ABSTRACT

Streambank Erosion Assessment: Application of Dendrogeomorphology,
Numerical Watershed Modeling, and Model Characterization

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This project uses a dendrogeomorphic method to assess streambank erosion at two ungauged streams in Central Texas: Cedar Creek, a small urban stream, and Mill Creek, a medium-sized rural stream. This method yields better erosion rate estimates than typical one- to two-year erosion-pin studies, while also offering insight into the magnitude and variability of sub-aerial processes, mass wasting, and fluvial entrainment. We used the results from this assessment in tandem with data gathered from available literature to parameterize, calibrate, and interrogate the watershed model SWAT-DEG. Through the linear analyses available in the software suite PEST, model predictive uncertainty, prediction sensitivity to parameters, and observation worth were assessed. The synthesis of the dendrogeomorphic channel assessment and SWAT-DEG modeling used in this study outline a method for characterizing past erosion and predicting future erosion accurately and efficiently.

Streambank Erosion Assessment: Application of Dendrogeomorphology, Numerical Watershed Modeling, and Model Characterization

by

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CHAPTER ONE

Introduction

Assessment and prediction of watershed erosion processes associated with land use and climate change are important for many reasons. Predicting erosion is especially of interest when assessing risk of land degradation and infrastructure damage. Moreover, mobilized sediment can lead to detrimental effects including: (1) sediment deposition in reservoirs that reduces storage capacity (2) increased water treatment costs, (3) damage to hydroelectric power facilities, (4) increased flood stages as stream channels fill with sediment (forcing an increase in lateral extent of floodwater), and (5) environmental and ecological impacts associated with suspended sediments (Schenk et al. 2013, Smith and Dragovich, 2008, USDA, 1966). This study used two methods to assess and predict watershed conditions in a small urban and a medium-sized rural watershed in Central Texas. First, a dendrogeomorphic method was used to analyze channel erosion processes and allowed post-hoc assessment of streambank retreat rates. These data were then used in tandem with data gathered from literature to parameterize and calibrate the hydrologic model SWAT-DEG (Allen et al., 2008). The models were interrogated to evaluate model predictive uncertainty, prediction sensitivities to parameters, and data worth, in order to determine what data is needed to reliably simulate watershed conditions with SWAT-DEG.

Two watersheds in Central Texas were studied: Cedar Creek and Mill Creek (Figure 1.1.). Cedar Creek is an urban first-order stream in the Dallas-Fort Worth metroplex and Mill Creek is a rural third-order stream approximately 70 km south. Both watersheds are within the Blackland Praire physiographic province. Based on prior studies by AECOM (2009) and Ridgeway (1997) both streams are actively eroding and following the channel evolution model (Leopold and Skibitzke, 1967; Hawley et al. 2012). These two streams were selected to compare the differences in watershed processes between Cedar and Mill Creek due to differences in land use and drainage area. We also examined how the methods used in this study perform in small urban and medium-sized rural watersheds, within the same physiographic region.

In Chapter One, a channel assessment using dendrogeomorphology for Cedar and Mill Creek was conducted. Dendrogeomorphology is the study of geomorphic processes using annual growth rings in trees. While dendrogeomorphic methods have been in practice since the 1960s (Alestalo, 1971), its application in stream channel erosion assessment is relatively recent. By examining anatomical changes in the annual growth rings of exposed tree roots from native riparian trees along channel corridors, historic erosion rates were determined. This method has advantages over more traditional techniques (e.g. erosion pins and photogrammetric techniques) because of its ability to determine erosion rates post-hoc in ungauged watersheds, without a lengthy monitoring period, or cumbersome data collection.

In Chapter Two, the hydrologic model SWAT-DEG was used in the Cedar and Mill Creek watersheds to predict stream discharge, sheet and rill erosion, channel degradation, and sediment yields. Data gathered from the dendrogeomorphic channel assessment and a literature survey were used to parameterize and calibrate these models. The software suite PEST interrogated these models to quantify predictive uncertainty and identify what site data best decreases uncertainty. A sensitivity analysis also determined which model parameters are most influential on model outputs.

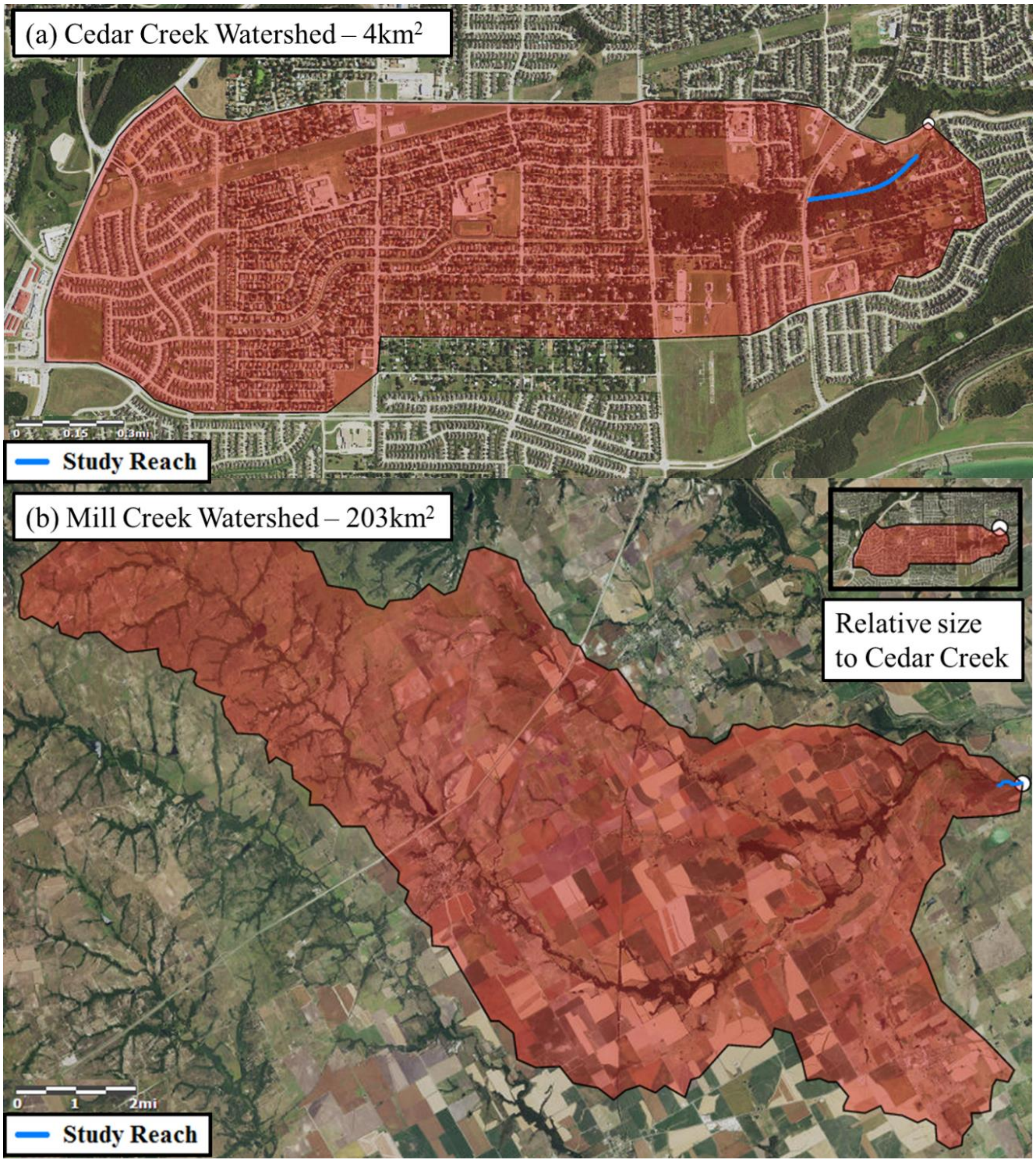

Figure 1.1. Watershed boundaries and study reaches for (a) Cedar Creek, and (b) Mill Creek; the relative size of Cedar Creek is inset on (b) Mill Creek

CHAPTER TWO

Quantifying Streambank Erosion in Ungauged Watersheds Using Dendrogeomorphology

Abstract

Stream channel erosion and sedimentation processes have negative economic, infrastructural, environmental, and water-resource impacts on numerous watersheds throughout the United States. Understanding and assessing these processes are important to effective watershed management. However, typical erosion assessment methods, such as erosion pins and photogrammetry, are not always feasible and are not suitable in previously unstudied basins. This study used dendrogeomorphology as a channel erosion assessment technique in Central Texas. This method was applied to a small urban and medium-sized rural watershed within the same physiographic region, which facilitated comparison of streambank erosion rates between land use types and basin sizes. By analyzing anatomical changes in exposed tree roots of common riparian trees, it was possible to estimate channel retreat with precision on the order of centimeters per year. This method also identified specific past and current channel processes, such as mass wasting, entrainment, and sub-aerial processes using roots sampled from various lateral and vertical channel positions. This study demonstrates that the dendrogeomorphic method accurately describes past and present streambank processes in unstudied watersheds without the need for long-term monitoring.

Introduction

Excessive erosion and resultant sedimentation are the combined result of complex interactions between climate, hydrology, geomorphology, and human land use (Belmont 2010). Since 1992, the biennial National Water Quality Inventory Reports (Section 305(b) Report to Congress) have indicated that sediment and nutrients are ranked as the leading causes of water-quality impairment of rivers and lakes (Langendoen et al. 2012), with numerous studies demonstrating that streambank erosion is the largest contributor to sediment load (Rosgen 1976, Jha et al., 2003). Streambank erosion within a watershed can lead to land degradation and infrastructure damage, as well as indirect damage to downstream to rivers, deltas, bays, and ocean systems from derived sediments (Schenk et al. 2013, Smith and Dragovich, 2008, USDA, 1966). Clearly, channel erosion processes are important from ecologic and economic perspectives.

Typical methods of channel erosion assessment include direct measurement techniques (e.g. erosion pins, scour chains, traditional surveys), remote sensing techniques (e.g. light detection and ranging (LiDAR) surveys, photogrammetry), and sedimentological/biological analyses (Lawler, 1993). However, each method has its drawbacks. For example, erosion pins can be lost or altered due to floods and human interference, and are considered inaccurate when monitored for less than 5 years because of the inability to capture the intermittent nature of channel erosion events (Couper et al, 2002, Pizzuto et al., 2009, Lawler 1993). Likewise, time-series techniques, such as LiDAR, photogrammetry, and traditional surveys, are labor intensive, expensive, and often do not provide the level of precision needed to effectively describe channel change processes; (Hooke, 1979, Nanson and Hickin, 1983, Brasington et al. 2003).

Photogrammetric techniques are especially prone to spatial-resolution issues caused by riparian vegetation obstructing the view of the geomorphic structure of a stream channel. Also, these methods only provide channel-change information during the monitoring time frame, making post-hoc erosion assessment impossible.

Riparian vegetation strongly affects channel erosion rates and channel morphology (Hession et al. 2003). Interaction between riparian vegetation and the three primary processes associated with fluvial erosion (mass failure, entrainment of sediment through scour, and sub-aerial processes) is complicated (Thorne, 1981; Rutherfurd 2007) and information about how specific vegetation types affect streambank erosion is limited (Saxton, 2012). In general, bank vegetation reduces channel erosion.Findings by Wynn (2004) found that large woody roots provide the greatest resistance to streambank erosion and that interactions between herbaceous vegetation and bank substrates are similar but less influential. Mass failures, due to bank instability, are the primary cause of erosion in cohesive channel banks (Rutherfurd 2007). Increased bank vegetation decreases channel erosion rates by increasing streambank stability (Simon and Collison, 2002; Pollen, 2007). Vegetation increases bank stability through increased soil matric suction, sediment buttressing from riparian tree trunks, increased tensile strength from root architecture, and reduction of flow velocities by vegetative drag (Thorne 1990, Vidal 1969, van de Wiel and Darby, 2007, Kouwen 1988, Thorne & Furbish, 1995). However, vegetation can also reduce bank stability through loss of cohesion from plant transpiration (Darby et al. 2000, Simon et al. 2000), development of vertical tension cracks (Darby & Thorne 1994, 1996, Thorne et al. 1982, Budhu & Gobin 1995), and preferential flow of infiltrating water along the root system (Collison & Anderson 1996, Simon & Collison

2002, Thorne 1990). Streambank vegetation also plays an important role by regulating sub-aerial processes such as temperature and moisture via evapotranspiration, shading of the bank, and altering of the soil matrix (Wynn and Mostaghimi, 2006). These effects typically lead to net-positive erosion reduction, but can vary seasonally and climatically (Pollen-Bankhead and Simon, 2010). Modification of sub-aerial processes by vegetation are more prominent in small upper catchments and upper banks above the capillary fringe compared to larger watersheds and lower banks (Wynn and Mostaghimi, 2006; Rutherfurd 2007).

Dendrogeomorphology, the study of geomorphic processes through growth anomalies in tree rings, has been used since the 1960s to estimate erosion rates (Alestalo, 1971). The foundation of the dendrogeomorphic method is based upon specific anatomical changes that occur in the annual rings of roots when exposed to atmospheric conditions. Analysis of annual growth rings in tree roots has been used to accurately date geomorphic processes associated with riverbanks, gullies, and hillslopes with yearly precision (e.g. Stoffel et al., 2013, Vandekerckhove et al., 2001, Corona et al., 2010). Most studies have used coniferous tree roots because of definitive anatomic changes in the root structure of these tree types (Gartner et al., 2001; Malik and Matyja, 2008; Bodoque et al., 2011). Others have determined that deciduous trees can be used to determine riverbank erosion (Dick et al., 2014; Stotts et al., 2014, Hitz et al., 2008). Dendrogeomorphology provides a valuable tool to estimate channel erosion because it can be used in previously unmonitored watersheds in a single sampling campaign while capturing erosion processes at decadal timescales (Stoffel at al., 2013). The dendrogeomorphic method can be used wherever woody riparian vegetation occurs along stream corridors.

In this study a dendrogeomorphic analysis using common, riparian trees native to Central Texas was undertaken to assess the accuracy of this method in estimating channel erosion. The two study reaches were typical of urban and rural streams in this region. Results from this study were compared to erosion rates from other studies to validate this method. Between-site comparisons were conducted to infer how land use affects local channel processes. Within-site comparisons of erosion rates were used to assess how planform and vertical channel positions affect results. This study is unique because it investigates dendrogeomorphology as a streambank erosion assessment method in a previously unstudied region for both rural and urban environments in Central Texas, as well as examining the influence of channel position on estimated erosion rates.

