The Pennsylvania State University
The Graduate School
College of Engineering

STREAMBANK CRITICAL SHEAR STRESS ESTIMATIONS USING SSURGO AND
EMPIRICAL EQUATIONS

A Thesis in
Civil Engineering
by
Kurt R. Smithgall

©2016 Kurt R. Smithgall

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2016
The thesis of Kurt R. Smithgall was review and approved* by the following

Peggy Johnson
Professor of Civil Engineering
Thesis Co-Adviser

Chaopeng Shen
Assistant Professor of Civil Engineering
Thesis Co-Adviser

Xiaofeng Liu
Assistant Professor of Civil Engineering

Patrick Fox
Head of the Department of Civil and Environmental Engineering
Professor of Civil and Environmental Engineering

*Signatures are on file in the Graduate School
Abstract:

Sedimentation of waterways is a growing problem. Sediment is the largest pollutant to the Chesapeake Bay, which can affect a variety of human elements. In watersheds across the country, eroding banks contribute the primary source of sediment to streams. To address bank erosion and stream instability, stream restoration is a common practice. Bank stabilization is a common component of stream restoration projects. Engineers and researchers utilize bank stability and erosion models to evaluate designs and to enhance resistance to bank erosion. A commonly cited criticism of stream restoration projects is the focus on the reach scale, yet the reach responds according to its contributing watershed. Few watershed-scale modeling studies exist due to current data limitations. This study evaluated the use of the SSURGO soil database combined with empirical equations to determine the critical shear stress of streambank soils across the country. Two phases of research were executed; first, measured soil parameters were compared to estimated soil database parameters. Second, existing soil empirical equations were evaluated for accuracy. The results show that on both site and national scales, SSURGO does not accurately represent streambank soil properties. Additionally, the results show that existing empirical equations are not accurate predictors of critical shear stress. The barrier of soil parameterization still exists for large-scale modeling. However, an unexpected result discovered in this research was the power law trend of critical shear stress in cohesive sediments has an exponent of -0.4. The coefficient of the power law relationship accounts for site-specific conditions and may include factors such as climate, land use, and vegetation. Further work is needed to develop the relationships for the coefficient.
# Table of Contents

List of Figures .......................................................................................................................... vi
List of Tables ........................................................................................................................... viii
List of Equations .................................................................................................................... ix
Acknowledgements ................................................................................................................ x
Introduction ............................................................................................................................. 1
Hypothesis / Objective / Research Question .............................................................................. 4
Literature Review ..................................................................................................................... 5
  Watershed Degradation .......................................................................................................... 5
  History of Stream Restoration ............................................................................................... 7
  Types of Bank Erosion ........................................................................................................... 9
  Bank Erosion Monitoring ...................................................................................................... 11
  Bank Erosion Modeling ........................................................................................................ 12
  Soil Parameters, Testing, and Theory ................................................................................... 13
Research Areas and Methodology .......................................................................................... 16
  Introduction .......................................................................................................................... 16
  Site Description .................................................................................................................... 16
  Fieldwork ............................................................................................................................. 18
  Laboratory Analysis ............................................................................................................ 20
  Bank Erosion Model Selection (CONCEPTS) ....................................................................... 21
  CONCEPTS Conceptual Framework .................................................................................... 21
  Regional Parameterization Framework ................................................................................ 25
  Database Introduction ......................................................................................................... 26
Results & Discussion ............................................................................................................... 28
  Oliver Run Design & Morphology ....................................................................................... 28
    Field Surveys ...................................................................................................................... 29
    Bed Material Sampling ...................................................................................................... 32
  Comparison between Measured and SSURGO estimated Soil Properties ......................... 33
    Oliver Run Soil Sampling and Analysis ............................................................................. 33
    Database Comparison of Properties ................................................................................... 35
  Evaluation of Empirical Equations ....................................................................................... 39

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvements to Soil Parameterization</td>
<td>45</td>
</tr>
<tr>
<td>Conclusions</td>
<td>48</td>
</tr>
<tr>
<td>Bibliography</td>
<td>50</td>
</tr>
<tr>
<td>Appendix A: Research Timeline</td>
<td>57</td>
</tr>
<tr>
<td>Appendix B: Program of Study (MS)</td>
<td>58</td>
</tr>
</tbody>
</table>
List of Figures

