station and Variable	Simulation Period: Calibration NSE	Calibration R^2	Validation NSE	Validation R^2
Near Eldon, Oklahoma (07197000)				
Monthly flow	0.82	0.82	0.78	0.80
Daily flow depth	0.56	0.64	0.54	0.56
Dutch Mills, Arkansas (07196900)				
Monthly flow	0.72	0.72	0.70	0.71
Daily flow depth	0.49	0.49	0.48	0.50

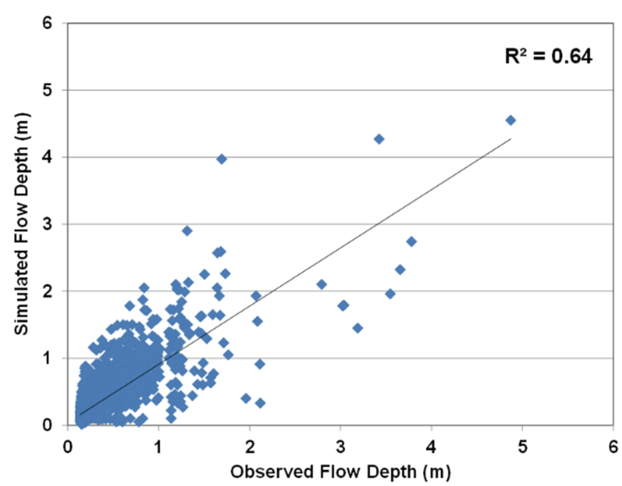


Figure 9. Observed versus SWAT-predicted daily flow depth from 2004 to 2013 at USGS gauge station 07197000 near Eldon, Oklahoma.

SWAT-Calculated vs. Measured Parameters

Digitally Available Data

Table 5 summarizes the measured and SWAT-estimated bed slope, radius of curvature, *BW*, *BD*, and τ_c. The bed slopes estimated using the topographic maps and NAIP aerial images and the estimated bed slopes from 10 m DEM

Table 5. Measured (Meas.) and SWAT-estimated (Est.) bed slope, radius of curvature, bankfull width, bankfull depth, and critical shear stress at the ten study sites on the Barren Fork Creek watershed. Flow directions is from upstream (site G) to downstream (site F).

Study	Bed Slope		Radius of Curvature (m)		Bankfull Width (m)		Bankfull Depth (m)		Critical Shear Stress ($N\ m^{-2}$)	
Site	Meas.	Est.	Meas.	Est.	Meas.	Est.	Meas.	Est.	Meas.	Est.
G	0.0033	0.0071	109	57	29	26	0.67	0.96	4.8	4.6
H	0.0030	0.0011	236	64	54	28	0.68	1.02	5.8	4.6
I	0.0030	0.0083	111	64	38	29	0.87	1.03	5.3	4.6
A	0.0018	0.0027	159	104	40	44	0.95	1.37	3.5	4.6
B	0.0018	0.0017	745	104	40	44	1.08	1.37	5.5	4.6
J	0.0013	0.0029	671	120	67	50	1.07	1.49	4.4	4.6
C	0.0016	0.0022	318	136	46	56	0.52	1.61	7.0	4.6
D	0.0013	0.0019	946	181	65	72	1.48	1.91	6.1	4.6
E	0.0015	0.0010	195	181	79	72	1.65	1.91	4.4	4.6
F	0.0015	0.0005	141	183	80	73	2.00	1.92	8.7	4.6
Mean	0.0020	0.0029	363	119	54	49	1.10	1.46	5.6	4.6

were not significantly different based on a Mann-Whitney rank sum test at a 95% confidence level. However, the bed slope calculated from the DEM was underestimated near the watershed outlet and overestimated at the headwaters. Kocian (2012) found low accuracy with 10 m DEM bed slope estimates compared to LIDAR and topographic maps. Based on these findings and those of Kocian (2012), bed slope derived from aerial images and topographic maps were used.