Study Sites

The studied stream channels were located in two Central Texas watersheds situated in the Blackland Prairie physiographic province: Cedar Creek and Mill Creek. Cedar Creek, is a first order tributary of the Trinity River Basin located within the rapidly urbanizing community of Grand Prairie, Texas, a suburban city of the Dallas-Fort Worth metroplex. The watershed is underlain by Cretaceous Eagle Ford Shale which dips gently to the southeast (Allen and Flannigan, 1986). The alluvial channel banks consist of a cohesive silty clay (hydrologic soil group D Ferris-Heiden Clay). The stream bottom consists of a loosely consolidated calcareous marl. Bed material in the channel is highly variable in size and composition. Large pieces of shale and marl bedrock, as well as limestone gravel and cobbles occur in riffles of Cedar Creek, while clay and sand-sized particles compose the bed material in pools of the reach, with an average D_{50} of 3.55 mm. The reach of interest is 1.1 km long and has a total drainage area of 4 km^2, with an average slope and sinuosity of 0.0058 m/m and 1.4, respectively. Active channel widths and depths are variable between 1.5 – 6 m (average of 2.5 m) of and 0.5 – 10 m (average of 2.5 m), respectively. Trees and shrubs are prevalent along the channel with taxa such as elms (*Ulmus* spp.), hoptree (*Ptelea trifoliata*), and osage orange (*Maclura pomifera*) dominating the large woody vegetation.

Cedar Creek is in a state of disequilibrium and is presently degrading, widening and losing riparian vegetation, as described by the channel evolution model (CEM; Leopold and Skibitzke, 1967; Hawley et al. 2012). This is caused by land use change from natural grasslands to agricultural lands in the late 1800s followed by rapid development and residential construction in the 1960s and 1990s as shown by historic photos (AECOM, 2009). Additionally, upstream of the study reach has been straightened and levied with concrete. Creation of more impermeable surfaces increases overland flow discharges; this coupled with new storm-water drainage systems, has changed the flow regime by allowing water to flow through the system at accelerated rates. Storm-water hydrographs now have higher peak discharges resulting in greater forces exerted on the stream channel (Leopold, 1968; Ferguson and Suckling, 1990; Booth and Jackson, 1997, Miller et al., 2014). In response, channel incision and widening is occurring and will continue until a new equilibrium is reached (Bledsoe et al., 2002). The channel evolution process can take longer than 20 years and happens at varying rates (Watson et al., 2002). Degradation and incision of the channel has led to construction of hard points, installation of riprap, and channelization in many portions of the watershed in attempt to stabilize the channel. However, degradation still occurs along much of Cedar Creek as evidenced by over-steepened banks, scour of channel banks, slumping trees and visible indications of mass wasting on channel cutbanks.

The second watershed studied was Mill Creek located in a rural agricultural area approximately 12 km east of Italy, Texas. Mill Creek is a third-order stream, a tributary of Chambers Creek, and a sub-watershed of the Trinity River. Mill Creek's headwaters are underlain by Cretaceous Austin Chalk with the portion of stream we studied underlain by the Ozan formation, which dips gently to the southeast (Texas Bureau of Economic Geology). The soils that form the channel banks are composed of fine-grained silty clays classified as Trinity Clay (hydrologic group D) and the channel bottom consists of exposed Ozan and Trinity Clays. With exception to concrete anthropogenic debris, there is very little bed material and the channel bottom is largely bare. While Mill Creek's total length is over 30 km, only a 0.5 km segment was investigated in the lower 1/3 of the 203 km^2 watershed. Widths and depths of the study reach are relatively consistent with channel heights between 3.5 and 4.5 m and channel widths from 11.5 to 14.0 m. The slope and sinuosity of the study reach are .0043 m/m and 1.12, respectively. Riparian vegetation comprises large trees with some shrubs consisting of elms (*Ulmus* spp.), hoptree (*P. trifoliata*), netleaf hackberry (*Celtis laevigata*), ash (*Fraxinus* spp.) and, oak (*Quercus* spp.) species.

Mill Creek has been in a state of disequilibrium since the 1960s (Ridgeway, 1997). While perturbations to channel flow regimes are generally small due to consistent land use practices, degradation in Mill Creek at the study reach is caused by channel discharges exceeding the sediment transport capacity for the available sediment supply

(Harvey and Watson, 1986). This was caused by upstream channel straightening and levee construction that results in steeper channel slopes driving corresponding channel change. Downstream of the study reach has much larger channel widths and is further along in the channel-evolution process compared to the study reach. This is due to downstream channelization and lowered base-levels from dam installation, resulting in upstream knick-point migration. Channel change in Mill Creek could take up to 100 years for equilibrium to be reached (Simon, 1995).

Cedar and Mill Creeks were chosen because they exemplify typical small urban channels and medium rural channels within the same region and climate zone (humid subtropical). Small channels are important to study because they comprise 60% of the streams within a stream network and nearly half of all river miles in the United States (Leopold et al. 1964) and urbanization can lead to rapid hydrologic changes to a watershed. Medium-sized rural channels within the Blackland Prairie region have historically been the focus of studies by local and national agencies, like the NRCS and U.S Army Corps of Engineers, due to high erosion rates and land degradation (NRCS, 1995). The choice of both channel systems will allow assessment of: (1) the scale of applicability of dendrogeomorphology, (2) the scale of occurring hydrologic processes, and (3) rates of erosion in the Blackland Prairie physiographic region.

Methods and Materials

In this study, 49 root samples were collected from 11 trees at Cedar Creek and 38 root samples were taken from 10 trees at Mill Creek. Sample collection consisted of a segment of root being cut with a hand saw from trees found within the stream channel. Seven commonly occurring tree taxa were used in this study, all of which were angiosperms and labeled as ring-porous wood types. Of the 87 samples taken, 70 were exposed by channel erosion while 17 remained buried and were used to compare pre- and post-exposure root anatomy. Roots were also collected at least 1 meter from the trunk of its respective tree to minimize tree ring distortion associated with primary stem anatomy (Bodoque et al., 2011) and from a variety of horizontal distances from the bank ranging from 5 to 178 cm between both sites. No other criteria were used to select root samples. Horizontal distances of a root samples to the streambank were recorded to be tested as the dependent variable against estimated time of exposure (independent variable, Figure 2.1.). Other features including root height on the channel, root locations, root orientation in space, channel top width, channel side-slope, and channel height were also recorded to help identify the controlling factors of erosion rates (Gartner, 2007).

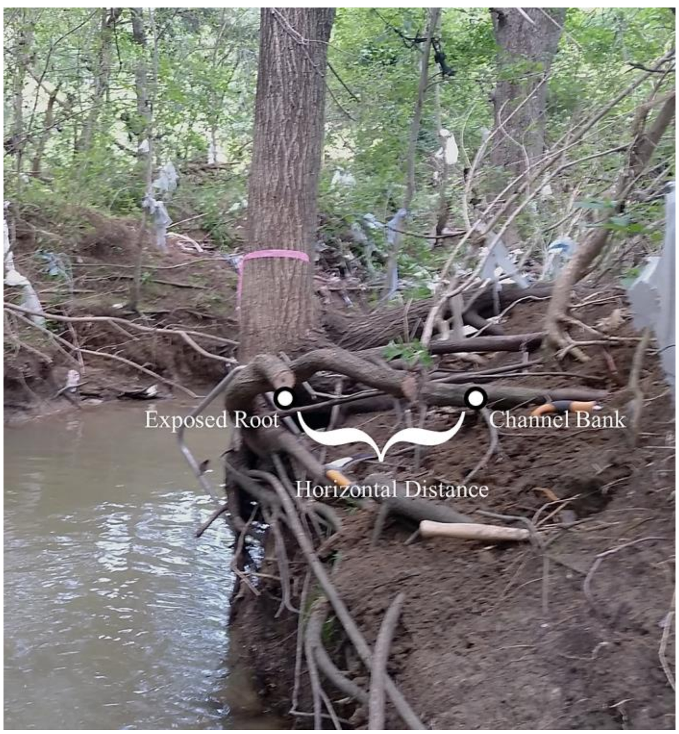

Figure 2.1. Exposed tree root example with horizontal distance to the channel bank (H_d)

To prepare samples for analysis, root segments were placed in a drying oven to eliminate moisture. After samples were sufficiently dried, root segments were cut into 3 to 6 cm discs with a high-torque circular saw and further prepared by hand sanding samples using continually finer grained sand paper until tree ring anatomy was optimally visible when viewed through an optical light microscope (Phipps, 1985).

The dendrogeomorphic method relies on wood-anatomical changes that occur and growth rings similar to those in the stem or branches being formed after root exposure (Fayle, 1968). A variety of anatomical changes can occur in root tissue to indicate the time of exposure including: a decrease in vessel size, a dramatic increase in annual ring width, bending rays, a decrease in fiber size, a switch from ring-porous vessel arrangement to diffuse-porous, ring eccentricity, and scarring of root tissue (Figure 2.2., Schweingruber at al. 2007, Stoffel & Bollschweiler, 2009). The total years of exposure can be calculated by subtracting the number of annual tree rings since anatomical change from the current year. False rings, an incomplete ring triggered by an abrupt change in weather during the same year that can yield erroneous ages values (Stokes and Smiley, 1968), were identified by assessing the continuity of the ring across the sample and were excluded from the ring counts. The horizontal distance of the root to the channel bank was divided by the time of root exposure to estimate the average bank retreat rate at each sampled site, visualized by:

$$Er = \frac{H_d}{L_e}$$

where *Er* (cm/yr) is the erosion rate, H_d (cm) is the horizontal distance to the streambank and L_e is the time span of exposure (years; Figure 2.1).

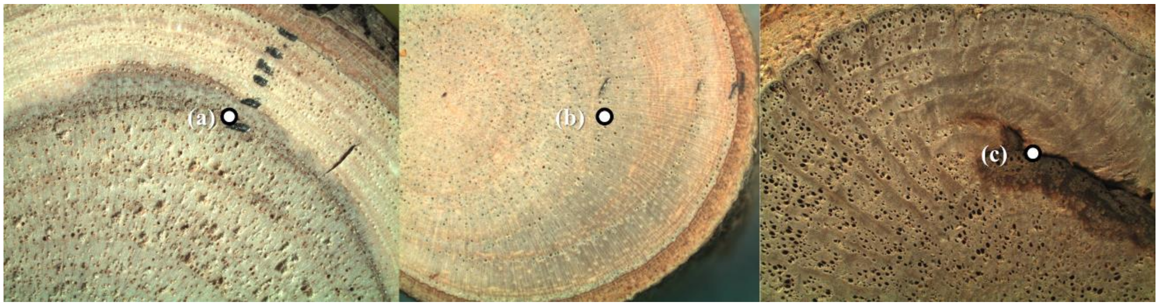

Figure 2.2. Year of root exposure is indicated by the anatomical features: (a) increased vessel size, (b) increase in ring eccentricity, (c) root scarring

An erosion rate was determined for each root sample when possible. Bulk erosion rates for each watershed were calculated as the average erosion rate from all root samples. To further analyze these bulk data we used an unpaired *t*-test to compare channel erosion rates between roots from the Cedar and Mill Creek watersheds. Next, erosion rates were compared separately in each watershed with an unpaired *t*-test to investigate differences in erosion rates between roots collected at specific channel locations. In Cedar Creek, 26 of the samples came from straight channel sections and 23 came from cutbanks, so estimated erosion rates between these groups were tested for significant differences. In Mill Creek, all samples came from straight channel sections; however we divided samples by relative height of the root collected on the channel bank, with 15 samples coming from the upper-third of the bank and 22 samples coming from the lower two-thirds. This same grouping was not feasible in Cedar Creek due to the large range of channel bank heights of that stream system. Finally, a least-squares linear regression assessed the correlation between horizontal distance to the streambank and length of exposure within the different groups for each watershed.

Results

Of the 70 exposed root samples collected from 21 different trees of 7 taxa, time of exposure could be identified in 59 cases. Root samples collected from tree species *M. pomifera* and *Q. macrocarpa* could not be used to determine year of exposure due to lack of sufficient anatomical evidence in the root structure of exposed roots. Remaining samples showed anatomical changes including decreased vessel sizes, bending rays, ring eccentricities, scarring from flowing debris, and dramatic changes in ring width post exposure (Figure 2.2).

In Cedar Creek, sampled roots had been exposed from less than a year to 16 years with an average exposure time of 4 years and had a bulk erosion rate of 24.4 cm/yr. When samples were split into groups by channel position, cutbank and straight channel sections, their respective erosion rates were estimated at 39.8cm/yr and 4.2 cm/yr (Table 2.1). An unpaired *t*-test revealed that these two groups are statistically different ($P<0.0001$), with the range of estimated erosion rates being much smaller in straight channel sections (Figure 2.3). For Cedar Creek the least-squares regression analysis for root distance to the bank and years of exposure by channel group showed that straight channel roots from Cedar Creek have a strong positive correlation with $R^2 = 0.81$ while cutbank samples showed a weak positive correlation with $R^2 = 0.07$ (Figure 2.4).

Samples from Mill Creek had been exposed between 1 and 26 years with an average exposure length of 8 years and had an average erosion rate of 9.26 cm/yr. When Mill Creek root samples were split into upper bank and lower bank samples, they had estimated erosion rates that were significantly different ($P=0.0018$). Lower bank erosion rates were estimated at 4.7 cm/yr and upper bank were estimated at 12.5 cm/year (Table

2.1). A least-squares regression analysis for root distance to the bank and years of exposure in Mill Creek revealed that lower bank samples have a strong positive correlation with $R^2 = 0.80$, while the upper bank samples had a weak positive correlation with $R^2 = 0.07$ (Figure 2.4).

A site-to-site comparison of the mean erosion rate for each watershed revealed that erosion rates are significantly different (*P*=0.0043) between watersheds. Cedar Creek is a smaller watershed within the same physiographic province as Mill Creek, but mean erosion rates are 2.6 times greater, showing that local controls such as land use have a great influence on channel erosion rate.