Fig 1: Different types of bank erosion. Source: [Langendoen, 2000] ......................................................... 10
Fig 2: Watershed overview map [Data Sources: PA DEP (2014), PennDOT(2016), ESRI(2015)]
........................................................................................................................................................................ 17
Fig 3: Oliver Run watershed characteristics [Data Sources: PA DCNR(2007), PA DCNR(2001),
US Department of Interior(2015)] ............................................................................................................................... 18
Fig 4: Soil sampling locations where the Map Unit Key (MUKEY) is shown [Data Source: USDA(2014)] ........................................................................................................................................ 20
Fig 5: Multi-layer approximation of sediment transport. Source: [Langendoen, 2000] ........ 22
Fig 6: SSURGO Hierarchy ........................................................................................................................................ 25
Fig 7: Soil Database Sampling Locations [Data Sources: ESRI(2015),USGS(2002)] .................. 27
Fig 8: Simulated and observed longitudinal profile changes ...................................................................................... 28
Fig 9: Longitudinal profile of relocated section of Oliver Run ............................................................................... 29
Fig 10: Changes in cross section 2 .......................................................................................................................... 30
Fig 11: Changes in cross section 4 .......................................................................................................................... 30
Fig 12: Oliver run boundary shear stress ............................................................................................................... 31
Fig 13: Riffle bed material size distribution ........................................................................................................... 32
Fig. 14: Pool bed material size distribution ............................................................................................................. 32
Fig 15: Measured oliver run soil particle size distributions .................................................................................... 34
Fig 16: SSURGO estimated particle size distribution for SSURGO horizons at oliver run site .. 34
Fig 17: Measured vs. predicted D_{50} [Data Source: Langendoen] ................................................................. 36
Fig 18: Comparison of measured vs. predicted percent clay [Data Source: Langendoen] .......... 37
Fig 19: Comparison of measured vs. predicted bulk density [Data Source: Langendoen] ........ 38
Fig 20: Histogram of measured critical shear stress values [Data Source: Langendoen] ........ 39
Fig 21: Evaluation of Smerdon and Beasley (1961) percent clay empirical equation [Data
Source: Langendoen] ................................................................................................................................................. 40
Fig 22: Critical shear stress as a function of percent clay [Data Source: Langendoen] ........ 41
Fig 23: Evaluation of Smerdon and Beasley (1961) D_{50} empirical equation [Data Source: Langendoen] ........................................................................................................................................................................ 42
Fig 24: Critical shear stress as a function of $D_{50}$ [Data Source: Langendoen] .......................... 43
Fig 25: Ratio of critical shear stress as a function of physiographic province [Data Source: Langendoen] .................................................. 44
Fig 26: Comparison of Briaud equations, Smerdon and Beasley (1961) equation with measured values [Data Source: Langendoen] ........................................................................ 46
Fig 27: Briaud equations [Data Source: Langendoen] .................................................................. 47
List of Tables

Table 1: Soil Sample Descriptions........................................................................................................ 19
Table 2: Sediment size fractions and corresponding transport equations. Source: [Langendoen, 2000].............................................................................................................................................. 23
Table 3: CONCEPTS data requirements .................................................................................................. 24
Table 4: Soil Parameterization Equations.................................................................................................. 26
Table 5: Oliver run measured properties .................................................................................................. 35
Table 6: SSURGO estimated properties .................................................................................................... 35
Table 7: Soil property correlation coefficients .......................................................................................... 45
List of Equations

Equation 1: Smerdon and Beasley (1961) percent clay equation. Error! Bookmark not defined.
Equation 4: Wang (2013) dimensionless critical shear stress equation. 45
Equation 5: Briaud equation 1. Error! Bookmark not defined.
Equation 6: Briaud equation 2. Error! Bookmark not defined.
Acknowledgements

I would like to sincerely thank Dr. Peggy Johnson for her constant support and guidance during the research process. Her technical competence and confidence in my abilities ensured the completion of this thesis. I also wish to express my gratitude to Dr. Chaopeng Shen. His large-scale modeling background helped develop a unique research area for this thesis. Additionally, I would like to thank Dr. Xiaofeng Liu for serving on my committee. A large thank you goes to Dr. Eddy Langendoen for providing the model CONCEPTS, the mini jet test database, and helping troubleshoot model errors. I would also like to thank Dr. Tong Qiu for providing soil testing guidance and verifying my soil classifications. Sebastian Redcay and Brian Halchak were critical to collecting survey data. Finally, I would like to thank my mother and father, Gary and Arlene Smithgall, for all the support in this academic pursuit.
Introduction

Sediment is one of the primary pollutants of the Chesapeake Bay [Hassett et al., 2005]. Waterway sedimentation can lead to a variety of ecological and infrastructure problems from reduced biodiversity such as fish and macroinvertebrate populations, to reservoir sedimentation, which can affect power generation and navigation. Current bank erosion modeling efforts feature limited feedbacks between surface water and groundwater. More complex coupled models exist; however, they require significant input data. The deficiency of necessary data for complex models is often a justification for the use of simpler models. Both the complexity and data requirements of bank erosion models continue to increase. The time and cost to collect the data needed to parameterize these types of models create a formidable obstacle. In this study, the parameterization and application of a physically based bank erosion model for predicting erosion at a stream restoration site using readily available data are tested.

