Modeling Channel Erosion at the Watershed Scale: A Comparison of GWLF, SWAT, and CONCEPTS

by: Nathan Andrew Staley

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Tess M. Wynn (Co-Chair)
Brian L. Benham (Co-Chair)
David F. Kibler

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Abstract

In 2005 an assessment of existing Total Maximum Daily Load studies by the U.S. Environmental Protection Agency showed sediment as the fourth leading cause of water quality impairment. A source assessment is important in developing a successful TMDL. Past research efforts have focused on controlling erosion sources in agricultural and urban land areas. New research suggests major contributions to overall sediment loads may be due to stream channel degradation. Monitoring and modeling techniques to assess the contribution of channel sediment to overall sediment load are needed to determine the reductions necessary to meet water quality standards. This research focused on testing the ability of watershed and reach-scale models to predict stream channel degradation. Model predictions were compared to estimates developed from a system of erosion pins and scour chains.

A 500-m experimental reach in Blacksburg, VA, USA, was selected as the focus of channel degradation monitoring and modeling efforts. A series of over 250 erosion pins and seven scour chains were installed systematically throughout the experimental reach. A monthly monitoring program measured channel degradation for the period from July 2005 – June 2006. Point data were interpolated across individual bank segments to produce an estimate of soil erosion volume. Measured soil bulk densities were then used to calculate the estimated mass loading to Stroubles Creek from channel degradation.

Two watershed models and one reach-scale model were developed to predict sediment loading to the stream channel from channel degradation. The Generalized Watershed Loading Function (GWLF) was selected to represent watershed models with limited channel degradation process detail; the Soil and Water Assessment Tool (SWAT) represented the level of channel degradation detail seen in the majority of watershed models; and the CONservation Channel Evolution and Pollutant Transport System

(CONCEPTS) reach-scale model was used to evaluate the effectiveness of a detailed process model. Monthly model predictions were compared to retreat rates measured using the erosion pin network.

Sediment loading to the stream from bank retreat was estimated as 41 tonnes/yr, based on erosion pin measurements. GWLF, SWAT, and CONCEPTS predicted stream channel sediment contributions of 8 tonnes/yr, 1500 tonnes/yr and 4 tonnes/yr, respectively. Theil-Sen non-parametric simple linear regression was used to test agreement between monthly model predictions and erosion pin estimates. No significant agreement was found between any model predictions and measured retreat, using a conservative α-value of 0.2. GWLF model predictions underpredicted measured channel degradation, but most closely approximated observed data. This result is likely due to similarities in climate and watershed characteristics for the Stroubles Creek watershed and the Pennsylvania watershed used in the empirical model development. SWAT predicted retreat rates exceeded measured values by two orders of magnitude. This result is explained by the inability of SWAT to predict daily flow and sediment discharge. Highly sensitive channel degradation parameters and the lack of calibration data also contributed to SWAT simulation error. CONCEPTS simulation predicted monthly retreat rates slightly less than GWLF. The lack of agreement between CONCEPTS simulation and observed data was mainly the result of limited input data availability. SWAT daily discharge predictions were used as CONCEPTS input data and likely contributed to poor model agreement. Poor estimation of sensitive sediment input parameters may have also contributed to underpredictions by CONCEPTS. Results showed the potential of screening-level watershed models in channel degradation prediction and the importance of flow and sediment time series discharge data in detailed process-based simulation. The limited flexibility of the GWLF channel degradation algorithm makes it unsuitable for evaluating the effects of stream restoration. SWAT and CONCEPTS should only be used for evaluation if appropriate input data are available.

Future research will focus on the development of a long-term flow and sediment monitoring data set. Few long-term data sets of this nature exist, making channel degradation modeling difficult. Development of long-term data will allow more accurate modeling and better assessment of channel restoration impacts on channel degradation.

Further modeling with GWLF in geographic regions outside the Eastern United States is also needed to determine the scope of applicability of the GWLF channel degradation empirical relationship. Additional research should also focus on the significance of subaerial processes for watersheds of various sizes and on the development of algorithms to simulate these processes.

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1. Glossary

bed scour – also referred to as bed erosion, the loss of sediment from a stream bed due to lift and shear forces created by streamflow

downcutting – also referred to as channel incision, the excessive scour of bed sediments, resulting in a channel with steep banks and limited access to the floodplain

channel degradation – the net loss of sediment from a stream cross section or reach; this includes sediment from bed scour and streambank[1] retreat

fluvial erosion – also referred to as channel erosion; the direct removal of soil particles or aggregates from submerged portions of a cross section or reach due to lift and shear forces created by streamflow

reach-scale model – a software program designed specifically for simulating the processes associated with the fate and transport of water and sediment through a channel and the resulting affects on channel shape and composition; examples include GSTAR-1D and CONCEPTS

streambank mass failure – also referred to as streambank failure or mass wasting; soil loss from the channel boundary due to geotechnical slope instability; typical forms include cantilever, planar, rotational, slab, and piping or sapping

streambank retreat – the net loss of sediment from a streambank due to all erosive mechanisms including: fluvial erosion, subaerial erosion, and mass failure

subaerial erosion – the loss of soil from areas above the water surface due to the action of subaerial processes

subaerial processes – climate-related phenomena that reduce soil strength, inducing direct erosion and making the bank more susceptible to fluvial erosion; examples include desiccation cracking, freeze-thaw cycling, and needle ice formation

tractive force theory – a theoretical method for evaluating stream stability, based on the concept that the channel sediments will not erode if the boundary shear stress remains below a critical value (the critical shear stress, τ_c)

watershed model – a software program designed to simulate processes[2] associated with the fate and transport of water and pollutants; examples include GWLF, SWAT, AGNPS, HSPF, and HEC-6

[1] the terms streambank and bank are used interchangeably

[2] the mathematical relationships used to simulate individual processes such as infiltration, entrainment, or deposition are referred to as equations, relationships, algorithms, or formulas

2. Introduction

The 1960's were marked by mounting concern for water pollution issues in the United States, leading to the passage of the Federal Water Pollution Control Act of 1972 (EPA, 2003). Further amendments were made and the legislation became known as the Clean Water Act (CWA). This act granted EPA the power to regulate pollution discharges to waters of the United States. The EPA used regulatory powers granted by the CWA and required states to develop EPA-approved water quality standards (WQS). The CWA created a program requiring a permit for any point source pollution discharge and Section 303(d) of the CWA mandated each state develop a list of impaired waters which fail to meet state water quality standards (EPA, 2002). The CWA also created the Total Maximum Daily Load program (TMDL).

Under Section 303(d) of the Clean Water Act water bodies in violation of state water quality standards are referred to as "impaired" and pollutant-specific TMDLs are required for these impaired waters. A TMDL is a document that specifies the maximum amount of pollutant that a water body can receive without violating applicable water quality standards. Developing a TMDL involves conducting an exhaustive watershed-scale study to identify the sources of the pollutant causing the water quality impairment; quantify the pollutant contribution from each source; and determine the pollutant reduction required from each source to meet applicable state water quality standards. While the Clean Water Act specifies that TMDL studies be conducted, it has no provisions related to implementing the pollutant-load reductions specified in a TMDL. Virginia state law, the Water Quality Monitoring, Information, and Restoration Act (62.1-44.19:4-8 Code of Virginia), requires the development of TMDL implementation plans A TMDL implementation plan (IP) is a "road map" that outlines how pollutant load reductions specified in a TMDL will be achieved. This act ensures that pollution reduction methods are employed most effectively (VADEQ, 2005).

Erosion prediction is an important component in the development of land management strategies and Total Maximum Daily Load (TMDL) studies where sediment is identified as the cause of impairment. Studies have shown that channel degradation rates may be as high as 1000 m/year, providing a significant portion of sediment loadings to streams (Thorne et al., 1997). Channel degradation can lead to the loss of agricultural land and floodplain structures. Additionally, excessive erosion reduces water quality through increased turbidity and the transport of sediment-bound pollutants. Sediment is the fourth leading cause of water quality impairment nationwide (EPA, 2005). In Virginia, aquatic life impairments, which are often caused by excessive sediment deposition, account for 11.5% of the total river mileage listed on the Department of Environmental Quality 2002 303(d) impaired waters report (VADEQ, 2002).

Watershed models are often used when developing a TMDL. Models help TMDL developers simplify complex watershed systems, allowing them to quantify the sources of impairment and predict the necessary reductions required to meet applicable water quality standards. Modeling software allows users to alter watershed characteristics and assess the impact on water quality and quantity. Using watershed software in this capacity helps decision makers choose how to most appropriately distribute funds in correcting the impairment. For TMDL studies where sediment is identified as the pollutant causing the water quality impairment, detailed process-based models are often avoided due to the extensive input data/parameterization requirements. The required data simply do not exist or collecting it is prohibitively expensive. Hydrologic models such as the Generalized Watershed Loading Function (GWLF), Soil and Water Assessment Tool (SWAT), and CONservation Channel Evolution and Pollutant Transport System (CONCEPTS), include channel degradation sub-models. The channel degradation routines used in these models vary from highly empirical to predominately process-based. Little research has been done to compare model predictions of stream bed and bank degradation to field measurements. A better understanding of the effects of differing model complexities on channel degradation simulation would allow river engineers and environmental managers to model stream systems more accurately and cost-effectively.

3. Goal and Objectives

The goal of this study was to compare stream channel erosion predictions from three models; GWLF, SWAT, and CONCEPTS. The project was broken down into two main objectives:

I. Summarize current methods of estimating channel erosion at the watershed scale.
II. Compare three models with varying levels of complexity to field measurements of bank retreat.

4. Literature Review

4.1 The Federal Water Pollution Control Act

The Federal Water Pollution Control Act of 1972, or Clean Water Act (CWA), outlines the guidelines for the protection of surface waters in the United States (EPA, 2005). This legislation provides the EPA with regulatory and non-regulatory means for improving and protecting the nation's water quality. The act provides funding for the development and improvement of wastewater treatment facilities and led to the development of programs to limit direct point source discharges to water bodies through the issuance of permits. Beginning in the 1980s, the importance of reducing nonpoint pollution sources came to the fore. Incentive and regulatory programs were created to help reduce pollution contributions from runoff and other nonpoint sources. Section 303(d) of the CWA mandated each state develop a list of impaired waters which fail to meet state water quality criteria (EPA, 2002). The CWA requires states to address impairments through the development of Total Maximum Daily Loads (TMDL).

A TMDL specifies the amount of pollution a water body can assimilate and still meet water quality standards (EPA, 2005). The TMDL program was created as a broad approach to water quality improvement, including the entire watershed in the evaluation of impairments. The first step in the TMDL process requires states to develop water quality standards (WQS) which must be approved by the EPA (EPA, 2002). Sections 303(d) and 305(b) of the Clean Water Act require water bodies in the United States to be evaluated in the context of applicable WQS. Water bodies in violation of state water quality standards are referred to as "impaired" and placed on the state's 303(d) impaired waters list. TMDL studies are required for all waters on the 303(d) list. A source assessment is then performed to characterize pollutant loads within the watershed including permitted and non-permitted point sources and nonpoint source areas, each with loading rate estimates (EPA, 2005). TMDL developers then estimate the required reductions using watershed and stream models to simulate purposed changes.

Literature Review

The rise in urbanization, combined with past channel manipulation, has caused channel erosion prediction to become an increasingly important issue. Urbanization increases storm runoff peaks, frequencies, and volumes, leading to channel downcutting and widening and increased sediment loads (Graf, 1975). Sediment is the fourth leading cause of water quality impairment nationwide (EPA, 2005) and benthic impairments, often caused by excessive sedimentation, account for 11.5% of the total non-attaining river mileage listed in the Virginia DEQ 2002 303(d) impaired waters report (VADEQ, 2002). Excessive erosion reduces water quality through increased turbidity and the transport of sediment-bound pollutants. High sedimentation rates can alter the streambed, destroying the habitat of benthic macroinvertebrates and shading out emergent aquatic vegetation. Sediment-bound nutrients can trigger algal blooms and damage aquatic ecosystems through eutrophication.

Studies have shown that channel retreat rates may be as high as 1000 m/year, providing a significant portion of sediment loadings to streams (Thorne et al., 1997). The contribution of channel erosion to overall sediment yields may be as high as 80% in urban watersheds (Simon & Thorne, 1996). Correctly predicting sediment sources and magnitudes is essential in the development of land management strategies and Total Maximum Daily Load (TMDL) plans where sediment is identified as the cause of impairment. Accurate models are needed to assess the impact of channel erosion on watershed sediment loads.

Currently, the extensive input requirements and complexity of process-based watershed software capable of simulating channel erosion have prohibited software implementation in TMDL studies with impairments caused by sediment. The time and money required for data collection and model development are unreasonable. Many commonly used watershed and stream models such as GWLF, SWAT, and CONCEPTS have channel erosion subroutines imbedded within the overall software structure. Little research has been done to verify the accuracy of such subroutines, thus limiting their application. Research providing a more thorough understanding of the effects of model complexities on channel erosion predictions would allow TMDL developers and land managers to more effectively assess the impact of anthropogenic actions on watershed sediment loading.

4.2 Natural Channel Hydraulics and Sediment Transport

W. H. Graf (1984) realized the importance of sediment movement in natural systems, stating, “[t]he understanding and formulation of movement and transportation of solid granular particles in or through liquid bodies represent an important issue within the fields of hydraulics, fluvial geomorphology, and others.” A study of the processes involved in the movement of sediment within a river system is fundamental to understanding the form and behavior of stream channels.

Knowledge of natural channel hydraulics is necessary for understanding sediment transport and fluvial geomorphology (Chang, 1988). The characteristics of flow in river systems are the driving force for sediment movement and channel morphological transformations. River systems are characterized as open-channel flow systems, bounded by a free-surface. The shape of the free-surface must be established to allow the determination of hydraulic parameters needed for open-channel flow calculations. This water surface profile is often determined using an energy balance approach. Flow velocity, hydraulic radius, depth, roughness, and other hydraulic parameters may then be used to predict the magnitude of sediment transport processes.

Assumptions are a necessary part of modeling natural channel flow systems. Uniform, gradually varied, and rapidly varied flow are common classifications for open channel flow regimes. The uniform flow assumption is valid in areas with constant physical properties along the flow path (Chang, 1988). Man-made or significantly altered river channels may reasonably meet this assumption, but uniform flow is not valid for natural river channels due to the constant variation in channel shape and composition. Uniform flow equations are, however, often applied to natural flow systems when the area simulated is an individual channel cross-section over whose length parameters can be said to remain constant.

Changes in flow properties must be considered with respect to distance and time. Systems are described as steady flow systems if physical properties can be said to remain constant over the time scale to which flow equations are being applied. Most natural channel flow systems are considered unsteady: changes in discharge, velocity, and depth with respect to time. The assumption of steady or unsteady flow is important in establishing the flow routing methods and equations to be applied to a river system.

The classification of flow as laminar or turbulent is also important in determining the equations which are applicable for a given system. Laminar flow is characterized by a velocity profile that can be assumed to vary linearly with depth (Chang, 1988). Flow may be considered laminar when the Reynolds number, Re, is sufficiently small ($Re < 11.6$). Reynolds number is calculated as follows:

$$\mathrm{Re} = {}^{uz}\!/_{v} \qquad \text{[Eq. 1]}$$

where u = velocity (L/T),
z = distance from the boundary (L), and
v = kinematic viscosity (L^2/T).

Flow adjacent to boundaries is considered to have three layers. The laminar sublayer is a thin layer in contact with the boundary surface. The transition layer encompasses the flow zone separated from the boundary layer only by the laminar region. This zone is characterized by Reynolds numbers between five and 70. The turbulent flow zone, most distant from the boundary layer, is characterized by Reynolds numbers greater than 70. This zone exhibits a greater flow resistance due to eddy formation and the velocity distribution with depth is non-linear. The rough boundary conditions of many natural channels have a roughness coefficient too great to allow the formation of a laminar sublayer.

The basic assumptions in establishing the characteristics of natural channel hydraulics for modeling have a significant impact on estimating the forces associated with the flow regime. The forces associated with moving water are best understood through a physics-based approach. As previously mentioned, an energy balance approach allows fluvial geomorphologists and river engineers to estimate hydraulic parameters. When modeling river systems assumptions and equations must be developed with this overall energy balance in mind.

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Three major characteristics of the water must be considered to understand the energy transfer throughout the river continuum; elevation, velocity, and discharge. Elevation and slope are basic basin characteristics and are available in the form of topographic maps or Digital Elevation Models (DEMs). Velocity is often calculated using Manning's equation (Schwab et al., 1993):

$$v = \frac{R^{2/3} s^{1/2}}{n} \qquad \text{[Eq. 2]}$$

where v = average flow velocity (m/s),
n = roughness coefficient,
R = a/p, hydraulic radius (m), and
s = hydraulic gradient or channel slope (m/m).

Discharge can then be found by multiplying the velocity predicted by Manning's equation with the channel cross-sectional area determined through field surveys or analysis of regional geometry curves provided by the Natural Resource Conservation Service.

River systems begin as headwater streams. These streams are characterized by high potential energy, due to elevation, and high velocity (kinetic energy) associated with relatively steep channel slopes. This energy is dissipated through the formation of a channel with an elevated roughness coefficient, creating high frictional losses. Streams in the upper reaches of a watershed are often characterized by straight channels with pools and drops which create a system for maximizing energy dissipation. In contrast, rivers in the lower parts of the watershed are characterized by decreased potential energy and shallower channel slopes. The energy buildup in higher order rivers is not due to elevation or velocity, though center channel velocities may be significant, but by the increased discharge associated with flow accumulation.

The frictional forces created by the interaction between water and the conduit through which it flows mitigate the energy buildup in river systems. The kinetic energy (KE) of water may be written as follows:

$$KE = \frac{1}{2}mv^2 \qquad \text{[Eq. 3]}$$

where m = mass of water (M), and
v = water velocity (L/T).

The frictional force on the channel boundary is created as the water is slowed due to boundary roughness. Newton's 2nd law states that force is equal to mass times the acceleration of the mass. As water decelerates a frictional force is created.

Shear stress, σ, is defined by Chang (1988) as the force, F, per unit area, A, in the flow direction.

$$\sigma = \frac{F}{A} \qquad \text{[Eq. 4]}$$

The forces on a sediment particle created by flowing water can be divided into two categories: (1) forces applied to the particle tending to cause motion and (2) resistive forces combining to hold the particle in place. Critical shear stress is known as the condition when forces holding a particle in place and those causing motion are in balance. Figure 1 shows the applied and resistive forces acting on a bed or bank particle. When the applied forces exceed those of the critical shear stress condition particle motion is initiated. This initiation of movement is known as detachment. The DuBoys' (1879) equation presented in the section **4.4** is an example of a model based on tractive force theory.

Literature Review

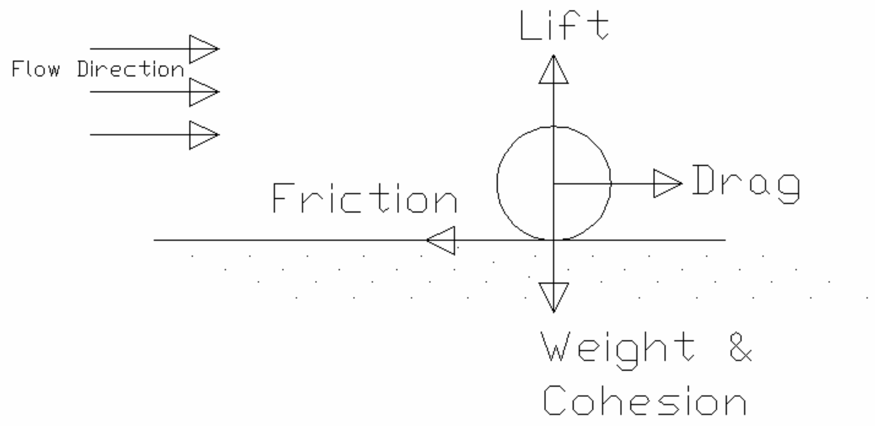


Figure 1. Simplified free-body diagram for a submerged, attached sediment particle.

The sediment transport capacity of a river is defined by Huang et al. (1999) as “the maximum amount of sediment that a flow can carry.” The transport capacity can be looked at as the amount of energy in a stream available to move sediment. Sediment transport capacity is dependent on the flow conditions and the physical properties of the sediment: size, shape, and composition (Thorne et al., 1997). Particles with different physical properties will require different energy levels, or critical shear stress forces, to detach the particle from the bed or bank surface. If a stream has not reached the transport capacity for a given particle size class and a particle is detached, the particle will be entrained and motion will be maintained until flow energy is reduced and deposition occurs.

Literature Review

Total stream power is defined as the power acting on a unit length (in the direction of flow) of stream channel (Bagnold, 1966). The stream power relationship is a function of channel dimensions and discharge and is given by:

$$\Omega = \omega W = \rho g R S V W \qquad \text{[Eq. 5]}$$

where Ω = total stream power (N),
ω = unit stream power (N/m),
W = width (m)
ρ = the density of the fluid (kg/m^3),
g = gravitational acceleration (m/s^2),
R = hydraulic radius (m),
S = dimensionless energy slope or channel bed slope, and
V = mean velocity of flow (m/s).

Stream power is a quantitative description of flow energy and may be used to develop estimates of sediment transport capacity.

The total load carried by natural streams is broken down into three components, each with distinct transport mechanisms (Knighton, 1998). The dissolved load component consists of particles which are transported in solution. It is not considered a part of the sediment load. Washload consists of fine particles, often cohesive, with diameters less than 0.062 mm and slow fall velocities. It may account for as much as 95% of the total load in some river systems. Once detached, washload particles remain in suspension, making the transport of this component commonly supply-dependent. Washload particles are often detached as aggregates. Strong cohesive forces between individual particles require very high shear stresses for detachment, making cracks between aggregates the most common failure surface (Knighton, 1998).

Bed-material load is comprised of particles with a diameter greater than 0.062 mm. This load component often consists of noncohesive sand and gravel particles. Excess shear stress, though still important in predicting the initiation of motion, is less representative of sediment transport for this load component. Though armouring or downcutting to bedrock may eliminate the bed material supply in some rivers, most systems are characterized by unconsolidated bed materials. In these systems, the channel bed provides the supply, but particles in this class cannot remain entrained until periods of increased transport capacity, associated with elevated flows. This condition of constant supply and limited transport due to high energy requirements for entrainment is known as a transport-limited system. Particles may be detached but not transported due to the high stream power required for larger bed material transport. Bed material transport is most responsible for the reshaping of stream channels.

The bed-material load is further divided into bedload and suspended load. The smaller bed-material particles are transported in suspension. Larger particles are transported either by rolling, sliding, or saltation and constitute the bedload fraction.

The combination of energy concepts and sediment transport mechanisms helps provide a better understanding of the formation and channel characteristics of streams. Referring back to the discussion of the high energy environment of many headwater streams, it can now be deduced that this environment would consist of mainly large, transport-resistant sediments. The small contributing areas feeding low order streams limit the supply of fine sediment from overland sources, and steep channel slopes allow them to readily transport fine sediment, creating an environment where little supply is available to contribute to the high demand for washload sediments. For these reasons, headwater streams have bed sediments consisting mainly of gravels, cobbles, and boulders. Any fine sediment with relatively slow fall velocities cannot be deposited in the highly turbulent flow.

Conversely, higher order streams in the lower reaches of a watershed are provided a supply of washload sediments from increasingly larger upland contributing areas. Fine sediment is supplied to these reaches by overland flow and transport from upstream sections. Larger, capacity-limited particles from upstream reaches settle out more rapidly as you move downstream leaving only small bed-material and washload particles to contribute to the sediment load. Washload particles remain in suspension while the fine bed-material particles fall out in pool sections where transport capacity is limited. The relationship of downstream fining and channel slope is depicted in Figure 2.

Literature Review

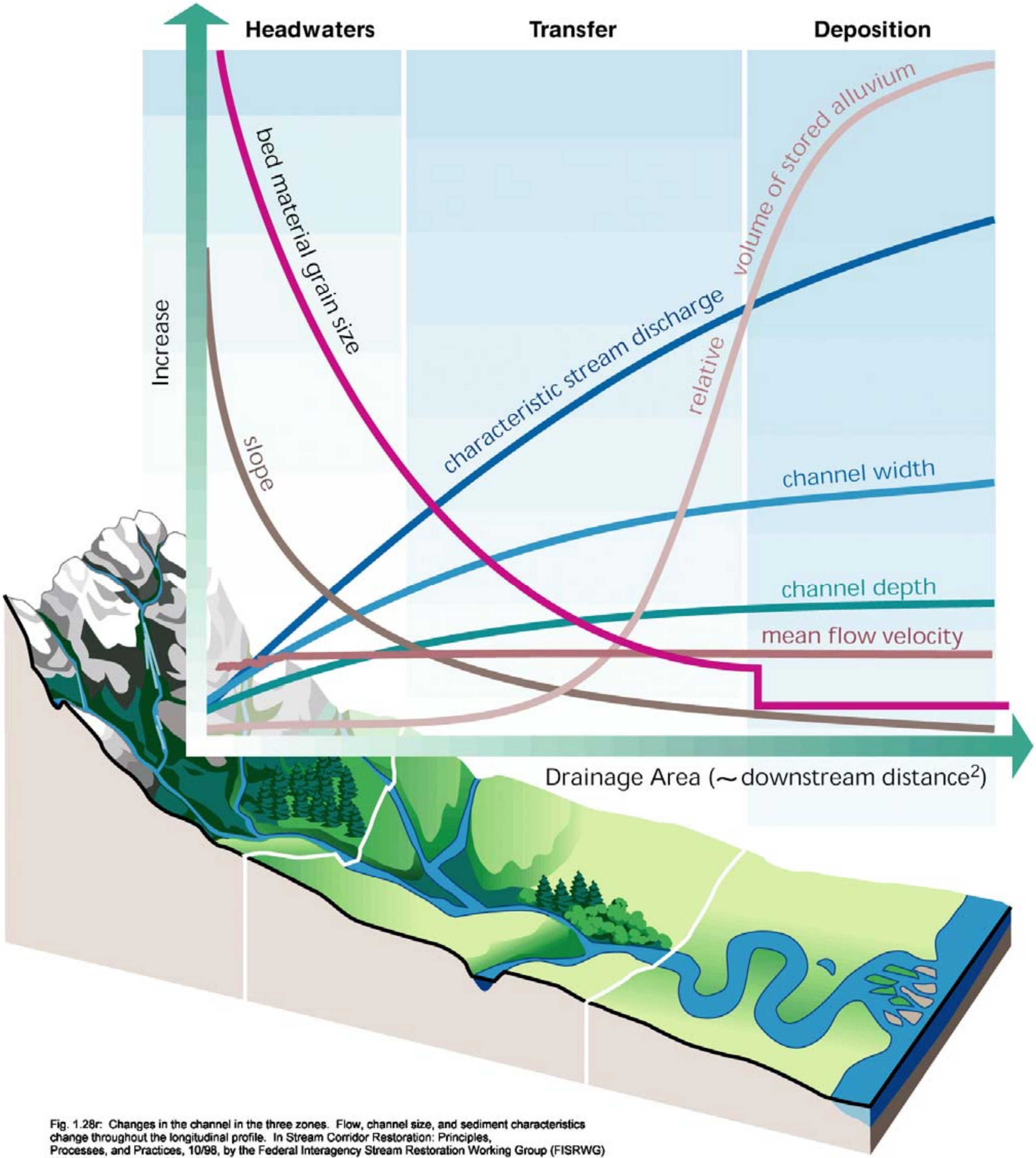


Fig. 1.28r: Changes in the channel in the three zones. Flow, channel size, and sediment characteristics change throughout the longitudinal profile. In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG) (15 federal agencies of the US government).

Figure 2. Particle size, channel shape, and flow characteristic changes in downward stream direction (FISRWG,1996).

The combination of increased washload supply and decreased channel slope creates an environment where the washload component of the total load becomes more dominant. The high supply and reduced transport capacity in these larger streams allows fine sediments to accumulate through sedimentation on the bed. This build up of particles then provides a steady supply of washload particles, even between runoff events.

A number of sediment transport relationships have been created to predict the movement of sediment through watersheds. These equations are dependent on particle size and are often combined in watershed and stream modeling software to increase prediction effectiveness and to improve the scope of software applicability. A number of sediment transport equations are explained in the section **4.6**.

4.3 Terms for Channel Sediment Movement

A number of terms are used to describe the loss of sediment from channel boundaries. These terms include channel erosion, streambank retreat, streambank erosion, scour, incision, and downcutting. Definitions of channel erosion vary depending on the source, be it fluvial geomorphology or river engineering texts. The United States Department of Agriculture defines channel erosion as the removal of sediment by water from land surfaces when water is concentrated, causing the development of channels (USDA, 1999). The American Society of Civil Engineers (1977) defines channel erosion as the sum of stream bed and bank erosion. In the context of this document, channel erosion is to describe the portion of sediment which is detached and entrained from the bed and banks as a result of shear stresses associated with streamflow. Channel degradation is used to refer to the net loss of sediment from a stream cross section or reach.

Channel erosion describes one component of the total sediment movement in a stream reach, which can be further broken down into its constituents; bedload transport, subaerial erosion, bank erosion, and bank mass failure. These components differ in their source location and the processes causing sediment detachment and transport. Instream sediment transport terms must be fully understood to facilitate a channel degradation discussion. "Scour" and "bank erosion" are used to describe the detachment and transport of particles from the streambed or streambanks, respectively, due to applied shear stresses in excess of the critical shear stress and adequate sediment transport capacity. Subaerial erosion is defined as soil lost from bank areas above the water surface due to freeze-thaw cycling, desiccation cracking, and other surface weathering processes. The term "deposition" is used to describe the process of sediment particles settling on the streambed or banks, while mass failure is defined as the collapse of the streambank due to geotechnical instability. The sum of subaerial and streambank erosion, and streambank mass failure is collectively referred to as the bank retreat rate (Thorne et al., 1997). Channel degradation is used to refer to the net loss of sediment from a cross section or reach. This term adds the scour of bed sediments to sediment lost from streambank retreat. Sediment contributions from the floodplain and upland areas are not considered part of channel degradation.