Table 2.1. Erosion rates produced by this study and other example studies

Stream/River	Drainage Area (km2)	Mean Erosion Rate (cm/yr)	Standard Deviation (cm/yr)	Reference
Cedar Creek All Samples, TX	4	24.4	26.4	-
Cedar Creek Cut Bank Samples, TX	4	39.8	26.1	-
Cedar Creek Straight Channel Samples, TX	4	4.2	1.5	-
Kings Creek Upper Bank, TX	5	3.1	1.8	Capello, 2007
Kings Creek Lower Bank, TX	5	4.1	1	Capello, 2007
Goodwin Creek, MS	10	53	Not Available	Simon and Darby, 1997
South River, VA	134	4.1	3.6	Stotts et al. 2014
Mill Creek All Samples, TX	203	9.3	7.1	-
Mill Creek Upper Bank Samples, TX	203	12.5	7.6	-
Mill Creek Lower Bank Samples, TX	203	4.7	2	-
Big Brushy Creek Upper Bank, TX	239	57.2	9	Capello, 2007
Big Brushy Creek LowerBank, TX	239	16.2	4.6	Capello, 2007
Rio Nutria, NM	294	8	Not Available	Gellis, 1998
Undisclosed River, MI	6600	6.9	Not Available	Dick et al. 2014

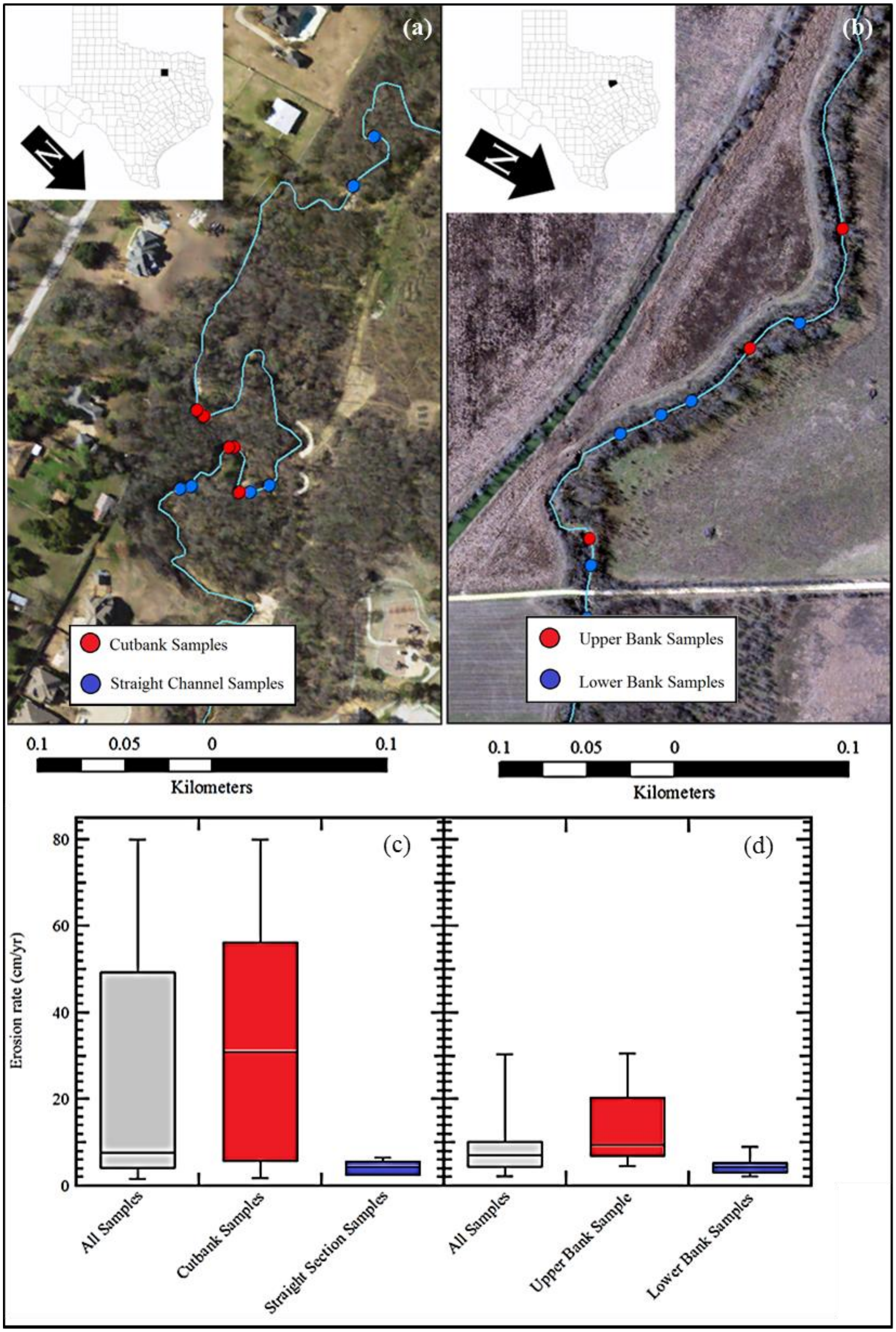

Figure 2.3. Site map of: (a) Cedar Creek, and (b) Mill Creek with associated root collection locations, and box plots of erosion rates for (c) Cedar Creek and (d) Mill Creek

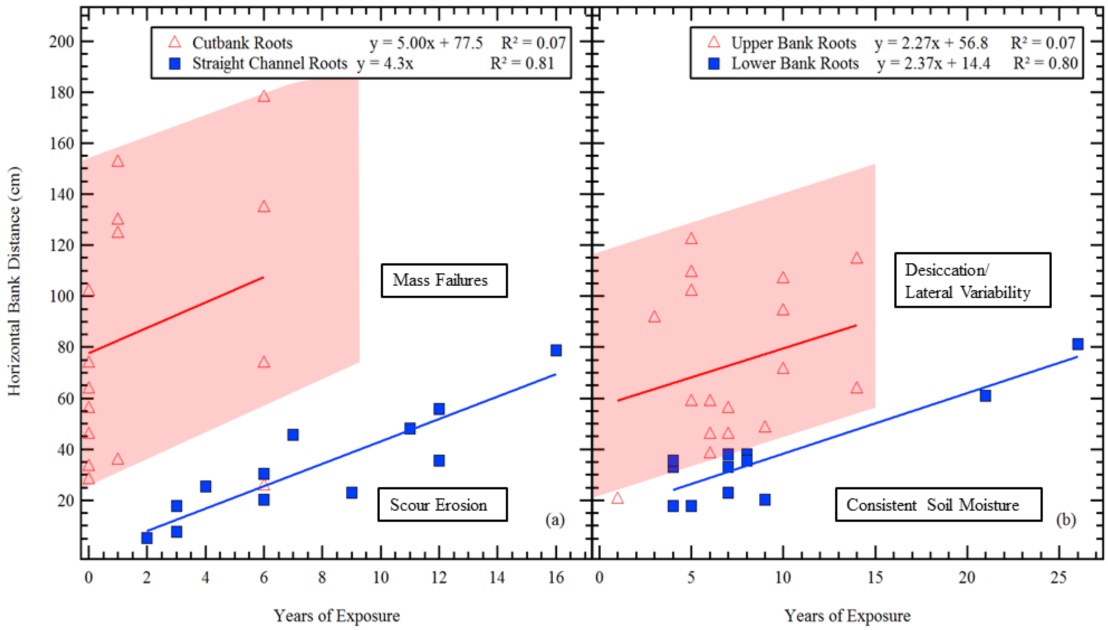

Figure 2.4. Years of exposure plotted against horizontal distance to streambank for roots collected from cutbanks and straight channel sections of Cedar Creek, and the upper and lower banks of Mill Creek with linear regression equation and coefficient of determination included

Discussion

Results from the dendrogeomorphic analysis show that bank retreat in Cedar and Mill Creek are on the same order of magnitude as other bank erosion studies (see Table 2.1). For example, an erosion-pin study, also within the Blackland Prairie, on severely eroding streambanks (Capello, 2008) had similar erosion rates and variabilities to this study, demonstrating that results produced commensurate with the precision of erosion-pin studies. This is in line with other dendrogeomorphic studies such as the results from Dick et al. (2014) on an undisclosed watershed in Michigan where erosion rates were also comparable to pin studies in similarly sized watersheds and Stotts et al. (2014) who showed that erosion rates determined by the dendrogeomorphic method were more reliable than photogrammetric techniques on the South River in Virginia. However, differences in erosion rates between sample groups at each site (straight channel and cutbank samples in Cedar Creek, and upper and lower bank sample in Mill Creek) suggest that bulk erosion rates do not accurately describe erosion processes occurring within either Cedar or Mill Creek.

Cedar Creek

Differences in erosion rates between sample groups based on channel location (cutbank or straight channel sections) in Cedar Creek were significant. Not only were erosion rates lower in the straight channel sample group, but the variability of erosion rates was much lower than cutbank samples (Figure 2.3). When horizontal root distance from the channel bank was plotted against years of exposure, straight channel samples were correlated at $R^2 = 0.81$ (Figure 2.4). A narrow erosion-rate distribution and a high coefficient of determination reveal that erosion in straight-channel sections is relatively consistent, both temporally and in magnitude. Scour erosion (entrainment) is most likely the dominant method of channel widening in these stream locations, as evidenced by consistent erosion rates and no visible signs of mass wasting.

Higher erosion rates and variation in cutbank samples likely occur because of higher local hydraulic forces and bank instability. Most often, fluvial erosion is conceptualized in a threshold manner based on Duboys (1879) channel scour equation:

$$Er = K_d(\tau_a - \tau_{cr})$$

where K_d is the soils erodibility (cm^3/N·s), τ_a (Pa) is the applied shear to the channel bank, and τ_{cr} (Pa) is the critical shear stress to erode particles (Foster 1982). In general, channel flow fields are controlled by channel geometry, curvature, and bed topography (Dietrich 1987).

Currently, the Federal Highway Administration (2005) express shear distribution on a channel bank as:

$$\tau_b = K_b \cdot \tau_d$$

developed by Young (1996) and based on Lane's (1955) equation, where τ_b (Pa) is the shear stress applied to the bank, K_b is the ratio between channel bank to bottom shear stress, and τ_d *(Pa)* is the shear stress at the maximum channel depth. K_b is a function of channel radius of curvature, *Rc* (m), and channel top width, *Tw* (m), in channel bends:

$$Kb = 2.0 \qquad \text{when} \quad (Rc/Tw) \leq 2$$

and is a function of bank side slope, *Z* (m/m), in non-bending channel sections:

$$Kb = 0.77 \qquad \text{when} \quad Z \leq 1.5$$

In Cedar Creek, channel geometries documented during sample collection yielded *Kb* values of 2.0 in all cutbank locations and 0.77 in all straight-channel locations. Figure 2.5 shows the relationship between shear stress exerted on the channel bottom and shear stress exerted on the channel bank given the same flow at both cutbank and straight channel locations in Cedar Creek. This was done using location-specific regression equations developed by the USGS (Land et al., 1982; Asquith and Slade, 1997), that estimate the peak stream discharge, *Q* (m^3/s), for the two, five, and 10 year floods in Cedar Creek. The use of Manning's Formula (1891):

$$Q = n \cdot A \cdot R^{2/3} \cdot S^{1/2}$$

where *n* (dimensionless) is Manning's roughness, *A* is channel cross-sectional area (m^2), *R* is hydraulic radius (m), and *S* is the channel slope (m/m) was then applied to cutbank and straight-section channel sections, yielding a rating curve that returns water depth in the channel for specific discharges at a given location within Cedar and Mill Creeks. Chow's (1959) equation for bottom shear stress:

$$\tau d = \gamma \cdot d \cdot S$$

where γ is the specific weight of water (kg/m^3) and d is the water depth (m), estimates the peak shear on the channel bottom, and therefore channel banks, for the two-, five-, and 10- year flood (Figure 2.5). This translates to greater potential for sediment entrainment on cutbanks compared to straight-channel sections due to increased applied shear stress, τa (Pa). However, as scour erosion occurs, bank undercutting and continually steeper channel side slopes result which leads to bank instability and mass wasting on cutbanks (Simon et al. 2000). Mass wasting events, while less frequent, remove more material from the channel banks than scour erosion alone and may account for the majority of erosion in cohesive channels (Rutherfurd, 2007). It follows that mass wasting events, being less frequent, are inherently more variable temporally than the more regular process of scour erosion. Due to the nature of mass wasting events, the dendrogeomorphic method may not be capable of precisely calculating a rate of bank retreat when mass wasting has occurred. However, results are still valuable, as they record what year mass wasting events occurred and to what magnitude.

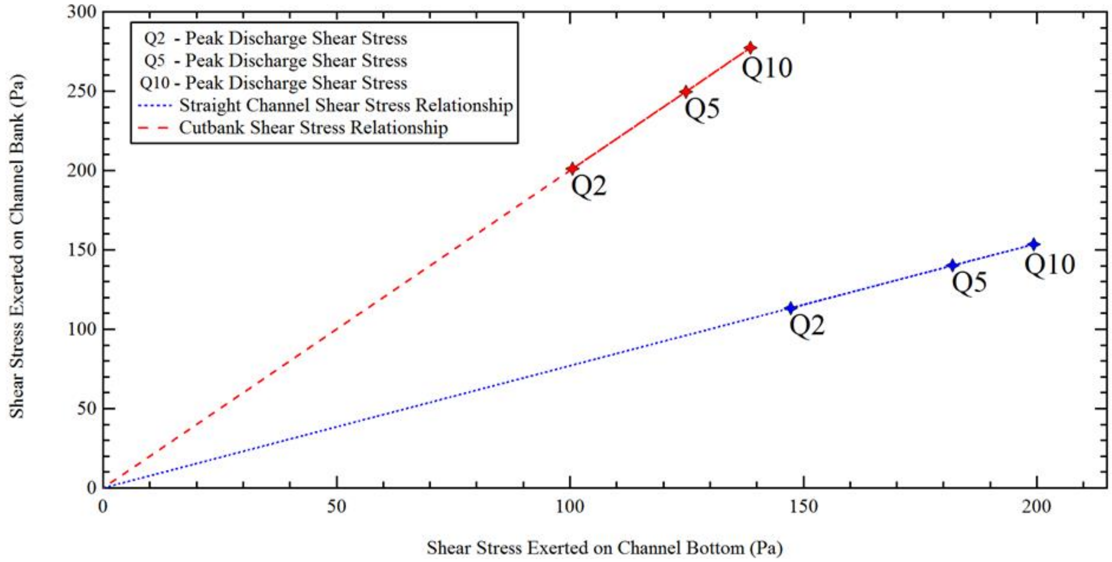

Figure 2.5. Plot showing the relationship between shear stress on the channel bottom (x-axis) and channel bank (y-axis) for straight channel and cutbank sections with estimated shear stress exerted during the two, five, and 10 year flood in Cedar Creek

Mill Creek

Though all samples collected from Mill Creek were collected from straight channel sections, variations in erosion rates based on sample location were evident. Erosion rates were lower and less variable in the bottom two-thirds of the channel bank compared to the upper third of the bank. However, erosion rate distribution and variability, while on the same order as numerous pin studies, can be explained by sub-aerial processes and root position on the channel bank. Wynn and Mostaghimi, (2006) showed that sub-aerial processes have a greater effect on upper channel banks compared to bottom portions. This is because lower banks are not subjected to the same wet-dry cycles as upper banks. Soil moisture in the lower channel bank is largely maintained by the hyporheic zone, which leads to more consistent cohesive forces in lower bank sediments. This leads to decreased variability and magnitude of erosion from flow events. Likewise, the soils in the upper bank are prone to desiccation, resulting in weakened aggregates that are more easily dislodged from the bank surface, in addition to a loss of soil cohesion due to lack of moisture (Couper & Maddock, 2002). This results in an upper bank that experiences less frequent flow events (compared to the lower bank) that are much more effective at removing sediment from the channel bank. As recorded by the dendrogeomorphic data, over time more sediment is ultimately removed from the upper bank than the lower bank, but, with greater temporal variability. This effect may be happening in in Cedar Creek, but was not observed. This is because other factors, such as mass wasting on cutbanks, have a more pronounced effect on erosion rates than subaerial processes. Moreover the impact of subaerial processes at different channel bank heights were unidentifiable due to the large range of channel bank heights within the reach.

Increased variability in calculated erosion rates on the upper bank in Mill Creek are also caused by a buttressing effect from the trunks of trees within the channel corridor. Sediment proximal to trees is reinforced by trunks, while bank sediment further from tree trunks are not. This is visually apparent by the undulating pattern in channel top widths (Figure 2.6.). Where large tree trunks are present the channel top widths are narrower, but between tree trunks channel top widths are wider, yielding erosion variability dependent upon lateral bank position. This undulating pattern is not present in the lower bank because it is below the trunks of trees that inhabit the channel corridor. If more samples had been collected it would have been possible to investigate how erosion rates on upper bank samples vary based on proximity to large tree trunks buttresses.