Different entities implement stream restoration projects across the United States to restore ecological function and return morphological stability. A significant component of many, if not most, of these projects is bank stabilization [Hassett et al., 2005]. Channel banks can destabilize over engineering time scales for many reasons, but most commonly due to channel modifications and urbanization. As bank degrade and destabilize, channels can widen, leading to scour and erosion predominantly during high flow events. In extreme cases, a new channel may be formed. Increased peak flows and flashier storm flows, resulting from urbanization and land use changes, can further exacerbate channel degradation. Physical modification of stream channels as part of stream restoration efforts can affect, and be affected, by all of these issues.

The design of stream restoration projects requires a multi-disciplinary approach, which may include processes from hydrology, hydraulics, ecology, and geomorphology. A morphologically stable stream exhibits no net erosion or deposition of sediment over time. A stable channel configuration, or geometry, is dependent on the hydrologic regime as well as the type and volume of sediment transported. The hydrologic regime is a function of climate, topography, land use, and groundwater interactions. The accurate prediction of the hydrologic regime on a watershed scale requires a model. For sediment modeling, the type of sediment determines the governing equations. Channel bed and streambank soil properties can be
determined through soil sampling. However, soil properties are highly heterogeneous and can vary by orders of magnitudes along a bank profile [Sutarto et al., 2014].

The addition and removal of instream structures modifies how a channel adjusts its long-term morphology. Grade control structures affect streams for decades or even longer. One example is the legacy effects of millponds throughout the North East. The creation of millponds reduces the slope of a short section of river which then leads to sedimentation [Schenk and Hupp, 2009]. The lack of sediment in the water below the pond can result in localized scour as the river attempts to regain its equilibrium sediment concentration. This phenomenon is seen below the Hoover Dam. The removal of dams results in changes to sediment transport since a significant amount of legacy sediment is now available to erode and be transported through the system [Schenk and Hupp, 2009]. The effect of stream restoration structures on a longer, multi-decadal, time scale is not well understood; as some structures perform as designed while others have failed [Thompson, 2002].

Bank erosion models provide a method of predicting erosion following bank stabilization. Models exist in a wide range of complexity, from simplistic to highly complex. A persistent problem area of erosion modeling is the difference between cohesive and non-cohesive soil. Non-cohesive soils erode as a function of sediment size, whereas cohesive soils are dependent on additional factors. Further complications in modeling result from the mixing of cohesive and non-cohesive fractions. Additionally, soil properties exhibit spatial heterogeneity; as soils can vary considerably within just a small area [Hanson and Simon, 2001]. Advances in soil theory have enabled the development of 3-D erosion models, such as Virtual StreamLab (VSL3D), yet these models require parameters that are seldom readily available [Khosronejad et al., 2014]. Typically, researchers and engineers apply these models on the reach scale. Model setup requires extensive soil testing to determine the necessary properties. Due to the time and financial requirements for testing soil properties, models are seldom seen as a viable option for consulting engineers.

The parameterization of physically based erosion models requires sufficiently detailed soil and bank material data. A variety of methods exist to either measure or predict soil strength parameters. Early work focused on developing empirical equations to predict parameters [Smerdon and Beasley, 1961]. Recent work has focused on determining the physical soil strength processes to create physically based equations [Sang et al., 2015]. Parameters required in bank
erosion models include, but are not limited to, critical shear stress, erodibility, water content, bulk density, cohesion, and particle size. A major current knowledge gap is the lack of a method to determine soil parameters over a large area without extensive soil testing [Langendoen, 2000].

Many researchers argue that a watershed scale is the most efficient scale for restoration [Wohl et al., 2005; Palmer et al., 2014; Ogston et al., 2015]. The measurement of erosion in a small watershed led to the conclusion that significant variation in erosion exists at individual sites. The total sediment discharge of a watershed is affected by the timing and magnitude of discharge events [Palmer et al., 2014]. However, instrumenting at a watershed scale is typically not economically or logistically feasible for many cases. The alternative approach is erosion modeling at the watershed scale. Working on a watershed scale results in its own unique difficulties. When applied to stream restoration, the correct link must exist between stream restoration and sediment budgeting. Stream restoration projects typically reduce erosion, which, in turn, reduces the sediment supply. In order to design an effective project, there must be an accurate understanding of the available sediment supply [Smith et al., 2011]. When comparing erosion across watersheds, soil erosion rates measured at one scale are often not representative of sediment yield at another spatial scale [de Vente and Poesen, 2005]. Looking forward, the modeling of erosion at a watershed scale is a research area that would have impacts on watershed planning, land use and restoration projects.