Bank retreat, much like bedload transport, is influenced by sediment characteristics and boundary flow conditions. Streambank sediments generally are finer than sediment found on the stream bed. The smaller particle size allows stronger cohesive forces to develop between the streambank soil particles as compared to bed sediment. The vertical orientation of streambanks also creates forces dissimilar to those found on the channel bed. Bank sediments are subject to a gradient of shear stresses created by differences in head: sediment particles at the toe of a slope experience a greater hydraulic head, and therefore stress, than points higher on the bank surface where hydraulic head is reduced. This gradient creates a zone of accelerated bank erosion at the bank toe, resulting in steep or overhanging slopes. Streambanks are also subject to weakening processes associated with fluctuating flow levels and changing atmospheric conditions. The cyclic wetting and drying of streambank sediments can increase bank erodibility, or the ease with which particles are detached. Soil desiccation also promotes bank erosion. Extreme temperature fluctuations combined with excessive drying of bank sediments has been shown to create cracking and spalling in bank sediments, increasing bank erodibility (Lawler, 1992). Significant bank sediment instability can also be created by subaerial freeze-thaw processes. The formation of needle ice and the cyclic expansion of banks associated with freeze-thaw cycling creates a friable, loose bank surface. The combination of subaerial processes allows gravitational forces or hydraulic shear stresses from elevated flows to remove loosened particles from the bank face. Bank instability can also be caused by the lowering, or downcutting of the channel bed. Practices such as urbanization, channelization, or straightening can initiate the development of downcutting. Headcutting may also contribute to streambank instability. Headcutting occurs when the elevation of the streambed is altered during a disturbance. The point of increased bed slope causes the migration of a downcutting front advancing in the upstream direction as the stream attempts to return the bed to a pre-disturbance slope. This can lead to the incision of entire channel networks, creating higher, more unstable streambanks.

Bed and bank erosion processes drive bank mass failure. Excessive scour of bed sediments and channel incision due to headcuts increases bank height. Fluvial erosion removes materials from the bank toe, increasing bank angles (Langendoen, 2000). Increased bank height and angle reduces slope stability, leading to mass failure. Bank stability is dependent on the balance of soil cohesive and frictional forces resisting movement with gravitational forces causing collapse. Failure is highly influenced by soil cohesion. The surface along which the maximum shear forces form is known as the failure plane. The failure plane for cohesive soils develops within the bank structure due to the buildup of shear stresses more quickly with depth than shear strength in cohesive soils. Failure in noncohesive sediments tends to occur near the soil surface where the ratio of shear stress to shear strength is greatest.

Bank failure can occur by a number of failure mechanisms, as shown in Figure 3. Rotational failure (Figure 3a) occurs when banks with shallow slopes (less than 60%) fail along a curved surface and the failure block rotates towards the bank surface. Failure in steeper banks tends to occur along a flat planar surface with the failure block sliding into the channel without rotating (Figure 3b). When bank materials are composed of heterogeneous sediment layers, cantilever bank failure can occur (Figure 3c). When more easily erodible sediments are overlain with erosion-resistant sediments, steep bank angles or overhangs can be created. The cantilevered block fails when resistive forces no longer support the weight of the overhanging block. When noncohesive sediments are found between two layers of cohesive sediment preferential flow paths may form in the confined layer. Seepage through the noncohesive layer creates erosion due to soil piping. As piping undermines the upper cohesive layer the failure block detaches from the bank, rotating away from the bank as it topples into the stream.

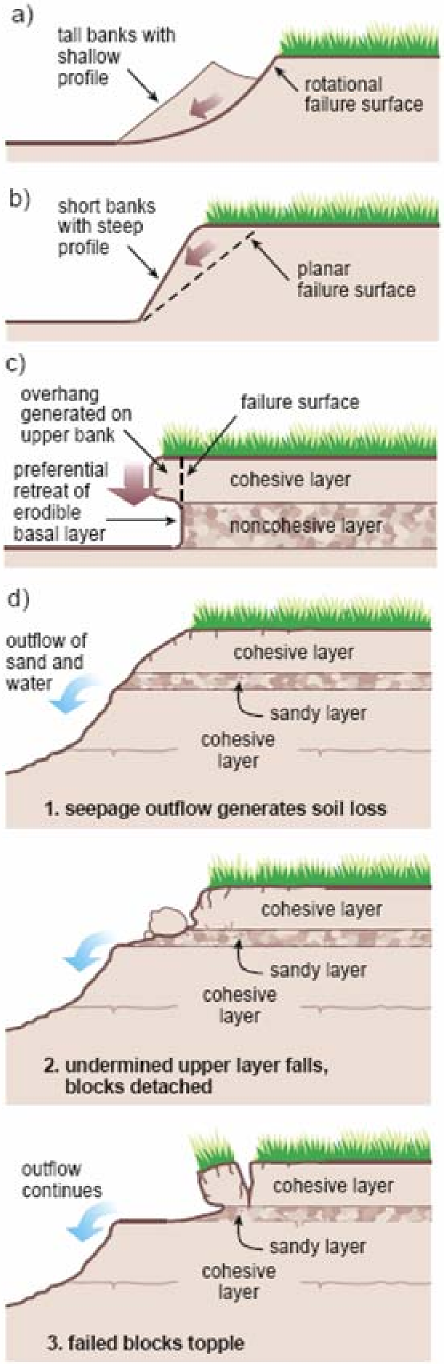


Figure 3. Bank failure mechanisms: a) rotational, b) planar, c) cantilever, and d) piping or sapping (Langendoen, 2000).

4.4 Erosion and Sediment Transport Equations

Sediment transport in stream channels is more difficult to calculate than overland erosion. Due to the complexity of instream sediment transport processes no single equation has yet been developed to simulate the movement of particles from all size classes. The sediment transport capacity (C; M/A) of individual size classes must be analyzed separately. This requirement demands watershed and stream modeling software employ a suite of transport equations to simulate the movement of all sediment within the basin. A framework of concepts, including tractive force theory and stream power, help relate channel transport equations to one another. This section describes some of the most common sediment transport equations used in watershed and stream modeling software, most of which are summarized in the Generalized Sediment Transport for Alluvial Rivers – One Dimensional, Version 1.0.2 (GSTAR-1D; USDI, 2005). The reader is referred to the GSTAR-1D manual or other sediment transport texts for a full explanation of these and other equations.

4.4.1 Einstein's Deposition Model (1968)

Einstein (1968) developed a deposition model for sediment based on the principal that sediment discharge can be determined from the product of sediment concentration and flow discharge. The form of Einstein's equation, which has been adapted for application to field conditions, can be written as (USDA, 1993):

$$q_{sd} = A\left({}^{v_f}\!/_{q_w} \right)\left(q_s - q_{sc} \right) \qquad \text{[Eq. 6]}$$

where q_{sd}= rate of unit-area sediment deposition along the flow length (lbs/sec/ft^2),

A = proportionality constant for a certain flow and particle size, between the depth-average suspended sediment concentration and the concentration at the laminar sublayer plane (non-dimensional),
q_{sc} = unit-width sediment transport capacity (lbs/sec/ft),
q_s = unit-width sediment discharge (lbs/sec/ft),
q_w = unit-width water discharge (ft^3/sec/ft),
v_f = particle fall velocity, (fps).

4.4.2 Duboys' Method for Noncohesive Sediment (1879)

Duboy's method is based on the excess shear stress approach and the concept that noncohesive sediment moves as independent layers sliding over one another (USDI, 2005). Although interactions between sediment layers do occur, the equation is useful in estimating bedload movement. The excess shear stress relationship used in the DuBoys model is written as follows:

$$q_b = K\tau(\tau - \tau_c) \qquad \text{[Eq. 7]}$$

where q_b = bedload discharge by volume per unit channel width (ft^2/s),
K = an empirical constant (defined below),
τ = bed shear stress (lb/ft^2), and
τ_c = critical tractive force along the bed (from Shields diagram; lb/ft^2).

The relationship for K was determined by Straub (1935) using an empirical relationship dependent only on the particle size diameter, d (mm), and given by the following equation:

$$K = \frac{0.173}{d^{3/4}}. \qquad \text{[Eq. 8]}$$

4.4.3 Ackers and White's Method (1973)

Ackers and White (1973) developed a dimensionless mobility number to approximate the transport of bed sediment. The equation is given as:

$$F_{gr} = U^{*n}\left[gd\left(\frac{\gamma_s}{\gamma}-1\right)\right]^{-1/2}\left[\frac{V}{\sqrt{32}\log(\alpha D/d)}\right]^{1-n} \qquad \text{[Eq. 9]}$$

where U* = shear velocity,

n = transition exponent, depending on sediment size,

g = gravitational acceleration,

γ_s = sediment specific gravity,

γ = water specific gravity,

α = 10, in turbulent flow,

d = sediment particle size, and

D = water depth.

Sediment size was also defined through a dimensionless grain diameter equation:

$$d_{gr} = d\left[\frac{g}{v^2}\left(\frac{\gamma_s}{\gamma}-1\right)\right]^{1/3} \qquad \text{[Eq. 10]}$$

where v = kinematic viscosity of water.

The generalized dimensionless sediment transport function can be expressed as:

$$G_{gr} = C\left(\frac{F_{gr}}{A}-1\right)^{m}. \qquad \text{[Eq. 11]}$$

The coefficients A, C, m, and n were derived from best-fit curves of laboratory data for sediment sizes larger than 0.04 mm and Froude numbers below 0.8. This formula is known to over predict transport rates for coarse sediments and fine sediment smaller than 0.02 mm. Modifications to the equations have been made to compensate for these over predictions. A table of coefficients and corrections is given in the referenced texts.

4.4.4 Meyer-Peter and Müller's Formula (1948)

The dimensionless form of the bedload formula developed by Meyer-Peter and Müller (1948), as presented in Fluvial Processes in River Engineering (Chang, 1988) for coarse textured bed materials is given by:

$$q_b^{2/3}\left(\frac{\gamma}{g}\right)^{1/3}\frac{0.25}{(\gamma_s-\gamma)d}=\frac{(k/k')^{3/2}\gamma RS}{(\gamma_s-\gamma)d}-0.047 \qquad \text{[Eq. 12]}$$

where γ and γ_s = the specific weight of water and sediment, respectively,

R = hydraulic radius,

S = slope of the energy grade line,

d = mean particle diameter,

q_b = bedload rate in submerged weight per unit time and width, and

(k/k')S = adjusted energy slope responsible for bedload motion.

Dimensional homogeneity allows for use of the equation with any consistent set of units. *k*-values are computed from the following relationships:

$$k=\frac{V}{R^{2/3}S^{1/2}} \qquad \text{[Eq. 13]}$$

and

$$k'=\frac{26}{d_{90}^{1/6}} \qquad \text{[Eq. 14]}$$

where V = cross-sectional average flow velocity,

R = hydraulic radius,

S = channel slope, and

d_{90} = the sediment size (m) for which 90 percent of sediment is finer.

4.4.5 Laursen's Formula (1958)

Developed in 1958, Laursen's formula predicts total bed-material load transport. The American Society of Civil Engineers Task Committee (1971) developed a dimensionally uniform version, as shown below:

$$C_t = 0.001\gamma \sum_i p_i \left(\frac{d_i}{D}\right)^{7/6} \left(\frac{\tau'}{\tau_{ci}} - 1\right) f\left(\frac{U^*}{\omega_i}\right) \qquad \text{[Eq. 15]}$$

where C_t = sediment concentration by weight per unit volume,

$U^* = \sqrt{gDS}$,

p_i = percentage of materials available in size fraction i,

ω_i = fall velocity of particles of mean size d_i in water,

D = average water depth, and

τ_{ci} = critical tractive force for sediment size d_i given by Shields diagram.

The bed shear stress, τ´, resulting from grain resistance derived in the use of Manning's equation is written as follows:

$$\tau' = \frac{\rho V^2}{58} \frac{d_{50}}{D}^{1/3} \qquad \text{[Eq. 16]}$$

Where τ' = bed shear stress due to grain resistance, found using the critical shear stress relationship given by Laursen ,

ρ = sediment density,
V = average velocity, and
d_{50} = particle size for which 50 percent of observed sediments are of equal or lesser diameter.

4.4.6 *Toffaleti's Method (1969)*

Based on work presented by Einstein (1950), Toffaleti's method provides a simplified transport equation. Simplifications include; a rectangular channel with a depth, R, equal to the hydraulic radius, and depth broken into four flow zones. The equation for bed material load, Q_{ti}, for a specific sediment size is given by:

$$Q_{ti} = B(q_{bi} + q_{sui} + q_{smi} + q_{sli}) \qquad \text{[Eq. 17]}$$

where B = channel width; and
q_{bi}, q_{sui}, q_{smi}, q_{sli} = sediment load per unit width in the bed zone, upper zone, middle zone, and lower zone, respectively.

The sediment load in each zone is derived by a combination of graphical and semi-empirical methods.

4.4.7 *Engelund and Hansen's Method (1972)*

The dimensionally homogeneous transport function developed by Engelund and Hansen (1972) is given as:

$$f'\phi = 0.1\,\theta^{5/2} \qquad \text{[Eq. 18]}$$

$$f' = \frac{2gSD}{V^2} \qquad \text{[Eq. 19]}$$

$$\phi = \frac{q_t}{\gamma_s}\left[\frac{\gamma_s - \gamma}{\gamma} g d^3\right]^{-1/2} \qquad \text{[Eq. 20]}$$

$$\theta = \frac{\tau}{(\gamma_s - \gamma)d} \qquad \text{[Eq. 21]}$$

where g = gravitational acceleration,

S = energy slope,

D = mean water depth,

V = average flow velocity,

q_t = total sediment discharge, weight/width,

γ_s and γ = specific weights of sediment and water, respectively,

d = median particle diameter, and

τ = bed shear stress.

4.4.8 Brownlie's Method (1981)

Brownlie's method (1981), derived with uniform dimensionality, best approximates sand transport. The equation for sediment concentration (ppm/weight) is given as:

$$C = 7115 C_F \left(F_g - F_{g0}\right)^{1.978} S_f^{0.6601} \left(\frac{R}{d_i}\right)^{-0.3301} \qquad \text{[Eq. 22]}$$

where C_F = Brownlie's field application coefficient = 1.268,

F_g and F_{g0} = Froude number and critical grain Froude number, respectively, which are given by:

$$F_g = \frac{V}{\sqrt{\left(\frac{\rho_s - \rho}{\rho}\right) g d_{50}}} \qquad \text{[Eq. 23]}$$

$$F_{g0} = \frac{4.596\ \tau_{*c}^{0.5293}}{S_f^{0.1405}\ \sigma_g^{0.1606}} \qquad \text{[Eq. 24]}$$

where σ_g = geometric standard deviation of bed-particle sizes = $\sqrt{d_{84}/d_{16}}$, and

τ_{*c} = critical shear stress, given by:

$$\tau_{*c} = 0.22Y + \frac{0.06}{(10)^{7.7Y}} \qquad \text{[Eq. 25]}$$

$$Y = \left(\sqrt{\frac{\rho_s - \rho}{\rho}} R_g\right)^{-0.6} \qquad \text{[Eq. 26]}$$

$$R_g = \frac{\sqrt{g d_{50}^3}}{v} \qquad \text{[Eq. 27]}$$

where R_g = grain Reynolds number and Y is a transition variable.

4.4.9 Yang's Sand (1973) and Gravel (1984) Transport Formulas

Yang's 1973 sand transport equation was developed to predict total bed-material load movement for sand sized particles. Over 400 laboratory flume studies were conducted and the data were used to determine the equation coefficients. The dimensionless unit stream power transport equation is given by Equation 28:

$$\log C_{ts} = 5.435 - 0.286 \log\frac{\omega d}{v} - 0.457 \log\frac{U*}{\omega} + \left(1.799 - 0.409 \log\frac{\omega d}{v} - 0.314 \log\frac{U*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \qquad \text{[Eq. 28]}$$

where C_{ts} = total sand concentration in parts per million by weight,

ω = sediment fall velocity,

d = sediment particle diameter,

v = kinematic viscosity of water,

U^* = shear velocity,

VS = unit stream power,

V = average flow velocity,

S = water surface or energy slope, and

V_{cr} = critical average flow velocity at incipient motion.

The critical unit stream power is the product of critical velocity and energy slope with

$$\frac{V_{cr}}{\omega} = \begin{cases} \dfrac{2.5}{\log(U^* d/v) - 0.06} + 0.66 & \text{if } 1.2 < \dfrac{U^* d}{v} < 70 \\ 2.05 & \text{if } 70 < \dfrac{U^* d}{v} \end{cases} \qquad \text{[Eq. 29]}$$

The equation for particles larger than two millimeters (Yang, 1984) takes the same form but the coefficients were adjusted through the collection of data from more than 150 laboratory flume studies to give the following equation:

$$\log C_{tg} = 6.681 - 0.633 \log\frac{\omega d}{v} - 4.816 \log\frac{U*}{\omega} + \left(2.784 - 0.305 \log\frac{\omega d}{v} - 0.282 \log\frac{U*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \qquad \text{[Eq. 30]}$$

where C_{tg} = total gravel concentration in parts per million by weight. Both the sand and gravel stream power equations were originally developed assuming a uniform bed layer and sediment transport estimates must be adjusted based on the composition of the bed being simulated, as described in Yang (1984).

4.4.10 Yalin's Bedload Formula (1963)

The transport of each particle size class, as proposed by Yalin (1963), is appropriate for sand and smaller particle sizes and is given by the following equations:

$$TF = P_s \cdot S_g \cdot \rho_W \cdot g \cdot dV \qquad \text{[Eq. 31]}$$

where

$$P_s = 0.635 \cdot \partial \cdot \left[1 - \ln(1+\sigma)/\sigma\right] \qquad \text{[Eq. 32]}$$

$$\sigma = 2.45 \cdot S_g{}^{-0.4} \cdot Y_{cr}{}^{0.5} \cdot \partial \qquad \text{[Eq. 33]}$$

$$\partial = \left(Y / Y_{cr} \right) - 1 \qquad if\ Y < Y_{cr}, \partial = 0 \qquad \text{[Eq. 34]}$$

$$Y = V^2 / \left[(S_g - 1) \cdot g \cdot d \right] \qquad \text{[Eq. 35]}$$

TF = transport capacity (kg/s),

P_s = number of particles in transport,

S_g = particle specific gravity (kg/m^3),

ρ_w = fluid mass density (kg/m^3),

g = gravitational acceleration (m/s^2),

Y_{cr} = critical shear stress from Shield's diagram (Pa), and

d = particle diameter (m).

Shear velocity, V (m/s), is given by the following:

$$V = \sqrt{g \cdot r \cdot s} \qquad \text{[Eq. 36]}$$

where S = slope of the energy gradeline, and
R = hydraulic radius (m).

The sediment transport equations described above are commonly used in watershed and stream modeling software. A more detailed discussion of sediment transport equations may be found in Yang (1996).

4.5 Modeling Channel Degradation

As the importance of channel degradation to stream sediment loadings has been recognized, watershed and stream model developers have incorporated channel degradation subroutines into existing model structures. The following sections provide a description of the channel degradation algorithms developed and integrated into a number of commonly used watershed and stream models. The descriptions provided represent a broad range of process detail and simulation flexibility.

4.6 Model Selection

In addition to GWLF, SWAT, and CONCEPTS, the channel degradation algorithms of eight other models were reviewed. A summary of each model is presented in Table 1 to show differences in model simulation complexity.

Table 1. Summary of channel degradation models and procedures.

Model	Simulated Degradation Processes	Channel Degradation Algorithm	Channel Adjustment Considered?	Surface Condition Adjustment Parameters	Applications
AnnAGNPS	Fluvial erosion	Bagnold stream power	Not specified	Variable K	SL; assessment of watershed management strategies
ANSWERS-2000	Fluvial erosion	critical shear stress, transport capacity	Widening after nonerodible bed layer is reached	K with root adjustment	SL; assess the impact of BMPs.
CCHE-1D	Fluvial erosion and planar bank failure	critical shear stress	Adjusts depth and width based on erosion rate prediction	multiple R per cross section	PL; designed to assess scour and deposition at hydraulic structures
CONCEPTS	Fluvial erosion and bank mass failure	critical shear stress, transport capacity	Width and depth	5 R per cross section, K, Tc	RL; assessment of stream restoration design practices
GSTAR-1D	Fluvial erosion and bank mass failure	critical shear stress, angle of repose adjustment	Width and depth adjustment	10 R per cross section	PL; simulation of hydraulic and sediment transport
GWLF		Empirical: *f* (monthly flow volume, % development, animal density, curve number, channel slope)	None	None	SL; not suitable for design assessment.
HEC-6	Fluvial erosion	Exner equation; bed sorting; critical shear stress, transport capacity	Vertical adjustment for user defined erodible channel.	Depth or discharge dependent R	SL; simulate long-term changes in channel shape due to desposition and scour in gaged watersheds.
HSPF	Fluvial erosion	critical shear stress, Partheniades' eq., Krone's formula	None	None	SL
SAM	Fluvial erosion	stream power; 13 bed material transport equations; one time nature poorly represents transport	N/A, snapshot simulation (single point in time)	R	SL; designed to assess channel stability at a single cross section for a single time. Riprap size calculations.
SWAT 2000	Fluvial erosion	Bagnold stream power	Yes, not effective for small reaches	Channel cover factor, and K	PL if calibrated; highly sensitive channel simulation; assessment of watershed scale land management changes
WARMF	Fluvial erosion	critical velocity, transport capacity	None	K	SL; integrated TMDL and Consensus modules for loadings calculations; limited flexibility for testing alternatives

K = erodibility
R = Manning's roughness
Tc = critical shear stress

SL = screening level channel erosion simulation
PL = planning level
RL = research level

Literature Review

GWLF, SWAT, and CONCEPTS were selected from the models summarized in Table 1 for a Stroubles Creek channel degradation modeling case study based on the availability of existing data and the level of process detail represented in each model. Existing GWLF and SWAT model setups were created in connection with the Stroubles Creek Benthic TMDL in 2003 (Mostaghimi et al., 2003). The use of existing models in this research expedited the modeling process and ensured that simulations were based on data appropriate for use in a TMDL study. The CONCEPTS model was designed to assess the impacts of stream restoration and was chosen to determine if more detailed, process-based models provided improved estimation of sediment loads contributed by channel degradation, as compared to standard watershed-scale modeling software.

The GWLF model was included in the channel degradation model comparison for the following reasons:

1. GWLF is a screening-level model with a channel erosion component. Commonly used in TMDL applications, the model detail is appropriate for TMDL development and much of the input data are readily available.
2. GWLF was applied to the Stroubles Creek system during the TMDL study (Mostaghimi et al., 2003). The availability of a pre-existing model setup for the Stroubles Creek watershed allowed researchers to draw from a developed data set, expediting model development.
3. GWLF was selected based on the simplicity of the channel erosion model component. The limited hydrologic flow routing detail in GWLF restricts complex hydraulic simulation. GWLF predicts fluvial erosion based on an empirical relationship (Evans et al., 2003). The relationship is a function of watershed characteristics such as percent developed land, slope, and USLE soil erodibility. GWLF was chosen to represent a model with detail suitable for preliminary channel degradation estimates on a monthly basis.

The SWAT model was selected for comparison based on similar criteria, as detailed below:

1. SWAT is commonly used in TMDL applications where sediment is identified as the cause of impairment. The model represents process detail

typical of planning models and includes a channel degradation routine with detail appropriate for watershed management. Input data requirements are more extensive than GWLF, but an ArcView GUI makes input file creation relatively straightforward.

2. The SWAT model was applied to the Stroubles Creek watershed as part of a paired watershed study (Wagner, 2004). An existing model framework helped standardize input parameters and accelerated model development for the research reported here. A consistent data source for GWLF and SWAT also eliminated bias from variations in input parameters and provided data resolution appropriate for TMDL studies.
3. The SWAT model was chosen to represent channel process detail comparable to many other planning level watershed models, such as AnnAGNPS and ANSWERS-2000. SWAT simulates deposition by the Bagnold (1977) stream power relationship and transport capacity. Peak velocity and tractive force theory are used to calculate channel scour. Despite increased process detail, SWAT simulates only the fluvial erosion component of streambank retreat.

CONCEPTS was chosen to represent the state-of-the-art technology for channel degradation and bank retreat prediction.

1. The model was designed as a research-level tool to assess stream restoration and BMP effects on channel stability. CONCEPTS was specifically designed to simulate in-channel processes with detail beyond that of watershed-scale models.
2. CONCEPTS simulates fluvial erosion and adds a streambank mass failure component.
3. Though not yet widely used, CONCEPTS represents a model appropriate for determining channel retreat contributions to overall sediment loads and for evaluating the impacts of stream restoration on sediment loading. As watershed managers seek to control sediment sources CONCEPTS may be

applied to watersheds where streams are incised and bank instability is a concern.

The applicability and effectiveness of both GWLF and SWAT have been evaluated in other studies (Mostaghimi et al., 2003; Wagner, 2004). GWLF, SWAT, and CONCEPTS are well supported by government agencies or university researchers. GWLF user-help is provided by Barry Evans, Ph.D of Pennsylvania State University or Gene Yagow, Ph.D of Virginia Tech. SWAT is supported by Jeff Arnold and the USDA. Help with CONCEPTS simulation is provided by Eddy Langendoen of the USDA.

4.7 Watershed Models

4.7.1 Generalized Watershed Loading Function

Model Overview and Theoretical Description

Researchers at Cornell University developed the Generalized Watershed Loading Function (GWLF) model for predicting sediment loadings to ungaged streams (Haith, 1985). The program was designed to use readily available data for the prediction of sediment and nutrient movement over time periods ranging from a few months to years (Wagner, 2004). GWLF is suitable for the simulation of small homogeneous watersheds, but may be applied to larger watersheds on a subwatershed by subwatershed basis. Program applicability is limited by the omission of flow routing routines. The hydrologic balance and sediment delivery are calculated using a daily time step, but monthly values are more closely approximated due to routing limitations (Haith, 1985).

GWLF hydrology predictions are made based on a mass balance approach. Precipitation provides the input for hydrologic predictions (Haith et al., 1992). Surface runoff for urban and rural areas is calculated using the Soil Conservation Service (SCS) curve number method described in the Erosion and Sediment Transport Equations section. Hydrology components simulated by the GWLF program include infiltration, evapotranspiration, runoff, interflow, percolation, and deep seepage. A conceptualization of the hydrologic processes simulated by GWLF is shown by Figure 4.

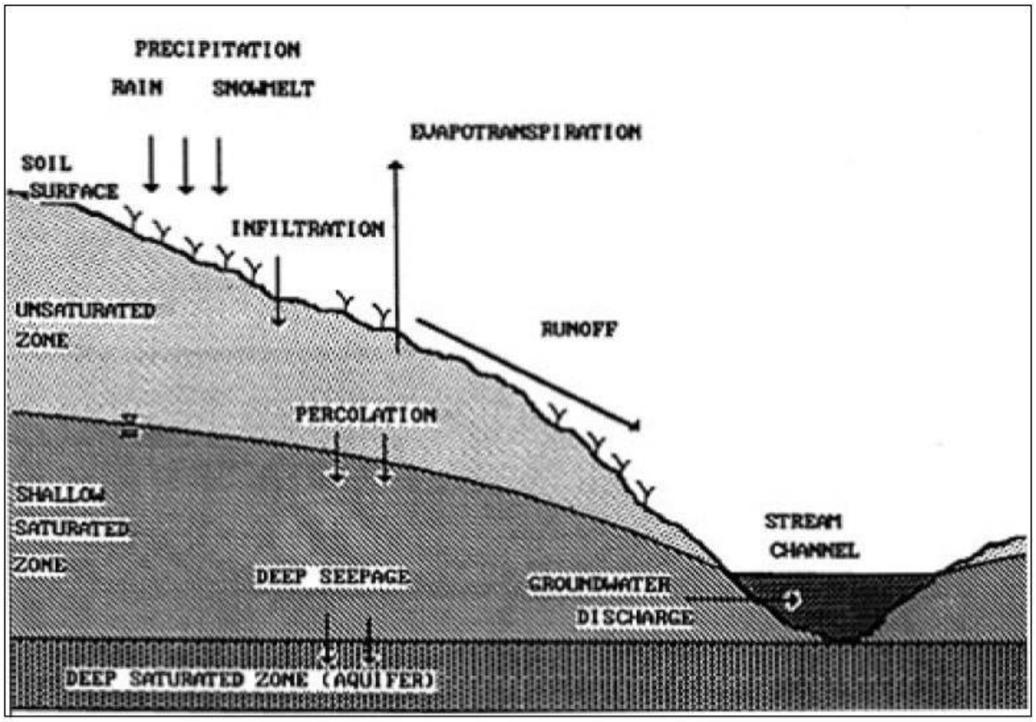


Figure 4. Generalized Watershed Loading Function hydrology components (Haith et al., 1992).

The surface soil erosion model in GWLF is designed to predict sediment yields for time periods of months to several years. The erosion model consists of four steps: 1) rainfall detachment, 2) rainfall transport, 3) runoff soil detachment, and 4) runoff transport (Meyer & Wischmeier, 1969). These processes are simulated based on the USLE parameters combined with delivery ratios to produce sediment yield predictions from each subwatershed. The difference in sediment measured at the outlet of a watershed and total erosion from upstream and upland sources is represented by the sediment delivery ratio. The sediment delivery ratio (SDR) for watershed areas less than 50 km^2 is calculated as (Wagner, 2004):

$$SDR = \left(5 \times 10^{-6}\right) \times A^2 - 1.4 \times 10^{-3} \times A + 0.198 \qquad \text{[Eq. 37]}$$

For watersheds greater than 50 km^2,

$$SDR = 0.4518 \times A^{-0.298} \qquad \text{[Eq. 38]}$$

Sediment yield predictions are calculated for each daily time step, but monthly predictions are more accurate due to the program's omission of flow routing routines (Haith et al., 1992).

A channel and streambank erosion component was not included in the original model program. This subroutine was added by Barry Evans of Pennsylvania State University as part of the ArcView GWLF version (Evans et al., 2003). The highly empirical channel and streambank erosion subroutine is based on the prediction of lateral erosion rate (LER) in meters per month, which is given as follows:

$$LER = a \times q^{0.6} \qquad \text{[Eq. 39]}$$

where a = empirical coefficient, and
q = monthly stream flow volume (m^3/month).

The empirical coefficient, a, is calculated as

$$\begin{gathered} a = \left(5 \times 10^{-4}\right) \times PD + \left(4.8 \times 10^{-5}\right) \times AD + \left(5 \times 10^{-6}\right) \times CN + \\ \left(6.28 \times 10^{-4}\right) \times KF - \left(3.0 \times 10^{-6}\right) \times KF - 5.67 \times 10^{-4} \end{gathered} \qquad \text{[Eq. 40]}$$

where PD = percent developed land in the watershed,
AD = animal density in animal units per area (AU/acre),
CN = area-weighted average curve number,
KF = area-weighted average USLE soil erodibility, and
SP = average slope for the watershed.