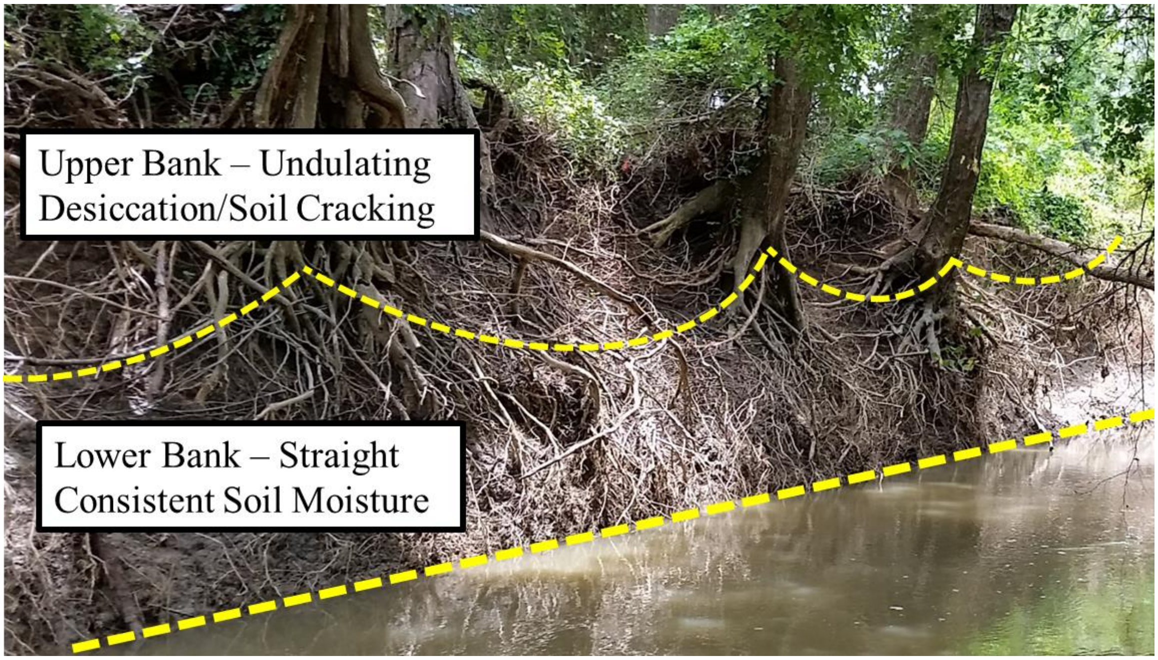

Figure 2.6. Mill Creek channel and depiction of subaerial processes between upper and lower banks and undulating pattern on the upper bank caused by tree trunk buttressing

Limitations and Considerations

While the dendrogeomorphic method yielded valuable information about the channel processes occurring within both Cedar and Mill creek, limitations exist. Biases related to root size, root position, relative uplift of roots after partial denudation, and variations in microtopography can lead to erroneous results (Stoffel at al. 2013, Bodoque et al. 2015). Uncertainty also increases the longer a root is exposed (Dick et al., 2014). Erosion rates estimated by this method are also point data that only describe the total sediment lost since root exposure at a specific location. The results found in this study show that erosion rates should be determined separately for different channel positions to best characterize bank retreat occurring within a stream system.

Conclusion

This study presents the first stream-channel erosion investigation using dendrogeomorphology in Central Texas. By analyzing the anatomy of exposed and buried riparian tree roots of commonly occurring trees it was determined, with exception to oak (*Quercus* spp.) and osage orange (*Maclura* spp.), that local taxa could be used to determine the extent of fluvial erosion occurring on streambanks. The results from ths study were at least as precise as data gathered using traditional erosion-pin methods, without requiring multi-year, multi-sample investigation.

Comparison of erosion rates between Cedar and Mill Creeks showed that more sediment was lost from streambanks within the urban watershed of the study region due to differences in land use, even though the drainage area is considerably smaller. Other urbanizing areas within Central Texas may also be prone to accelerated stream erosion rates due to land use changes altering flow regimes of previously stable watersheds.

This dendrogeomorphic method also identified differences in erosion based on channel position. In Cedar Creek, much smaller and more consistent erosion rates were found in straight-channel sections, suggesting that entrainment is the primary method of channel erosion in these locations. Erosion rates could be estimated at both yearly and decadal timescales at these locations. On cutbanks, the dendrogeomorphic method revealed much higher erosion rates and corresponding variability. Coupled with visible evidence and an analysis of channel hydraulics, it was deduced that mass wasting had occurred on cutbanks due to undercutting and unstable bank slopes. While consistent erosion rates were not observed at cutbank locations, the dendrogeomorphic method identified the magnitude and time of mass wasting events with yearly precision.

At Mill Creek, where all samples came from straight channel sections, bank height had a large impact on erosion rate and variability. Erosion on the highest third of the bank was greater and much more variable than erosion rates found in the lower two-thirds of the channel. Sub-aerial processes play a significant role in regulating channel-erosion processes in the upper bank, as sediment in these locations are more prone to desiccation and additional variability results from buttressing effects of large riparian tree trunks. This study showed that the dendrogeomorphic method is effective for assessing streambank retreat and identifying channel erosion processes.

CHAPTER THREE

Calibration and Interrogation of the Watershed Model: SWAT-DEG

Abstract

Hydrologic models are powerful tools for simulating watershed processes and are routinely used in environmental investigations to provide decision-making support. To use models effectively, it is important to understand model behavior, establish the confidence in model predictions, and recognize model limitations. SWAT-DEG is a hydrologic model designed to predict watershed processes such as channel change, sediment yields, and flow regime in small to medium-sized watersheds. In this study, a small urban and a medium-sized rural watershed in Central Texas were modeled with SWAT-DEG. Models were then interrogated to determine model predictive uncertainty, prediction sensitivities to model parameters, and data worth. Results showed that when calibrated, SWAT-DEG made reliable channel-change predictions from available data, but additional data were needed to reliably predict sediment yields and flow regimes. Identification of sensitive input parameters and assessment of data worth yielded a procedure to effectively parameterize and calibrate additional watersheds. Results from this study offer a guide to accurately predict watershed processes and allow SWAT-DEG models to be used as a platform for hypothesis development regarding potential changes to watershed conditions, such as urbanization or stream-restoration projects.

Introduction

Numerical environmental models are used extensively in research, management, and decision making. These models serve to: (1) compile all known information about a system, (2) make incremental predictions with time, and (3) provide a platform to hypothesis test how changes in system characteristics alter system behavior (Doherty, 2010; Trucano et al., 2006). However, numerical models are sensitive to their conceptualization, complexity (number of equations, parameters, etc.), and scale of application (Piegay et al., 2005). Numerical models also require calibration, which makes them subservient to the quality and availability of data.

SWAT-DEG is a hydrologic model developed to provide a practical and easily deployable technique to assess how changes in climate, land use, and other watershed processes affect stream-channel geomorphology and sedimentation for small-to-medium sized watersheds (Gassman et at. 2007; Ditty et al., 2014). This model is versatile and can simulate watershed processes in a wide range of environments at daily to decadal time scales. However, predictions from SWAT-DEG have never been formally evaluated and model behavior is relatively unknown.

Model calibration is the process of estimating model parameters by matching model outputs to historical system observations (Moriasi et al., 2007; Rajib et at., 2015). Unfortunately, even predictions made by a model that matches historical data perfectly may be considerably in error (Moore and Doherty, 2004) because an infinite number of parameter combinations can exist that produces equally reasonable simulation results (Beven, 1993). Because of this, evaluation of model performance and behavior may be needed, even after model calibration.

Assessing model performance and behavior is crucial to justifying a model's continued use (Bennett et al., 2012) and is intrinsically case-dependent for each model and specific modeling objective (Krause et al., 2005; Jakeman et al., 2006). There are many different approaches to assess model performance and behavior (Arnold et al., 2015; Alexandrov et al. 2011; Mcintosh et al. 2011) and the literature is rich with studies that discuss different systematic model-evaluation techniques (Moriasi et al., 2007; Dawson et al., 2010; Beck, 2006; Matott et al. 2009).

The objectives of this study were to calibrate and simulate watershed processes with SWAT-DEG, evaluate model performance, and interrogate model behavior. This paper describes this process for two SWAT-DEG modeled watersheds in Central Texas. Through the use of the software suite PEST (Doherty, 2010), a model-independent tool designed to calibrate and evaluate numerical models, we assessed model predictive uncertainty, prediction sensitivity to parameters, model behavior, and data worth. Results of this study should guide future data-collection efforts so that accurate models can be created efficiently and effectively.

Materials and Methods

SWAT-DEG Model Description

The hydrologic model SWAT-DEG was created by modifying and simplifying the river-basin-scale model Soil Water Assessment Tool (SWAT) to address channel change in first- and second-order streams (Allen et al., 2008, Gassman et al., 2007, Ditty et al. 2014). SWAT-DEG was developed to assess how changes in climate, land use, and other watershed processes affect stream-channel geomorphology and sedimentation. While SWAT-DEG is typically used for assessing stream-channel dynamics, such as erosion and degradation with changing land use and climate, it is also a fully operational water budget model capable of assessing the entire water balance including soil moisture, groundwater baseflow, and aquifer recharge among other components. This model affords a practical and easily deployable technique for estimating future watershed conditions (Ditty et al., 2014).

SWAT-DEG is a continuous-time-step model that incorporates three primary components: basin characteristics, channel characteristics, and climate inputs (Figure 3.1). Basin characteristics are defined by 28 parameters listed in an input file named h*ru-lte.hru* (Table 3.1 and Table 3.2). At each modeled time step, the Modified Universal Soil Loss Equation (MULSE; USDA, 1980) calculates basin runoff and sediment yield to be routed into the stream channel. This equation uses runoff volumes and peak flows from weather events to simulate sheet and rill erosion based primarily on soil characteristics and land use (USDA, 1986).

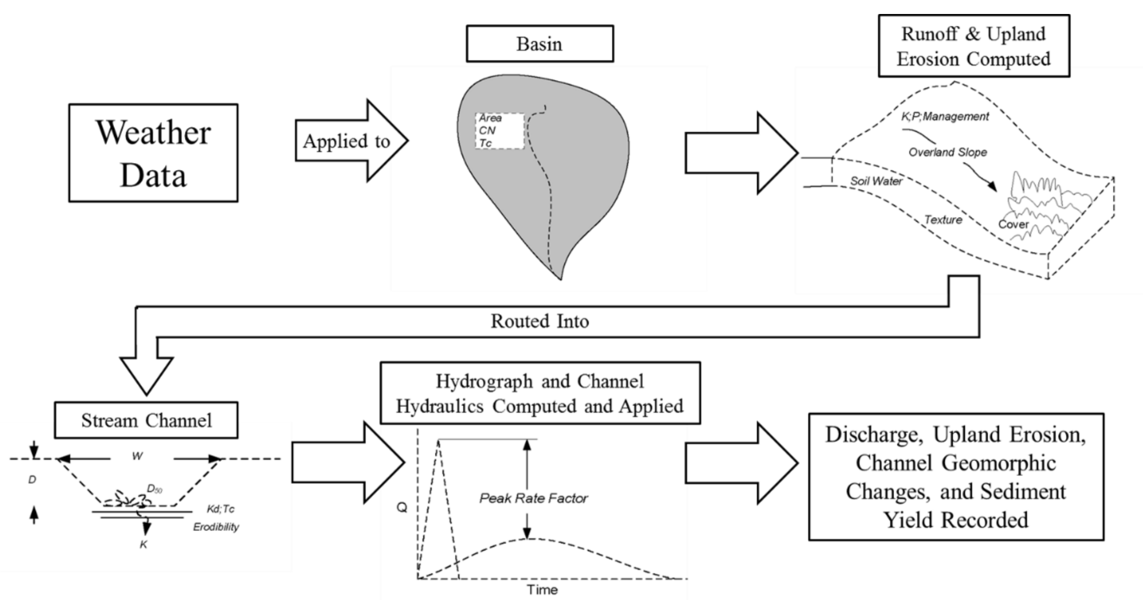

Figure 3.1. SWAT-DEG computer flow; the basin is defined by the input file *hru-lte.hru* and the channel is defined by *channel-lte.cha*

The stream channel is defined by 19 input parameters in an input file named *channel-lte.cha* (Table 3.3 & Table 3.4). The flow and sediment routed into the channel and sediment deposition and channel erosion are calculated. This is done on a storm-by-storm basis by first generating and discretizing a hydrograph using NRCS techniques from watershed and rainfall data (USDA 2007). Channel hydraulics are estimated assuming a trapezoidal channel cross section with depth-weighted shear stresses applied to the channel bottom and channel bank for the storm duration. If the computed shear force due to flow is greater than the bedload critical tractive force and there is available sediment transport capacity (taking into account incoming sediment from the upstream reach), sediment is mobilized. Remaining shear stress after sediment transport is applied to the channel bottom and will erode and deepen the channel if the critical shear strength of channel bottom is exceeded. On the banks, if the shear stress exceeds the critical stress of the bank material, it will erode. Shear stresses acting on the bank are decreased by vegetation cover (NRCS, 2007). A channel will continue to widen or deepen until the shear stresses drop below the critical shear stresses. The slope of the stream channel degrades to a predetermined channel equilibrium slope as widening and deepening occur. If the flow shear stress is insufficient to mobilize the bed material, sediment deposition may occur, and erosion will not occur. The system state is recorded at the end of each time step and carried forward during the model run.

Flow resulting specifically from precipitation, is the driving force for this model and daily precipitation data are supplied to the model. Weather data, comprising daily rainfall and temperature at each study site, were gathered from PRISM Climate Group (http://www.prism.oregonstate.edu/explorer/) and used for model simulations in this study. Weather data from personal or government climate stations are also viable options when gathering historic weather data. If historical weather data are not available, or simulation of future conditions are sought, SWAT-DEG is also capable of generating weather conditions based on historic climate data.