Measured sinuosity at the ten study sites ranged from 1.0 to 2.5 with an average of 1.3, with sites H, B, J, and D classified as straight reaches (sinuosity less than 1.1); sites I, A, and C classified as sinuous (sinuosity between 1.1 and 1.5); and sites G, E, and F classified as meandering (sinuosity greater than 1.5) (Dey, 2014). Note that radius of curvature estimates using equation 9 were valid for reaches with a sinuosity greater than 1.2 (Williams, 1986). The measured average radius of curvature for sites G, A, E, and F with a sinuosity greater than 1.2 was 151 m (table 4). Applying equation 9, the average radius of curvature for these four sites was 131 m and 216 m using *BW* and *W*, respectfully. Based on the ANCOVA, neither the slope nor slope intercept were significantly different for either *W* or *BW*.

Field-Measured Parameters

Field measurements at cross-over points and their corresponding drainage areas were used to derive equations for *BW* and *BD* (Dutnell, 2000). These measured *BW* and *BD* values were then compared to the bankfull measurements derived from the global, regional, and U.S. equations and the measured *W* and *SBH*. For *BW*, neither the slope nor the slope intercept for the SWAT global regression were significantly different from the measured *BW* (table 6). For the regional regression equation, the slope was significantly different, but the slope intercept was not. Both the slope and slope intercept were significantly different for the U.S. regression. Neither the slope nor the slope intercept were significantly different for the measured *BW* and *W*. These findings signify that the *BW* estimates derived from the SWAT global regression were similar to the field-measured *BW* and *W*. For the regional regression, the estimated *BW* was similar to the measured values toward the headwaters but deviated from the measured values farther downstream as the drainage area and *BW* increased. The U.S. regression equation poorly estimated *BW* along the entire Barren Fork Creek. It consistently underpredicted *BW*, with the deviation increasing as drainage area and *BW* increased. These results support the findings of Bieger et al. (2015), who concluded that the regional curves were more reliable than the U.S. equations.

Table 6. ANCOVA results comparing measured bankfull width and depth to estimates derived from global, regional, and U.S. equations, and measured top width and streambank height to derived estimates. The ANCOVA used measured and derived parameters as the independent and dependent variables, respectively.

Parameter and Derived Regression Source	Derived Parameter	Statistical Comparison	p-Value[a]
Bankfull width			
Global	BW	Slope	0.23
		Slope and intercept	0.07
Regional	BW_{IHR}	Slope	0.04*
		Slope and intercept	0.08
U.S.	BW_{US}	Slope	0.03*
		Slope and intercept	0.04*
Top width			
Local	W	Slope	0.27
		Slope and intercept	0.08
Bankfull depth			
Global	BD	Slope	0.07
		Slope and intercept	0.02*
Regional	BD_{IHR}	Slope	0.49
		Slope and intercept	0.11
U.S.	BD_{US}	Slope	0.19
		Slope and intercept	0.72
Streambank height			
Local	SBH	Slope	0.04*
		Slope and intercept	0.02*

[a] Asterisks (*) indicate significant difference at $\alpha = 0.05$.

The measured *BD* versus drainage area was also compared to the values derived from the three empirical equations and *SBH*. The slope was not significantly different for the SWAT global regression, but the slope intercept was significantly different. For the proposed regional and U.S. regressions, neither the slope nor the slope intercept were significantly different. Both the slope and slope intercept were significantly different for the measured *SBH* and *BD*. These findings signify that *BD* derived from the proposed regional and U.S. regressions were similar to the measured *BD*, while the SWAT global regression consistently underpredicted *BD*. Not surprising, the measured *BD* was much lower than the *SBH*. The difference in the measured *BD* and *SBH* did narrow as *BD* and drainage area increased.

Although the bankfull parameters were estimated reasonably well with the regional equations, they can be improved with the incorporation of more sites, especially for the Internal Highlands (seven sites) and Laurentian Upland (six sites)

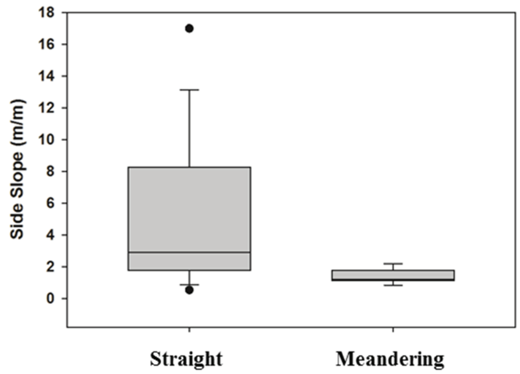


Figure 10. Measured side slopes for straight and meandering reaches on the Barren Fork Creek.