The lateral erosion rate is then used to calculate the channel and streambank erosion (CSE) in metric tons as

$$CSE = LER \times streamLength \times BD \times chanDepth \qquad \text{[Eq. 41]}$$

where streamLength = length of perennial stream channels in watershed (m),
BD = soil bulk density (kg/m3), and
chanDepth = mean channel depth at bankfull (m).

The channel erosion subroutine does not allow the user to account for changes in stream surface conditions through the adjustment of a roughness coefficient, thus the impacts of stream restoration cannot be simulated using GWLF.

Program Input and Output Requirements

The GWLF program requires two input files to supply necessary simulation parameters. Developing the TRANSPORT.dat file is the first step in the simulation development process (Haith et al., 1992). The user must modify an existing file or create a new one. Parameters for the TRANSPORT.dat file include initial soil moisture conditions, delivery ratios, and land cover and management factors. A complete list of the required parameters with units and typical ranges are given in Table 2. The WEATHER.dat file contains the daily climate and precipitation data for the simulation time period. The NUTRIENT.dat file is not required, but must be modified or created if nutrient loadings are of interest. All input data files must be stored on the default drive to allow program access.

Table 2. Generalized Watershed Loading Function Input Parameters, Units, and Typical Ranges (Yagow, 2005).

		Typical	
Transport Parameters	**Units**	**Min**	**Max**
Recession coefficient	day^{-1}	0	0.2
Seepage coefficient	day^{-1}	0	
Initial unsaturated storage	cm	0	
Initial saturated storage	cm	0	
Initial snow	cm	0	
Sediment delivery ratio		0.04	0.35
Unsaturated soil moisture capacity	cm	4.0	35.0
Antecedent rainfall	cm	0	
ET cover coefficient, pervious areas		0.3	1
ET cover coefficient, annual crops		0.3	1.58
ET cover coefficient, impervious areas		0	0
Mean number of daylight hours	hours	9.2	14.7
Erosivity coefficient - cool season		0.06	0.3
Erosivity coefficient - warm season		0.13	0.42
Curve Number		30	99
K-factor		0.02	0.6
Slope	%	0.5	30
Length of slope	meters	15.2	121.9
C-factor		0.0005	1
P-factor		0.25	1
a-Factor		0.0000001	0.000438
Total stream length	meters		
Mean channel depth	meters	0.3	4.6
Livestock density	AU/ac		
% developed area	%	0	1
		Typical	
Nutrient Parameters	**Units**	**Min**	**Max**
Sediment-N	mg/kg	400	4,000
Sediment-P	mg/kg	132	1,980
Groundwater N	mg/L	0.07	5.04
Groundwater P	mg/L	0.006	0.104
Dissolved runoff N	mg/L	1.8	29.3
Dissolved runoff P	mg/L	0.1	5.1
Impervious sediment build-up rate	kg/ha-day	2.8	6.2
Impervious N build-up rate	kg/kg sediment	0.0143	0.0360
Impervious P build-up rate	kg/kg sediment	0.0017	0.0040
Dissolved runoff N from manured areas	mg/L	12.2	36
Dissolved runoff P from manured areas	mg/L	1.9	8.7
Septic system effluent N	g/person-day	12	
Septic system effluent P	g/person-day	1.5	2.5
Plant N uptake - growing season	g/day	1.6	
Plant N uptake - dormant season	g/day	0	
Plant P uptake - growing season	g/day	0.4	
Plant P uptake - dormant season	g/day	0	

In addition to the three data files, users must have four compiled program module files. These files are necessary for the simulation of each component of the overall simulation. The four module files include: GWLF20.exe, TRANS20.exe, NUTR20.exe, and OUTP20.exe. These modules are run by typing GWLF20 in the command prompt. After simulation, two additional files are created: RESULTS.dat and SUMMARY.dat. These files provide output data from simulation runs. Output parameters supplied by GWLF are listed in Table 3 (Haith et al., 1992).

Table 3. GWLF principal model output description.

Monthly Output	Annual Output
• Streamflow • Watershed Erosion and Sediment Yield • Total N and P Loads in Streamflow • Precipitation and Evapotranspiration • Ground Water Discharge to Stream • Watershed Runoff • Dissolved N and P Loads from Each Land Use	• Erosion from Each Land Use • N and P Loads from Each Land Use • Dissolved N and P Loads from Each Land Use • Dissolved N and P Loads from Septic Systems

4.7.2 SWAT

The Soil and Water Assessment Tool (SWAT) was developed by Dr. Jeff Arnold of the Grassland, Soil, and Water Research Laboratory in Temple, Texas for the USDA Agricultural Research Service (Neitsch et al., 2002b). SWAT is a physically based watershed-scale model created to predict impacts of “land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land uses, and management conditions over long periods of time (Neitsch et al., 2002a).”

Literature Review

The Simulator for Water Resources in Rural Basins (SWRRB) model was combined with the Routing Outputs to Outlet (ROTO) model to create the underlying core of the SWAT program. SWRRB, and therefore SWAT, is a continuous simulation model. SWAT also incorporates elements of the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) and Groundwater Loading Effects on Agricultural Management Systmes (GLEAMS) models

The following is description of the Soil and Water Assessment Tool (SWAT) by Rachel Wagner (2004) of the Virginia Tech Biological Systems Engineering department.

> "AVSWAT is an interface of the SWAT model with ArcView 3.x (ESRITM) Spatial Analyst (DiLuzio et al., 2002). Use of a [*sic*] geographic information system (GIS) software is valuable is [*sic*] determining model parameters, and the AVSWAT interface allows the user to evaluate values for the necessary parameters and creates the model input files automatically.
>
> ### *Use and Limitations*
>
> The SWAT model was developed to "predict the effect of management decisions on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, ungaged river basins" (Arnold et al., 2002). It has been used to evaluate management decisions in a number of studies, including a study of Best Management Practices (BMPs) for dairy waste and municipal wastewater on the water quality in the impaired North Bosque River Watershed in central Texas (Santhi et al., 2001). A study in the Rock River Basin in southern Wisconsin successfully used SWAT to evaluate two specific BMPs: change from conventional tillage to conservation tillage and change of fertilizer application rates from a high level to a recommended level (Kirsch et al., 2002).
>
> SWAT is not effective for modeling individual storms, but rather for providing long-term analysis of watershed processes (Neitsch et al., 2002a). The model is applicable to medium sized watersheds (of a few hundred square miles) to large watersheds (thousands of square miles) (Neitsch et al., 2002a; Neitsch et al., 2002b). Although no limit is imposed for the number

of subbasins created in a watershed, the subbasins should be large enough to be suitable for the equations employed by SWAT but small enough to show the variability within a watershed. The SWAT development team recommends between 1 and 10 hydrologic response units (HRUs) in a subbasin (Neitsch et al., 2002b). An HRU is a unique soil-land use combination.

SWAT is intended for use in ungaged watersheds and therefore without calibration (Neitsch et al., 2002b). However, in many studies where observed data is [*sic*] available, hydrologic calibration is used to improve model performance. Both studies referenced above (Santhi et al., 2001 and Kirsch et al., 2002) calibrated SWAT to improve model performance.

SWAT Hydrology Model

In SWAT, runoff is divided into two phases: the land phase, which controls runoff to channels, and the routing phase, which controls routing in channels. The land phase is based on a water balance. Precipitation can either be intercepted by vegetation or reach the land surface. Water that reaches the land surface can runoff or infiltrate into the root zone and the unsaturated zone. Water can be exchanged between this upper soil layer and the unconfined aquifer layer below, or it can move as lateral flow into the main channel. From the unconfined aquifer, water can be transported into the main channel as return flow or recharge the deep aquifer. As in the deep saturated zone in GWLF, water in SWAT's deep aquifer is lost from the system (Neitsch et al., 2002a). The processes of the land phase of the hydrologic cycle are illustrated in Figure [5]. During the channel routing phase water may be lost via evaporation or seepage, or added via rainfall and baseflow.

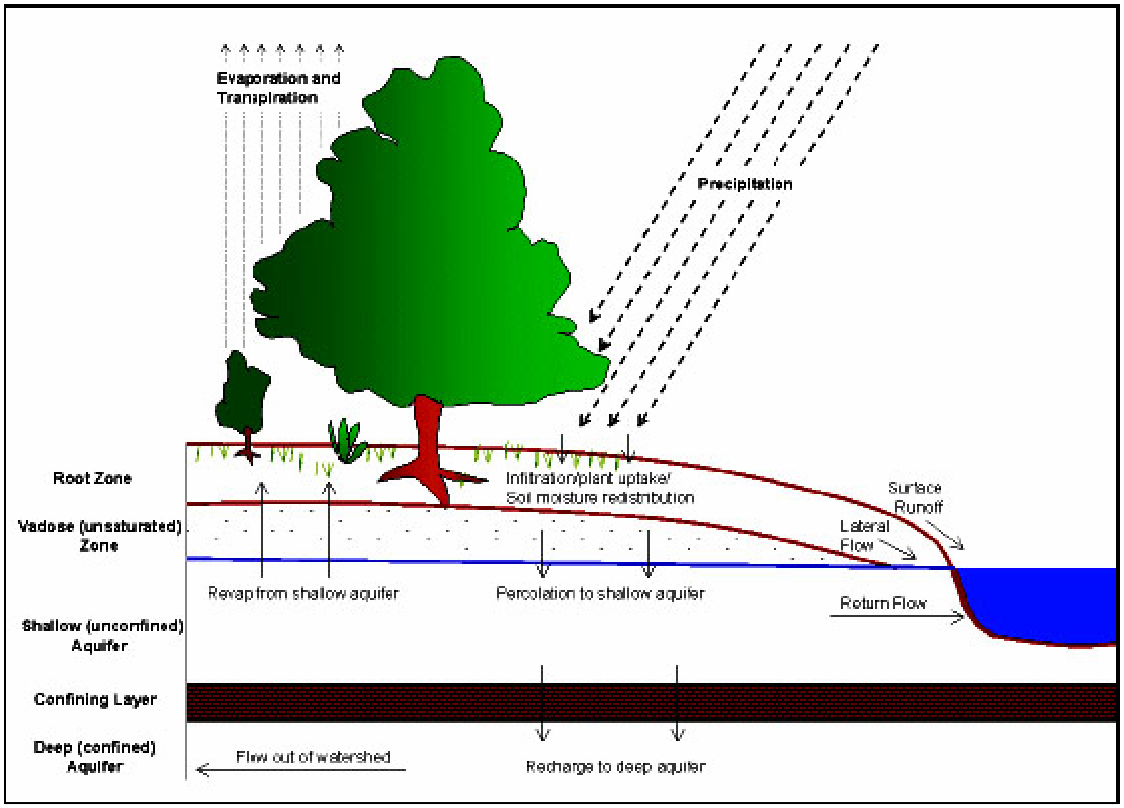


Figure 5. SWAT Hydrologic Cycle: Land Phase. (Neitsch et al., 2002a)

SWAT offers two procedures for determining runoff volume: the SCS curve number method, and the Green and Ampt infiltration method (Neitsch et al., 2002b). The Green and Ampt method requires break-point precipitation data, which is not as widely available as the daily precipitation data required by the SCS curve number method…

Peak runoff rate, used in estimating erosion and sediment yield, is calculated with a modified rational method as a function of area, runoff volume, time of concentration, and the fraction of daily rainfall that occurs during the time of concentration. In the model, the surface runoff volume and the peak runoff rate are determined for each HRU. (Neitsch et al., 2002a)

SWAT Erosion Model and Channel Transport

> Erosion in SWAT is computed using the Modified Universal Soil Loss Equation (MUSLE) (Neitsch et al., 2002a)… MUSLE (Williams, 1975) determines sediment yield using the same parameters as the original USLE except that the rainfall erosion factor is replaced by a runoff factor. The energy that governs the transport of eroded sediment in flow across the land surface is dependent on runoff variables in MUSLE, while this energy is a function of rainfall in the original USLE (Williams, 1995). With this method, the sediment delivery ratio is incorporated into the equation and does not need to be specified separately."

Channel Hydrology

SWAT uses Manning's equation to predict stream velocity and discharge. The model assumes all channels have trapezoidal cross sections with 2:1 side slopes. The user must specify channel width, depth, length, and roughness.

Channel flow routing is modeled based on a modification of the kinematic wave routing method. Two routing options are available: variable storage and Muskingum routing. The variable storage routing method, developed by Williams (1969), is based on the continuity equation. Travel time through the reach is calculated as the quotient of reach water volume over flow rate. The variable storage relationship can be written as:

$$q_{out,2} = \left(\frac{2 * \Delta t}{2 * TT + \Delta t} \right) \cdot q_{in,ave} + \left(1 - \frac{2 * \Delta t}{2 * TT + \Delta t} \right) \cdot q_{out,1} \qquad \text{[Eq. 42]}$$

where Δt = time step,

$q_{in,ave}$ = average inflow rate during the time step (m^3/s),

$q_{out,1}$ = outflow rate at the beginning of the time step (m^3/s),

$q_{out,2}$ = outflow rate at the end of the time step (m^3/s), and

TT = travel time (s).

The similar coefficient method equation is given by the following relationship:

$$q_{out,2} = SC \cdot q_{in,ave} + (1 - SC) \cdot q_{out,1} \qquad \text{[Eq. 43]}$$

where SC = storage coefficient.

The storage coefficient equation is the basis for the Muskingum method. The reader is referred to the SWAT 2000 theoretical documentation for a full explanation of the channel routing methods used in the SWAT model (Neitsch et al., 2002a).

While water is routed through the stream channel it is subject to transmission losses, including bank storage, percolation, or evaporation. The outflow from a reach is calculated based on a water balance which includes inflow from groundwater, the upstream reach, and overland sources less any transmission losses.

Channel Sediment Routing

SWAT simulates the two dominant sediment transport processes of degradation and deposition for channel sediments (Neitsch et al., 2002a). Degradation is simulated based on a simplified version of the Bagnold stream power relationship (Bagnold, 1977). Maximum transport is based on the peak channel velocity ($v_{ch,pk}$, m/s) calculated as:

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \qquad \text{[Eq. 44]}$$

where $q_{ch,pk}$ = peak flow rate (m^3/s), and
A_{ch} = cross sectional area of flow (m^2)

The maximum sediment concentration ($conc_{sed,ch,mx}$, ton/m^3 or kg/L) the flow can transport is given by the following equation:

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{\,sp\exp} \qquad \text{[Eq. 45]}$$

where c_{sp} = user defined coefficient, and
spexp = user-defined exponent varying between 1.0 and 2.0.

At the beginning of each time step SWAT checks the inflow sediment concentration against the concentration limit. If the inflow concentration exceeds the limit then deposition occurs until $conc_{sed,ch,mx}$ is reached. However, if the inflow sediment concentration is less than $conc_{sed,ch,mx}$ degradation (sed_{deg}, metric tons) is simulated by:

$$sed_{\deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) V_{ch} \cdot K_{CH} \cdot C_{CH} \qquad \text{[Eq. 46]}$$

where $conc_{sed,ch,I}$ = initial sediment concentration in the reach (kg/L or ton/m^3),
V_{ch} = volume of water in the channel (m^3),
K_{CH} = channel erodibility factor (cm/hr/Pa), and
C_{CH} = channel cover factor.

Channel erodibility is a function of the bed and bank sediment characteristics and the surface cover. The final amount of sediment in the reach is then calculated based on a sediment mass balance relationship which accounts for incoming sediment and degradation minus deposited sediment (Neitsch et al., 2002a). Erodibility can be determined using a submerged vertical jet test device or a flume study. Channel cover factor is defined as the ratio of degradation from a channel with a certain cover condition over the degradation from a similar channel with no vegetative cover (Neitsch et al., 2002a).

SWAT allows the user the choice of simulating channel degradation and deposition while maintaining a constant channel boundary or allowing channel downcutting and widening to adjust channel dimensions (Neitsch et al., 2002a). The downcutting and widening algorithm of SWAT updates depth, width, and slope when the volume of water in the reach exceeds 1,400,000 m^3. Channel dimensions may not be adjusted if the volume of the simulated reach is less than this threshhold value.

SWAT Output

SWAT provides a number of output files and can present output on a daily, monthly, or yearly basis. A summary of the primary input variables are provided in an input summary file (INPUT.STD) for review by the model user. The summary output file (OUTPUT.STD) provides some average annual values in addition to an overview of the average loadings from HRUs to the stream (Neitsch et al., 2002b). The HRU output file (.SBS) gives summary information for each hydrologic response unit. The main channel output file (.RCH) gives simulation output for each reach used in simulation. This file provides the variables necessary to calculate the net channel erosion. SED_IN gives the amount of sediment (metric tons) entering the specified reach over the duration of a time step. SED_OUT gives the amount of sediment leaving during the time step. Channel degradation may be estimated as the difference of these two output variables. Additional output information is given for ponds, wetlands, and depressions in the HRU impoundment output file (.WTR). Reservoir output information is specified in the .RSV output file. Data from each output file is given in spreadsheet format to allow further data analysis.

4.8 Reach-scale Models

Reach-scale models focus on in-stream flow, sediment, and nutrient dynamics. Reach-scale models require input flow and sediment specification and can be combined with watershed models to provide increased process detail and better simulation of flow and sediment routing and nutrient transport. The increased process detail for sediment transport processes afforded by reach-scale models may be necessary when a watershed has been deemed impaired and a TMDL study is required. Added channel process detail is necessary especially in urban watersheds where increased impervious areas create elevated flow volumes leading to excessive channel degradation.

A reach-scale model was evaluated to determine if the extra data input and modeling effort of a reach-scale model would improve predictions of channel degradation. CONCEPTS was chosen for evaluation because it was specifically designed to model channel degradation and stream restoration.

4.8.1 CONCEPTS

Introduction

The Conservation Channel Evolution and Pollutant Transport System (CONCEPTS) is a computer model created by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) at the National Sedimentation Laboratory (NSL) in Oxford, Mississippi. Two versions of the CONCEPTS model were created to simulate open-channel flow hydraulics, sediment transport, and channel morphology (Langendoen, 2000). A watershed-scale version was created to simulate watershed-scale processes and the connectivity of stream networks. The stream corridor version is a reach-scale model created to focus on the hydraulics, sediment movement, and channel shaping processes with increased detail in modeling in-stream processes. Due to the focus of this document on channel erosion the following description is provided for the CONCEPTS 2000 reach-scale model.

The CONCEPTS model was designed as a tool for the assessment of stream corridor restoration projects. When combined with watershed-scale modeling programs, CONCEPTS may be used to assess the long term effectiveness of restoration efforts and provide engineers, planners, and ecologists with quantitative simulation output useful in design implementation procedures (Langendoen, 2000). It is important to note that CONCEPTS requires a daily discharge timeseries and sediment input by size class for the upstream simulation boundary. Often, these data must be obtained through the development of a watershed-scale model such as AGNPS or SWAT. CONCEPTS was designed by the NSL to work as part of an integrated palette of design tools built around the AGNPS98 technology and is supported by the USDA Natural Resource Conservation Service (NRCS).

CONCEPTS Version 1.0 is designed to simulate unsteady, one-dimensional flow, sediment transport processes, and bank erosion and failure in stream channels

(Langendoen, 2000). It tracks sediment flow through in-stream structures and accounts for changes in channel morphology by simulating channel scour and mass failure. Stream systems consisting of both cohesive and cohesionless sediment, as well as variations in vegetative cover may be simulated through the SEDTRA submodel and alterations in the channel-boundary roughness. Other applications include the evaluation of in-stream grade control structures to assess the size, location, and effectiveness of such measures and the evaluation of stream corridor restoration scenarios and their ability to provide stability and habitat improvement. (Langendoen, 2000).

Future model versions will include the capability to simulate riparian buffers, vegetated streambanks, and the evolution of channel planform due to alternating patterns of deposition and scour (Langendoen, 2000).

Assumptions or limitations of the current CONCEPTS model are the following: four types of in-stream structures including pipe and box culverts, trapezoidal bridge crossings, trapezoidal drop structures, and generic structures with trapezoidal cross sections; channels with little or no sinuosity; variation in hydraulic roughness for bed, banks, and floodplain; total load sediment transport; homogenous bed sediment composition in horizontal direction; linear lateral erosion rate founded on the excess shear stress equation; slab or planar bank failure; (quasi-) hydrostatic groundwater pressure in the streambanks; and the use of only Metric units (Langendoen, 2000).

Flow Hydraulics

Though not the focus of this document, the following provides a brief description of the theoretical basis and governing equations used in the flow hydraulics portion of the CONCEPTS model. For additional detail refer to the complete CONCEPTS manual (Langendoen, 2000).

CONCEPTS simulates one-dimensional flow and neglects variations in flow along a stream cross-section created by in-stream features such as riffles, logs, or point bars. It is a distributed flow routing model allowing it to accurately represent the effects of in-stream hydraulic structures.

Literature Review

CONCEPTS simulates open channel flow using a simplified version of the Saint Venant equations composed of a continuity equation for mass conservation of water and a momentum equation describing the conservation of fluid momentum (Langendoen, 2000). The continuity equation is given as follows:

$$B\frac{\partial y}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad \text{[Eq. 47]}$$

where y = stage (m),
Q = discharge (m^3/s),
B = top width of flow (m),
q = lateral flow per unit length entering the channel (m^2/s),
x = distance along the channel (m), and
t = time (s).

The momentum equation consists of the following:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\left(\frac{\partial y}{\partial x}+S_f\right)=0 \qquad \text{[Eq. 48]}$$

where A = flow area (m^2),
g = gravitational acceleration (m^2/s), and
S_f = friction slope (m/m).

Combining equations yields the dynamic wave equations. Neglecting the acceleration terms gives the following simplified version:

$$\frac{\partial y}{\partial x}+S_f=0 \qquad \text{[Eq. 49]}$$

Equations 47 and 49 together are known as the diffusive wave equations. This form of the Saint Venant equations is both more efficient and numerically robust. Depending on the characteristics of the input parameters, CONCEPTS automatically switches between the dynamic and diffusion forms of the Saint Venant equations (Langendoen, 2000).

The CONCEPTS model simulates flow hydraulics using a framework of boundaries. External boundaries determine the extent of the model stream reach and internal boundaries represent those locations along the reach where flow characteristics cannot be classified as gradually varying, such as rapids or in-stream structures. Internal boundaries mark the locations of areas where the Saint Venant equations are not valid. A thorough explanation of the governing equations used for simulation of internal boundaries is given in the CONCEPTS 2000 Users Manual including equations for culverts, bridges, drop structures, and generic structures.

Sediment Transport and Bed Adjustment

Sediment transport is frequently modeled by dividing the stream channel into three or more layers (Armanini and Di Silvio, 1988). The uppermost layer is referred to as the wash load layer in which sediment is suspended in the water column. The middle layer is… The bed load layer is composed of a zone of flow adjacent to the bed of the stream in which particles skid, roll, or saltate. The stream bed is often stratified and represented my multiple layers to describe the variation in sediment particle size with depth. CONCEPTS combines the wash load and bed load layers into a total load layer. This simplification makes calculations more efficient and is better suited to the analysis of changes in stream channel morphology.

The sediment transport governing equations used in CONCEPTS are based on the mass conservation equation, which separates the sediment balance by size fraction, as indicated in Equation 50:

$$\frac{\partial C_k}{\partial t} + \frac{\partial u C_k}{\partial x} = E_k - D_k + q_{S_k} \qquad \text{[Eq. 50]}$$

where u = flow velocity (m/s),

E = entrainment rate of bed particles (m^2/s),

D = deposition rate of particles on the bed (m^2/s),

q_s = sediment inflow rate (m^2/s),

k = size class subscript, and

C is the sediment mass (m^2) defined as;

$$C = \frac{1}{1\times10^6 \frac{\gamma_s}{\gamma}} \int_A c \, dA \quad \text{[Eq. 51]}$$

where

c = point concentration (ppmw),

γ_s = sediment specific weight (N/m^3), and

γ = specific weight of water (N/m^3).

Variations in the bed area over time are represented using;

$$(1-\lambda)\frac{\partial A_{b_k}}{\partial t} = D_k - E_k \quad \text{[Eq. 52]}$$

where λ is porosity and A_b (m^2) is the cross-sectional area of the mixing layer.

The simulation of cohesionless streambeds in CONCEPTS is facilitated by the Bennett (1974) formulation. The formulation assumes erosion or deposition rate is proportional to the rate of sediment transport and the sediment transport capacity (Eqn. 53; Langendoen, 2000).

$$E_k - D_k = \frac{1}{T_k}\left(\hat{C}_k - C_k\right) \quad \text{[Eq. 53]}$$

where T = time scale representing the adjustment rate of the sediment mass (s), and

$\hat{C}$ = equilibrium sediment mass (m^2).

The T proposed by Armanini and Di Silvio (1988) for particles in suspension is used in CONCEPTS. Although not derived to simulate bed load, Equation 54 provides a good simulation of transport for coarse particles, which are likely to be cohesionless.

$$\frac{T\omega}{h} = \frac{a}{h} + \left(1 - \frac{a}{h}\right)\exp\left[-1.5\left(\frac{a}{h}\right)^{-1/6}\frac{\omega}{u_*}\right] \qquad \text{[Eq. 54]}$$

where ω = fall velocity (m/s),

h = flow depth (m),

a = active layer thickness (m), and

u* = shear velocity (m/s).

The erosion rate for cohesive bed materials as described by the CONCEPTS manual and formulated by Ariathurai and Arulanandan (1978) is;

$$E = eB\left(\frac{\tau_b}{\tau_e}\right) - 1 \qquad \text{[Eq. 55]}$$

where e = erosion rate constant (m/s),

B = wetted streambed width (m),

τ_b = applied bed shear stress (Pa), and

τ_e = shear strength of the bed material (Pa).

The erosion rate constant and bed shear strength vary with changes in type of sediment, water content, salt concentration, ionic species present in solution, pH, and temperature (Mehta et al., 1989). A modified equation is used for partially consolidated beds given by Parchure and Mehta (1985) as follows:

$$E = \varepsilon_f B \exp\left(\varepsilon \sqrt{\tau_b - \tau_e}\right) \qquad \text{[Eq. 56]}$$

where ε_f = floc erosion rate and ε is a rate constant (m/s).

CONCEPTS simulates cohesive particles individually after entrainment as a constituent of wash load or part of bed-material load. Deposition rate is then simulated through the application of Krone's (1962) formulation as described in the HSPF model description.

CONCEPTS predicts no deposition when bed shear stress is greater than the critical shear stress value for deposition to occur. Deposited material is assumed to have the same characteristics as the bed layer. This simplification is necessary due to the complexity of mixing effects on deposited sediment.

The transport of bed materials is a function of the physical properties of the materials and their stratification. The bed is composed of a mixing layer, which is subdivided into an upper surface layer and a subsurface layer. Constant exchange of particles occurs between the surface layer and the water column, but the subsurface layer is only affected during scour and deposition events. The volumetric fraction content by size class is given by the following equation:

$$\frac{\partial \beta_k^s A_s}{\partial t} = D_k - E_k + S_{u_k} \qquad \text{[Eq. 57]}$$

where β^s_k = fractional content by volume of size class k in the surface layer,
A_s = the layer area (m^2), and
S_u = the sediment flux between the subsurface and surface layers (m^2/s).

The model assumes the surface layer thickness is equal to 10% of the flow depth

CONCEPTS uses the SEDTRA sediment transport predictor developed by Garbrecht et al. (1996). This predictor uses methodology given by Laursen (1958) for silt and fine sand, Yang (1973) for sand, and Meyer-Peter Mueller (1948) for gravel classes. Model creators added a size class for very fine particles, which when entrained, will remain in suspension as washload. The general transport equations are described in section **4.4**. CONCEPTS uses fall velocities reported by the U.S. Interagency Committee on Water Resources, Subcommittee on Sedimentation (1963) for well-rounded natural sediment particles. Other compounding factors which affect fall velocity are not considered.

CONCEPTS uses conservation of mass and an advection differential equation as the basis for the bed material transport submodel (Langendoen, 2000). The equation source term represents the sediment influx from runoff and bank retreat. The runoff sediment yield is user-specified input. Transformations in streambed elevation are also computed using the change in the bed material storage equation. Cross-section geometry adjustments are performed on either a partly or fully wetted channel. Bed surface elevations are adjusted evenly, resulting in a new bed surface parallel to the original surface with bank geometry remaining the same. An inflection point at the soil surface/water surface interface is added for partly wetted channels to allow the development of a slope break feature. Figure 6 illustrates channel erosion and deposition as simulated by the CONCEPTS model.

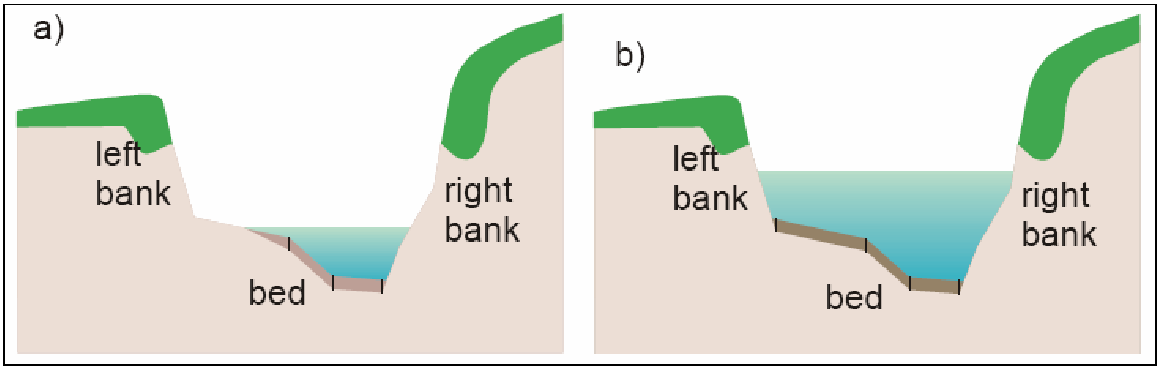


Figure 6. Channel erosion processes for a partly wetted bed (a) and a fully wetted bed (b). Dark areas designate erosion or depositional features (Langendoen, 2000).

CONCEPTS tracks surface and subsurface layers of the channel bed. Each layer is simulated using a separate mass balance. Mixing between the surface layer and subsurface layers may occur during transport events. Erosion events result in the removal of the surface layer, therefore exposing the uppermost subsurface layer, which is then considered the bed surface. Depositional events create a new surface layer, burying the current surface layer, which becomes subsurface layer 1. Further detail on the bed material transport algorithms can be found in the CONCEPTS 2000 Users Manual (www.ars.usda.gov/SP2UserFiles/Place/64080510/AGNPS/Concepts/Doc/manual.pdf).