Table 3.1. Parameter descriptions and pre/post calibrated values included in SWAT-DEG input file *'hru-lte.hru'* for the Cedar Creek watershed

Parameter Name	Description	Unit	Pest Parameter	Initial Value	Calibrated Value
dakm2	Drainage Area	km2	N	3.88	-
cn2	Curve Number	Integer (30-80)	Y	80	85.5
tc	Time Of Concentration	min	Y	26	26.0271
soildep	Soil Profile Depth	mm	Y	1500	2260
slope	Land Surface Slope	m/m	Y	0.043	0.0429017
slopelen	Land Surface Slope Length	m	Y	64.2	64.2093
sy	Specific Yield Of The Shallow Aquifer	mm	N	0.05	-
abf	Alpha Factor Groundwater	unitless	N	0.05	-
revapc	Revap Coefficient Amt Of Et From Shallow Aquifer	unitless	N	0	-
percc	Percolation Coeff From Shallow To Deep	unitless	N	0.01	-
sw	Initial Soil Water (Frac Of Awc)	Fraction	N	0.5	-
gw	Initial Shallow Aquifer Storage	mm	N	3	-
gwflow	Initial Shallow Aquifer Flow	mm	N	0	-
gwdeep	Initital Deep Aquifer Flow	mm	N	300	-
snow	Initial Snow Water Equivalent	mm	N	0	-
xlat	Latitude	Latitude	N	31.6	-
itext	Soil Texture	Integer (1-12)	N	8	-
tropical	0 = Non-Tropical 1 = Tropical	Integer	N	0	-
igrow1	Start of Growing/Monsoon Season	Julian Day	N	60	-
igrow2	End of Growing/Monsoon Season	Julian Day	N	201	-
icrop	Plant Type (As Listed In Plants.Plt)	Integer	N	3	-
ipet	Potential ET Method	unitless	N	1	-
irr	Irrigation Code 0=No Irr 1=Irrigation	Integer	N	0	-
irrsc	Irrigation Source 0=Outside Basin 1=Shal Aqu 2=Deep	Integer	N	0	-
uslek	USLE Soil Erodibility Factor	None (0-1)	Y	0.32	0.149617
uslec	USLE Cover Factor	None (0-1)	Y	0.2	0.09018
uslep	USLE Equation Support Practice (P) Factor	None (0-1)	Y	0.8	0.396715
uslels	USLE Equation Length Slope (LS) Factor	None (0-10)	N	0.53	-

Table 3.2. Parameter descriptions and pre/post calibrated values included in SWAT-DEG input file '*hru-lte.hru*' for the Mill Creek watershed

Parameter Name	Description	Unit	PEST Parameter	Initial Value	Calibrated Value
dakm2	Drainage Area	km2	N	203	-
cn2	Curve Number	Integer (30-80)	Y	81	79
tc	Time Of Concentration	min	Y	480	478
soildep	Soil Profile Depth	mm	Y	2500	2484
slope	Land Surface Slope	m/m	Y	0.015	0.015
slopelen	Land Surface Slope Length	m	Y	250	252
sy	Specific Yield Of The Shallow Aquifer	mm	N	0.05	-
abf	Alpha Factor Groundwater	unitless	N	0.05	-
revapc	Revap Coefficient Amt Of Et From Shallow Aquifer	unitless	N	0.1	-
percc	Percolation Coeff From Shallow To Deep	unitless	N	0.01	-
sw	Initial Soil Water (Frac Of Awc)	Fraction	N	0.5	-
gw	Initial Shallow Aquifer Storage	mm	N	3	-
gwflow	Initial Shallow Aquifer Flow	mm	N	0	-
gwdeep	Initital Deep Aquifer Flow	mm	N	300	-
snow	Initial Snow Water Equivalent	mm	N	0	-
xlat	Latitude	Latitude	N	31.6	-
itext	Soil Texture	Integer (1-12)	N	5	-
tropical	0 = Non-Tropical 1 = Tropical	Integer	N	0	-
igrow1	Start of Growing/Monsoon Season	Julian Day	N	60	-
igrow2	End of Growing/Monsoon Season	Julian Day	N	201	-
icrop	Plant Type (As Listed In Plants.Plt)	Integer	N	3	-
ipet	Potential ET Method	unitless	N	1	-
irr	Irrigation Code 0=No Irr 1=Irrigation	Integer	N	0	-
irrsc	Irrigation Source 0=Outside Basin 1=Shal Aqu 2=Deep	Integer	N	0	-
uslek	USLE Soil Erodibility Factor	None (0-1)	Y	0.32	0.12
uslec	USLE Cover Factor	None (0-1)	Y	0.2	0.09
uslep	USLE Equation Support Practice (P) Factor	None (0-1)	Y	0.7	0.71
uslels	USLE Equation Length Slope (LS) Factor	None (0-10)	N	0.7	-

Table 3.3. Parameter descriptions and pre/post calibrated values included in SWAT-DEG input file *channel-lte.cha* for the Cedar Creek watershed

Parameter Name	Description	Unit	PEST Parameter	Initial Value	Calibrated Value
chw	Channel Width	m	N	7.62	-
chd	Channel Depth	m	N	1.3	-
chs	Channel Slope	m/m	N	0.0058	-
chl	Channel Length	km	N	1.151	-
chn	Manning's n (roughness coefficient)	Manning's n	Y	0.07	0.04
chk	Channel Bottom Conductivity	mm/hr	N	1	-
cherod	Channel Erodibility	cm3/N-s	Y	0.03	0.013
chcov	Vegitation Cover Factor	%	Y	0.25	0.39
chwdr	Width/Depth Ratio	m/m	N	3.6	-
chseq	Equilibrium Slope	m/m	Y	0.00089	0.00089
d50	Median Particle Size	mm	Y	1.3	1.29904
clay	Percent Clay	%	Y	23	26.5008
bd	Bulk Density	tons/m3	Y	1.6	1.6474
sidesl	Side Slope	m/m	N	0.83	-
bedld	Bedload Coefficient	% of Sediment t	Y	0.2	0.199867
tc	Time of Concentration	Minutes	Y	26	31.22
hc_kh	Headcut Erodibility	cm3/N-s	N	0	-
hc_hgt	Headcut Height	m	N	0	-
hc_ini	Initial Gully Channel Length	km	N	0	-

Table 3.4. Parameter descriptions and pre/post calibrated values included in SWAT-DEG input file *channel-lte.cha* for the Mill Creek watershed

Parameter Name	Description	Unit	PEST Parameter	Initial Value	Calibrated Value
chw	Channel Width	m	N	11.57	-
chd	Channel Depth	m	N	2.52	-
chs	Channel Slope	m/m	N	0.0043	-
chl	Channel Length	km	N	8.53	-
chn	Manning's n (roughness coefficient)	Manning's n	Y	0.03	0.028
chk	Channel Bottom Conductivity	mm/hr	N	2.5	-
cherod	Channel Erodibility	cm3/N-s	Y	0.015	0.0153
chcov	Vegitation Cover Factor	%	Y	0.65	0.54
chwdr	Width/Depth Ratio	m/m	N	3.5	-
chseq	Equilibrium Slope	m/m	Y	0.00082	0.00082
d50	Median Particle Size	mm	Y	1.097	20.9
clay	Percent Clay	%	Y	26	25.6
bd	Bulk Density	tons/m3	Y	1.63	1.6
sidesl	Side Slope	m/m	N	1.42	-
bedld	Bedload Coefficient	% of Sediment t	Y	0.2	0.199867
tc	Time of Concentration	Minutes	Y	480	491
hc_kh	Headcut Erodibility	cm3/N-s	N	0	-
hc_hgt	Headcut Height	m	N	0	-
hc_ini	Initial Gully Channel Length	km	N	0	-

Watershed Descriptions

The SWAT-DEG model was applied to two watersheds within the Blackland Prairie physiographic province: Cedar Creek, a first-order tributary of the Trinity River basin located within the rapidly urbanizing community of Grand Prairie, Texas (a suburban city of the Dallas-Fort Worth metroplex), and Mill Creek a rural third-order stream located approximately 12 km east of Italy, Texas, also a sub-watershed of the Trinity River. Both watersheds are within the same humid sub-tropical climate region, underlain by cretaceous bedrock that dip gently to the south-east, and have clay rich soils in the D hydrologic soil group (Ferris-Heiden Clay in Cedar Creek and Trinity Clay in Mill Creek). Woody vegetation occurs on the banks of both stream channels, but Cedar Creek has visible signs of slumping and channel degradation throughout the reach. Channel bottoms are composed of loosely consolidated calcareous marls in both watersheds, but sediment within the channel in Cedar Creek has a more variable composition of large cobbles of shale and gravel in riffle zones and silt to sand sized particles in pools; while the Mill Creek channel bottom is bare exposed marl.

Differences between these two watersheds beside drainage areas are related to their land-use histories. Land use in Cedar Creek changed from natural grasslands to agricultural lands in the late 1800s followed by rapid development and residential construction in the 1960s and 1990s as evident in historic photos (AECOM, 2009). Changes to hydrologic processes, such as more frequent and larger peak flows resulted in degradation, widening, and loss of riparian vegetation (Leopold and Skibitzke, 1967; Hawley et al. 2012). Degradation and incision of the channel due to land use change has led to construction of hard points, installation of riprap, and channelization in many portions of the watershed in attempt to stabilize the channel. Degradation still occurs along much of Cedar Creek as evident by over-steepened banks, scour of channel banks, slumping trees, and visible indications of mass wasting on channel cutbanks. Active channel widths and depths are variable between 1.5 and 6 m (average of 2.5 m) and 0.5 and 10 m (average of 2.5 m), respectively.

Mill Creek also has a history of degradation, but has remained rural agricultural land since the 1800s. This is due to downstream channelization and a lowered base-level due to dams that initiated knick-point migration starting in the 1960s. Degradation in Mill Creek is also due to channel discharges exceeding the sediment transport capacity for the available sediment supply (Harvey and Watson, 1986) caused by upstream channel straightening or levee construction that yield steeper channel slopes, resulting in channel change. Channel change in Mill Creek could take up to 100 years for equilibrium to be reached (Simon, 1995). Widths and depths of the study reach at Mill Creek are relatively consistent with channel heights between 3.5 and 4.5 m and channel widths from 11.5 to 14.0 m.

The modeled study reaches span the lowest 1.1 km of stream channel in the 4 km^2 Cedar Creek watershed and the lowest 8.5 km of stream channel in the 203 km^2 Mill Creek watershed. These two watersheds were selected because: (1) of available literature and historical studies, (2) both watersheds are located in the same physiographic region, and (3) we could examine how SWAT-DEG performs at two different watershed scales.

Model Input and Observation Data

To parameterize SWAT-DEG for the Cedar and Mill Creek watersheds, model input data were collected from a variety of sources. Cedar Creek initial-condition data were gathered from a Fluvial Geomorphology Report (AECOM, in 2009). A study of channel evolution in the Blackland Prairie was used to parameterize the Mill Creek watershed (Ridgeway, 1997). The soil-properties input data required by SWAT-DEG (bulk density and sediment size) were collected in 2015 field surveys. Channel soil bulk density was measured using the Clod Method (Blake 1965) and sediment sizes and distributions were determined with a Malvern Mastersizer 2000 (ASTM D422). Any additional input data (e.g. soil depth, channel soil erodibility, bedload coefficient) required by SWAT-DEG were estimated using expert knowledge.

Observation data used to calibrate the Cedar and Mill Creek models consisted of channel-width and erosion data that were collected from field surveys in 2015. The channel width in 2015 and the average annual erosion from the streambank were determined in both watersheds through a dendrogeomorphic channel assessment. This method allows the determination of historical channel erosion rates through the analysis of annual growth rings in riparian tree roots exposed on the channel banks due to erosion. Work by Dick et al. (2014), Stotts et al. (2014) and Norair (2016, Chapter 2) exemplify how to employ this method. The observed final channel width in Cedar and Mill Creeks were 8.21 m and 13.27 m, respectively. The average annual channel erosion in the study reaches were measured at 266 tons/yr in Cedar Creek and 5,509 tons/yr in Mill Creek.

The hydrologic model SWAT-DEG was parameterized, calibrated, and run for Cedar Creek from 2009 through 2015 and Mill Creek from 1997 through 2015. The durations of model simulations were selected to correspond to the available initial condition data. SWAT-DEG predicted yearly, and average annual: discharge, tons of sediment into and out of the reach, tons of sediment scoured from the channel bottom and channel bank, and channel slope, width, and depth for both study sites.

Calibration and Model Interrogation

PEST (Doherty 1994) is a model-independent suite of software used to calibrate and interrogate computer models. It was chosen because of its ability to interface with any model and provide robust implementation of a variety of statistical measures for model interrogation. This software suite is freely accessible and heavily documented, providing the tools to appropriately calibrate and interrogate models.

The procedure for model calibration and interrogation is illustrated in Figure 3.2. Before the PEST software suite can be used to calibrate and interrogate each model, information about the parameters and calibration data need to be provided. Three PEST were applied in this study in the following order: (1) PEST - estimation mode, (2) GENLINPRED (the GENeral LINear PREDictive uncertainty analyzer), and (3) SENSAN.

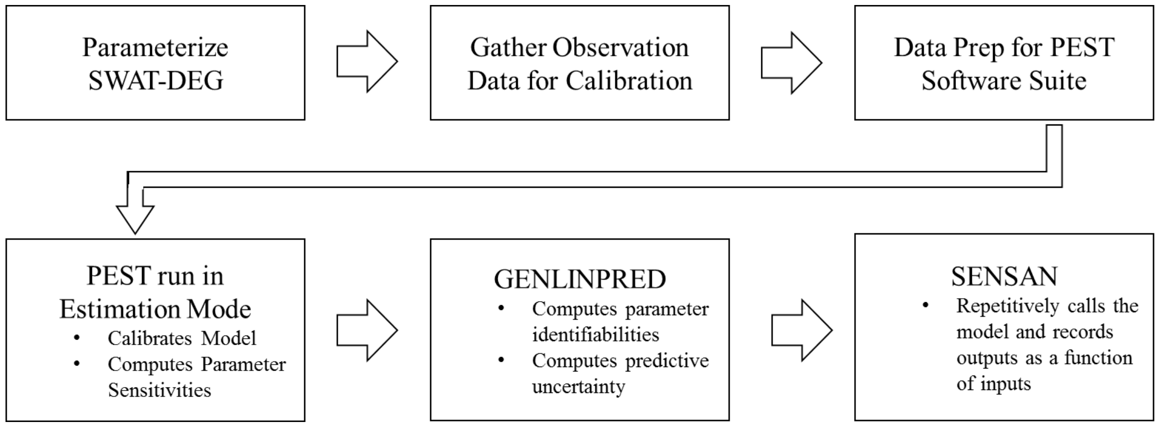

Figure 3.2. PEST workflow

Setting up PEST. Identification and constraints on adjustable parameters (noted in Table 3.1 – 3.4) and observation data (channel widths and erosion rates) were supplied to PEST. Parameters were considered adjustable if they were not physically well defined (Santhi et al., 2001). Parameters were allowed to be varied by PEST with each parameter's expected 95% confidence limit determined by expert knowledge and a literature survey (AECOM, 2009; Ridgeway, 1997; USDA, 2015). This means PEST was provided with a range of input values that we are 95% certain contain the actual value of a specific input parameter.

The individual observations comprising the calibration data set were weighted in accord with the confidence of accuracy for each observation. This means that if there was less confidence in the value of an observation being correct, it had a lower weight. Specifically an observation's weight was assigned as the inverse of the standard deviation in its measurement certainty, which dependent on the data-collection technique used to make an observation (Hill and Tiedeman 2007). For example, this study used a dendrogeomorphic channel assessment to gather observation data, so measurement weights were assigned as the inverse of the standard deviation for the erosion rates produced by that method.