(Bieger et al., 2015). With the large number of SWAT users outside the U.S., there is a need for countries outside the U.S. to develop their own regional or watershed-specific regression equations.

The default bank composition of a gravel streambank in SWAT is 65% gravel, 15% sand, 15% silt, and 5% clay. The average particle size distribution of the samples taken from the gravel layer at each of the ten study sites was similar to the SWAT default, i.e., 68% gravel, 15% sand, 10% silt, and 7% clay. Based on the measured *SC* content of the banks (Julian and Torres, 2006), τ_c was 4.6 Pa, and k_d was 0.093 $cm^3\ N^{-1}\ s^{-1}$ (eqs. 2 and 3). Using the measured d_{50} of the ten study sites (1.3 to 2.5 cm) and equation 14, τ_c ranged from 3.5 to 8.7 Pa with an average of 5.6 Pa (table 4). Both methods produced similar results for τ_c (4.6 vs. 5.6), but the soil types were completely different between the Barren Fork Creek streambanks and those used to derive the empirical equation. Average measured side slopes for the straight reaches and meanders were 4.8:1 and 1.4:1, respectively (fig. 10). Based on an ANOVA with Tukey's multiple comparison test at a 95% confidence level, the measured side slopes from straight and meandering reaches and SWAT default values were all significantly different.

Observed vs. Simulated Streambank Erosion

Channel Characterization

SWAT-estimated parameters were replaced with measured data using a regression equation with *DA* as the independent variable or an average measured value. The following regression equations were derived for measured bed slope and top width:

$$BS = 4.3\times10^{-9}DA^2 - 6.7\times10^{-6}DA + 0.00369 \quad (21)$$

$$W = 0.0787DA + 35.384 \quad (22)$$

where *BS* is the bed slope ($m\ m^{-1}$), *W* is the top width (m), and *DA* is the watershed area (km^2). The R^2 for the measured versus derived values using equations 21 and 22 were 0.84 and 0.64 for *BS* and *W*, respectively. The sinuosity measured at each site using aerial photographs was used in the model. However, the radius of curvature could not be measured using aerial photographs for large reaches; thus, equation 9 was used to estimate the radius of curvature based on *W*. It should be noted that the radius of curvature measurements taken from the aerial photographs were not significantly different at the 95% confidence level from the estimates using equation 9. Since there was no longitudinal trend with drainage area along the length of the Barren Fork Creek, the average τ_c (5.6 Pa), k_d (0.085 $cm^3\ N^{-1}\ s^{-1}$), side slope (3.1:1), streambank height (2.8 m), and area-adjustment factor (0.73) were used for each reach in the model simulations.

Simulation Results

The average observed streambank erosion (gravel and topsoil) from 2004 to 2013 at the ten sites was 2,830 Mg $year^{-1}$ and ranged from 219 Mg $year^{-1}$ at site J to 10,300 Mg $year^{-1}$ at site F (fig. 11). The simulated streambank erosion was not calibrated. The average simulated streambank erosion (scenario 1) using the empirical equation was 1,360 Mg $year^{-1}$, compared to 2,510 Mg $year^{-1}$ for the process-based equation (fig. 11). Both models underpredicted the streambank erosion at sites F and E and overpredicted the erosion at several other sites, such as D and J. Although the correlation with observed erosion was poor for both equations, the NSE was higher using the effective shear-stress equation.

Table 7 summarizes the predicted erosion for each of the simulated scenarios. Incorporating measured bed slope (eq. 21) into the model (scenario 2) resulted in an improvement in both the R^2 and NSE. Much of this improvement was