Bank Erosion and Adjustment

CONCEPTS uses a variation of the excess shear stress equation explained in the section **4.4**. Stream channel cross-sections are divided into a number of sections, each having different characteristics. The bed is composed of a series of stacked homogenous horizontal layers. Banks are subdivided into subsections to allow the simulation of each individual soil layer. The average shear stress (Pa) for each soil layer is defined as follows:

$$\tau_j = \gamma R_j S_f \qquad \text{[Eq. 58]}$$

where γ = the unit weight of water (N/m^3),
R_j is the hydraulic radius (m), and
S_f = friction slope from the hydraulic algorithm (m/m) (Langendoen, 2000).

The erosion rate for each layer is used to calculate the flux of sediment leaving the bank and entering the channel. CONCEPTS assumes all sediment leaving the banks is instantly broken down into individual particles. This assumption is reasonable for erosion simulated using the excess shear stress equation, but fails when simulating mass failure events.

Literature Review

Mass failure is simulated in CONCEPTS using a force equilibrium approach. Failure blocks are subdivided into five slices for the estimation of internal shear forces. Vertical forces acting on each slice are used to compute the normal force. Horizontal forces are summed to determine the internal shear stresses, and the horizontal forces on all slices are summed to determine the factor of safety for the failure block. The user specifies the elevation interval Ne, defining the failure surfaces for which the factor of safety, Fp, will be tested. Failure may occur at the toe of the slope or any elevation interval. The program algorithm determines the angle of the slip surface to minimize Fp and then computes Fp at each elevation. If any surface has a factor of safety less than unity failure is assumed to occur along that slip surface. See the CONCEPTS 2000 Users Manual for the force balance equations used in the bank erosion and widening algorithm.

Model Input

CONCEPTS model input data are divided into four main input file types with internal subdivisions or blocks (Langendoen, 2000):

1. Run control data,
2. Upstream boundary discharge data,
3. Cross-section input files, and
4. Hydraulic structure input files.

1. Run Control Data

Run control data are composed of three data blocks. Block 1 includes general project data and reach characteristics (Langendoen, 2000). This file has 31 lines plus a line for each reach link, defined as a section of stream with no internal boundaries. A link may be a subreach of the larger simulation reach, or an in-stream hydraulic structure. Components of this file include project title, input file names, flow data, initial loading rates, initial time step, and submodel simulation options. Block 2 contains data to describe the internal boundaries and link characteristics for the simulation. Link file names are given, as well as link boundary locations, and the number and timing of storm events. Block 3 data includes the output specification. Three output options are available: location and event specific output; location specific time-series output; and, subreach specific event output. Specific output parameters such as peak discharge, peak stage, and sediment yield are user-specified using numeric code given in the CONCEPTS 2000 Users Manual.

2. Upstream Boundary Data

This file includes data to describe the input conditions at the upstream, external boundary for the simulated reach. Input data for this file includes daily baseflow discharge, runoff characteristics, daily sediment input, and runoff event initiation and duration.

3. Cross-section Data

This file includes geometry and composition characteristics specific to each cross-section. Blocks corresponding to the floodplain, banks, and bed make up this input file. Floodplain and bank components are distinct for each side of the stream corridor. Block 1 holds the general cross-section characteristics such as name, location, and inflow. Blocks 2 and 6 are for floodplain characteristics. These files include elevation data and overall floodplain roughness. Blocks 3 and 5 provide streambank data. Streambank data requirements consist of the number of soil layers, soil properties, elevations, overall roughness, and ground water elevation. Block 4 describes the characteristics of the stream bed. Parameters to describe the elevation, composition, and particle size and shape are required.

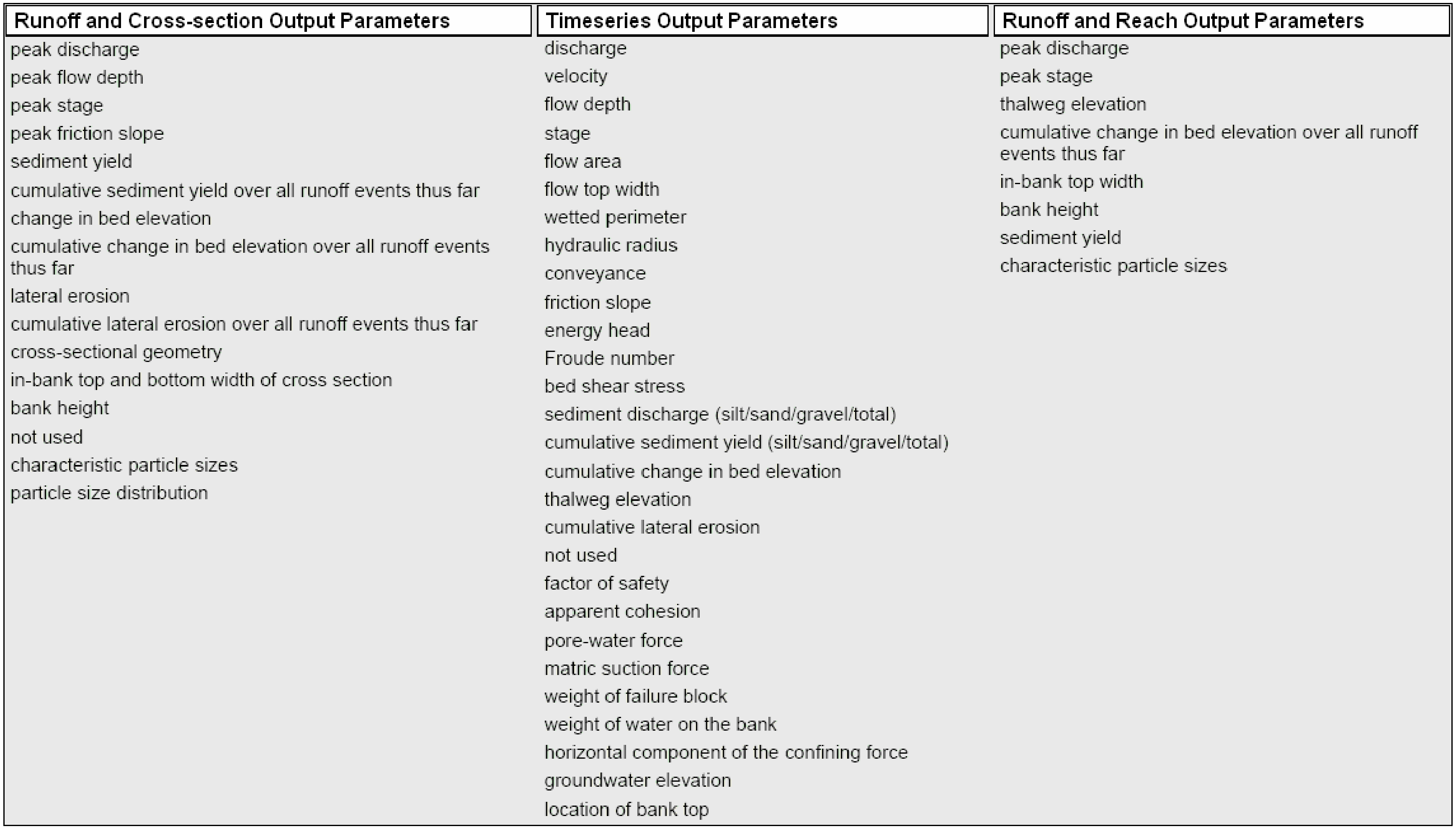
4. Hydraulic Structures

This file describes the characteristics of in-stream hydraulic structures found within the simulated reach. Each structure must be described based on one of four simulated structures: drop, culvert, bridge, or generic. Data are required to describe the name, size, location, and surrounding streambed elevation for any structure. Structure-specific data requirements are described fully in the CONCEPTS 2000 Users Manual.

Model Output

CONCEPTS has three output options available to the user. The user may specify the location and event of interest, the location for time-series output, or output for a specific stream link and storm event. Input data requirements for each output scenario vary slightly, but all contain basic information on the time, duration, and location of desired output. Table 4 shows the possible output parameters for each of the available simulation scenarios.

Table 4. Available output parameters for a specified runoff event and cross-section (Langendoen, 2000).



Runoff and Cross-section Output Parameters	Timeseries Output Parameters	Runoff and Reach Output Parameters
peak discharge	discharge	peak discharge
peak flow depth	velocity	peak stage
peak stage	flow depth	thalweg elevation
peak friction slope	stage	cumulative change in bed elevation over all runoff events thus far
sediment yield	flow area	in-bank top width
cumulative sediment yield over all runoff events thus far	flow top width	bank height
change in bed elevation	wetted perimeter	sediment yield
cumulative change in bed elevation over all runoff events thus far	hydraulic radius	characteristic particle sizes
lateral erosion	conveyance	
cumulative lateral erosion over all runoff events thus far	friction slope	
cross-sectional geometry	energy head	
in-bank top and bottom width of cross section	Froude number	
bank height	bed shear stress	
not used	sediment discharge (silt/sand/gravel/total)	
characteristic particle sizes	cumulative sediment yield (silt/sand/gravel/total)	
particle size distribution	cumulative change in bed elevation	
	thalweg elevation	
	cumulative lateral erosion	
	not used	
	factor of safety	
	apparent cohesion	
	pore-water force	
	matric suction force	
	weight of failure block	
	weight of water on the bank	
	horizontal component of the confining force	
	groundwater elevation	
	location of bank top	

4.9 Monitoring Channel Degradation

A number of acceptable methods have been developed for measuring channel degradation. Methods can be grouped into categories based on timescale. Longer timescale methods, measuring degradation for decades or centuries, apply to larger areas with less sensitivity (Lawler, 1993). Long-term methods include stratigraphy studies and evaluation of historical data. Medium-timescale techniques, applicable to durations of years to decades, involve periodic resurvey to assess changes in channel morphology. Short-term methods include terrestrial photogrammetry and erosion pins. These short-term methods can be used to monitor relatively small changes in channel shape for individual storm events.

Since first being introduced in 1939 in Ireland, erosion pins have emerged as the method of choice due to their relative ease of use and low cost. Much of the work establishing criteria for designing erosion pin studies was conducted in the United Kingdom for conditions common in that region. However, recommendations have been made for a wide variety of slope conditions and those recommendations can be adapted for use in other regions (Lawler, 1993).

Erosion pins are lengths of material (usually metal) installed orthogonal to the streambank soil surface. A known length of pin is left exposed and when soil is eroded re-measurement theoretically reveals a greater exposed length. Through subsequent measurements after pin installation, one can estimate the rate of bank erosion based on the difference between the new exposed pin length and the original exposed pin length.

Several choices must be made when designing an erosion pin experiment. According to Haigh (1977), key erosion pin experiment design decisions include: erosion pin material and dimensions, use of a washer, initial length of pin left exposed, number and distribution of the pins across the slope of interest, frequency of data recording, and measurement recording method.

Erosion pins have been fashioned from everything from wood to welding rods. Most authors (Haigh, 1977, Lawler, 1993) recommend a metal pin that is resistant to rust since rust may serve to strengthen the soil structure in the vicinity of the pin. In arid regions, materials should be resistant to corrosion due to the alkaline environment (Haigh, 1977). Brass or silicon bronze is the preferred welding rod materials. Lawler (1993) also suggested the use of plastic-coated needles commonly used for knitting.

The length of the erosion pin depends partially on the site characteristics. Sites with loose soil or high erosion rates may require longer erosion pins to prevent complete exposure and pin loss. Historically, pin lengths range from 0.2 to 0.5 m (Lawler, 1993); Haigh (1977) recommended pin lengths ranging from 0.5 to 0.6 m, while Couper et al. (2002) utilized pins ranging from 0.25 to 0.50 m in length.

Another monitoring consideration is the diameter of the erosion pin. Smaller diameter erosion pins are the most easily inserted in soil; however, small diameters can make relocation of the pin difficult. Larger diameter pins are required for longer pins as longer pins may require hammering to insert them into bank. Lawler (1993) found typical pin diameters range from 2 to 6 mm. Haigh (1977) recommended a diameter of about 5 mm.

The second consideration is the use of a washer. A washer fits around the pin and rests on the soil surface. Washers can be permanent or used only during measurement. Several reasons are used to justify the use of a washer. Washers may help distinguish between the net erosion (erosion plus deposition) and maximum erosion since deposition would collect on top of the washer. Washers also reduce measurement variability due to roughness of the soil surface. Washers have drawbacks; permanent washers protect the soil surface from rain drop impact, which is a potentially important factor in erosion processes. The use of a washer in measurement also reduces the replicability of the measurements, rather than decreasing the variability. Haigh (1977) recommended the use of a loose-fitting rust-resistant washer if the washer is permanent and close-fitting, provided the bank slope is relatively uniform and does not contain considerable rock fragments. Washers were not recommended for cut and fill slopes.

The length of erosion pin left exposed is important in measurement as well as in pin relocation. A longer exposed length is easier to locate; however, it is also easier for potential vandals to spot. A longer exposed length introduces additional uncertainty in the experiment. Changes in the exposed length due to erosion will be small and easier to recognize in reference to a short exposed length as compared to a long exposed length.

Shorter exposed lengths also minimize pin effects on slope hydraulics. Lawler (1993) recommended a 35-mm exposed length. Haigh (1977) recommended an exposed length between 15 and 200 mm. Couper and Maddock (2001) used a 0.3-m exposed length.

A reference point on the exposed length of the erosion pin is often useful in measurement. The top of the pin is a valid reference; paint is commonly used (Couper and Maddock, 2001) as it simplifies readings with Vernier calipers. Paint also aids in relocation of the pins. However, creating and maintaining a reliable reference point with paint is difficult. Heat-shrink material is another option, providing the benefits of paint while avoiding the downfalls (Lawler, 1993)

The distribution of pins across the slope of interest is related to the goal of the study. If there is a specific area of the slope of interest, more erosion pins should be located at the area. Haigh (1977) recommended a grid design with horizontal rows parallel to the slope and columns that traverse the slope vertically. Clusters of pins at areas of interest also provide good results. Spacing between columns of pins should be no greater than 1 m and spacing between rows of pins should be between 3 to 6 m, depending on the severity of the slope. Couper and Maddock (2001) used a grid network with 1-m horizontal spacing and 0.3- m vertical spacing. The number of pins located at one site ranged from 39 to 145.

The frequency at which readings are taken depends on the time period of interest. For a multiple-year study, pin readings should be taken at longer intervals. The frequency should be greater for seasonal studies. In general, the precision of the erosion rate estimation increases with the number of pin readings; however, repeated site visitation may interfere with the erosion processes either by compacting or disturbing the soil. Haigh (1977) recommended measuring erosion rates at least twice a year. Care should be taken at higher measurement frequencies to minimize soil disturbance. If perceptible changes in the site due to trampling are noticed, the frequency should be reduced. The experimenter may also decide to take additional measurements after each significant runoff event to best capture the erosion process.

Erosion pin measurements are most often made with Vernier calipers (Couper et al., 2002, Couper and Maddock, 2001, Lawler, 1993, Haigh, 1977). A standard measurement location on the pin should be chosen to ensure consistency. While multiple readings around the circumference of the pin may provide insight into patterns of erosion at the site, multiple readings of one pin may disturb the soil surface. Pins are usually reset to the original exposed length following measurement.

To avoid disturbing the soil surface around each pin at each measurement, Couper and Maddock (2001) utilized a random number table to choose which pins in the grid to measure. Each pin was measured a maximum of 10 times. Most authors (Lawler, 1993, Haigh 1977) recommend a “stabilization period” of one month to one year following pin installation to allow disturbed bank soils to reconsolidate.

While erosion pins are widely used, there are several sources of error that can occur. Some of these sources of error, such as tampering or vandalism and installation and measurement disturbances, can be avoided by following some of the previous recommendations. Other sources of error cannot be easily avoided. The presence of the pin may cause changes in the hydraulic conditions at the soil surface and changes in the soil structure (Haigh, 1977). Additionally, differences in the physical properties of the erosion pin and the soil may cause preferential ice formation and preferential movement of the pin in relation to the soil. The pin may also be moved by the shrinking (ground retreat) and swelling (ground advance) of the soil due to everything from temperature fluctuation, freeze-thaw cycling, or shrink-swell caused by wetting and drying. Couper et al. (2002) found that freeze-thaw cycling was a possible source of negative erosion pin readings. Negative erosion pin readings may be caused by any number of factors, from shrink-swell of clays to deposition (Couper et al., 2002). Statistical analysis of pin data did not reveal a statistically significant cause for the negative values in the Couper et al. study (2002). Other errors occur due to the measurement of erosion pin. Couper and Maddock (2001) calculated a standard error for each erosion pin in their study. Values ranged from 0.17 to 0.33 mm, below the 0.5 mm maximum limit set by Stott (1999) for measurement accuracy.

Erosion pins capture only the streambank retreat portion of channel degradation. Different methodologies are needed to measure channel bed deposition and scour. The most common method for monitoring the movement of bed sediment is the scour chain. A scour chain is a length of chain which is driven vertically into the streambed (Nawa and Frissell, 1993). The length of chain remaining on the surface is recorded after installation. Scour is indicated by changes in the length of chain laying horizontally on the streambed. Deposition occurring between measurements is indicated by the excavation depth necessary to reach the last horizontal link. Scour chains are commonly installed in a transect of multiple chains at a given cross section. Measurements are used to describe changes in bed elevation over time frames similar to erosion pins.

5. Methods

5.1 Watershed Description

A case study was conducted within the Stroubles Creek watershed, in the Town of Blacksburg, Virginia, USA, to compare GWLF, SWAT, and CONCEPTS channel degradation algorithms. An erosion pin monitoring study provided observed data for comparison with model predictions.

The Stroubles Creek watershed, located in Montgomery County, Virginia, USA, is approximately 2,500 ha of urban, residential, agricultural, and forested land, which includes the Town of Blacksburg and the Virginia Tech main campus. Urban land and residential areas cover 46%, located mainly in the upstream portion of the watershed. Forested areas, which make up 28% of the watershed, are located mainly in the downstream reaches. The remaining 26% is agricultural land. Stroubles Creek is a tributary of the New River, which drains portions of North Carolina, Tennessee, Virginia, and West Virginia before discharging to the Ohio River. The Stroubles Creek watershed lies in the Valley and Ridge physiographic province and is characterized by karst topography. Stroubles Creek was originally listed on the 303(d) TMDL priority list in 1996 for an aquatic life use impairment (Mostaghimi et al., 2003).

Methods

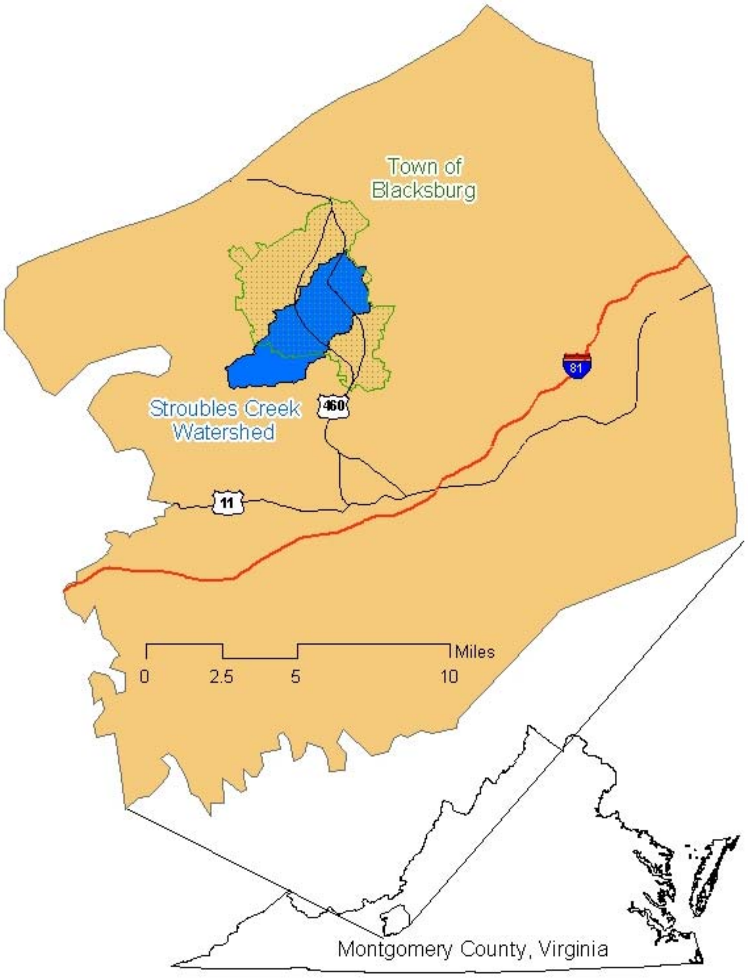


Figure 7. Location of Stroubles Creek watershed (Mostaghimi et al., 2003)

The experimental reach used in this study is located on the Virginia Tech Foundation's Heth Farm within Blacksburg town limits, approximately 2.5 km downstream from the Virginia Tech Duck Pond, located on the main campus. The drainage area used in this case study includes 1,440 ha, almost all of which lie in the Town of Blacksburg. The reach was selected because it is experiencing severe bank retreat. The upstream terminus of the study reach is located just downstream of a small tributary and the modeled section extends 500 m downstream. To simplify modeling procedures, the study reach was chosen to avoid hydraulic structures and tributary inflows.

Methods

A natural levee separates the incised channel from floodplain areas. The immediate area surrounding the experimental reach is pasture grazed by non-lactating dairy cattle, but the overall contributing area is dominated by residential and urban development. Cattle have unlimited access to the stream corridor and contribute to streambank instability. The floodplain vegetation surrounding Stroubles Creek on Heth Farm is composed of cool season grasses. Pocket wetlands formed in abandoned oxbows harbor zones of wetland vegetation, such as rushes (*Scirpus* sp.). Abandoned meander bends are visible on high resolution aerial photography suggesting past channel straightening (Figure 8).

Figure 8. Aerial photograph of Stroubles Creek on Heth Farm, Blacksburg, VA, USA.

(Town of Blacksburg, WebGIS - http://arcims2.webgis.net/blacksburg/default.asp)

Methods

The Stroubles Creek watershed has been influenced by human activity since the 18th century. Upland sediments, exposed by logging and agricultural activities, were eroded and transported downslope to floodplain areas. Significant silt deposits are now visible in Stroubles Creek bank profiles, with deposit depths ranging from several centimeters to over 50 cm. These fine textured legacy sediments are particularly susceptible to weakening and erosion due to subaerial processes. A clearly defined layer of McGary silt loam is visible on exposed bank faces throughout the reach. Ongoing development and past disturbance have resulted in an experimental reach characterized by unstable actively eroding stream banks. Downcutting has disconnected Stroubles Creek from the floodplain creating banks as high as 2.0 m and resulting in increased flow velocities and boundary shear stresses. Portions of the channel have downcut to an underlying erosion resistant saprolite layer. Underlying bedrock now prevents further downcutting and limits bed sediment supply. This natural bed control forces the stream to adjust laterally as it attempts to convey larger peak discharges associated with urban development.

Urban development has significantly altered the natural hydrology of Stroubles Creek. Changes in discharge occur rapidly following periods of rainfall. Observations indicate a two-hour time of concentration. Urbanization has also intensified differences between baseflow discharge and peak discharges. Baseflow discharge ranges from 0.03-0.17 cms, while bankfull discharges are approximately 8.5-9.9 cms.

5.2 GWLF Modeling Procedure

This case study utilized ArcView GWLF version 2005b software for channel degradation simulation. GWLF simulation was broken into two phases: a channel erosion sensitivity analysis phase and a one-year channel erosion prediction phase, concurrent with monthly erosion pin measurements. The sensitivity analysis of GWLF to flow and channel parameters was performed before the GWLF case study simulation.

GWLF Sensitivity Analysis

The GWLF channel erosion routine sensitivity analysis was performed to assess flow and sediment parameter changes on model predictions. A series of six parameters were varied and channel erosion simulation impacts were recorded. The parameters used in sensitivity analysis were selected based on the recommendations of a GWLF modeling expert (Gene Yagow, personal communication, May 2006). Three flow parameters, including the recession coefficient, seepage coefficient, and evapotranspiration, were chosen to determine the impact of flow differences on channel erosion prediction. Three additional channel-specific parameters, including channel length, channel depth, and percent imperviousness, were also adjusted. Each parameter was tested at five levels with an interval selected to evenly space tested values throughout the suggested range. The value appropriate for simulation of the Stroubles Creek watershed will henceforth be referred to as the “default” value for sensitivity analysis purposes. An initialization period of more than two years was simulated. Reported average annual results are given for the three-year period from 1992-1994. Results of the sensitivity analysis are presented in the ***Results and Discussion*** section.

GWLF Case Study Simulation

Methods

Input files for GWLF were divided into weather data, transport parameters, and nutrient parameters. GWLF input files are in **Appendix B**. The weather data input file contained average daily precipitation and temperature values for the simulation period. Parameter values used in GWLF simulation were taken from Stroubles Creek Benthic TMDL sources (Mostaghimi et al., 2003). Weather data from the Blacksburg Airport weather station was used in the 2005 – 2006 model simulation for comparison with erosion pin estimates. The data were obtained from the National Climatic Data Center website, available online at: http://www.ncdc.noaa.gov/oa/ ncdc.html.

Transport parameters used to simulate sediment generation and movement included USLE factors, landuse and management data, curve numbers, and evapotranspiration coefficients (Wagner, 2004). The sediment buildup rate, required for erosion and sediment transport prediction, was specified in the nutrient transport file. All other nutrient variables were populated by dummy values. The 2005 – 2006 input parameters were adapted from the Wagner (2004) GWLF simulation dataset. Input file creation and parameter adjustments were made using Microsoft Excel spreadsheets and macros created by the Virginia Tech TMDL Development Group (Yagow, 2003). The "LANDUSE" and "WATERSHED" spreadsheets provided lookup tables, soils information, and landuse data appropriate for Virginia watersheds. The spreadsheets create input files automatically, resulting in greater consistency during parameter development. A watershed-appropriate value from the sensitivity analysis was used during the simulation period of 2005-2006. This parameter set was chosen based on model parameter selection guidance and best professional judgment. Model parameterization was performed using methods and data deemed appropriate for use in a TMDL study. Any parameter modifications were made using Stroubles Creek Benthic TMDL data (Mostaghimi et al., 2003).

ArcMap version 8.3 software was used to process Stroubles Creek TMDL DEM, landuse, and soils data and to generate GWLF input files. The data sets and coverages were those used by Wagner (2004), but the extent of the watershed and subwatershed delineation were altered using automatic watershed delineation tools in ArcMap to isolate and generate output from the study reach. Three subwatersheds were created using the automatic delineation tool as shown in Figure 9.

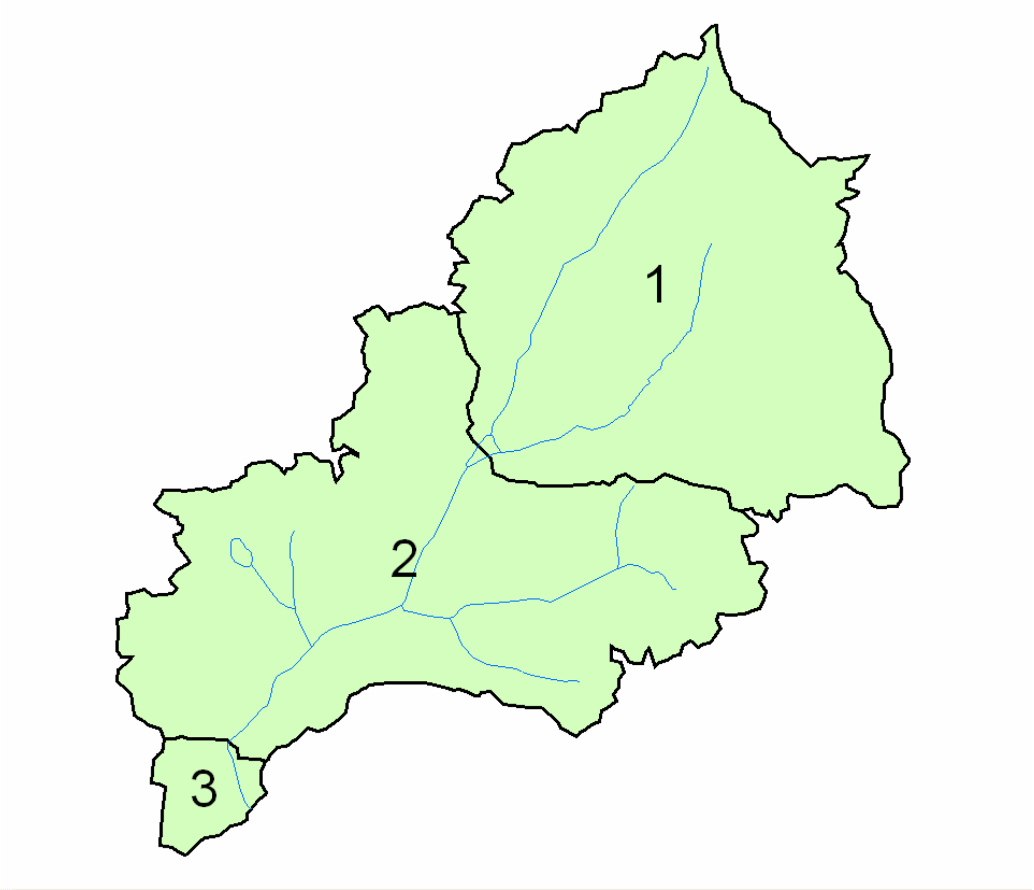


Figure 9. Stroubles Creek ArcMap watershed delineation used in GWLF.

The uppermost subbasin outlet (1) was aligned with the location of the Virginia Tech Duck Pond. The outlet of subbasin 2 is located at the upstream end of the study reach on Heth Farm. The outlet of subbasin 3 is located approximately 500 m downstream at the downstream end of the study reach. This subbasin division was necessary for channel degradation calculations to coincide with erosion pin observations. Discrepancies between models were limited by using the same data resources for both the GWLF and SWAT simulations.

5.3 SWAT Modeling Procedure

Methods

The July 2005 update of SWAT 2000 (B. Narasimhan, personal communication, August 3, 2006), was used in the model comparison case study. The July update of SWAT 2000 includes corrections to the sediment routing algorithms. The ArcView SWAT 2000 (AVSWAT 2000) GUI was used to parameterize the model and create the input files.