PEST – Estimation Mode. When run in estimation mode, PEST takes an uncalibrated model, treats it as a black box, and repetitively calls the model, adjusting the unknown parameters to achieve the best fit between simulated and observed data. A calibrated model and sensitivity of supplied calibration data to parameters results. To PEST, SWAT-DEG is merely a matrix that transforms parameters (**p**) into outputs (**h**) as described by:

$$\mathbf{h} = \mathbf{X}\mathbf{p} + \varepsilon$$

where **X** is the model (or Jacobian matrix of observation sensitivities to model parameters), and ε is noise (measurement error). By matching model outputs to corresponding system measurements (observations) model parameters are selected such that model simulations most closely replicate measured observations. PEST minimizes a least-squares objective function (Φ), defined by Doherty (2015) as the sum of squared weighted differences between calibration data and corresponding model outputs (how well model predictions match observation data). This is described as:

$$\Phi = \sum (w \cdot r)^2$$

Where w are observation weights, and r are the differences between model outputs and calibration data. PEST alters parameter values with each model run until the objective function (Φ) is minimized to the lowest value possible. When model outputs match observation data exactly the objective function will be 0.0. This provides a metric to assess calibration success.

GENLINPRED. After the Cedar and Mill Creek models were calibrated, the PEST utility program GENLINPRED was used to run a linear predictive uncertainty analysis (Doherty et al., 2010). This utility estimates the reduction in a predictions uncertainty through the calibration process. Reduction in uncertainty for each prediction due to individual observations are quantified using uncertainty variance. Uncertainty variance describes the range of values that are possible for a prediction given the available data. A smaller uncertainty variance means we are more certain a prediction is reliable, while a large uncertainty variance means we do not have confidence in a prediction. This affords a metric to evaluate model performance and data worth with respect to decreasing uncertainty in a prediction.

GENLINPRED also assesses parameter identifiability, the ability of the observation data to constrain parameter values (how sure we are that the estimated value of a parameter is correct). Identifiability ranges from 0.0 to 1.0; where 0.0 indicates the data do nothing to inform the parameter's value, and 1.0 indicates that observation data perfectly constrains the parameter's value. This analysis reveals how well an observation characterizes watershed parameters and provides a metric to assess data worth.

SENSAN. SENSAN further investigated parameter sensitivities by quantifying how changes in individual parameters affect model predictions. SENSAN automates the model-call process and records model outputs for each variation in parameter value. This process facilitates visualization of the effects that individual parameters have on model predictions. In this study, SENSAN investigated 396 unique parameter combinations between the Cedar and Mill Creek watersheds, making adjustments to curve number, soil depth, USLE factors, channel cover percent, soil erodibility factor, Manning's *n*, median sediment size, and bulk density.

Further investigation with hypothetical data. After model calibration was completed, further investigation of model behavior was conducted with synthetically generated observation data. PEST was run in estimation mode again, with additional hypothetical observations, to investigate sensitivity of predictions to data types that were not in the calibration data-set. This exercise is useful because it identifies the most important data for reduction in prediction uncertainty, which suggests how site-characterization of future watersheds should be prioritized.

Hypothetical data were generated for average mean annual discharge, average annual sheet and rill erosion, average annual sediment yield, average annual tons of sediment degraded from the channel bottom, final channel slope, and final channel depth (Table 3.5). Hypothetic sediment loads were estimated from studies by Greiner (1982) and Coonrid et al. (1998), final channel slope and depth observations were provided by the calibrated model predictions, and discharge data were determined using USGS historical flow data from analog watersheds.

Table 3.5. Values used in hypothetical data set

Hypothetical Observation Datum	Cedar Creek	Mill Creek
Final Channel Width (m)	8.21	13.25
Final Channel Depth (m)	1.80	4.00
Final Channel Slope (m/m)	0.0053	0.00
Average Annual Bottom Degradation (tons/yr)	1,066.00	24,520.00
Average Annual Bank Degradation (tons/yr)	266.00	5,459.00
Average Annual Sheet and Rill Erosion (tons/yr)	1,680.00	13,000.00
Average Annual Sediment Yield (tons/yr)	2,934.00	21,111.00
2015 Mean Annual Discharge (m^3/s)	15.50	75.59

Results and Discussion

Calibration

Results of the calibrated Cedar and Mill Creek watershed models are listed in Table 3.6 and 3.7. These tables show annual and averaged simulation results. For years with higher mean annual discharges, greater channel degradation was predicted. Sediment deposition was never predicted, meaning that these streams are actively degrading throughout both model simulations. Sediment yield, sheet and rill erosion, channel change, and discharge predictions are consistent with other sediment yield studies, USGS flow data, and the calibration data (Greiner, 1982; Coonrid et al., 1998; USGS, 2015).

Both watershed models were able to perfectly match observation data with simulated outputs (objective functions (Φ) equal to 0). However, just because a model is calibrated does not mean it is optimally parameterized to make accurate predictions (Moore and Doherty, 2005) as there are an infinite number of parameter combinations that can calibrate these models equally well. All input parameters were adjusted to realistic values, except for D_{50} for Mill Creek, which was adjusted from 1.1 to 20.9 mm, despite no such field observation. The channel bottom in Mill Creek is composed of calcareous Marl, not the same material as the more easily eroded channel banks, so this is compensated for during model calibration by increasing the size of the bed material, to make it more difficult to erode.

Table 3.6. Calibrated SWAT-DEG model results for the Cedar Creek watershed at the annual time interval

Year	Mean Annual Discharge (m^3/s)	Channel Width (m)	Channel Depth (m)	Channel Slope (m/m)	Sheet and Rill Erosion (tons)	Sediment Deposited (Tons)	Channel Bottom Degredation (tons)	Channel Bank Degredation (tons)	Total Sediment Yield (tons)
2009	16.4	7.8	1.4	0.0057	3844	0	2147	509	6500
2010	12.3	7.9	1.6	0.0055	2638	0	2190	442	5270
2011	2.8	8.0	1.6	0.0055	617	0	577	122	1316
2012	6.7	8.0	1.7	0.0055	1698	0	624	173	2496
2013	3.3	8.1	1.7	0.0054	752	0	579	127	1457
2014	2.0	8.1	1.7	0.0054	478	0	261	62	800.8
2015	15.0	8.2	1.9	0.0053	3622	0	1956	428	6005
Avg.	8.3	-	-	-	1950	0	1191	266	3406

Table 3.7 Calibrated SWAT-DEG model results for the Mill Creek watershed at the annual time interval

Year	Mean Annual Discharge (m^3/s)	Channel Width (m)	Channel Depth (m)	Channel Slope (m/m)	Sheet and Rill Erosion (tons)	Sediment Deposited (Tons)	Channel Bottom Degredation (tons)	Channel Bank Degredation (tons)	Total Sediment Yield (tons)
1997	30.0	11.6	2.6	0.0043	1171	0	194	660	2025
1998	278.4	11.8	2.8	0.0043	13540	0	30784	13010	57340
1999	101.3	11.9	2.9	0.0043	5402	0	19175	6993	31570
2000	160.5	12.0	3.1	0.0042	8355	0	21466	7883	37700
2001	105.8	12.1	3.1	0.0042	4609	0	1577	1682	7868
2002	404.3	12.4	3.4	0.0042	20970	0	58509	21090	100600
2003	498.4	12.7	3.7	0.0042	25250	0	40432	17120	82800
2004	228.7	12.7	3.7	0.0042	10720	0	2926	2862	16510
2005	237.4	12.9	3.8	0.0042	12010	0	21805	8275	42090
2006	165.9	12.9	3.8	0.0042	8114	0	1987	1802	11900
2007	235.1	12.9	3.8	0.0042	11610	0	2434	2486	16530
2008	177.6	13.0	3.8	0.0042	7701	0	1445	2994	12140
2009	499.9	13.2	4.0	0.0041	24830	0	24176	10650	59660
2010	253.8	13.2	4.0	0.0041	12190	0	3675	2775	18640
2011	98.2	13.2	4.0	0.0041	4237	0	1267	1507	7012
2012	64.5	13.2	4.0	0.0041	2648	0	584	1125	4357
2013	67.2	13.3	4.0	0.0041	3285	0	1008	674	4967
2014	7.6	13.3	4.0	0.0041	301	0	49	148	498
2015	64.1	13.3	4.0	0.0041	2813	0	751	926	4490
Avg.	193.6	-	-	-	9461	0	12332	5509	27300

Model Performance

The watershed models calibrated with channel width and erosion data were able to make accurate predictions for channel geomorphic changes, but were not able to make reliable predictions for stream discharges, sheet and rill erosion, or sediment yields. This makes sense because a single channel width measurement and average erosion rate data do not contain any information about flow through the creeks or overland sheet and rill erosion. Figure 3.3 compares predicted sediment masses in Cedar and Mill Creeks before and after calibration. Note that pre-calibration parameters were specified according to the available data and expert judgment, but yields predictions that do not match the calibration data. This figure also reveals that calibrated average annual sheet and rill erosion and total sediment yields predictions are notably less when the model is calibrated. This highlights the importance of model calibration. A predictive uncertainty analysis will determine whether channel width and erosion data lead to reliable estimates of discharge, sheet and rill erosion, and sediment yield predictions.

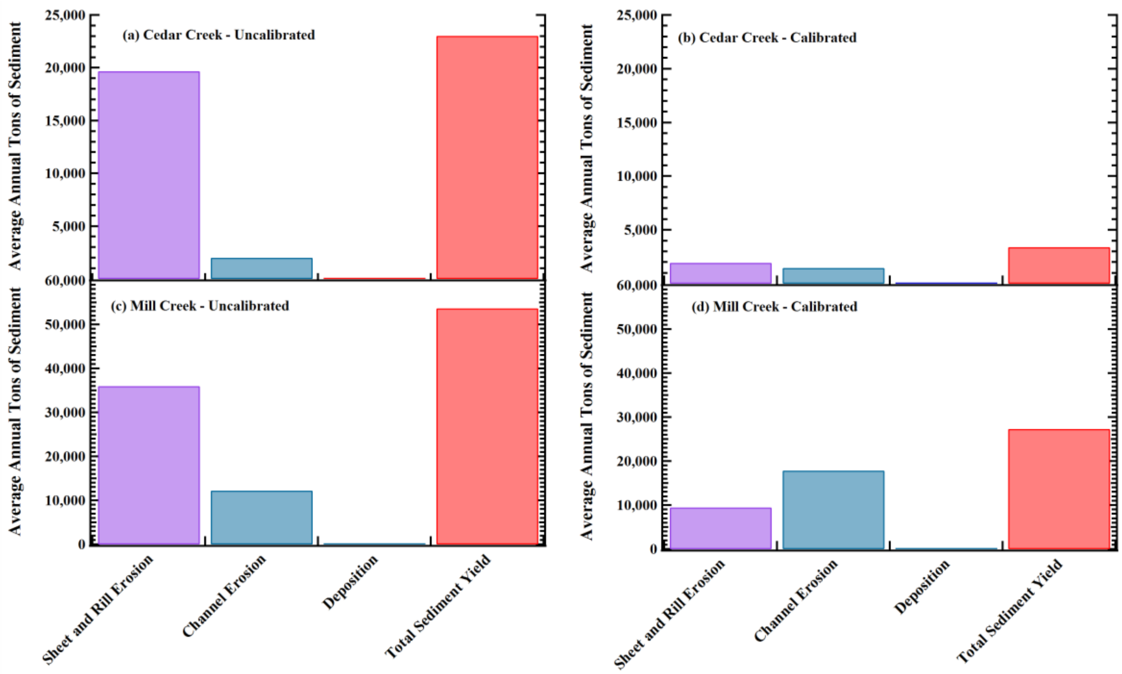

Figure 3.3 Average annual pre- and post-calibration sediment mass model results for (a) and (b) Cedar Creek, and (c) and (d) Mill Creek watersheds

The current calibration process was able to reduce uncertainty satisfactorily for channel depth predictions, but not flow or sediment yield predictions. By quantifying model predictive uncertainty (using uncertainty variance as a metric) we assessed model performance, which is critical to decision makers because as predictive uncertainty is reduced the confidence in the model grows. Table 3.8 lists uncertainty variances before and after model calibration for 2015 mean annual flow, average sediment yield, and final channel depth predictions in Cedar and Mill Creeks. Uncertainty variance is not considerably reduced after calibration for flow and sediment yield predictions. This reveals that the calibration data does little to reduce uncertainty in these prediction types. Uncertainty variance is also very high for sediment yield in both watersheds and is high for flow predictions in Mill Creek, showing that these predictions are not reliable. Values for uncertainty variance were low for depth predictions before, and even more so, after calibration. This shows that these predictions can be made reliably.

Table 3.8. Uncertainty Variance for selected SWAT-DEG predictions before and after model calibration in Cedar and Mill Creek watersheds

SWAT-DEG Prediction	Pre-calibration Uncertainty Variance	Post-Calibration Uncertainty Variance
2015 Mean Annual Flow - Cedar Creek	11.68	11.47
2015 Mean Annual Flow - Mill Creek	621,701.50	340,391.80
Average Annual Sediment Yield - Cedar Creek	15,458,053.00	11,989,349.00
Average Annual Sediment Yield - Mill Creek	10,640,533.00	9,083,623.00
Final Channel Depth - Cedar Creek	0.83	0.43
Final Channel Depth - Mill Creek	0.75	0.48

Exploration of model performance with additional observations (accomplished by re-analyzing watershed models with hypothetical observations) reveal what data improve model-prediction accuracy. Figure 3.4 shows the results of the uncertainty analysis. This figure shows how individual observations reduce the uncertainty in predictions for 2015 mean annual flow, average annual sediment yield, and channel depth. For example, in Figure 3.4 (a) and (b) uncertainty variance for 2015 mean annual flow predictions were most reduced by average annual sediment yield observations.

Predictive uncertainty analyses using hypothetical calibration data revealed that no specific observation type reduces predictive uncertainty most effectively across all model outputs. However, mean annual discharge observations can reduce uncertainty in all prediction types. It can be inferred that if daily discharge data were available that model performance would improve considerably.