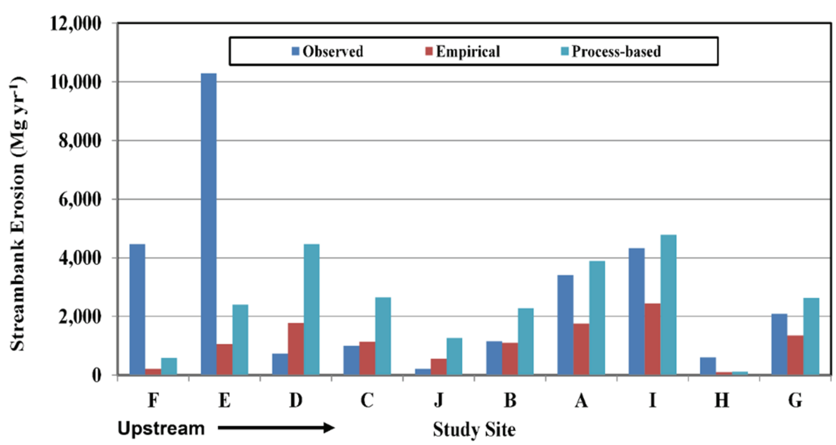


Figure 11. Measured and simulated streambank erosion using empirical and process-based effective shear stress equations using the SWAT model with default parameters at ten study sites on the Barren Fork Creek from 2004 to 2013. "Empirical" is the effective shear stress equation currently used by SWAT, and "Process-based" is the proposed effective shear stress equation.

Table 7. Scenarios simulated with SWAT 2012 streambank-erosion routine with empirical and process-based effective shear stress.[a]

	Empirical			Process-Based		
Scenario	Erosion (Mg year^{-1})	R^2	NSE	Erosion (Mg year^{-1})	R^2	NSE
1	1,150	0.02	-0.33	2,510	0.01	-0.16
2	1,000	0.03	-0.20	2,230	0.57	0.38
3	1,090	0.02	-0.12	2,410	0.65	0.49
4	680	0.01	-0.55	1,750	0.05	-0.14
5	1,100	0.55	-0.35	2,260	0.01	-0.26
6	2,600	0.65	-0.47	3,660	0.01	-0.92
7	850	0.27	-0.37	1,800	0.32	0.10
8	1,960	0.38	0.16	3,240	0.35	0.31
9	720	0.30	-0.42	1,740	0.46	0.15
10	1,250	0.28	-0.14	2,350	0.46	0.32
11	2,960	0.34	0.31	3,080	0.47	0.41
12	1,924	0.58	0.42	1,936	0.66	0.52

[a] "Empirical" is the effective shear stress equation used by SWAT, "Process-based" is the proposed effective shear stress equation, NSE = Nash-Sutcliffe efficiency, and R^2 = coefficient of determination.

due to the incorporation of measured bed slopes for sites E and F. The DEM-calculated bed slope at sites E and F were 0.00095 and 0.00054, respectively, compared to the measured values of 0.0015 for both sites. Incorporating the measured sinuosity and radius of curvature further improved model predictions (scenario 3). Based on these results, model simulations can be improved by incorporating measured bed slope, sinuosity, and radius of curvature, which can all be measured without field-collected data. There was a large increase in streambank erosion when the 2:1 side slope was replaced with the measured 3.1:1 side slope (scenario 8) and with the incorporation of the area-adjustment factor (scenario 11). Modifying the side slope and area-adjustment factor, but using the smaller *BW* instead of the *W*, decreased the stream channel cross-sectional area and resulted in excessive shear stress applied to the streambanks. Likewise, there was a large reduction in streambank erosion when the bankfull parameters were replaced with *W* and *SBH* (scenario 9). Of the field-measured parameters, it is recommended that only τ_c be modified independently. To accurately represent the channel cross-sectional area and simulate the water depth, the side slope, *W*, *SBH*, and area-adjustment factor should be replaced simultaneously.

The average observed streambank erosion from 2003 to 2013 at the three unprotected sites was 6,160 Mg year^{-1}, compared to 1,450 Mg year^{-1} for the protected sites. Including the channel cover factor improved overall model predictions (scenario 12) (table 7 and fig. 12). The R^2 and NSE were 0.58 and 0.42, respectively, when using the empirical equation and 0.66 and 0.52, respectively, when using the process-based equation. Both shear stress equations using the channel cover factor adequately predicted streambank erosion except at reaches E and I. Reach E had an unusually large quantity of erosion, more than twice as much as the other two unprotected sites. Although reach I had good riparian protection in 2003 (fig. 13), it had 4,330 Mg year^{-1}