Watershed data input requirements for SWAT are broken down into three groups based on watershed subdivision structure: watershed, subbasin, or Hydrologic Response Unit (HRU) level parameters (Neitsch et al., 2002b). The SWAT parameter set used in this research was adapted from the Wagner (2004) SWAT simulation. Necessary modifications to the Wagner (2004) parameter set, such as subbasin redistribution, were made using data available in the Stroubles Creek TMDL (Mostaghimi et al., 2003). Sample input files are presented in **Appendix C**. Before running the 2005-2006 SWAT simulation a sensitivity analysis was performed.

SWAT Sensitivity Analysis

Spruill et al. (2000) documented the changes in SWAT discharge predictions corresponding to alterations in hydrologic parameters. The research was performed on a small karst-influenced watershed in North Central Kentucky. This study tested the effect of 15 parameters on discharge predictions. Results showed that 11 of the 15 parameters had a significant effect on discharge prediction. Significant parameters included: alpha baseflow factor (ABF), available water capacity, channel hydraulic conductivity, channel length (CL), channel width (CW), drainage area, groundwater delay, initial groundwater height, recharge (RC), saturated conductivity, slope length (SL), and maximum rooting depth.

Based on the results of Spruill et al. (2000) the sensitivity of channel degradation predictions to ABF, CL, CW, RC, and SL were tested. In addition, the USLE crop management practice coefficient (PF), subbasin slope (SS), linear sediment reentrainment coefficient (SPCON), sediment reentrainment exponent (SPEXP), channel erodibility (CHE), and channel cover factor (CHC) were evaluated. The parameters ABF, CL, CW, RC, and SL were chosen to assess compound affects on channel degradation associated with changes in sediment concentration and flow. Theoretically, decreased flow is associated with decreased fluvial erosion. CL and CW affect flow and channel dimensions. PF, SL, and SS were tested to assess the affect of differing input sediment concentrations on channel degradation (the reader is referred to the discussion of SWAT sediment transport equations, section **4.7.8**). SPCON, SPEXP, CHE, and CHC are suggested sediment calibration parameters and specifically affect the SWAT channel degradation equations.

Each sensitivity analysis parameter mentioned above was varied individually across five levels. Levels were distributed evenly throughout the suggested parameter range as given by SWAT 2000 user guidance (Neitsch et al., 2002b). Parameter ranges for CL, CW, and SS were varied by ± 20% in 10% intervals. The suggested ± 10-m variation for SL was also applied.

Excel was used to process model output. A macro was written to extract sediment inflow (SED_IN) and outflow (SED_OUT) predictions for the experimental reach. Channel degradation was calculated as the difference between sediment leaving and entering the reach. Lateral sediment input from overland erosion was not considered since it does not enter the sediment mass balance until the downstream outlet. SWAT sensitivity analysis parameter values are in section **6.2**.

SWAT Case Study Simulation

Watershed-level parameters include weather data, such as precipitation, wind speed and solar radiation. The SWAT case study simulation used precipitation data collected at the Virginia Tech Airport weather station. Additional weather parameters, such as wind speed and solar radiation, were simulated using the SWAT simulation option.

The AVSWAT GUI was used to process Stroubles Creek TMDL DEM, landuse, and soils data needed for input file generation. Subbasins were delineated using the AVSWAT automatic delineation tool to exactly match those used in GWLF simulation.

Methods

A graphical representation of the SWAT model is shown in Figure 10. Watershed outlets were aligned as described in the section **5.3**.

Methods

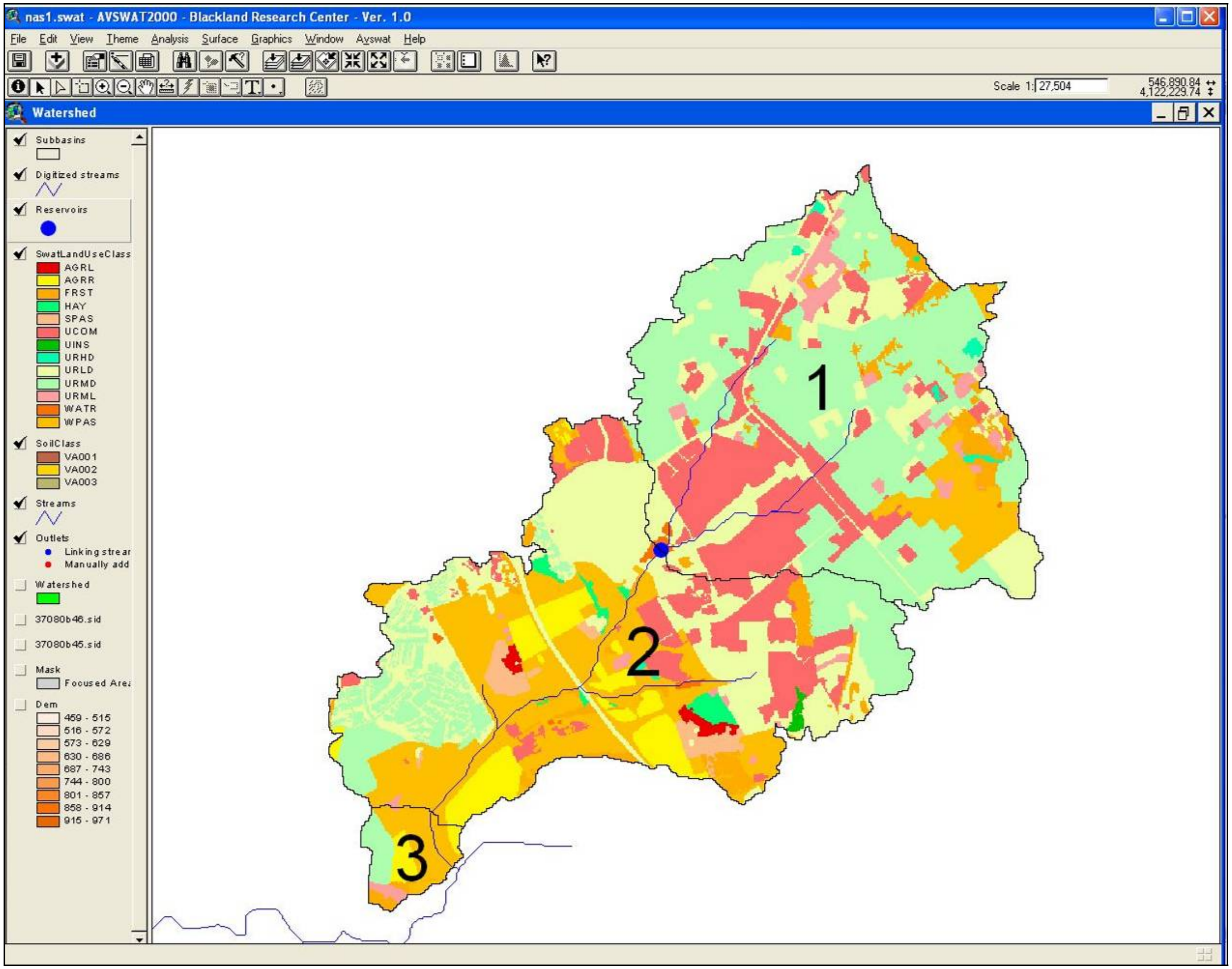


Figure 10. Stroubles Creek Subbasin distribution for SWAT model simulation.

Methods

Bingner et al. (1997) found SWAT sediment transport predictions are influenced by variations in subbasin size and distribution. The same DEM, landuse, and soils files were used in SWAT and GWLF simulations, with outlets placed at the same points to ensure that subbasin delineation did not create differences in model predictions.

The Duck Pond system at the subbasin 1 outlet was simulated using parameter values developed by Wagner (2004). The HRU distribution was created using the automatic delineation option in AVSWAT at maximum HRU sensitivity. The highest sensitivity was used to simulate every distinct landuse/soil combination and to allow maximum landuse variability. Input files were created using the SWAT input file generator. Manning's n values for the main channel and tributaries were left at the suggested default value. Plant heat units were simulated by SWAT.

5.4 CONCEPTS Modeling Procedure

The CONCEPTS reach-scale model was used to simulate channel degradation for the Stroubles Creek Heth Farm study reach and compare the output with GWLF and SWAT. The objective of this effort was to evaluate if a more process-based, reach-scale model, coupled with a watershed-scale model, more accurately predicts channel degradation. A sensitivity analysis of CONCEPTS channel parameters was performed before simulating the case study scenario.

CONCEPTS Sensitivity Analysis

A channel degradation sensitivity analysis was performed on several CONCEPTS parameters. Selected parameters within the bank stability algorithm were chosen for analysis based on recommendations from the CONCEPTS model developer (E. Langendoen, personal communication, June 22, 2006).

Effective friction angle was varied between 20 and 35 degrees, in five degree increments. Effective cohesion was varied by 2.5 Pa increments between 0.0 and 7.5 Pa.

These ranges represent typical values for the Eastern U. S. The groundwater table elevation was varied from 1.0 m to 1.75 m above bedrock by 0.25 m increments; groundwater effects on soil properties and interstitial soil forces may significantly alter bank stability. The measured critical shear stress for each soil layer was varied by a range of ± 20%. This parameter impacts the magnitude of sediment lost to fluvial erosion. The bank Manning's n values were also analyzed. Changes in Manning's n values allow vegetative cover manipulation when assessing stream restoration design alternatives. The value appropriate for Heth Farm experimental reach simulation was varied by ± 20%. Results are given in the ***Results and Disscusion*** section.

CONCEPTS Case Study Simulation

CONCEPTS uses four modeling: hydraulic structures information, upstream boundary conditions, cross section input files, and run control specifications. There are no hydraulic structures within the experimental reach.

The CONCEPTS reach-scale model focuses on instream processes. It requires discharge and sediment upstream boundary conditions. The upstream boundary discharge timeseries was the simulated daily discharge simulated with SWAT at the subbasin 2 outlet (see Figure 9). Data were imported into Excel and an additional column field was added to indicate beginning and ending of storm events. A one was input to mark an initial rise in daily discharge. A two was placed in rows where discharge stabilized following a storm event. A zero was placed in all other rows. **Appendix D** gives an example upstream boundary condition file. CONCEPTS allows the model user to specify the upstream sediment load boundary condition inflow as either a timeseries or as a function of discharge. For this study, sediment was specified as a percentage of the daily sediment transport capacity. Size class percentages are typically based on the extent, composition, and distribution of upland soils. After consultation with E. J. Langendoen (personal communication, June 22, 2006) size class percentages were set as 20% clay, 25% fine silts, 25% larger silts, and 20% fine sands, representing 90% of the sediment transport capacity.

Methods

Channel cross section location, geometry, and surface conditions are specified in cross section input files. The stream distance from Stroubles Creek headwaters to the first cross section was measured using GIS software. Cross section files include five independent blocks, representing left floodplain, left bank, channel bed, right bank, and right floodplain characteristics. Channel geometry was specified by stream-channel surveys collected at 50-m intervals along the 500 m study reach. Manning's n values for each 50 m segment were estimated according to Chow (1959) and ANSWERS 2000 model documentation (Byne, 2001). A 200-sample pebble count was used to describe channel bed characteristics. The Colby (1964) equation was used to calculate bed porosity. Intact soil samples were taken from upper and lower bank for direct shear stress testing. Testing revealed an effective cohesion, c', of 0^{o} and an effective stress friction angle, ϕ', of 35^{o} for both soil samples. The average critical shear stress, average specific gravity, and soil-layer particle size distributions were calculated based on Heth Farm samples collected by Henderson (2006) and Wynn (2004). Groundwater elevation and bed sediment hiding factors were set based on guidance from model developers at the NSL (E. Langendoen, personal communication, June 22, 2006). **Appendix D** provides a sample cross section file used in the CONCEPTS simulation.

CONCEPTS requires "Run Control" input file to perform simulations. This file contains hydrology and cross-section input file names, specifies process algorithms, and determines output format. The Run Control file specifies the rate of lateral inflow, downstream boundary conditions, and upstream boundary conditions. Within the Run Control file, the user specifies the bank failure analysis process to be simulated, the type of flow resistance equation to be used, and the simulation period. The lateral surface inflow rate used in this case study was adjusted according to recommendations from model developers at the NSL (E. Langendoen, personal communication, June 22, 2006). A loop-rating curve option was used for the downstream boundary condition since actual discharge data were not available. Channel bed and bank degradation algorithms were the primary research focus; therefore, all forces represented in the CONCEPTS bank stability algorithm were simulated. In addition, bed adjustment, fluvial toe erosion, and mass wasting processes were utilized. The CONCEPTS simulation was run for the 11-

month period from August 2005 to July 2006, concurrent with erosion pin data collection.

5.5 Erosion Pin and Scour Chain Methodology

In conjunction with the stream degradation modeling effort, an erosion pin monitoring study was conducted to quantify streambank retreat within the experimental reach. Streambank retreat rates were measured using erosion pins and scour chains on the 500-m long reach. Pins made from #316, 6-mm diameter stainless steel rod stock measuring 50 cm in length were marked on one end with 2.5 cm of brightly colored heat-shrink tubing and placed on actively eroding stream banks in a systematic 10-m horizontal and 0.3-m vertical grid. The tributary marking the most upstream point of the study reach (Figure 8) was used to set erosion pin placement locations. The first pin set was placed on the cut bank approximately 2 m downstream from the tributary. A tape was laid along the left bank (facing downstream) at bankfull elevation to establish the 10-m grid spacing. Pins were placed only in actively eroding areas showing little evidence of livestock interference, as determined by field personnel. In addition to the regular 10-m horizontal spacing, pins were placed at 2-m intervals along severely eroding banks in sharp meander bends. These sites were selected based on bank height, bank slope, evidence of recent failure, and surface conditions.

Pins were installed perpendicular to the horizontal bank surface, as estimated by the prevailing horizontal bank direction immediately surrounding the pin (1 m upstream and downstream of the pin). Smaller fluctuations in bank direction were not considered when placing pins. Pins were identified with a cross section number (numbered sequentially from upstream to downstream) and a letter indicating the vertical placement, beginning with A at the bank toe. The first pin in each cross section was placed on the bank toe approximately 3 cm above baseflow water surface elevation. This elevation was chosen to allow pin measurement during normal flow conditions. Subsequent pins were added at each cross section with a 0.3-m vertical spacing up to floodplain elevation. Pins were inserted at a vertical angle less than 15° above horizontal, as shown in Figure 11. The slight upward angle helped minimize pin loss.

Methods

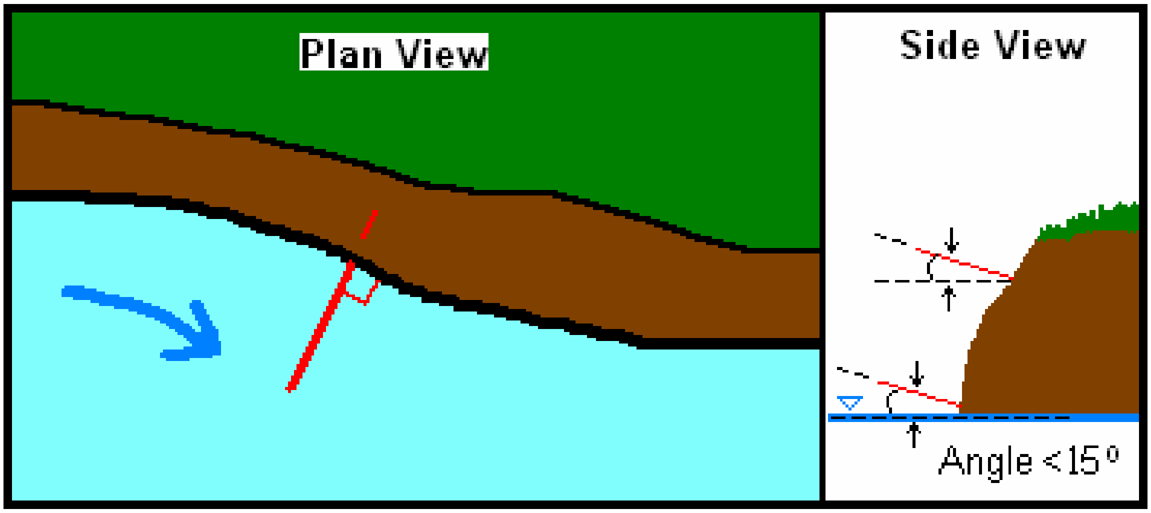


Figure 11. Illustration of erosion pin placement.

Soil surface disturbance was minimized as much as possible while placing pins. During installation in July 2005 pins were pressed into the soil or lightly tapped with a hammer until four cm of the pin remained exposed. Pins were reset to the four cm exposed length (L_e) value during monthly monitoring visits. The original and reset value for L_e was set at four cm to facilitate future location and minimize flow interference due to protruding erosion pins, as suggested by Haigh (1977).

A high-precision 30-cm dial caliper with integrated depth gage (McMaster-Carr, Atlanta, GA) was used to measure L_e for initial placement, resetting, and all subsequent measurements. Measurements were taken from the pin end to the bank surface at the vertical centerline along the downstream side of the pin until contact was made with the soil surface and slight sediment movement was observed without compaction. All measurements of L_e were taken in this manner to maintain a consistent reference location. Pins with a net change in exposed length greater than 1.0 cm ($\Delta L_e > 1.0$ cm; $L_e < 3.0$ or $L_e > 5.0$ cm) were reset to the initial 4.0 cm length. Pins with changes in L_e of less than 1.0 cm were not reset to the 4.0-cm reset value in order to minimize disturbance and error resulting from resetting.

Methods

Pins which had deposition rates greater than 4.0 cm (buried pins) were noted on the field data sheet. If field personnel felt that the buried pin would reappear before the next measurement visit or surface conditions were unstable, the pin was left undisturbed. If significant aggradation (pin burial) was encountered and surface conditions were stable a new pin was installed at the approximate location of the previous pin to measure retreat rate until the original pin was exposed again. If during future visits multiple pins were found at a given location both pins were measured and one was removed. This procedure created overlapping data for continuous monitoring.

Measurements of L_e were estimated by field personnel for pins located in mass failure areas where pin displacement or erosion rates greater than 30 cm (pin was lost) were observed. L_e was estimated at such locations by field personnel and bank failure was noted and described on the field data collection sheet. These pins were then reset in a location as close to the original location as allowed by surface conditions.

Scour chains made from #316 5-mm diameter stainless steel straight link tangle-resistant chain measuring 1 m in length with an inside link width ~12.5 mm were distributed evenly across the experimental reach. The first scour chain set was placed approximately 150 m downstream of the first set of erosion pins with chain sets two and three installed approximately 100 m and 200 m downstream of the first set, respectively. Scour chains were anchored by attaching one end link to a disposable broadhead stake and driving the stake into the channel bed vertically using rebar. The rebar section was then removed and the chain checked to make sure the anchor had locked into place to prevent chains from pulling out. Chains were buried to the maximum depth allowed by bed sediments, with depths ranging from 30 to 70 cm. After installation the L_e, or portion of the chain lying horizontally on top of bed sediments, was measured. Subsequent scour chain measurements included an estimate of sediment depth covering each chain and measurement of the new L_e. Both deposition depth and L_e were estimated using a measuring tape. Bed roughness and the nature of underwater measurements did not allow measurement beyond centimeter resolution. Deposition depths less than 1 cm were not measured, but were recorded as the minimum detection limit of <1 cm. L_e for scour chains was measured after working the chain to the surface with minimum sediment disturbance. L_e was then measured as the length of chain from the end link to the first vertical link.

In total, 268 erosion pins and 7 scour chains were initially installed along the 500-m reach. Pins were checked monthly between July 2005 and June 2006, except during November 2005 and April 2006 when scheduling conflicts and elevated flows prevented data collection. Pin identification numbers, deposition depth, and new L_e were recorded on the field data collection form along with any additional notes. Additional pins were installed during monthly monitoring to replace lost or disturbed pins. Measurements were recorded in centimeters to three decimal places unless otherwise specified. Three decimal places were recorded for the estimation of measurement error. When processing data, pin measurements were rounded to the nearest mm.

Replicate measurements were performed each month by multiple field personnel to provide a measure of experimental error and as a quality control measure. Additional information on quality control procedures is available in the Quality Assurance Project Plan (Center for TMDL and Watershed Studies, unpublished, 2006. Virginia Tech).

The point data collected through erosion pin monitoring was transformed into monthly mass sediment loadings to the stream. Point data were extrapolated to create an average predicted retreat surface. In an effort to limit extrapolation error, pin data were only applied to the continuous bank surface surrounding the pin, i.e. the directly connected, actively eroding portion adjacent to the pins. A measuring tape was used to estimate bank segment height and length. The erosion pin measurements were compiled and averaged for each individual bank. The average segment-specific retreat rate was multiplied by an estimated segment surface area. The soil volume was then multiplied by an average bulk density of 1300 kg/m^3 as reported by Wynn, 2004 and Henderson, 2006.

5.6 Statistical Analysis

Model simulations were run for 11 months from July 2005 - June 2006, corresponding with erosion pin observations. Model output was manipulated to obtain monthly channel degradation estimates in metric tons. GWLF model output included monthly estimates of streambank retreat for each subwatershed. The streambank retreat for subwatershed three was used in the data analysis. SWAT produced output for sediment entering and exiting each subbasin. SWAT monthly channel degradation estimates were calculated as the difference between sediment entering and exiting subbasin three. CONCEPTS channel degradation estimates were based on the difference in sediment yield between the cross-section marking the upstream end of the experimental reach and the cross section at the downstream end. The resulting data set included four treatments: GWLF, SWAT, CONCEPTS, and erosion pin observations. Data were analyzed using Minitab Release 14 software (Minitab, 1998). The Shapiro-Wilks nonparametric normality test and Rank von Neumann test for independence were used to test the distribution and independence of the data. The Theil-Sen nonparametric simple linear regression procedure was used to compare the model predictions with actual data.

Preliminary analysis of descriptive statistics indicated non-normality and unequal variances. The Shapiro-Wilks nonparametric normality test was performed to verify non-normality (Royston, 1982).

The dependence of channel degradation on flow conditions suggested possible serial correlation in field and model data sets. The Rank von Neumann's test for independence was conducted to check for possible serial correlation (Bartels, 1982; Gibbons and Chakraborti, 1992). The rank version was used to insure an accurate non-normal analysis. A conservative p-value (0.2) was used to test the randomness hypothesis and results showed that output from all the models was serially correlated ($p>0.2$).

The Theil-Sen non-parametric simple linear regression procedure was used to determine if there was a linear relationship between model predictions and measured values (Sen, 1968; Theil, 1950). With this procedure, monthly model predictions were plotted against the corresponding monthly field measurements. Regression slopes significantly different from 1.0 indicated either model overprediction or underprediction.

6. Results and Discussion

Weather conditions in Blacksburg, VA for the duration of this case study were generally mild and dry. Blacksburg weather data from the Southeast Regional Climate Center (SERCC), operated by the Land, Water, and Conservation Division of the South Carolina Department of Natural Resources, were used to form historical temperature and precipitation averages. A period of record from 1952 to 2005 was used for historical averages (SERCC, 2006). Measured monthly temperatures for the Blacksburg Airport weather station, within the Stroubles Creek watershed, were retrieved from the NCDC website (http://cdo.ncdc.noaa.gov/ulcdsw/ULCD). Measured average monthly minimum and maximum temperatures were above the 50-yr average for 10 of the 12 months. November was colder than average, but the winter months were warmer than normal. January was recorded as the warmest on record.

The annual precipitation total for the simulation period was 48 cm, less than half the 50-yr average of 103 cm. November was the wettest month, with rainfall approximately equal to the 50-yr average. Pocket wetlands on the floodplain surrounding Stroubles Creek remained dry for much of the simulation period. Little channel degradation was measured during the months of August through December 2005. Loose, unstable surface layers associated with freeze-thaw cycling were observed during the months of December – March. Data collected by Henderson (2006) measured eight freeze-thaw cycles during December 2005 and five cycles during January 2006. The abnormally warm January temperatures coincided with a spike in measured bank retreat.

Results and Discussion

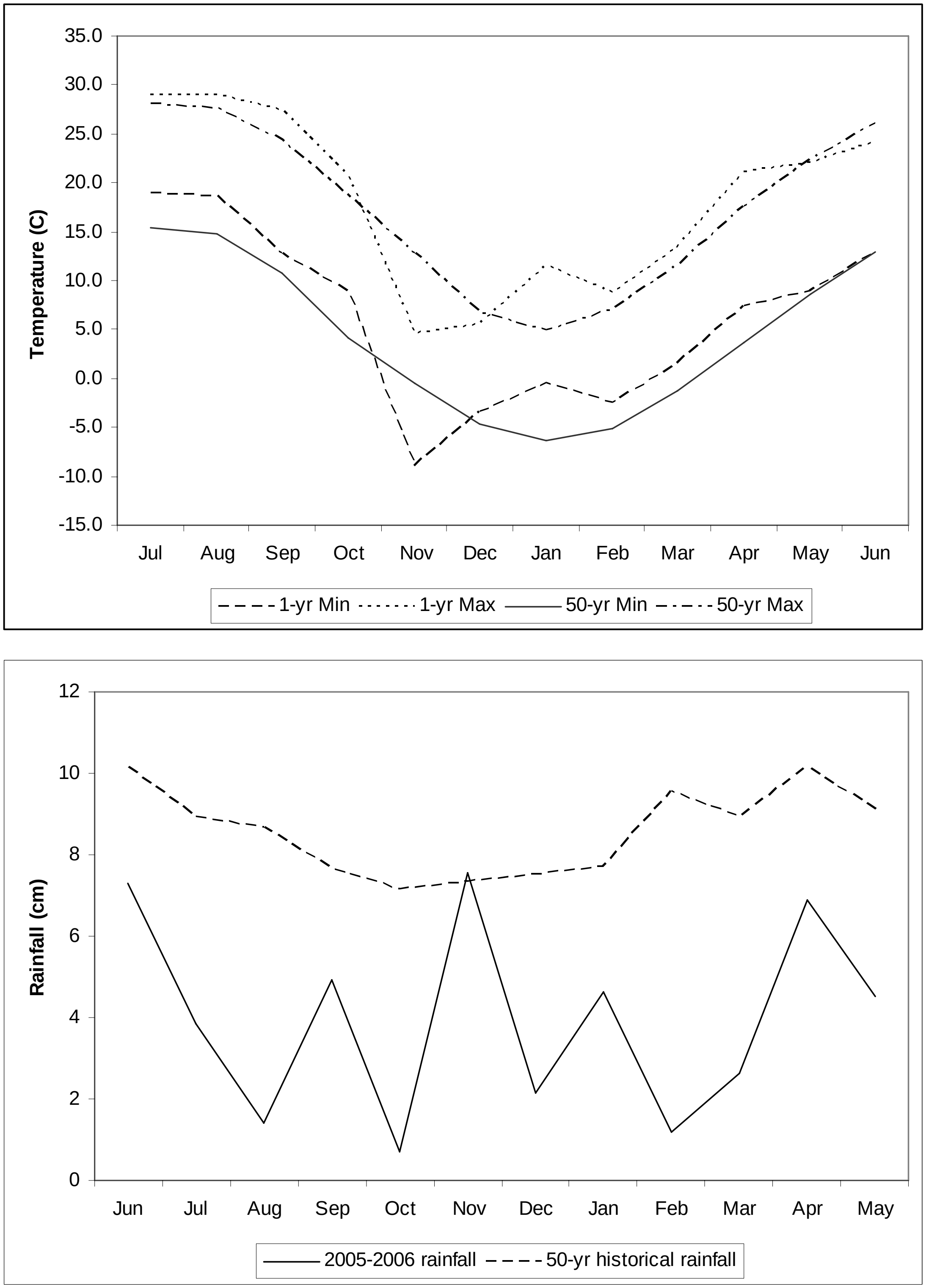


Figure 12. a) July 2005- June 2006 data compared with 50-yr average maximum and minimum monthly temperature; b) 50-yr average monthly rainfall compared to July 2005 - June 2006 rainfall; Blacksburg, VA, USA.

6.1 Monitoring Data

Erosion pins measurements were made nine times between the July 21, 2005 installation date and June 22, 2006. Logistics and scheduling conflicts prevented recording observations in November 2005 and April 2006; however, site conditions were observed during these months and no bankfull storm events occurred. Table 5 provides a summary of the erosion pin and scour chain data. The complete erosion pin data set is given in **Appendix A**.

Table 5. Summary statistics for monthly erosion pin data collected on the Heth Farm in Blacksburg, VA, USA between July 2005 and June 2006.

	Minimum Retreat (cm)	Maximum Retreat (cm)	Average Retreat (cm)	Median Retreat (cm)	Standard Deviation (cm)
Erosion Pins	-17.3	43.7	2.1	0.8	5.5
Scour Chains	-6.0	5.0	-0.5	-0.1	2.3

All data were included in the data summary given in Table 5. Negative values indicate deposition and positive values indicate soil loss.

Scour chain data were used only to provide a general estimate of reach-wide bed sediment movement. Scour chain installation and measurement difficulties limited this study to the monitoring of seven chains at three cross sections. Scour chain cross sections were spaced throughout the reach. The most upstream chain set was approximately 150 m downstream of the first erosion pin set. The second and third chain sets were 100 m and 200 m downstream of the first chain set, respectively. Difficulty in retrieving chains also resulted in data collection in only six out of eleven months, including September, October, December, January, March, and June. The precision of scour chain data was estimated at ±1 cm, based on field observation and measurement techniques. Approximately 87% of measurements showed deposition less than the 1 cm detection limit. Often chains were partially buried or merely covered by algae and a thin layer of fine sediment. The average streambed retreat given in Table 5 indicates that no significant annual deposition or scour occurred during the monitoring period. During the 11-month monitoring period no bankfull flow events were observed. Baseflow conditions are shown in Figure 13.

Figure 13. Baseflow conditions for Stroubles Creek on Heth Farm, Blacksburg, VA, USA (January 2006).

Based on scour chain field observations, observed streamflow, and measurement resolution, scour chain data were not included in the estimation of sediment load. It is valuable to note that multiple bankfull events, associated with short-duration high intensity thunderstorms, were observed in the month following the case study monitoring period (Figure 14). These events resulted in significant bed scour and observed deposition as much as 6.0 cm and changes in exposed chain length as high as 17 cm.

Figure 14. Flood conditions for Stroubles Creek on Heth Farm, Blacksburg, VA, USA. Sampling bridge is nine meters long (June 2006).