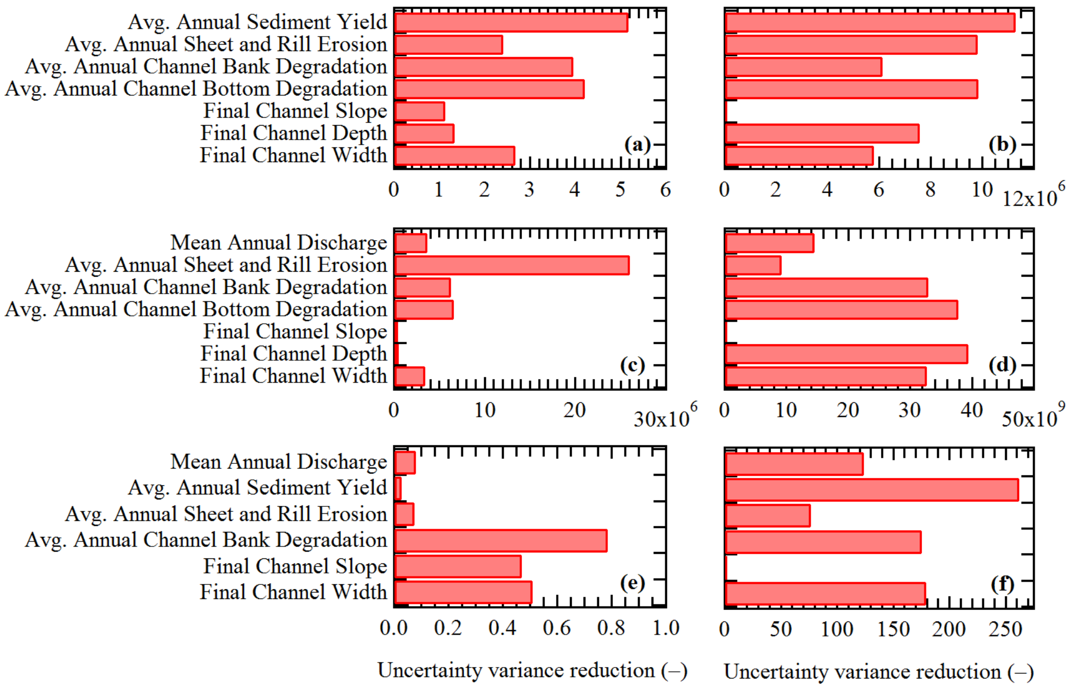

Figure 3.4. Contribution to uncertainty variance reduction in predictions from specific observation data types: (a) 2015 mean annual flow – Cedar Creek, (b) 2015 mean annual flow – Mill Creek, (c) average annual sediment yield – Cedar Creek, (d) average annual sediment yield – Mill Creek, (e) final channel depth – Cedar Creek, (f) final channel depth – Mill Creek

Model Sensitivity

Prediction sensitivities to parameters were different between the two watersheds. The sensitivities of observations to adjustable parameters are shown in Figure 3.5. In Cedar Creek, final channel width and average annual bank degradation observations were sensitivity to channel roughness, channel erodibility, channel vegetation percent, percent clay, bulk density, time of concentration, and soil depth. Predicted final channel width and average annual bank degradation in Mill Creek were sensitive to all parameters, except channel equilibrium slope, and basin slope length. But, curve number was the most impactful parameter on these predictions in Mill Creek.

Based on the results of the sensitivity analysis, parameters that define the stream channel are more impactful than basin parameters on channel change predictions in smaller watersheds. But, basin parameters become increasingly influential on channel change predictions in larger watersheds. This makes sense because the relative area of upland to stream channel is greater in larger watersheds.

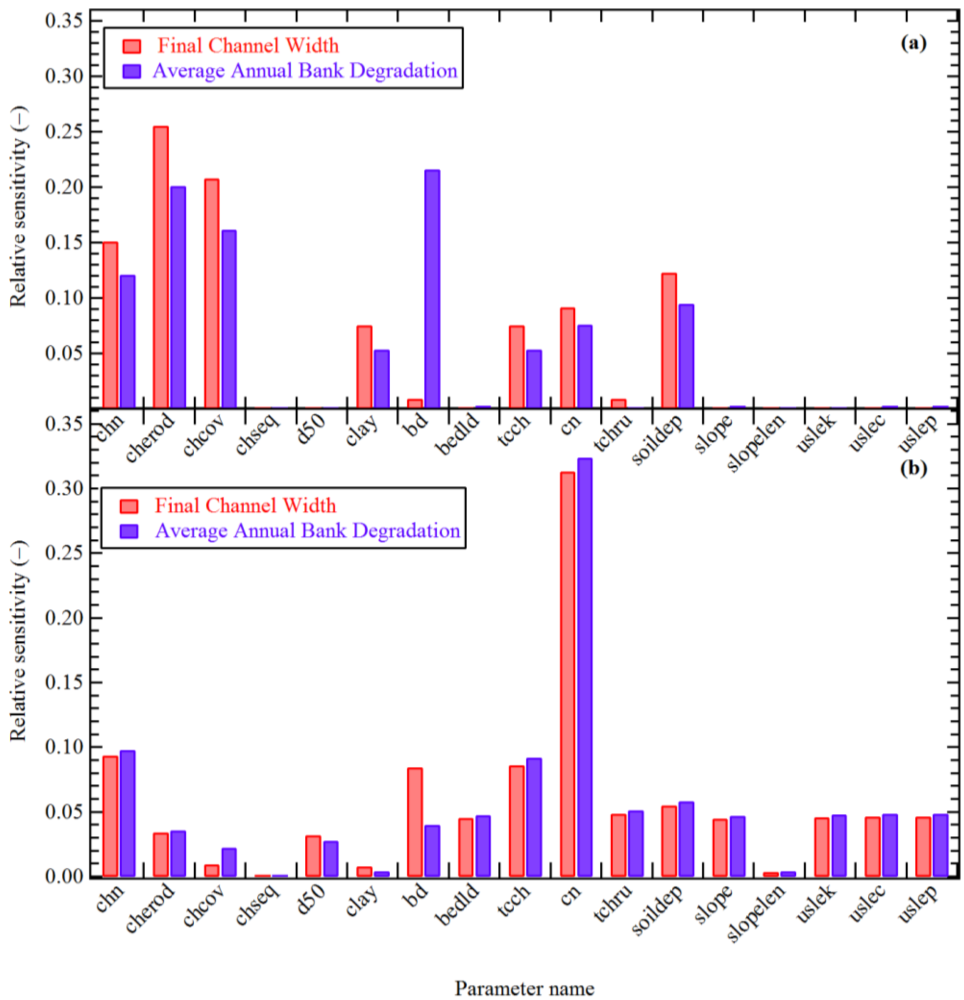

Figure 3.5. Observation sensitivities to parameters for (a) SWAT-DEG modeled Cedar Creek watershed, and (b) SWAT-DEG modeled Mill Creek watershed; parameter abbreviation descriptions can be found in tables 3.1 through 3.4

Mean annual discharge, sheet and rill erosion, and sediment yield prediction sensitivity to parameters were explored using the hypothetical data set (Figure 3.6). Under hypothetical conditions these model predictions are sensitive to the same parameters in Cedar and Mill Creek. Findings showed that curve number and soil depth were the only sensitive parameters on flow predictions. Sheet and rill erosion predictions were most sensitive to curve number, basin slope, and USLE factors. Sediment yield predictions were also sensitive to these parameters but were sensitive to Manning's *n*, channel erodibility, and channel cover factor as well.

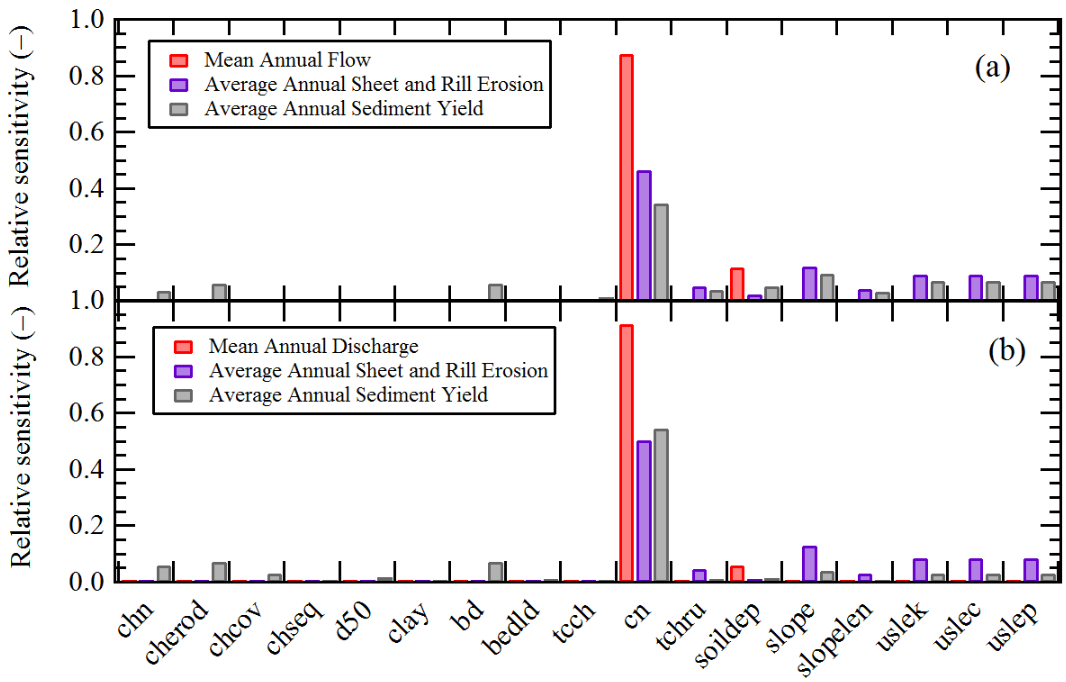

Figure 3.6. Hypothetical observation sensitivities to parameters in (a) Cedar Creek and (b) Mill Creek; parameter abbreviation descriptions can be found in Tables 3.1 through 3.4

Model Behavior

Model behavior, explored by adjusting individual input parameters (using SENSAN), revealed that model predictions changed as anticipated with no discontinuities observed in model outputs as parameters were altered incrementally. This demonstrates that SWAT-DEG behaves systematically to input parameters. An example of how a model prediction changes when an individual parameter is adjusted is shown in Figure 3.7, which plots final channel width as a function of curve number. This shows that when all other parameters are held constant at calibrated values, channel width predictions increase as curve number increases. Note that curve number has little effect on channel width predictions until higher values in Cedar Creek, exemplifying how it is a less influential parameters in smaller watersheds.

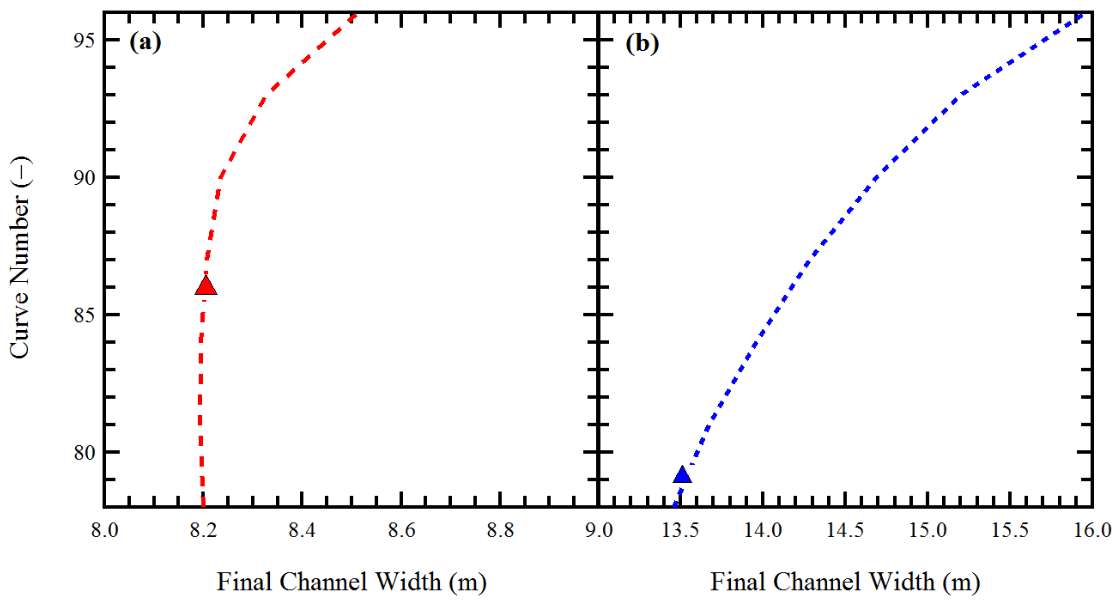

Figure. 3.7. Plot showing how curve number affects predicted channel widths in (a) Cedar Creek, and (b) Mill Creek; calibrated values are indicated by the triangles

SENSAN results also show how parameter influence over predictions change under altered circumstances. For example, Figure 3.8 is a contour plot that shows how channel width predictions vary with soil erodibility and channel vegetation cover, when all other parameters are held at calibrated values. At low erodibilities, channel vegetation has little effect on channel width predictions but as soil erodibility increases, vegetation becomes more influential. This is because vegetation decreases bank erodibility, but if erodibility is already low, then the impact is not as noticeable. Another example is figure 3.9, which plots mean annual discharge as a function of soil depth and curve number. This revealed that the influence of curve number on mean annual discharge increases as its value increases, while the opposite is true for soil depth. This is because as curve number increases the volume of water that enters the subsurface is reduced.

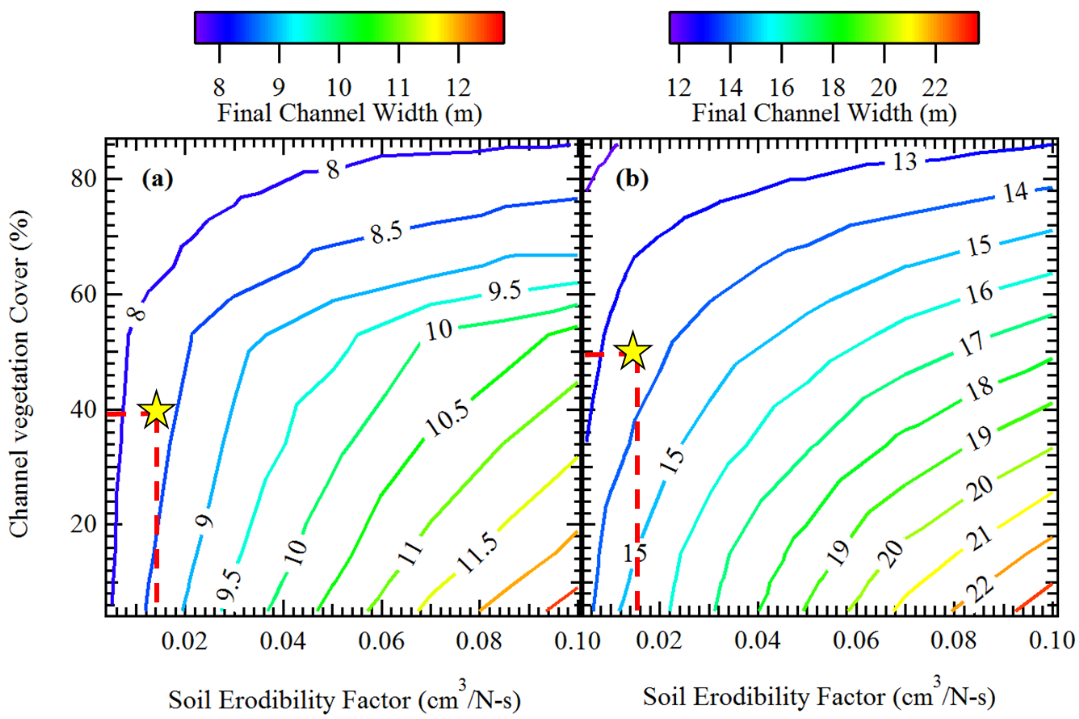

Figure 3.8. Contour plots showing how soil erodibility factor and channel vegetation cover affect predicted final channel width in (a) Cedar Creek and (b) Mill Creek when all other parameters were held constant at calibrated values; the star indicated calibrated conditions