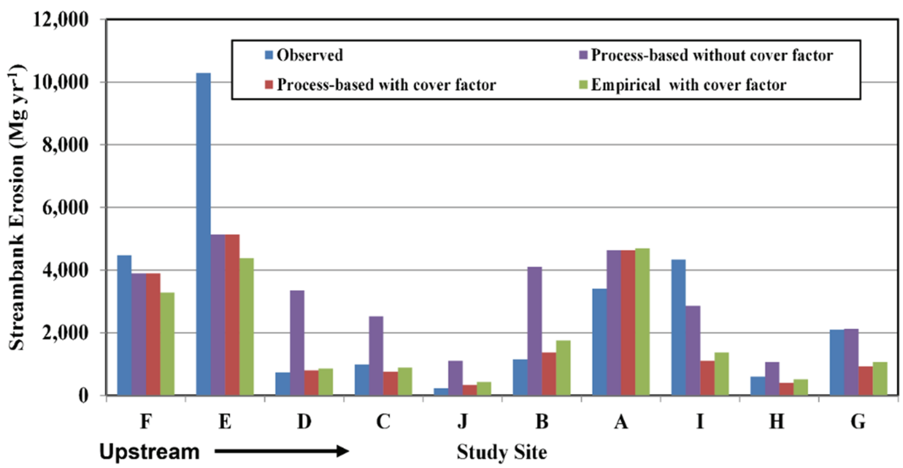


Figure 12. Observed streambank erosion compared to SWAT-simulated erosion with and without the channel cover factor for the Barren Fork Creek from 2004 to 2013. "Empirical" is the effective shear stress equation currently used by SWAT, and "Process-based" is the proposed effective shear stress equation.

Figure 13. USDA National Agricultural Imagery Program aerial images showing streambank erosion from (a) 2003 to (b) 2013 for reach I on the Barren Fork Creek. The red line is the location of the reach in 2003.

streambank erosion compared to a combined total of 5,800 Mg year^{-1} for the remaining six protected sites. Results from these two reaches demonstrate that models cannot account for all processes that occur in the natural world.

CONCLUSIONS

The proposed streambank-erosion routine for the SWAT model improved the predicted streambank erosion for composite streambanks. For each scenario, the R^2 and NSE were higher when applying the proposed streambank-erosion routine versus the SWAT 2012 routine. Although the process-based applied shear stress equation was the most influential modification, incorporating the top width, streambank height, and area-adjustment factor more accurately represented the measured irregular cross-sections and improved the model predictions compared to observed data. The model predictions further improved when the critical shear stress was modified to account for riparian protection. Because field data collection is not feasible for every project, simulations were performed using digital and field-measured data.

If collecting stream data to estimate channel parameters is not possible due to financial, geographic, or time constraints, digitally based data can provide good streambank erosion estimates. The current SWAT and proposed regional regression equations adequately estimated bankfull width and bankfull depth. The proposed U.S. equation, on the other hand, produced poor results and therefore should not be used for the conditions studied. While equation 9 provided an adequate estimate of the radius of curvature, the measured bed slope using aerial images and topography maps should be used in place of the DEM-derived estimates. Incorporating the radius of curvature, sinuosity, bed slope, and the global or regional bankfull parameters improved model predictions at the ten study sites. The R^2 increased from 0.01 to 0.65, and the NSE increased from -0.92 to 0.49.

Although the results from this study demonstrated that using field-measured parameter estimates may not statistically improve model predictions for the conditions studied, other time periods or watersheds may be different. If limited field work can be conducted, multiple measurements of the critical shear stress (τ_c) are recommended. The τ_c was one of the most sensitive parameters, and it can be incorporated into the model without affecting the cross-sectional area of the stream channel. If resources permit, complete cross-section surveys should be conducted throughout the stream system to quantify the top width, streambank height, side slope, and area-adjustment factor. Each of these parameters affects the cross-sectional area, and they should be replaced together. In general, the more watershed-specific measured data incorporated into the model, the more confident the user can be in the model predictions.

Further testing of the ability to predict τ_c using the silt and clay content is needed, as well as exploring other τ_c and erodibility coefficient relationships. More research is needed to quantify how root density from different types of riparian vegetation impacts τ_c. Future research also needs to address the streambank-erosion routine limitations, specifically incorporating multi-layer banks and the modification of channel dimensions throughout the simulation.

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