Erosion pin data analysis yielded a loading estimate of 41 tonnes (t) from the test reach over the study period. Monthly sediment load estimates ranged from 21.0 t/mo in January to -2.0 t/mo in February (all values reported in tonnes). Monitoring data were compared to computer model output from GWLF, SWAT, and CONCEPTS and results are shown in Figure 15.

The methods used to measure bank retreat likely created bank retreat rates higher than natural levels. Erosion pin monitoring is inherently invasive and a certain degree of human-caused retreat, associated with pin measurement and movement, is unavoidable. The greatest contributing factor to elevated measured retreat is the inability of erosion pins to adequately capture deposition. Pin burial was most commonly encountered at the toe of the bank and the inability of erosion pins to capture deposition inflated toe erosion estimates. Quality control procedures were strictly followed to minimize this measurement error component (Incorporating Stream Erosion and Restoration in Watershed Models, QAPP, unpublished material, 2005. Blacksburg, VA: Virginia Tech.)

Gravel lenses in the lower bank profile created conditions conducive to excessive toe scour and preferential flow, both of which helped make cantilever mass failure the most common bank failure mechanism on the Heth Farm experimental site. Patterns seen in monthly erosion pin monitoring data also result from past channel manipulation practices. Abandoned meanders visible on recent aerial photography suggest past channel straightening. The conditions seen on the Heth Farm represent one step in the morphologic progression of Stroubles Creek as the channel works to regain a natural planform and sinuosity. The effects of past logging activities also explain the significant bank retreat observed on Heth Farm. A layer of fine grained sediments eroded from upland areas and deposited on the floodplain. These legacy sediments are highly susceptible to subaerial processes.

6.2 Sensitivity Analysis

Model parameter sensitivity describes the relationship between changes in input parameters and resulting differences in predicted output. Although analyzing sensitivity on a parameter-by-parameter basis is sometimes helpful, comparisons between various model parameter sensitivities are more useful. Commonly inconsistencies in parameter units do not allow direct comparison of parameter sensitivity. Calculation of relative efficiencies, S_r, allows such between-parameter comparisons. The relationship for relative efficiency, as reported in Byne (2000), is given by:

$$S_r = \frac{\frac{\partial O}{O}}{\frac{\partial P}{P}} \qquad \text{[Eq. 59]}$$

where O is output and P is input. Absolute S_r values greater than one indicate an amplified output response and values less than one indicate a damped output response. Negative values indicate an inverse association between parameter and predicted output and positive values designate a direct relationship. S_r was used to describe the sensitivity of GWLF, SWAT, and CONCEPTS model parameters. Results are shown in Tables 6 – 8.

GWLF

Table 6 gives the predicted average annual streamflow (watershed-cm) and annual bank erosion (tonnes) for the Stroubles Creek watershed case study scenario using a ten-year data record from 1985 – 1995.

Results and Discussion

Table 6. Results of GWLF sensitivity analysis for streamflow and bank erosion as applied to the Stroubles Creek watershed in Blacksburg, VA, USA.

Parameter	Levels	Total Annual Bank Erosion	Relative Sensitivity
		tonnes	
Recession Coefficient	0	23	0.4
	0.06095	41	0.0
	0.1219	**42**	
	0.18285	42	0.0
	0.2438	43	0.0
Seepage Coefficient	0	45	0.0
	0.01	43	0.0
	0.02	**42**	
	0.03	41	0.0
	0.04	40	0.0
	0.5	28	0.0
*ET, (dormant, active)	0.5	47	-0.3
	0.6	44	-0.2
	0.748	**42**	
	0.9	38	-0.4
	1	35	-0.4
Mean Channel Depth (m)	0.3	25	1.0
	0.5	**42**	
	0.7	59	1.0
	0.9	76	1.0
	1.1	93	1.0
Channel Length (m)	6.975	21	1.0
	10.4625	31	1.0
	13.95	**42**	
	17.4375	53	1.0
	20.925	63	1.0
Percent Impervious	50	27	0.2
	60	34	0.2
	70	**42**	
	80	48	0.2
	90	55	0.2

* active used for purposes of S_r calculation

<u>Recession Coefficient (RC)</u>- As RC approaches 0.0 the greatest impact on streamflow and bank erosion occurs. Significant effects on streamflow and bank erosion were seen between the -100% of default and -50% of default levels. Slight differences between the

higher levels were also observed. Changes in the RC more heavily effect months with higher predicted runoff. Months with less rainfall were less influenced by changes in RC. Bank erosion predictions followed the same trend as streamflow and indicate a direct proportionality between streamflow and bank erosion.

Seepage Coefficient (SC)- The seepage coefficient exhibits a slight inverse relationship with streamflow and bank erosion. As SC approaches 0.0 the streamflow and bank erosion predictions are highest. S_r values indicate that SC manipulation has a lesser effect than changes in recession coefficient. An additional level was tested for SC representing the suggested upper limit; a value 25 times greater than the default. This additional level was tested to more completely cover the suggested range of values. The other five levels cover the reasonable range for the Stroubles Creek watershed. The net effect due to this jump is comparable to that seen in the RC sensitivity analysis. As seen in the RC sensitivity analysis, dry summer months were less impacted by changes in SC.

Evapotranspiration (ET)- The value range used for ET sensitivity analysis was higher than typical foliated watershed values. The study reach location intensifies urbanization effects by excluding large forested areas just downstream. Evapotranspiration sensitivity analysis results are appropriate for heavily urbanized watersheds. S_r values indicate a greater relative effect on streamflow and channel degradation predictions due to changes in ET when compared to the results of RC and SC sensitivity analyses.

Stream Bank Erosion Calibration Parameters

Mean Channel Depth (MD)- The bank erosion subroutine in GWLF uses the USGS bankfull regional curves to approximate the mean channel depth. This depth provides one of the dimensions of the surface to which the lateral erosion rate is applied (the other being channel length). The approximate bankfull depth for Stroubles Creek was taken from the USGS Valley and Ridge regional curves. Regional curves were developed for unurbanized watersheds, therefore this value is likely an underestimate of actual bankfull depth. Based on regional curve data the mean channel depth for Stroubles Creek at the outlet of the experimental reach is 0.5-m. The urbanized condition of the Stroubles Creek watershed has caused the experimental reach to incise and bank heights range from approximately 0.5-m to 1.2-m. Based on the observed watershed conditions, MD sensitivity analysis included values ranging from 0.3-m to 1.1-m. Results showed a direct linear relationship between bank erosion mass and mean depth. Predicted bank erosion is directly proportional to changes in MD and the relative change in channel erosion prediction is equal to that of input parameter changes. When modeling urbanized watersheds the observed bankfull depth or mean channel depth may differ significantly from that predicted by the regional curve. This should be considered when applying the GWLF bank erosion subroutine. The MD provides the bank height to which the erosion relationship is applied. Affects of MD on bank erosion prediction are presented in Table 6.

Channel Length- Bank erosion rates estimated by GWLF are influenced by changes in channel length in addition to mean channel depth. The channel length sensitivity analysis included values ranging from 50% to 150% of the default value, in 25% increments. The relationship of channel erosion mass estimates and channel length is linear, much like the relationship described for mean channel depth (Table 6). Differing methodologies used to develop the GWLF stream network cause variations in channel length. Multiple data sources, such as the National Hydrography Dataset, provide channel network detail. Geographic Information System Digital Elevation Models (DEM) are often used to create stream networks. When developing a stream network from DEM data the data user must specify a minimum contributing area, or threshold value, for adequate flow concentration to occur. This threshold value is user defined and will affect the extent of the stream network, therefore influencing the channel length used in simulation. Values within this expected variation were tested.

% Impervious Cover- The percent of the land surface in a watershed considered impervious affects the prediction of bank erosion in GWLF. Impacts on the stream channel are a function of the type and density of urban development in a watershed. Impervious cover is estimated based on landuse categories, i.e., low density housing has a smaller fraction of impervious areas than high density housing. Differences in the total impervious area of a watershed are subject to variability associated with landuse determination and the assigned fraction of impervious area within each landuse. The magnitude of the effect of landuse changes on bank erosion prediction is indicated by the range of predicted values presented in the GWLF sensitivity analysis Table 6. A direct, but damped relationship is shown by S_r values.

SWAT

Eleven SWAT parameters were chosen for sensitivity analysis testing. Values were varied within the recommended range. The results of the analysis are presented in Table 7.

Table 7. Sensitivity analysis testing for eleven SWAT model parameters for simulation of the Stroubles Creek watershed in Blacksburg, VA.

Parameter	Levels	Avg Annual Channel Degradation	Relative Sensitivity
		(tonnes)	
ALPHA_BF	0.05	25500	-0.1
	0.10	25800	-0.2
	0.15	23900	
	0.20	26000	0.2
	0.25	26000	0.1
RCHRG_DP	0.00	27800	-0.1
	0.10	26800	-0.2
	0.20	23900	
	0.30	25300	0.1
	0.40	24800	0.0
CH_L2	2.51	27400	-0.7
	2.82	26600	-1.1
	3.14	23900	
	3.45	25300	0.5
	3.76	24800	0.1
CH_W2	3.29	27200	-0.6
	3.70	26500	-1.0
	4.11	23900	
	4.52	25400	0.6
	4.93	29900	0.2
USLE_P	0.20	26300	-0.1
	0.40	26100	-0.2
	0.60	23900	
	0.80	25700	0.2
	1.00	25500	0.1
SLSUBBSN	51.00	24000	0.0
	56.00	24000	0.0
	61.00	23900	
	66.00	23900	0.0
	71.00	23900	0.0

Table 7, con't. Sensitivity analysis testing for eleven SWAT model parameters for simulation of the Stroubles Creek watershed in Blacksburg, VA.

Parameter	Levels	Avg Annual Channel Degradation	Relative Sensitivity
		(Mg or tonnes)	
SLOPE	0.06	24100	0.0
	0.06	24000	0.0
	0.07	23900	
	0.08	23800	0.0
	0.09	23700	0.0
SPCON	0.002	7400	1.0
	0.004	15700	1.0
	0.006	23900	
	0.008	32200	1.0
	0.010	40500	1.0
SPEXP	1.00	16700	1.5
	1.13	20000	1.6
	1.25	23900	
	1.38	28700	1.9
	1.50	34400	2.1
CH_EROD	0.00	-1.2	1.0
	0.10	12600	0.9
	0.20	23900	
	0.30	34000	0.8
	0.40	42800	0.7
CH_COV	0.10	5200	0.9
	0.30	15000	0.9
	0.50	23900	
	0.70	32100	0.8
	0.90	39400	0.8

Results and Discussion

ALPHA_BF- This parameter affects the amount of baseflow simulated in SWAT flow routing algorithms. Four levels were tested ranging from 0.05 to 0.25, in addition to the default value of 0.15. Results showed that changes in ABF had a damped effect on channel degradation predictions.

RCHRG_DP- The recharge parameter determines the amount of soil water which goes to groundwater storage. Values between 0.0 and 0.4 were tested in the sensitivity analysis. As the percentage of groundwater increased channel degradation predictions decreased as less water reaching the stream was simulated. The impact on channel degradation was comparable to that of ALPHA_BF.

CH L2 and CH W2- The channel length and width parameters affect channel hydraulics and degradation prediction. Changes in these parameters alter the magnitude of the soil/water exchange surface. These parameters were adjusted by ±20% in 10% steps. Sensitivity analysis results showed a slight impact on channel degradation predictions due to manipulation of the channel length and width parameters. A direct linear relationship more significant than ALPHA_BF and RCHRG_DP is indicated.

USLE P- The USLE crop practice factor influences both hydrology and overland sediment transport. Altering this factor also influences the amount of sediment reaching the stream channel. As more sediment is supplied to the channel by overland erosion less transport capacity is available to transport sediment supplied by the channel boundary. This parameter was varied between 0.2 and 1.0. As P-factor was increased channel degradation decreased, but only by a marginal amount. The response was comparable to that of ALPHA_BF and RCHRG_DP.

SLSUBBSN- This variable represents the slope length for sheet flow on upland areas. Increases in SLSUBSN translate into decreased overland erosion prediction. The value was varied by ±10-m, as suggested by model documentation. Very little affect was seen on channel degradation predictions.

SLOPE- Representing the overall subbasin slope, this variable can affect the quantity of runoff and the concentration of sediment delivered to the channel. Increases in slope result in a lower available streamflow transport capacity due to increased upland erosion. Values representing ±20% of the default value were tested. A slight inverse relationship is indicated by S_r values.

Channel Specific Parameters

SPCON- The linear sediment reentrainment coefficient was varied between 0.002 and 0.01, throughout the suggested range. As shown in Table 7, these changes in SPCON resulted in substantial changes in predicted channel degradation, causing variations in predictions from 7,400 t/yr to 40,400 t/yr. Channel degradation algorithms in SWAT are sensitive to this parameter. S_r values indicate a direct and amplified relationship.

SPEXP- The sediment reentrainment exponent was varied, as suggested in model documentation, between 1.0 and 1.5. As shown in Table 7, these changes in SPCON resulted in substantial changes in predicted channel degradation, causing variations in predictions from 17,000 t/yr to 34,000 t/yr. Channel degradation algorithms in SWAT are most sensitive to SPEXP, showing a direct and heavily amplified relationship.

CH EROD- Adjustment of channel soil erodibility is afforded by this parameter. The parameter was varied between 0.0 and 0.4 to test SWAT channel degradation sensitivity. Results shown in Table 7 indicate that this parameter has the most profound affect on channel degradation prediction. SWAT predictions associated with erodibility changes varied from -1.2 t/yr to 42,800 t/yr. This indicates the importance of channel soil properties in obtaining accurate channel degradation prediction. S_r values indicate that this parameter is less sensitive than SPEXP, but the acceptable range intensifies this parameters effect.

CH COV- The channel cover factor represents differences in vegetation density on channel banks and floodplains. Values between 0.1 and 0.9 were tested for this analysis. Results revealed variations in degradation predictions from 5,200 t/yr to 39,400 t/yr. Alterations in channel cover factor have an affect comparable to the range associated with channel erodibility variation.

Sensitivity analysis of upland and channel parameters exposed model sensitivity to channel parameters. None of the parameters which affect flow or upland erosion had significant affects on channel degradation prediction. This indicates that variations in the prediction of upland erosion have little impact on the channel degradation algorithm. Manipulation of each one of the four channel level parameters produced significant impacts on channel degradation predictions. Combined affects were not tested. If detailed monitoring data are available calibration of channel parameters would significantly improve model predictions.

CONCEPTS

Five CONCEPTS parameters were chosen for sensitivity analysis testing. These five parameters were chosen after consultation with CONCEPTS software developers at the National Sedimentation Lab in Oxford, MS (E. Langendoen, personal communication, June 22, 2006). Ranges were set based on guidance provided by model developers. Each parameter was varied individually with other parameters held constant at a mid-range value. The results of the analysis are presented in Table 8. Absolute predictions are less important than the relationship between predictions as test parameters are varied.

Results and Discussion

Table 8. Sensitivity analysis testing for five CONCEPTS model parameters for simulation of the Stroubles Creek watershed in Blacksburg, VA.

Parameter	Levels	Avg Annual Channel Degradation (tonnes)	S_r
Bank n-value	Default + 20%	-12.70	n/a
	variable	-56	n/a
	Default - 20%	-57	n/a
ϕ'	20	0	2.3
	25	0	3.5
	30	-48	1.0
	35	-56	
c'	0.01	-56	
	2.5	-34	-0.0
	5	-31	-0.0
	7.5	-46	-0.0
Groundwater Elevation, m	1	-55	0.0
	1.25	-45	1.2
	1.5	-56	
	1.75	error	n/a
τ_c	2.53,7.79	-56	n/a
	3.79,11.69	-56	n/a
Inflow Sediment (% of TC*)	30	0	1.5
	60	0	3.0
	90	-56	

* TC = transport capacity

<u>Bank n-value</u>- Manning's roughness coefficients are specified in CONCEPTS cross section files. Separate values are required for the channel bed, left bank, right bank, left floodplain, and right floodplain of each cross section. Baseline n-values used for this case study were set using guidance provided in ANSWERS-2000 (Byne, 2001) model documentation. Right and left bank n-values were varied by ±20 percent for purposes of

sensitivity analysis. Channel degradation predictions associated with n-value changes differed by 45 t/yr indicating significant sensitivity to the bank n-value parameter.

Effective stress friction angle, ϕ'- Sensitivity analysis of ϕ' tested a range of values between 20 and 35 degrees. Thirty-five degrees was used for case study simulation based on soil laboratory test results. Results showed a significant decrease in channel degradation predictions as ϕ' increased. The high measured effective shear stress angle may have contributed to the under predictions seen in the CONCEPTS case study simulation. S_r values indicate a directly proportional relationship more sensitive than any other tested parameter.

Effective cohesion, c'- The sensitivity analysis for c' included a range of values from 0.0 Pa (field measurement) to 7.5 Pa. Increases in c' translated into decreases in predicted retreat rates. Although not as sensitive as bank roughness or friction angle, effective cohesion had a slightly inverse affect on model predictions. The value of 0.0 Pa used in the case study represents the lower limit for this parameter disallowing further adjustment to improve model simulation.

Groundwater elevation, GWE- The ground water elevation parameter was tested to assess the affects of soil moisture and lateral inflow on bank stability. Testing also provided a better understanding of instabilities commonly encountered in model simulation when GWE is not properly specified. R. Wells (personal communication, April 27, 2006) at the National Sedimentation Lab described such errors as a common simulation problem. As shown by the sensitivity analysis, the attempt to test GWE at 1.75 m failed. GWE must be less than the minimum floodplain elevation specified in any cross section file to avoid simulation failure. The two successfully tested levels indicate a predictable trend in channel degradation estimates. As GWE is lowered channel degradation is reduced. The affect is less intense than that seen in ϕ' analyses.

Critical shear stress, τ_c - Analysis of changes in critical shear stress on channel degradation predictions yielded unsuspected results. Three total levels of critical shear stress were tested, with levels ranging between ±20 percent of the baseline value used in case study simulation. Results showed that critical shear stress had no affect on predicted channel degradation. These results may reflect modeling error or an incorrect software algorithm. Further testing and investigation is needed to determine the cause of insensitivity.

Inflow Sediment Composition- The percentage of transport capacity occupied as flow enters the reach was tested. A 90% occupied rate was used for case study simulation based on the recommendation of model developers (E. Langendoen, personal communication, June 22, 2006). Values of 60% and 30% were also tested to assess the affect on channel degradation prediction. The data necessary for setting this parameter do not usually exist so variability is common. Sensitivity analysis indicated that this parameter was almost as sensitive as ϕ'.

6.3 Monthly Sediment Loading Estimates

Model output for GWLF, SWAT, and CONCEPTS was analyzed as described in the *Statistical Analysis* section. Using a conservative α of 0.2, the analysis results indicated no significant correlation between any of the three model predictions and the erosion pin data. GWLF predicted monthly contributions to sediment load from channel degradation ranging from 0.06 metric tons (t) per month in September 2005 to 1.05 t/mo in January 2006. The annual prediction from GWLF was 7.6 t. SWAT predictions varied widely, ranging from 0.0 t/mo in February to 764 t/mo in March for a total yearly loading equaling 1466 t. CONCEPTS channel degradation and retreat predictions varied from -1.0 t/mo to 3.5 t/mo. The annual sediment load total predicted by CONCEPTS was 3.05 t. Figure 15 compares simulated monthly retreat rates and erosion pin observations.

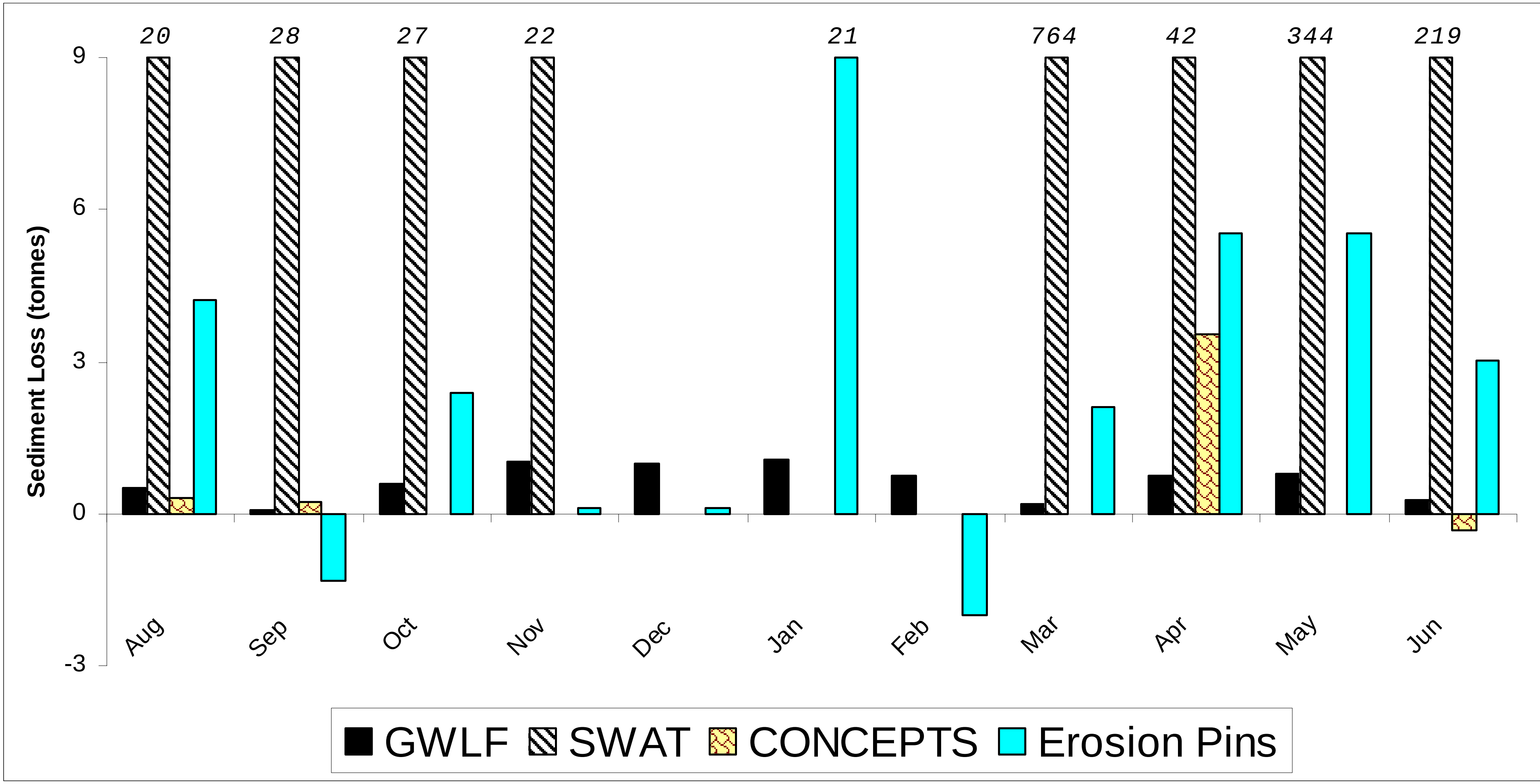


Figure 15. Measured and predicted monthly degradation and retreat rates for the 500-m study reach of Stroubles Creek in Blacksburg, VA beginning in August 2005 and ending in June 2006.

Results and Discussion

Erosion Pins

Streambank retreat observations for the monitoring period of August 2005 – June 2006 were directly affected by weather conditions. Average monthly temperatures were above the 50-yr average for all months except November 2005. Monthly rainfall totals were well below the 50-yr average rainfall for all months except November. No bankfull events were observed during the monitoring period. These unusually warm dry conditions likely limited the contribution of fluvial erosion to streambank retreat. If weather conditions had been more representative of long-term averages results may have shown fluvial erosion to be a more significant portion of watershed sediment loads.

Analysis of monthly erosion pin data indicated a multi-level cyclical retreat pattern. Although the period of record available for this case study did not allow verification of annual bank retreat cycle observations, climate patterns likely translate into predictable trends in channel degradation associated with fluvial and subaerial erosion. Research by Henderson (2006) indicates that seasonal variations in streambank erodibility contribute to an annual erosion cycle. The high peak in measured bank retreat during the month of January indicates the dominance of subaerial processes on channel degradation in Stroubles Creek. Based on this observation, the annual trend in erosion pin measurements is likely linked with subaerial processes. The greatest effect on streambank retreat due to subaerial processes occurred in December, January, and February for Stroubles Creek. Retreat rates then declined for the remainder of the year as loose sediment created during the winter was depleted and more resistant soils were exposed. Additional observations are needed to verify this hypothesis.

A second cycle, repeating every two to three months, involved soil surface particle loosening by weathering processes. Subaerial processes, such as desiccation cracking and freeze-thaw cycling, loosened soil aggregates allowing gravitational forces to detach upper bank legacy sediments. Detached particles from the upper bank zone collected on the lower bank slope creating a zone of loose unconsolidated material resting at the angle of repose. Refreezing of loosened sediments contributed to the formation of cantilevered bank toes known as erosional notches. Erosional notches formed as warmer water eroded underlying sediments not affected by freezing. When temperature allowed thawing the overhanging notch collapsed releasing the unconsolidated materials.

Erosion pin measurements were heavily affected by the above process. Upper bank pins showed a steady loss of sediment throughout winter months. Difficulty was encountered when monitoring toe pins. Toe pin measurements fluctuated drastically during winter months. The high number of freeze-thaw events in December resulted in toe pin burial as upper bank sediments migrated downward and settled on the shallower slopes of the lower bank. Buried pins could not be measured and unconsolidated sediments did not allow new pin insertion. January measurements revealed significant toe erosion as the unconsolidated materials accumulated during December and early January collapsed or were entrained by elevated streamflows. The image below shows this subaerial dominated erosion process.

Figure 16. Evidence of subaerial process dominance on Heth Farm, Blacksburg, VA, USA. ©Theresa Wynn

Variations in soil chroma indicate soil loss from the upper bank due to subaerial processes and the buildup of unconsolidated material on the lower bank zone. After loosened particles were removed by fluvial erosion, a new more resistant layer was exposed, resulting in reduced retreat while a new layer of colluvial material reformed. As newly exposed bank soils were subjected to weathering the process continued.

A third retreat cycle was evident at the cross section level through differences in retreat rates between upper and lower bank pins. Vegetation and high root densities in the upper 15 – 30 cm created an erosion resistant zone. The dense fibrous root network created by bank top grasses effectively held soil peds against collapse. In some instances large soil clods were completely suspended by roots. This rooting zone was underlain by a zone of similar soil composition with limited rooting, ranging in depth from 30 – 75 cm. This zone just below rooting depth, described in the previous paragraph, was actively eroded by subaerial processes. The accelerated erosion of the 30 – 75 cm zone created a cantilevered streambank condition. An example is shown in Figure 17. A failure block which has collapsed and now rests at the toe of the slope is outlined.

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Figure 17. Evidence of cantilever failure on Heth Farm, Blacksburg, VA, USA. ©Theresa Wynn

A similar condition was also observed in the lower layers of the bank profile. The portion of the streambank at and below water surface elevation contained a higher percentage of coarse sand and gravel material. The lower cohesive forces associated with these coarser particles and constant shear stresses created by streamflow created a zone of accelerated toe erosion. The layer directly above this zone of increased coarse fragments was a gleyed clay layer. The high cohesive forces of clay made this layer resistant to erosion. The combination of the clay layer and scour at the bank toe resulted in steep cantilevered bank formations. Failure of the lower bank cantilever occurred when toe scour created geotechnical bank instability (Figure 18).

Figure 18. Lower bank cantilever failure observed along Stroubles Creek, Heth Farm, Blacksburg, VA, USA.

Figure 18 shows an example of a buried toe pin. The pin was placed under an overhang at the toe of the bank slope. Mass failure deposits prevented monitoring until the colluvial material was removed by fluvial erosion.

GWLF

Figure 15 illustrated that of the three models evaluated in this study, GWLF channel degradation mass loss predictions were closer to observed values in ten of eleven months Annual channel degradation predicted by GWLF was 7.6 t/yr, compared to 41 t/yr based on erosion pin data. GWLF channel erosion predictions are also the most consistent for the duration of the modeling period. GWLF channel erosion predictions are based on monthly flow volumes, not peak velocity or discharge. This contributes to the consistency in model predictions. The peak in bank retreat observations occurred in January 2006. GWLF simulated the greatest channel degradation during January 2006. Net deposition was measured during the month of September 2005. This negative retreat corresponded to the lowest simulated monthly retreat in GWLF.

Trends in GWLF prediction can be described based on the underlying empirical relationship used to form the channel degradation algorithm. Data from 29 experimental watersheds throughout Pennsylvania were used to construct the channel degradation relationship (Evans et al., 2003). GWLF channel degradation model developers refer to the algorithm as a "channel erosion" relationship. Based on language established in this document the term is used incorrectly. The empirical nature of the channel degradation relationship in GWLF does not allow for the separation of bank retreat mechanisms.

The agreement between observed bank retreat and GWLF predictions may be attributed to the similar climate, geography, and history of parts of Pennsylvania and the reach used in this case study. Though the GWLF model is simple, the empirical relationship may have integrated the effects of subaerial processes on channel degradation predictions. GWLF predictions in November – February are the highest. Most other predicted GWLF erosion occurs in the months of April and May during the average wettest part of the year in the eastern United States.

The simplified character of the GWLF model makes it valuable as a screening tool for initial assessments of channel stability. The relative ease of setup and limited number of input parameters allow TMDL developers to use resources more efficiently. If channel degradation is not indicated to significantly contribute to watershed sediment load then further model development is unnecessary. However, if significant channel degradation is predicted in GWLF watershed managers can use available resources to initiate a monitoring program to facilitate the development of a more detailed reach-scale model suitable for simulating the effects of stream restoration. The simplified structure of GWLF limits its ability to assess changes in channel morphology and surface conditions. The channel degradation equations in GWLF have few meaningful parameters available for manipulation of channel characteristics. GWLF should not be used to model channel specific changes associated with stream restoration or riparian buffer zone management.

SWAT

The SWAT modeling effort included in this case study was developed using data and methodologies appropriate for a TMDL study. Monitoring data were not available for model calibration, as often the case when developing a TMDL study.

A review of model results (Figure 15) shows SWAT predictions which are two orders of magnitude greater than measured channel degradation. The SWAT channel degradation algorithm is dependent on the estimation of daily flow and sediment timeseries. The predicted channel degradation would indicate that SWAT is greatly overpredicting streamflow or significantly underpredicting the incoming sediment load. Table 9 presents average monthly flow and sediment estimates from SWAT simulation output.