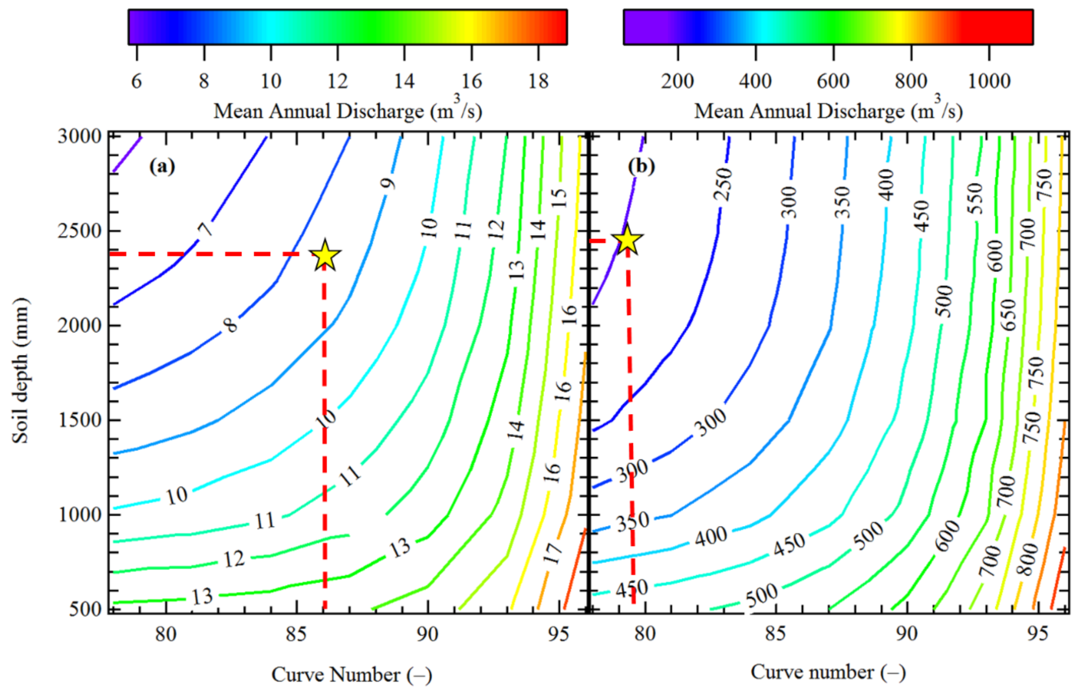

Figure 3.9. Contour plots showing how curve number and soil depth affect predicted mean annual discharge in (a) Cedar Creek and (b) Mill Creek when all other parameters were held constant at calibrated values; the star indicated calibrated conditions

Parameter Identifiability

One metric for data worth is to evaluate by parameter identifiabilities after calibration. When parameters have higher identifiabilities the calibration data is able to well characterize system variables (constrain parameter values). In this study the calibration data (channel width and erosion rate observations) constrained the parameter values differently between Cedar and Mill Creeks (Figure 3.10). In Cedar Creek, channel erodibility and channel vegetation cover were well constrained by the calibration data, with identifiabilities of 0.57 and 0.36, respectively. In Mill Creek, the calibration data was able to well constrain channel vegetation cover, soil bulk density, and curve number with identifiabilities of 0.91, 0.94, and 0.45 respectively. Other parameters, such as channel roughness, channel erodibility, D_{50}, and time of concentration, were also slightly constrained through calibration in Mill Creek.

The observations gathered for calibration (channel widths and erosion rate data) are further exemplified as useful to make accurate channel change predictions by well constraining variables that are impactful on channel change predictions (e.g. channel erodibility and channel vegetation cover). However, many parameters are not well constrained by the calibration data. This shows that additional observations may be needed to make sediment yield, sheet and rill erosion, and stream discharge predictions. This is in line with the results of the uncertainty analyses.

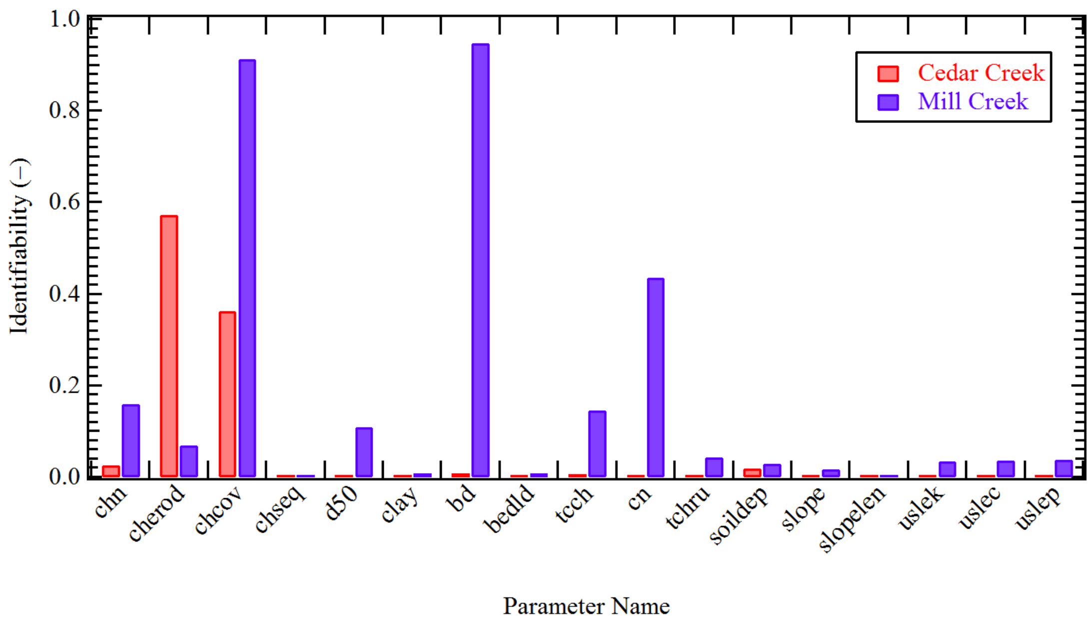

Figure 3.10. Parameter identifiabilities after calibration for SWAT-DEG modeled Cedar and Mill Creek watersheds; parameter abbreviation descriptions can be found in tables 3.1 through 3.4

Modeling Additional Watersheds

The process of parameterizing and calibrating future watersheds can be improved if the importance of data to reduce model uncertainty is known beforehand. To characterize a new watershed the most important parameters (channel roughness, channel erodibility, channel vegetation cover, curve number, and USLE factors) though empirically derived, meaning they cannot be directly measured, should be prudently estimated through GIS analysis, literature review, and tools such as the submerged jet test (ASTM D5852-95) for determining soil erodibility. For example, in a watershed the size of Mill creek, discharge and sediment yields are particularly sensitive to curve number, especially when curve number exceeds 90. Extra attention should be paid to identify curve number. Parameters that are easily measurable through GIS analysis or field surveys (D50, basin slope, basin slope length, bulk density, percent clay) should be collected despite being less influential on model predictions.

Many influential parameters, such as channel roughness (Manning's *n*), channel erodibility, curve number, and USLE factors are empirical parameters, and are difficult to measure or only estimable (Barnes, 1967, USDA, 1986). Therefore these parameters need to be constrained through observation data. For example, the calibration data (channel width and erosion rate observations) were able to constrain Manning's *n*, channel erodibility, and channel vegetation cover, as seen in Figure 3.5.

The overall worth of observation data depend on the specific to modeling project objectives. For example, to accurately predict future channel degradation an observation data-set consisting of daily flow, channel width, and erosion rates would likely be sufficient. These data could be acquired feasibly with a data-logger or flood stage recorder and channel erosion measurements (e.g. through dendrogeomorphology).

When comprehensive data are not available to parameterize and calibrate a SWAT-DEG watershed model, other strategies to generate useful data are needed. The inclusion of soft data, information on individual processes that are not directly measured and may be an average or estimate with considerable uncertainty (Arnold et al., 2015), can improve model predictions. Examples of soft data include data collected from analogous watersheds, or studies that speak to general trends within a physiographic region. Likewise if bounds can be prescribed for a prediction (e.g. through an analytic model) SWAT-DEG can be commensurately constrained. For example, USGS peak flow rate region regression equations (USGS, 1982) provide estimates for estimating the magnitude of flood events for streams in the Dallas-Fort Worth metropolitan area. These techniques demonstrate the advantage of using numerical models to incorporate all available data types in order to generate accurate watershed predictions

Conclusion

The objectives of this study were to calibrate and make predictions with quantified uncertainty for SWAT-DEG models of two watersheds in Central Texas. Moreover, model behavior was interrogated to inform future SWAT-DEG models of the most important data required to reliably predict channel conditions, sediment regimes, and water budgets. The data used to calibrate Cedar and Mill Creek models yielded reliable channel change predictions in both watersheds. Post-calibration flow and sediment yield predictions appeared realistic, but through model interrogation it was revealed that uncertainty in these predictions was not reduced using available data.

Model interrogation using PEST utilities revealed how sensitive predictions were to parameters and also indicated what additional data decreased uncertainty in flow and sediment yield predictions. In general, the parameters curve number, Manning's *n*, channel erodibility, channel vegetation cover, soil depth, and USLE factors showed high sensitivity on model results. In future modeling endeavors, special care should be taken to measure and prescribe these model parameters. Also, flow and sediment yield predictions could be greatly improved through addition of daily flow data. Results from the thorough interrogation of these SWAT-DEG models will be particularly useful to future model-development efforts because the most important data are identified with regard to reducing uncertainty in predictions. Future watershed models produced in accordance with this study could then be used as a platform for hypothesis development regarding potential changes to watershed conditions, such as urbanization or stream-restoration projects.

CHAPTER FOUR

Conclusion

This project used dendrogeomorphology to assess streambank erosion in the Cedar and Mill Creek watersheds. This assessment evaluated channel processes in a typical small urban and medium-sized rural stream in Central Texas. Analysis with this method determined erosion rates with the same precision as typical 1- to 2- year pin studies and identified the effects of specific erosion processes occurring within stream channels. This study showcases the utility of dendrogeomorphology as an erosion-assessment technique that provides decadal-scale erosion data in previously ungauged stream channels without long term monitoring.

Erosion-rate and channel-geometry data from the dendrogeomorphic assessment were used to calibrate SWAT-DEG hydrologic models for Cedar and Mill Creeks. Investigation of model predictive uncertainties, sensitivity of predictions to parameters, and data worth were evaluated with the PEST software suite. This identified which model inputs are most influential on model predictions and what observation data best calibrate the model. Data gathered from the dendrogeomorphic study sufficiently calibrated the model to make channel degradation predictions, but did not reduce uncertainty in flow, sheet and rill erosion, or sediment yield predictions. Inclusion of additional data, such as daily flow rates, would allow the SWAT-DEG model to more confidently assess watershed conditions and serve as a platform for hypothesis testing of future watershed processes. This study forms a framework for accurately evaluating past stream-channel erosion in ungauged watersheds, and provides a guide to prioritize data collection in additional watersheds to accurately predict watershed conditions with the SWAT-DEG hydrologic model.

APPENDIX

APPENDIX

Dendrogeomorphic Data

Table A.1. Descriptions of root samples collected at Mill Creek, from downstream to upstream

Location	Species	Channel Position	Sample	Horizontal Distance to Bank (cm)	Years of Exposure
1	Cedar Elm, *Ulmus crassifolia*	Upper Bank	1	45.7	6
			2	101.6	5
2	American Elm, *Ulmus americana*	Lower Bank	1	33	4
			2	35.6	4
			3	17.8	4
3	Green Ash, *Fraxinus pennsylvanica*	Lower Bank	1	33	7
			2	38.1	8
			3	20.3	9
			4	Unexhumed	-
4	Hoptree, *Ptelea trifoliata*	Upper Bank	1	114.3	14
			2	106.7	10
			3	58.4	6
			4	Unexhumed	-
5	Hackberry, *Celtis laevigata*	Lower Bank	1	63.5	14
			2	94	10
			3	71.1	10
				Unexhumed	-
6	Green Ash, *Fraxinus pennsylvanica*	Lower Bank	1	81.3	26
			2	61	21
			3	Unexhumed	-
7	Green Ash, *Fraxinus pennsylvanica*	Lower Bank	1	35.6	8
			2	17.8	5
			3	38.1	7
			4	22.9	7
8	American Elm, *Ulmus americana*	Upper Bank	1	48.3	9
			2	55.9	7
			3	45.7	7
			4	38.1	6
9	Burr Oak, *Quercus macrocarpa*	Lower Bank	1	124.5	Undetermined
			2	129.5	Undetermined
			3	121.9	Undetermined
			4	86.4	Undetermined
10	Green Ash, *Fraxinus pennsylvanica*	Upper Bank	1	91.4	3
			2	20.3	1
			3	58.4	5
			4	121.9	5
			5	109.2	5

Table A.2. Description of root samples collected from Cedar Creek

Location	Species	Channel Position	Sample	Horizontal Distance to Bank (cm)	Years of Exposure
1	Hoptree, *Ptelea trifoliata*	Straight Section	1	5.1	2
			2	7.6	3
			3	Unexhumed	-
			4	Unexhumed	-
2	Osage Orange, *Maclura pomifera*	Straight Section	1	40.6	Undetermined
			2	25.4	Undetermined
			3	61	Undetermined
			4	Unexhumed	-
3	Cedar Elm, *Ulmus crassifolia*	Cut Bank	1	124.46	1
			2	129.5	1
			3	63.5	<1
			4	1524.4	1
			5	101.6	<1
			6	Unexhumed	-
			7	Unexhumed	-
4	Cedar Elm, *Ulmus crassifolia*	Cut Bank	1	117.8	6
			2	134.6	6
			3	73.7	6
			4	25.4	6
			5	Unexhumed	-
5	Cedar Elm, *Ulmus crassifolia*	Cut Bank	1	33	<1
			2	35.6	1
			3	Unexhumed	-
6	American Elm, *Ulmus americana*	Straight Section	1	30.5	6
			2	20.3	6
			3	7.6	3
			4	Unexhumed	-
7	Osage Orange, *Maclura pomifera*	Straight Section	1	66	Undetermined
			2	55.9	Undetermined
			3	22.9	Undetermined
			4	Unexhumed	-
8	Cedar Elm, *Ulmus crassifolia*	Cut Bank	1	101.6	<1
			2	101.6	<1
			3	55.9	<1
			4	Unexhumed	-
9	Cedar Elm, *Ulmus crassifolia*	Cut Bank	1	27.9	<1
			2	73.7	<1
			3	45.7	<1
			4	Unexhumed	-
10	Cedar Elm, *Ulmus crassifolia*	Straight Section	1	48.3	11
			2	25.4	4
			3	78.7	16
			4	45.7	7
			5	17.8	3
11	American Elm, *Ulmus americana*	Straight Section	1	55.9	12
			2	35.6	12
			3	22.9	9
			4	Unexhumed	-
			5	Unexhumed	-

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