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Table 9. Average monthly streamflow and sediment discharge to Stroubles Creek, Blacksburg, VA, USA, as predicted by SWAT simulation.

Date	Average Monthly Streamflow (cms)	Average Monthly Sediment Inflow (tonnes)
Jul-05	0.01	12.39
Aug-05	0.04	337.40
Sep-05	0.03	36.17
Oct-05	0.02	31.32
Nov-05	0.02	23.91
Dec-05	0.00	0.00
Jan-06	0.00	0.00
Feb-06	0.00	0.00
Mar-06	0.22	833.20
Apr-06	0.04	49.53
May-06	0.15	397.00
Jun-06	0.15	235.30

Table 9 shows streamflow at or below the normal baseflow range. Sediment entering the experimental reach at the upstream boundary ranges from 0.00 to 833.20 t/mo. The low streamflow and sediment inflow values for December – February are likely due to the below average rainfall for those months, which may have limited the prediction of overland erosion. Low predictions during months when freeze-thaw cycling occurred emphasizes that subaerial processes are not simulated as part of the SWAT channel degradation algorithm. A direct relationship between streamflow, sediment inflow, and channel degradation prediction is apparent when comparing data in Table 9 and Figure 15.

Not only were SWAT predictions grossly overestimating channel degradation, the timing of predictions is also misaligned. Periods of active retreat during winter months, including the highest measured value, are coincident with SWAT predictions of limited channel degradation activity. The SWAT model was ineffective in capturing cyclical bank retreat processes. Sediment eroded from channel boundaries in the SWAT model is assumed to occur as individual soil particles which are completely entrained. The inability of SWAT to simulate the detachment and rapid deposit of soil aggregates may contribute to over predictions. SWAT model developers have created a new channel degradation model component SWATDEG. Improved estimates for actual detached sediment sizes may allow more accurate representation of detachment and deposit dynamics (Jeff Arnold, personal communication, August 14, 2006).

Poor simulation may also be due to the use of peak velocity in the SWAT channel degradation algorithm. The SWAT model is not designed to simulate daily flows and, therefore, cannot be expected to accurately simulate daily peak velocity. The small size of the Stroubles Creek watershed also contributes to error in peak velocity estimation. SWAT was designed for large watersheds where average daily flow provides a reasonable estimate of peak velocity. Field observations showed that the time of concentration for the study watershed is between two and three hours. The short time of concentration and flashy nature of the watershed would require flow measurements or predictions at sub-hourly intervals to adequately capture peak velocity. If daily flow and sediment discharge monitoring data were available, the SWAT model channel degradation algorithm could be calibrated to produce more accurate results.

SWAT was unable to simulate changes in channel shape associated with channel degradation processes. The SWAT model includes a channel adjustment routine, but implementation of this routine does not occur until the volume of water in the simulated reach exceeds 1.4 million m^3. This value is a reminder that SWAT was developed for large to medium sized watersheds. The size of the Stroubles Creek watershed and limit of model application to a 500-m reach prevented reach volume from ever achieving the channel adjustment cut-off value. Failure to simulate cross section changes may have contributed to over prediction by not allowing the channel to downcut or widen. Simulation of a larger cross sectional area would have reduced stream velocity, likely reducing erosion predictions. This affect would likely become more significant over longer simulation periods, but was significant in this case study due to the significantly elevated channel degradation predictions. Efforts to correct this error have resulted in the development of the SWATDEG improved channel degradation modeling component (Jeff Arnold, personal communication, August 14, 2006).

Table 9 indicates that the high simulated channel degradation in SWAT is not caused by flow predictions beyond the observed range. Variations in sediment inflow range from 833.20 to 0.00. This indicates that poor SWAT predictions are more likely due to sediment related parameters. Sensitivity analysis showed that SWAT channel degradation parameters, such as SPCON, SPEXP, CH_EROD, and CH_COV, were highly sensitive and could cause variations in channel degradation predictions ranging from -1 to 42800 t/yr. Calibration of these parameters is suggested, but limited streamflow and sediment gaging data for the Stroubles Creek watershed did not allow such calibration and uncalibrated simulation is more indicative of modeling efforts typical of TMDL studies. Without adequate data to calibrate these parameters the model user is forced to set parameters based on model guidance, knowledge of watershed characteristics, and experience. Each of the parameters was set at a value in the accepted range based on watershed characteristics, but sensitivity analysis indicated that changes within the suggested range for a single channel degradation parameter can significantly alter model predictions. Based on slight deposition seen in scour chain measurements, the measured monthly estimates of streambank retreat represent a maximum estimate of channel degradation. This adds to the observation that SWAT model predictions are severely inflated.

CONCEPTS

The CONCEPTS reach-scale simulation was applied to the Stroubles Creek experimental site without detailed flow and sediment discharge monitoring at the upstream end. This data is typically unavailable to TMDL study developers. The CONCEPTS case study simulation was applied using data commonly available to watershed managers with the addition of cross section geometry surveys and soil test data for the experimental reach. This data would be reasonable under the scope of a TMDL if field observations and initial modeling indicated channel degradation to be a significant contributor to watershed sediment load. The application of the CONCEPTS model to the ungaged Stroubles Creek watershed did not allow model calibration, as commonly the case in many TMDL scenarios.

The CONCEPTS model predicted the least channel degradation for the duration of the study period. The highest rates were predicted for the months of August, September, and April. The September and August predictions are not easily explained since precipitation in those months was below normal. Measured retreat in August may be linked to subaerial desiccation cracking brought on by the abnormally hot dry conditions. This process is not simulated in the CONCEPTS model. The highest CONCEPTS predicted retreat did, however, agree with increased rainfall in April. Much like SWAT, CONCEPTS failed to simulate any significant degradation during winter months, indicating the inability of the model to simulate subaerial processes.

The CONCEPTS under prediction of annual channel degradation may also be linked to the methods used in simulating fluvial erosion. As previously mentioned, SWAT uses peak velocity to calculate the forces causing fluvial erosion. Similarly, CONCEPTS uses daily peak discharge, in combination with the Mannings' equation, to calculate the forces causing fluvial erosion. The small size of the Stroubles Creek watershed and short time of concentration do not allow daily discharge values to adequately capture peak discharge rates. CONCEPTS underprediction may be due to the fact that limited fluvial erosion was simulated due to the poor representation of peak discharge.

CONCEPTS was the only model to predict net deposition, though the timing of aggradation predictions did not match observed data. The added ability of CONCEPTS to predict cantilever bank mass failure was expected to yield predictions higher than that of GWLF or SWAT. Results suggest that, despite field observations of bank mass failure, subaerial processes are the dominant degradation mechanism for the Heth Farm experimental reach.

CONCEPTS is a reach-scale model. It requires either measured or predicted streamflow and sediment discharge timeseries data to allow channel process simulation. The limited availability of streamflow and sediment discharge data forced the use of SWAT daily flow predictions as CONCEPTS input. SWAT is not intended to produce reliable daily predictions. This likely had a significant impact on CONCEPTS prediction accuracy. The poor temporal agreement between CONCEPTS simulation and measured data is likely also the result of SWAT input. Despite the use of daily flow data from SWAT, CONCEPTS produced channel degradation results deemed acceptable by model developers. Predictions were within one order of magnitude of observed annual degradation. This shows that when limited data are available and flow data are provided by a watershed-scale model CONCEPTS may be used as a screening tool for channel degradation, much like GWLF. If more detailed monitoring data are available CONCEPTS can utilize the data for calibration and the assessment of stream restoration design effectiveness.

The second component of the upstream boundary condition needed for CONCEPTS simulation is a sediment discharge time series. Since this data was not available sediment input was specified as a percentage of available transport capacity. Characteristics of upland soils along with professional guidance were used to set the percentages of transport capacity occupied by each size class as flow entered the CONCEPTS experimental reach. This was necessary because sediment monitoring data were unavailable. Initial conditions used in the CONCEPTS case study simulation specified 90% of inflow transport capacity as occupied. This high initial sediment load may have limited channel degradation or contributed to predicted deposition. Sensitivity analysis indicated that CONCEPTS channel degradation simulation is significantly influenced by the specification of this sediment upstream boundary condition. The range of values used in sensitivity analysis produced a range of channel degradation predictions differing by 56 t/yr. Sensitivity analysis results suggest that, were this parameter specified to represent watershed conditions more accurately, CONCEPTS would have produced annual channel degradation predictions more representative of observed conditions.

CONCEPTS requires added strength parameters of channel soils for model simulation. The CONCEPTS model is the only one of the three models used in this case study able to simulate the affects of pore water pressure on bank sediment stability. Pore water pressure data are not typically known. The value for the pore water pressure coefficient, ϕ_b, used in this case study was set through consultation with the model developer (E. Langendoen, personal communication, June 22, 2006). Though model developers suggested pore water pressure would not significantly affect channel degradation its affect needs further investigation and may have contributed to CONCEPTS under predicting monthly sediment loss.

7. Conclusions

The ability of GWLF, SWAT, and CONCEPTS to predict channel degradation was tested through the application of models to the Stroubles Creek watershed in Blacksburg, Virginia, USA. Model predictions for channel degradation between July 2005 and June 2006 were compared with erosion pin observations for a 500-m reach of Stroubles Creek. Results of the case study showed that SWAT poorly predicted annual channel degradation for the experimental reach. GWLF and CONCEPTS predicted channel degradation reasonably, but the process-based CONCEPTS model was no more accurate in predicting annual channel degradation than the highly empirical GWLF. This finding illustrated that, without detailed monitoring data, additional model complexity does not translate into more accurate model predictions.

If models are needed to assess the impacts of stream restoration the development of a more complex process-based model may be required. The simple empirical nature of GWLF does not allow the adjustment of channel parameters necessary for simulating changes such as vegetation and construction of a bankfull bench. CONCEPTS requires cross section geometry data and allows the adjustment of bank and floodplain roughness and erodibility.

Data with a resolution suitable for use in a TMDL study was used to develop each of the models. CONCEPTS requires specification of flow and sediment discharge at the upstream boundary. Few watersheds have daily flow and sediment monitoring data available for modeling and TMDLS are typically developed for such ungaged watersheds. The CONCEPTS model simulation was developed based on SWAT daily flow predictions and estimates of sediment loading at the upstream boundary. Flows were not available to calibrate SWAT hydrologic predictions and the model was not designed to predict daily flows. Despite the use of lower resolution data from SWAT, CONCEPTS performed within the expectations of model developers.

When selecting a model for channel degradation it is most important to choose a model which conforms to the resolution of available data. Model selection must also consider the scale to which a model is applicable. The dominant channel degradation mechanism may differ based on watershed size. A model able to simulate the dominant degradation mechanism is essential.

Field observations showed significant degradation and deposition resulting from the influence of freeze-thaw cycling during the months of January – March 2006. Even though GWLF was unable to simulate the movement of soil from upper to lower bank zones as noted in field observations, the model did predict significant soil loss during the winter months. The simulation of significant winter retreat in GWLF and prediction of insignificant channel degradation by SWAT and CONCEPTS for the same months suggests differences in process simulation among the models. The empirical channel degradation algorithm used in GWLF was developed based on data from Pennsylvania watersheds. Though no processes are explicitly simulated by the simple GWLF channel degradation routine the empirical nature of the relationship lumps the components of fluvial, mass bank failure, and subaerial erosion. The data obtained through monthly erosion pin monitoring showed that the most significant retreat occurred during January 2006. The relative success of GWLF simulation may be due to similarities between the area where the channel degradation was developed and the Stroubles Creek watershed.

The SWAT model simulation overestimated observed annual channel degradation by two orders of magnitude. Elevated predictions stemed from highly sensitive channel degradation model parameters. Sensitivity analysis of model parameters specific to the channel degradation algorithm revealed drastic changes in predicted sediment loadings as parameters were varied within the suggested range. Variation within the suggested range for the SWAT channel degradation parameters SPCON, SPEXP, CH_COV, and CH_EROD resulted in channel sediment loading predictions of 7400 – 40400 t/yr, 16700 – 34400 t/yr, 5200 – 39400 t/yr, and -1.2 – 42800 t/yr, respectively. Little guidance is provided to help SWAT model users in selecting these channel parameters, making channel degradation simulation dependent on professional judgment. Available data for the Stroubles Creek watershed were not detailed enough to warrant calibration of the SWAT channel parameters. Case study results suggest that the SWAT channel degradation routine only be applied to gaged watersheds with daily streamflow and sediment data.

CONCEPTS simulation yielded channel degradation predictions comparable to those of GWLF. Based on the detail of available watershed data, CONCEPTS provided an adequate prediction of sediment loadings from channel boundaries. Despite the addition of mass bank failure process simulation, CONCEPTS underestimated the rate of channel degradation. Observed data showed that 50% of annual retreat occurred during January. The significant measured and observed winter retreat, coupled with CONCEPTS underprediction and inability to simulate subaerial processes, suggests that subaerial erosion is the dominant channel degradation mechanism for the study reach.

The high percentage of bank retreat attributable to subaerial erosion is also due to the limited number of significant rainfall events over the duration of the study period. Monthly rainfall totals were below the 50-yr average for all months except November 2005. No bankfull events were observed during the monitoring period. The unusually dry conditions limited the extent of fluvial erosion. If a similar study were performed during an average weather year additional fluvial erosion would be expected, thus reducing the significance of subaerial erosion on overall watershed sediment load.

When a watershed is listed as impaired, watershed managers must perform an initial assessment to document possible causes of the impairment. Channel stability investigation is required in the case of sediment impairments, especially in urbanized watersheds where streams are susceptible to downcutting. Ungaged watersheds with limited monitoring data are most appropriately modeled using an empirical model, such as GWLF. GWLF may be confidently applied to assess channel degradation for watersheds in the Eastern U.S., but may perform unsatisfactorily for watersheds characterized by geography and climate significantly different from that of Pennsylvania. If screening with GWLF indicates channel degradation, development of a new model should be required to assess management alternatives. GWLF allows little flexibility to assess management changes necessary to meet required reductions and is therefore inadequate for TMDL Implementation level modeling. The GWLF model provides watershed managers in the Eastern U.S a tool to assess the significance of channel degradation with minimal model development time. The results of GWLF simulation may then be used as evidence of significant channel erosion, providing the basis for a request for better monitoring data in anticipation that future modeling efforts will focus on assessing changes associated with stream restoration.

Gaged impaired watersheds with flow and sediment discharge data available to watershed managers are better suited to process-based model application from the onset of a TMDL study. Models such as SWAT or AnnAGNPS are appropriate for watershed simulation. As the study progresses additional model detail may be incorporated. If channel degradation is pinpointed as a major contributor to sediment loadings the existing SWAT or AnnAGNPS model can provide inputs for CONCEPTS reach-scale simulation. Watershed managers and TMDL developers now recognize the significance of channel degradation on overall watershed sediment loadings to streams. The results of this research emphasize the importance of model selection when predicting channel degradation contributions to watershed sediment loads. When TMDL source assessment identifies channel degradation as a significant source of sediment, appropriate watershed modeling software is necessary to assess the impact of management strategies. The range of annual channel degradation predictions seen in this research indicate that simulated contributions of channel degradation to overall sediment load can vary widely depending on the model used in a TMDL study. GWLF and CONCEPTS predictions would suggests that channel degradation contributes only a small percentage to the watershed sediment load, thus limited resources would be directed to address the channel degradation problem. Had SWAT been used for the TMDL study, significant resources would have been directed to curb excessive channel degradation when observed data showed that channel degradation had a much smaller effect than predicted by SWAT on watershed sediment loads. Accurately predicting channel degradation is essential when deciding where funds would be best used to reduce watershed sediment loads. Channel degradation simulation flexibility is also paramount when assessing the impacts of stream restoration. Considerable resources may be poorly used if models do not correctly predict the effect of specific practice implementation on channel degradation. CONCEPTS simulation requires watershed managers to collect some additional soil parameters and basic survey data. The cost of additional data is warranted if the assessment of stream restoration practices and riparian buffer zone management strategies is desired. Most watershed-scale models are not suited to predict the before and after differences in channel degradation associated with stream restoration practices.

8. Future Research

Sediment is the source of ever-increasing environmental concern. Elevated sediment loads to waterbodies are increasingly considered environmentally harmful and a mechanism for pollutant transport (Osterkamp, et al., 2004). A significant effort is underway to develop a more detailed sediment monitoring network to better characterize loading rates. Researchers across the country have been asked to join in a cooperative effort to help develop this enhanced sediment monitoring network (Osterkamp, et al., 2004). This research marks an attempt to establish one such sediment monitoring database. Limited long-term sediment monitoring data are available. The monthly streambank retreat monitoring effort developed for this research will continue. In addition to monthly bank retreat monitoring, additional measurements for discharge, turbidity, temperature, and suspended sediment will allow the development of a detailed data set for use in future research efforts.

Improved sediment monitoring will help identify increased sediment load sources and causes in impaired watersheds. The development of additional monitoring data will allow researchers to more confidently apply watershed models. Better modeling results will allow researchers to more accurately assess the effectiveness of erosion and sediment control strategies.

The conclusions of this research were restricted due to flow and sediment data limitations. Improved monitoring efforts will facilitate the development of watershed models which include the additional process detail needed to fully understand sediment and pollutant dynamics in stream systems. Existing model algorithms will also improve as models are adapted to utilize increased monitoring detail. Even screening level models will improve as additional data are available.

This research tested the ability of the GWLF empirical channel degradation algorithm on only one watershed. Additional testing of the model in other regions will allow researchers to determine areas where the existing empirical relationship can be reasonably applied. An enhanced monitoring network may allow researchers to develop new GWLF empirical relationships which apply to different climatic and watershed conditions.

This research found that subaerial processes dominate retreat for the Heth Farm section of Stroubles Creek. Future research is needed to assess the extent of subaerial process dominance in other regions. New watershed and reach-scale model algorithms should also be developed to include subaerial process simulation.

The Stroubles Creek TMDL Implementation Plan has recently been completed. Continued monitoring will allow researchers to see the impact of changes in watershed management strategies and conservation practice installation effects on channel stability and water quality.

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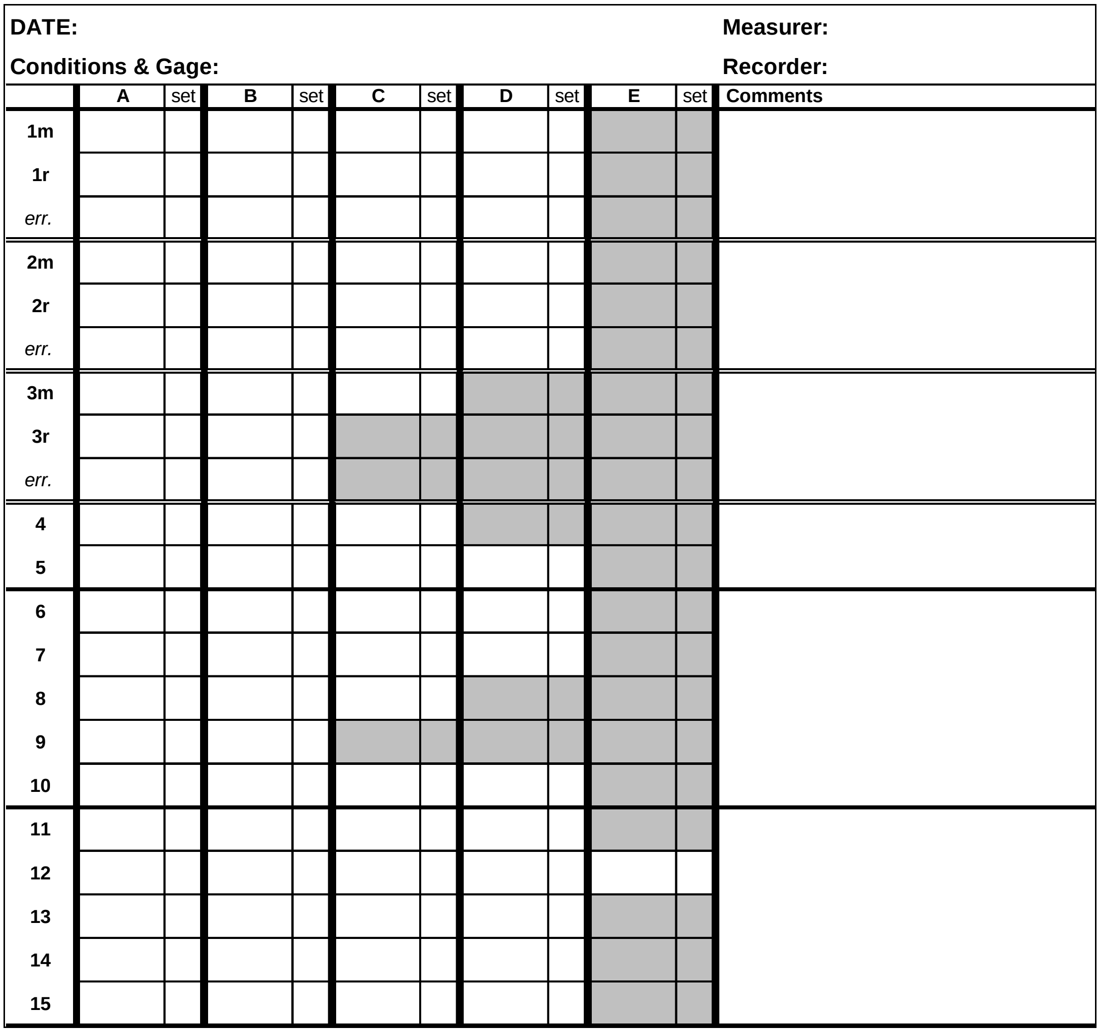
Appendix A - Stroubles Creek Erosion Pin Monitoring Data

The following is a portion of the field data form used to collect and organize erosion pin and scour chain monitoring data.



DATE: **Measurer:**

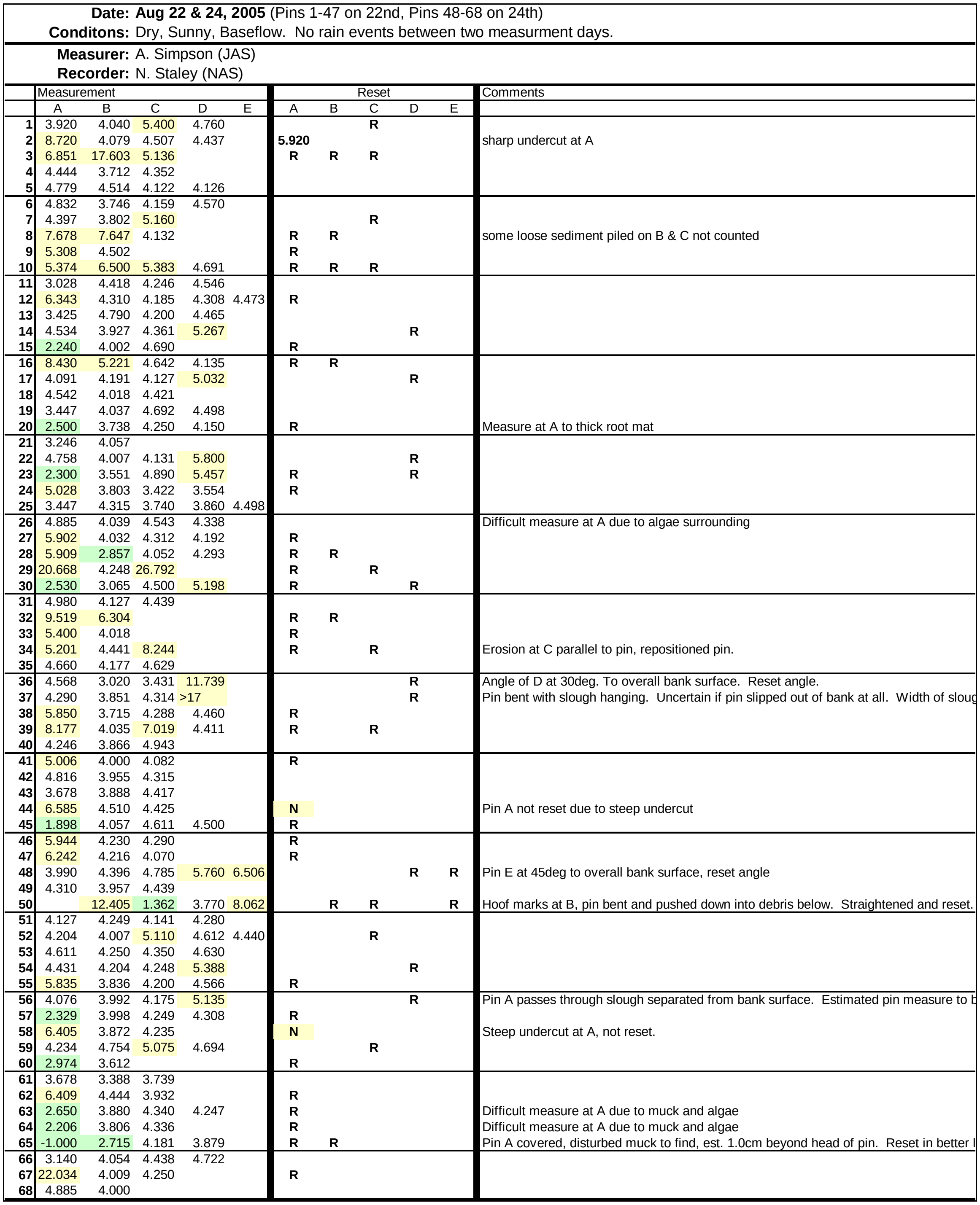
Conditions & Gage: **Recorder:**

	A	set	B	set	C	set	D	set	E	set	Comments
1m									▨	▨	
1r									▨	▨	
err.									▨	▨	
2m									▨	▨	
2r									▨	▨	
err.									▨	▨	
3m							▨	▨	▨	▨	
3r					▨	▨	▨	▨	▨	▨	
err.					▨	▨	▨	▨	▨	▨	
4							▨	▨	▨	▨	
5									▨	▨	
6									▨	▨	
7									▨	▨	
8							▨	▨	▨	▨	
9					▨	▨	▨	▨	▨	▨	
10									▨	▨	
11									▨	▨	
12											
13									▨	▨	
14									▨	▨	
15									▨	▨	

Figure A1. Sample of field form used for collecting erosion pin and scour chain monitoring data.

Appendix

Sample data collected during August 2005 is given in Figure A2.



Date: **Aug 22 & 24, 2005** (Pins 1-47 on 22nd, Pins 48-68 on 24th)
Conditons: Dry, Sunny, Baseflow. No rain events between two measurment days.

Measurer: A. Simpson (JAS)
Recorder: N. Staley (NAS)

	Measurement					Reset					Comments
	A	B	C	D	E	A	B	C	D	E	
1	3.920	4.040	5.400	4.760				**R**			
2	8.720	4.079	4.507	4.437		**5.920**					sharp undercut at A
3	6.851	17.603	5.136			**R**	**R**	**R**			
4	4.444	3.712	4.352								
5	4.779	4.514	4.122	4.126							
6	4.832	3.746	4.159	4.570							
7	4.397	3.802	5.160					**R**			
8	7.678	7.647	4.132			**R**	**R**				some loose sediment piled on B & C not counted
9	5.308	4.502				**R**					
10	5.374	6.500	5.383	4.691		**R**	**R**	**R**			
11	3.028	4.418	4.246	4.546							
12	6.343	4.310	4.185	4.308	4.473	**R**					
13	3.425	4.790	4.200	4.465							
14	4.534	3.927	4.361	5.267					**R**		
15	2.240	4.002	4.690			**R**					
16	8.430	5.221	4.642	4.135		**R**	**R**				
17	4.091	4.191	4.127	5.032					**R**		
18	4.542	4.018	4.421								
19	3.447	4.037	4.692	4.498							
20	2.500	3.738	4.250	4.150		**R**					Measure at A to thick root mat
21	3.246	4.057									
22	4.758	4.007	4.131	5.800					**R**		
23	2.300	3.551	4.890	5.457		**R**			**R**		
24	5.028	3.803	3.422	3.554		**R**					
25	3.447	4.315	3.740	3.860	4.498						
26	4.885	4.039	4.543	4.338							Difficult measure at A due to algae surrounding
27	5.902	4.032	4.312	4.192		**R**					
28	5.909	2.857	4.052	4.293		**R**	**R**				
29	20.668	4.248	26.792			**R**		**R**			
30	2.530	3.065	4.500	5.198		**R**			**R**		
31	4.980	4.127	4.439								
32	9.519	6.304				**R**	**R**				
33	5.400	4.018				**R**					
34	5.201	4.441	8.244			**R**		**R**			Erosion at C parallel to pin, repositioned pin.
35	4.660	4.177	4.629								
36	4.568	3.020	3.431	11.739					**R**		Angle of D at 30deg. To overall bank surface. Reset angle.
37	4.290	3.851	4.314	>17					**R**		Pin bent with slough hanging. Uncertain if pin slipped out of bank at all. Width of sloug
38	5.850	3.715	4.288	4.460		**R**					
39	8.177	4.035	7.019	4.411		**R**		**R**			
40	4.246	3.866	4.943								
41	5.006	4.000	4.082			**R**					
42	4.816	3.955	4.315								
43	3.678	3.888	4.417								
44	6.585	4.510	4.425			**N**					Pin A not reset due to steep undercut
45	1.898	4.057	4.611	4.500		**R**					
46	5.944	4.230	4.290			**R**					
47	6.242	4.216	4.070			**R**					
48	3.990	4.396	4.785	5.760	6.506				**R**	**R**	Pin E at 45deg to overall bank surface, reset angle
49	4.310	3.957	4.439								
50		12.405	1.362	3.770	8.062		**R**	**R**		**R**	Hoof marks at B, pin bent and pushed down into debris below. Straightened and reset.
51	4.127	4.249	4.141	4.280							
52	4.204	4.007	5.110	4.612	4.440			**R**			
53	4.611	4.250	4.350	4.630							
54	4.431	4.204	4.248	5.388					**R**		
55	5.835	3.836	4.200	4.566		**R**					
56	4.076	3.992	4.175	5.135					**R**		Pin A passes through slough separated from bank surface. Estimated pin measure to
57	2.329	3.998	4.249	4.308		**R**					
58	6.405	3.872	4.235			**N**					Steep undercut at A, not reset.
59	4.234	4.754	5.075	4.694				**R**			
60	2.974	3.612				**R**					
61	3.678	3.388	3.739								
62	6.409	4.444	3.932			**R**					
63	2.650	3.880	4.340	4.247		**R**					Difficult measure at A due to muck and algae
64	2.206	3.806	4.336			**R**					Difficult measure at A due to muck and algae
65	-1.000	2.715	4.181	3.879		**R**	**R**				Pin A covered, disturbed muck to find, est. 1.0cm beyond head of pin. Reset in better
66	3.140	4.054	4.438	4.722							
67	22.034	4.009	4.250			**R**					
68	4.885	4.000									

Figure A2. Erosion pin and scour chain field data collected during August 2005 for the Stroubles Creek monitoring site.

Appendix B - GWLF Sample Input and Output Files

The following GWLF parameter descriptions were written by Dr. Gene Yagow (2004). Information regarding the values and methodologies associated with individual parameters associated with Stroubles Creek modeling are described in Wagner (2004).

Watershed-Related Parameter Descriptions

No. of Rural Land Uses: The number of land uses simulated with both runoff and sediment components.
No. of Urban Land Uses: The number of land uses simulated with a build-up/wash off component.
Recession coefficient (day-1): The recession coefficient is a measure of the rate at which stream flow recedes following the cessation of a storm, and is approximated by averaging the ratios of stream flow on any given day to that on the following day during a wide range of weather conditions, all during the recession limb of each storm's hydrograph. Calculate using GWLF manual guidance, or use a default value = 0.0, then calibrate.
Seepage coefficient (day-1): The seepage coefficient represents the amount of flow lost as seepage to deep storage. Use a default value = 0.0, then calibrate.
Initial unsaturated storage (cm): Initial depth of water stored in the unsaturated (surface) zone. Use the recommended default value of 10 cm.
Initial saturated storage (cm): Initial depth of water stored in the saturated zone. Use the recommended default value of 0 cm.
Initial snow (cm): Initial amount of snow on the ground at the beginning of the simulation. Use the recommended default value of 0 cm.
Sediment delivery ratio: The fraction of erosion – detached sediment – that is transported or delivered to the edge of the stream.
Unsaturated Soil Moisture Capacity (SMC): The amount of moisture in the root zone.
Climatic Records: Model simulations are run from April through December in the first year to initialize storages denoted by and were not included in the model output load

summaries. Therefore, the number of years that need to be input to GWLF is the full number of calendar years of data + 1 for the initialization period.

A. No. of Years: The number of years of weather data in the weather.dat file to be used in any given simulation run.

B. Beg. Year: The 4-digit calendar year corresponding to the beginning month of weather data.

C. End Year: The 4-digit calendar year corresponding to the last month of weather data.

Antecedent Rainfall for each of 5 previous days (cm): The amount of rainfall on each of the five days preceding the first day in the weather file. Use a default value = 0 for each day.

Channel Erosion Parameters (Evans, 2003)

% Developed land: percentage of the watershed with urban-related land uses – defined as all land in MDR, HDR, and COM land uses, as well as the impervious portions of LDR.

Animal density: calculated as the number of beef and dairy 1000-lb equivalent animal units (AU) divided by the watershed area in acres.

Stream length: calculated as the total stream length of natural stream channel, in meters. Excludes the non-erosive hardened and piped sections of the stream.

Stream length with livestock access: calculated as the total stream length in the watershed where livestock have unrestricted access to streams, resulting in stream bank trampling, in meters.

Mean channel depth (m): calculated from relationships developed for the Chesapeake Bay Watershed Model by physiographic region, of the general form $y = a * Ab$, where y = mean channel depth in ft, A = drainage area in square miles, and “a” and “b” are regional coefficients.

A full description of GWLF channel erosion algorithms are provided in Chapter 4.

GWLF RSP File

The RSP files specifies the name and location of files used in GWLF simulation.

```
transport\transport6001.dat, nutrient\nutrient6001.dat, weather\weather600.dat, STE1
transport\transport6002.dat, nutrient\nutrient6002.dat, weather\weather600.dat, STE2
transport\transport6003.dat, nutrient\nutrient6003.dat, weather\weather600.dat, STE3
transport\transport6102.dat, nutrient\nutrient6102.dat, weather\weather600.dat, STE2x
transport\transport6103.dat, nutrient\nutrient6103.dat, weather\weather600.dat, STE3x
```

Transport, nutrient, and weather data files were written using an input file generator macro (Yagow, 2003). A file was created for each subwatershed individually with additional files for all contributing areas at the outlet of downstream subwatersheds.

Transport Input Files

The following is the transport file for subwatershed one used in the 2005-2006 GWLF model simulation.

transport6001.dat

```
10,5,0.0
0.2021,0.02,10,0,0,0.1886,12.35,10,1984,1994,0,0.0013651,4970.6,0.404
0
0
0
0
0
"APR",0.659,12.96,0,0.1
"MAY",0.659,13.92,1,0.3
"JUN",0.659,14.42,1,0.3
"JUL",0.659,14.22,1,0.3
"AUG",0.659,13.36,1,0.3
"SEP",0.659,12.2,1,0.3
"OCT",0.656,11.04,0,0.1
"NOV",0.653,10.04,0,0.1
"DEC",0.652,9.48,0,0.1
"JAN",0.651,9.78,0,0.1
"FEB",0.655,10.64,0,0.1
"MAR",0.658,11.8,0,0.1
"forest",28.71,61.39,0.0074,"for"
```

```
"water",1.99,1.00,0.0000,"h2o"
"cropland",0,78.21,0.9290,"crop"
"rural residential",0,70.07,0.0000,"RurR"
"pasture2",44.58,70.07,0.0000,"pas"
"pur_inst",0,70.07,0.0414,"puI"
"pur_H_com",30.42,70.07,0.0000,"puC"
"pur_L_resid",106.35,70.07,0.0369,"puL"
"pur_H_resid",1.49,70.07,0.0367,"puH"
"pur_M_resid",241.72,70.07,0.0405,"puM"
"imp_inst",0,98.00,3.5186,"iuI"
"imp_H_com",114.43,98.00,0.0000,"iuC"
"imp_L_resid",14.5,89.32,0.0000,"iuL"
"imp_H_resid",2.77,98.00,0.0000,"iuH"
"imp_M_resid",103.6,98.00,0.0000,"iuM"
```

The following is the transport file for the combined subwatersheds above subwatershed outlet two used in the 2005-2006 GWLF model simulation. The remaining transport files are available upon request by contacting Dr. Tess Wynn of the Biological Systems Engineering Department at Virginia Tech.

<u>transport6102.dat</u>

```
10,5,0.0
0.1242,0.02,10,0,0,0.1794,13.21,10,1984,1994,0,0.0009139,13454.6,0.496
0
0
0
0
0
"APR",0.741,12.96,0,0.1
"MAY",0.743,13.92,1,0.3
"JUN",0.743,14.42,1,0.3
"JUL",0.743,14.22,1,0.3
"AUG",0.743,13.36,1,0.3
"SEP",0.742,12.2,1,0.3
"OCT",0.731,11.04,0,0.1
"NOV",0.721,10.04,0,0.1
"DEC",0.717,9.48,0,0.1
"JAN",0.714,9.78,0,0.1
"FEB",0.729,10.64,0,0.1
"MAR",0.738,11.8,0,0.1
"forest",28.71,61.39,0.0074,"for"
"water",1.99,1.00,0.0000,"h2o"
```

```
"cropland",0,78.21,0.9290,"crop"
"rural residential",0,70.07,0.0000,"RurR"
"pasture2",44.58,70.07,0.0000,"pas"
"pur_inst",0,70.07,0.0414,"puI"
"pur_H_com",30.42,70.07,0.0000,"puC"
"pur_L_resid",106.35,70.07,0.0369,"puL"
"pur_H_resid",1.49,70.07,0.0367,"puH"
"pur_M_resid",241.72,70.07,0.0405,"puM"
"imp_inst",0,98.00,3.5186,"iuI"
"imp_H_com",114.43,98.00,0.0000,"iuC"
"imp_L_resid",14.5,89.32,0.0000,"iuL"
"imp_H_resid",2.77,98.00,0.0000,"iuH"
"imp_M_resid",103.6,98.00,0.0000,"iuM"
```

GIS data, including DEM, land use, and soils data, were taken from data compiled by Rachel Wagner (2004).

Nutrient Input Files

The following is the nutrient file for subwatershed one used in the 2005-2006 GWLF case study simulation. Only the values for sediment buildup rate, given in bold, are relevant. The remaining parameters are dummy values.

nutrient6001.dat

```
1400,2532,1.08,0.013
1,4,11,11,2
0.125,0.01
2.9,0.2
3.07,0.37
2.05,0.25
4,0.51
2.05,0.25
2.05,0.25
2.05,0.25
2.05,0.25
2.05,0.25
2.8,0.036,0.004
2.8,0.036,0.004
2.5,0.018,0.0018
3.9,0.023,0.0029
```

```
6.2,0.015,0.0018
0,0,0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
1
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
4.72,1.5,1.6,0.4
```

The following file provides the nutrient data for the combined subwatersheds one and two.

nutrient6102.dat

```
1400,2532,0.89,0.021
1,4,11,11,2
0.125,0.01
2.9,0.2
3.07,0.37
2.05,0.25
4,0.51
2.05,0.25
2.05,0.25
2.05,0.25
```

```
2.05,0.25
2.05,0.25
2.8,0.036,0.004
2.8,0.036,0.004
2.5,0.018,0.0018
3.9,0.023,0.0029
6.2,0.015,0.0018
0,0,0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
1
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
4.72,1.5,1.6,0.4
```

Weather Input Files

Weather data files necessary for GWLF simulation contain average daily temperature and daily rainfall in a comma-separated variable file. The weather files used in this research are available upon request by contacting Dr. Tess Wynn of the Biological Systems Engineering Department at Virginia Tech.

GWLF Model Output

GWLF provides two output files for each subwatershed; a summary file, and a breakdown of loadings from each land use category. An example summary file, **STE3dx-sum.csv**, for the entire watershed is given in Figure A3.

Appendix

```
STE3dx summary file   Thursday, Jun 29 2006, 09:56:53 AM
Average Monthly Values
Metric Units          (cm)       (cm)       (cm)       (cm)       (cm)       (Mg)       (Mg)       (kg)       (kg)                  (kg)       (kg)       (Mg)
Month                 Precip     Evapo TraiGr Wat FloRunoff     Strm Flow  Erosion    Sediment   Dis N      Tot N                 Dis P      Tot P      Stream Bank Erosion
APR                        3.845     2.5747          0   0.445758     0.4458      42.78      12.17       4.93                250.78       0.61      32.21    0.97495
MAY                         3.92     3.2901          0   0.315668    0.31565          0      14.19          0                311.38          0      37.23    1.02094
JUN                         1.73     3.8724          0   0.125065    0.12505          0        3.7          0                 79.96          0       9.71    0.36029
JUL                        4.025    5.18615          0   0.411096    0.41115     127.23      20.87       0.04                260.28          0      53.67    0.73609
AUG                        2.615     3.6184          0   0.244055    0.24405          0       7.58          0                170.71          0       19.8    0.65098
SEP                        0.355     0.7395          0   3.78E-03    0.00375          0       0.18          0                  4.11          0       0.47    0.07437
OCT                        3.075      2.044          0   0.456693     0.4567      38.44       22.9      20.22                213.96        2.5      60.92     0.7685
NOV                        6.135    2.30915          0    0.69147     0.6914      42.78      28.31       4.93                504.52       0.61      74.03    1.31481
DEC                         5.62    1.75385    0.52395   0.649696    1.17365      11.46      28.96      53.75                564.43        2.2       77.4    1.74889
JAN                        1.905    1.80365     1.1091   0.210102     1.3192       7.91       5.57     113.72                215.04       4.65      19.09    1.68647
FEB                         3.86     2.6776     0.3813   0.495727     0.8771      42.41      24.83      39.98                324.56       1.71      65.38    1.13682
MAR                        0.715    3.29905      0.065   2.42E-02    0.08925          0       1.94       6.66                 48.45       0.27       5.35    0.28855

Average Annual Values:
(Mg)                  (Mg)       (Mg)       (cm)
Sediment Yield        Stream BaiErosion    Runoff
               171.19    10.7617     313.01   4.073349


Average Land Use Values
Metric Units          (ha)       (cm)       (Mg)       (Mg)       (kg)       (kg)       (kg)       (kg)       (cm)
Source                Area       Runoff     Erosion    Sediment   Dis N      Tot N      Dis P      Tot P      Area-weighted RO
forest                     62.52       0.01      0.262      0.047          0        0.1          0        0.1         4.33E-04
water                       4.77          0          0          0          0          0          0          0                0
cropland                   60.81        0.4    237.125     42.422        7.4       66.8        0.9      108.3         1.69E-02
rural residential           5.91       0.09      0.134      0.024        0.1        0.1          0        0.1         3.69E-04
pasture2                  290.07       0.09     13.875      2.482         11       14.5        1.4        7.7      0.018093063
pur_inst                    2.25       0.09      0.052      0.009          0        0.1          0          0         1.40E-04
pur_H_com                   48.7       0.09      0.271      0.049        0.9          1        0.1        0.2         3.04E-03
pur_L_resid               277.46       0.09     18.039      3.227        5.4        9.9        0.7        8.8         1.73E-02
pur_H_resid                 1.79       0.09      0.249      0.044          0        0.1          0        0.1         1.12E-04
pur_M_resid               323.74       0.09     42.998      7.692        6.3         17        0.8       20.2         2.02E-02
imp_inst                    1.78       17.3          0      0.404          0       14.6          0        1.6         2.13E-02
imp_H_com                 183.19       17.3          0     41.604          0     1497.7          0      166.4       2.19641622
imp_L_resid                37.83       2.75          0      2.359          0       42.5          0        4.2         7.21E-02
imp_H_resid                 3.32       17.3          0       1.05          0       24.2          0          3         3.98E-02
imp_M_resid               138.75       17.3          0     69.775          0     1046.6          0      125.6      1.663588354
Groundwater                                                              213        213        8.7        8.7
Point Source                                                               0          0          0          0
Septic Systems                                                             0          0          0          0
```

Figure A3. STE3dx-sum.csv, GWLF output summary file for the outlet of the Stroubles Creek experimental reach.

Appendix C - SWAT Sample Input and Output Files

SWAT input files used by Wagner (2004) were used to create the SWAT simulation for this research. Subwatershed boundaries were adjusted through the ArcView 3.2 GUI and weather files were updated. All other information remained unchanged. Only parameters used for sensitivity analysis were manipulated. The following SWAT .bsn file provides general watershed characteristics.

```
Basin data          .bsn file Fri Aug 04 11:22:13 2006 AVSWAT2000 - SWAT interface MDL
        14.413    | DA_KM : Area of the watershed [km2]
         0.000    | DT : . Time step for infiltration and channel routing [hr]
         1.000    | SFTMP : Snowfall temperature [ºC]
         0.500    | SMTMP : Snow melt base temperature [ºC]
         4.500    | SMFMX : Melt factor for snow on June 21 [mm H2O/ºC-day]
         4.500    | SMFMN : Melt factor for snow on December 21 [mm H2O/ºC-day]
         1.000    | TIMP : Snow pack temperature lag factor
         1.000    | SNOCOVMX : Minimum snow water content that corresponds to 100% snow cover [mm]
         0.500    | SNO50COV : Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover
         1.000    | RCN : Concentration of nitrogen in rainfall [mg N/l]
         4.000    | SURLAG : Surface runoff lag time [days]
         1.000    | APM : Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)
         1.000    | PRF : Peak rate adjustment factor for sediment routing in the main channel
         0.006    | SPCON : Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel
                              sediment routing
         1.250    | SPEXP : Exponent parameter for calculating sediment reentrained in channel sediment routing
         0.000    | PARM1 : Not active
         0.000    | PARM2 : Not Active
         0.000    | PARM3 : Not Active
         0.000    | PARM4 : Not Active
         0.000    | PARM5 : Not Active
```

Appendix

```
   1.000    | EVRCH : Reach evaporation adjustment factor
   3.000    | EVLAI : Leaf area index at which no evaporation occurs from water surface [m2/m2]
   0.000    | FFCB : Initial soil water storage expressed as a fraction of field capacity water content
   0.003    | CMN : Rate factor for humus mineralization of active organic nitrogen
  20.000    | UBN : Nitrogen uptake distribution parameter
  20.000    | UBP : Phosphorus uptake distribution parameter
   0.200    | NPERCO : Nitrogen percolation coefficient
  10.000    | PPERCO : Phosphorus percolation coefficient
 175.000    | PHOSKD : Phosphorus soil partitioning coefficient
   0.400    | PSP : Phosphorus sorption coefficient
   0.050    | RSDCO : Residue decomposition coefficient
   0.500    | PERCOP : Pesticide percolation coefficient
     0    | IRTPEST : Number of pesticide to be routed through the watershed channel network
   0.000    | WDPQ : Die-off factor for persistent bacteria in soil solution. [1/day]
   0.000    | WGPQ : Growth factor for persistent bacteria in soil solution [1/day]
   0.000    | WDLPQ : Die-off factor for less persistent bacteria in soil solution [1/day]
   0.000    | WGLPQ : Growth factor for less persistent bacteria in soil solution. [1/day]
   0.000    | WDPS : Die-off factor for persistent bacteria adsorbed to soil particles. [1/day]
   0.000    | WGPS : Growth factor for persistent bacteria adsorbed to soil particles. [1/day]
   0.000    | WDLPS : Die-off factor for less persistent bacteria adsorbed to soil particles. [1/day]
   0.000    | WGLPS : Growth factor for less persistent bacteria adsorbed to soil particles. [1/day]
 175.000    | BACTKDQ : Bacteria partition coefficient
   1.070    | THBACT : Temperature adjustment factor for bacteria die-off/growth
   0.000    | MSK_CO1 : Calibration coefficient used to control impact of the storage time constant (Km) for normal flow
   3.500    | MSK_CO2 : Calibration coefficient used to control impact of the storage time constant (Km) for low flow
   0.200    | MSK_X : Weighting factor controlling relative importance of inflow rate and outflow rate in determining water
                          storage in reach segment
```

Appendix

Default channel parameters for SWAT simulation are reported in the .rte main channel input file. The following is a table of the default values for .rte channel parameters used in sensitivity analysis for the simulation of the Stroubles Creek watershed. Values not specified were left at the default setting.

Table A1.

Variable	Description	Value
CH_W(2)	Width of channel at top of bank (m)	4.1
CH_L(2)	Length of main channel (km)	3.1
CH_COV	Channel cover factor	0.5
CH_EROD	Channel erodibility factor (cm/hr/Pa)	0.2

SWAT provides a variety of output files and output can be given daily, monthly, yearly, or for the duration of the simulation. SWAT output files contain large amounts of data. Microsoft Visual Basic was used to create an Excel macro to extract sediment loading information used in this research. Sediment loading from the experimental reach was calculated as the difference in sediment entering and leaving subbasin three. The following table shows output from SWAT simulation of the Stroubles Creek watershed.

Appendix

Table A2. SWAT monthly sediment output extracted using the Excel macro.

	Subbasin 2			Subbasin 3			Sed Total
Date	Flow	Sed_out	Syld	Flow	Sed_out	Syld	tons
Jul-05	0.00533	12.39	0.016	0.00535	13.06	0.009	0.67
Aug-05	0.0376	337.4	0.424	0.03787	357.7	0.22	20.3
Sep-05	0.02755	36.17	0.004	0.02777	64.23	0.005	28.06
Oct-05	0.02392	31.32	0.004	0.0243	58.65	0.004	27.33
Nov-05	0.01689	23.91	0.003	0.01732	45.71	0.003	21.8
Dec-05	0.00018	0.00189	0	0.00018	0.00323	0	0.00134
Jan-06	0.00015	0.00166	0	0.00015	0.00273	0	0.00107
Feb-06	0.00017	0.00167	0	0.00017	0.00268	0	0.00101
Mar-06	0.2172	833.2	0.026	0.2237	1597	0.028	763.8
Apr-06	0.03858	49.53	0.003	0.03923	91.83	0.004	42.3
May-06	0.1456	397	0.02	0.1477	740.5	0.023	343.5
Jun-06	0.1549	235.3	0.017	0.1581	453.9	0.02	218.6

Appendix D - CONCEPTS Input/Output

The main file necessary for CONCEPTS simulation is the Run Control file. The Run Control file used for the 2005 – 2006 simulation of the Stroubles Creek watershed is shown below.

Run Control

```
!
! Main Input File
!
! case name
STR
! project title
Stroubles Creek model run 07/20/2005 to 06/21/2006
!-------------------------- Run Control Data -----------------------------
! upstream flow discharge file
STRHydrography0506.txt
! lateral inflow, and downstream boundary condition (0.08 is baseflow per Gene)
  0.00008  0 0
! sediment discharge at upstream end of the channel
 0.2 0.25 0.25 0.2 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
! silt fraction and downstream bed control
 1.0  1.0  0.5
! bank failure analysis
 7  5  5 0.
! type of flow resistance formulation
 1
! water temperature (20+ year avg for Stroubles Creek beginning in 1972)
 12.0
! sediment and streambank mechanics options
 1  1  1
!------------------------ Simulation Times -------------------------------
!       start                 end       time step
  07/20/2005 12:00:00  06/21/2006 12:00:00    100
!------------------------ Makeup of Modeling Reach -----------------------
! number of links
1
! linktypes for the above number of links
1
!----------------------------- Link 1 -----------------------------------
! REACH: number of cross sections and their data filenames
12
xs01.txt
```

Appendix

```
xs02.txt
xs03.txt
xs04.txt
xs05.txt
xs06.txt
xs07.txt
xs08.txt
xs09.txt
xs10.txt
xs11.txt
xs12.txt
!---------------------------- Output -----------------------------------
!single point and time
 1
 2
 1 10
 2
  07/21/2005 12:00:00
  06/21/2006 12:00:00
!single point, continuously in time
 2
 134471743
  1   1
  1
  07/21/2005 12:00:00  06/21/2006 12:00:00
 134471743
  1   10
  1
  07/21/2005 12:00:00  06/21/2006 12:00:00
!profile at specific time points
 1
 67
 1 1 1 10
 1
  06/21/2006 12:00:00
```

CONCEPTS simulation used daily streamflow data predicted by SWAT. The discharge timeseries file, STR Hydrography 0506, is shown below.

Appendix

STRHydrography0506

```
! Inflow data file for Stroubles Creek
! Baseflow
            0.03
! Sediment Rating Curve
              0
! Time series of flow and sediment discharges
07/20/2005 12:00:00  0   0.00003
07/21/2005 12:00:00  0   0.00003
07/22/2005 12:00:00  0   0.00003
07/23/2005 12:00:00  0   0.00003
07/24/2005 12:00:00  0   0.00003
07/25/2005 12:00:00  0   0.00003
07/26/2005 12:00:00  0   0.00003
07/27/2005 12:00:00  1   0.00003
07/28/2005 12:00:00  0   0.07044
07/29/2005 12:00:00  2   0.00001
07/30/2005 12:00:00  0   0.00001
07/31/2005 12:00:00  1   0.00000
08/01/2005 12:00:00  2   0.00101
08/02/2005 12:00:00  1   0.00001
08/03/2005 12:00:00  2   0.05451
08/04/2005 12:00:00  1   0.00001
08/05/2005 12:00:00  0   0.20160
08/06/2005 12:00:00  0   0.09138
08/07/2005 12:00:00  0   0.10040
08/08/2005 12:00:00  2   0.00002
08/09/2005 12:00:00  0   0.00002
08/10/2005 12:00:00  0   0.00002
08/11/2005 12:00:00  0   0.00002
08/12/2005 12:00:00  1   0.00002
08/13/2005 12:00:00  0   0.23550
08/14/2005 12:00:00  0   0.09994
08/15/2005 12:00:00  0   0.05563
08/16/2005 12:00:00  2   0.00002
08/17/2005 12:00:00  0   0.00002
08/18/2005 12:00:00  0   0.00002
08/19/2005 12:00:00  0   0.00002
08/20/2005 12:00:00  1   0.00002
```

Cross section files were specified at ten evenly spaced locations through the experimental reach. A sample cross section file is shown.

Appendix

Cross Section 1

```
!
! Input file of cross section 1.
!
! Name of xsection and rivermile in (km)
Cross Section 1 Stroubles Creek 1
    5.85
! friction factor (for total section)
  0.035
! tributary inflow
 0
!--------------------- Left FloodPlain -----------------------
! number of nodes
   5
! station and elevation for above number of coordinates in (m)
    0.00         4.35
    0.30         2.83
    36.58        2.81
    48.77        2.81
    56.27        2.81
! Manning's n of left Floodplain  (ANSWERS 2000 input file variable guide)
  0.12
!----------------------- Left Bank -------------------------
! number of nodes
   4
! station and elevation for above number of coordinates in (m)
    56.27        2.81
    57.76        2.30
    63.19        2.00
    63.43        1.59
! Soil layer data
! number of soil layers in the bank
   2
! layer 1: elevation of layer top (should be valley elevation)
    2.81
! layer 1: strength parameters (c',phi',phib,gamma_s)
    0.0    35    15.0 25950
! layer 1: erodibility, i.e. critical shear stress (Pa)
   3.16
! layer 1: sediment composition
   18.4
   12.0
   17.0
   35.5
   16.4
    0.7
```

```
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
! layer 2: elevation of layer top
    2.36
! layer 2: strength parameters (c',phi',phib,gamma_s)
    0.0    35    15.0 24065
! layer 2: erodibility, i.e. critical shear stress (Pa)   (includes Dr. Wynn data)
   9.74
! layer 2: sediment composition
   25.7
   12.8
   15.2
   28.6
   15.4
    2.3
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
! groundwatertable
    1.5
! Manning's n  (ANSWERS 2000)
  0.08
!----------------------- Channel Bed -------------------------
! number of nodes
  6
! station and elevation for above number of coordinates in (m)
    63.43          1.59
    64.40          1.45
    65.01          1.37
    65.44          1.26
    66.05          1.09
    66.35          1.06
! Elevation of bedrock (m)
     0.0
! porosity (using Colby option, 1963)
```

```
   0.41
! hiding factor
   0.25    0.8    0.65
! Surface layer and Substratum data
! number of sediment layers composing the bed
  1
! Layer 1, layer depth below bed surface
     0.00
! bed composition
   0.000
   0.000
   6.522
   5.652
   2.174
   4.782
   4.783
   8.696
  16.521
  30.870
  13.913
   3.913
   1.739
   0.435
! critical shear stresses for erosion of and deposition on cohesive beds,
! and erodibility coefficient (bed considered cohesionless ---dummy variables)
   0.10    5.00  0.00
! Manning's n (from Chow)
 0.065
!----------------------- Right Bank ------------------------
! number of nodes
 4
! station and elevation for above number of coordinates in (m)
    66.35          1.06
    66.72          1.97
    67.21          2.08
    67.33          2.70
! Soil layer data
! number of soil layers in the bank
  2
! layer 1: elevation of layer top (should be valley elevation)
     2.70
! layer 1: strength parameters (c',phi',phib,gamma_s)
    0.0    35    15.0 25950
! layer 1: erodibility, i.e. critical shear stress (Pa)
  3.16
! layer 1: sediment composition
```

```
   18.4
   12.0
   17.0
   35.5
   16.4
    0.7
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
! layer 2: elevation of layer top (should be valley elevation)
     2.25
! layer 1: strength parameters (c',phi',phib,gamma_s)
    0.0    35    15.0 23680
! layer 2: erodibility, i.e. critical shear stress (Pa)   (includes Dr. Wynn data)
   9.74
! layer 2: sediment composition
   25.7
   12.8
   15.2
   28.6
   15.4
    2.3
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
    0.0
! groundwatertable
    1.5
! Manning's n
  0.05
!--------------------- Right FloodPlain ----------------------
! number of nodes
  4
! station and elevation for above number of coordinates in (m)
    67.33         2.70
    82.30         2.70
    84.73         2.83
```

```
    84.76          4.35
! Manning's n of right Floodplain
  0.12
```

The user chooses the type of output given by CONCEPTS through the output specification section of the Run Control file. A section of the output file containing the sediment transport data used in this research is shown.

Appendix

```
Output    time-series  file      for       cross     section   Cross Section 1 Stroubles Creek 1   at        river     kilometer     5.85

Output    type         =         134471743
Output    periods      are:      from      7/21/2005  12:00:00 to                               6/21/2006    12:00:00


TIME      DISCHARGE    VELOCITY  DEPTH     STAGE     AREA      TOP                               WIDTH     SILT      DIS       SAND      DIS       GRAVEL    DIS       TOTAL     DIS       SILT      YLD       SAND  YLD  GRAVEL
(CMS)     (M/S)        (M)       (M)       (M2)      (M)       (CMS)                             (CMS)     (CMS)     (CMS)     (TONS)    (TONS)    (TONS)    (TONS)    (M)       (M)       (M)       (M)       (M)

  7/21/2005    12:05:23      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:13:36      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:21:49      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:30:02      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:38:15      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:46:28      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    12:54:41      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    13:02:54      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    13:11:07      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    13:19:20      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
  7/21/2005    13:27:33      0.03     0.077     0.385     1.443                          0.387     2.058  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  0.00E+00  -0.001  1.059      0  2.81    2.7
```

Figure A4. Sample section of CONCEPTS time series output file.

The data necessary for channel degradation calculations was extracted from the above file using an Excel macro. The macro was designed to calculate the net channel degradation from the experimental reach as the difference in sediment discharge at the upstream and downstream ends of the reach. Table A3 gives CONCEPTS output after manipulation using the CONCEPTS Excel macro.

Table A3. CONCEPTS simulation output for the Stroubles Creek simulation (showing monthly loading in tones) after processing with the CONCEPTS Excel macro.

506\0506output\STR0506_052.txt	
07/2005	0.3223
08/2005	0.2264448
09/2005	0.0009502
10/2005	0.000419
11/2005	7.3E-05
12/2005	0
01/2006	0
02/2006	0
03/2006	3.544813
04/2006	0
05/2006	-0.337

Vita

Nathan Staley was born on 5 January 1983, in Marion, VA. Until age four he was raised on a dairy farm in Rich Valley, VA, at which time his family moved over the mountain to Marion, VA. Nathan graduated from Marion Senior High School in 2001 and began college the following fall at Virginia Tech. In May, 2005, he graduated from Virginia Tech with a Bachelor of Science in Biological Systems Engineering and a Minor in Biology. Nathan has accepted a job as a Water Resources Engineer with Wetland Studies and Solutions, Inc., in Gainesville, VA. After gaining career experience, Nathan plans to return to the mountains of Southwest Virginia and pursue a career in water resource management.