The watershed scale is becoming more important for decisions and prioritizing restoration projects. Bank erosion can be a major contributor to the overall sediment load of a stream, and physically based erosion models have the advantage of being able to determine spatial patterns of erosion. However, the more complex the model, the more elaborate the data input requirements. Further development of soil parameterization methods would reduce the difficulty in setting up the complex erosion models. In reality, heterogeneous soil properties lead to hotspots of erosion, which are an important characteristic that should be captured in a model, yet this requires detailed spatial soil data. Since traditional soil testing is often an expensive and time-consuming option, alternative options of soil parameterization will be explored. This research is noteworthy since it creates a method of soil parameterization for a bank erosion model based on currently available datasets. The results and shortcomings identified will help guide further parameterization work, which will ultimately facilitate the complex modeling of erosion.
Hypothesis / Objective / Research Question

Hypothesis:
Sufficient publicly available soil characterization data exists for the prediction of bank erosion, particularly in the design of stream channel modifications with present bank erosion models.

Objective:
The objective of this study was to determine the availability, feasibility, and reliability of soil data to parameterize a selected streambank erosion model that could potentially be coupled with a hydrologic model. Data examined included existing field data, SSURGO data, and local data from a restored stream channel. Changes in the constructed restoration site over a decade was used as a case study to illustrate the geomorphic changes of a stream channel for the case in which the groundwater-surface water regimes and channel responses were largely unknown; hard points were used in the original design to accommodate those uncertainties.

Research Questions:
To satisfy the objective, several research questions were addressed. First, what physically-based models exist to model bank processes? What are their limitations and input parameters? Next, the restoration site was studied. How has the Oliver Run site changed over the last 10 years? What effect has the hard points had on channel development? How does this compare to an earlier study’s (Niezgoda, 2004) geomorphic model (FLUVIAL-12) predicted changes? Since different models are used in academia versus industry, there could be interesting findings. After the site investigation of Oliver Run, the SSURGO dataset will be utilized and there will be several questions related to it. Can simple soil characterization or Spatial Soil Data (SSURGO) be used to parameterize a physically based bank erosion model (CONCEPTS)? For this question, there will be a study site investigation as well as a regional study utilizing SSURGO data. One question remains which ties together all of the previous questions. Based on the results specified above, for watershed-scale modeling of erosional processes in streams, do we have bank material data that is sufficient to support realistic output from bank erosion models?
Literature Review

Watershed Degradation

The earth is changing from human influence with time and gradual, yet persistent variations. From the initial clearing of forests to create small farms and villages, to the development of highly populated urban areas and the accompanying infrastructure, the landscape of the world has progressively changed. The primary driving force for these changes has been growing human populations, yet there are consequences for these actions. Converting forestland to residential or urban land use affects the local surface and groundwater hydrology. Agricultural operations increase the amount of sediment and nutrients contributed to surface waters. Large hydroelectric projects, and even colonial millponds, modify the ability of rivers to convey sediment. Extracting natural resources, in the form of logging or mining, also changes local hydrology and sediment transport of affected watersheds. Currently in the US, 42% of the nation’s stream are listed in poor biological condition [US EPA, 2006]

Urbanization, or the process of converting natural, permeable land to impermeable land, affects the ecology, hydrology, and geomorphology of a region. Developed, impermeable areas disconnect surface water from groundwater since infiltration and groundwater recharge are greatly reduce. In urban areas, the volume of surface runoff and peak flows increase, resulting in “flashier” systems with high peak flows that achieve maximum discharge in less time as compared to a natural system. The flashier systems then affect the fluvial geomorphology, since the faster and deeper runoff erodes more sediment. The habitat of native, aquatic may no longer be suitable.

Worldwide food demand is increasing, while the amount of farmable land is decreasing, requiring more intensive and productive farming operations [Döös, 2002]. Historically, wetlands were converted to farmland; it was common to farm to the edge of streams and rivers. Now it is known that both those practices result in environmental degradation [McCorvie and Lant, 1993]. Wetlands provide a multitude of valuable ecosystem services, such as improving water quality from reducing sediment and nutrient inputs to surface waters. Excess nitrogen can lead to eutrophication in freshwater; while excess phosphorus leads to the same problem in saltwater. If nutrient levels are high, algal blooms reduce dissolved oxygen levels and areas can go hypoxic resulting in fish kills [Thronson and Quigg, 2008]. A lack of riparian buffers prevents vegetation
from entraining sediment. Buffers themselves can also reduce nutrient inputs to streams. The roots in riparian buffer vegetation reinforce bank material; they increase the effective cohesion of soil, making it less susceptible to erosion and scour [Pollen-Bankhead and Simon, 2010].

The construction of dams, both large and small, result in changes to hydrology and sediment transport. Colonial millponds serve as substantial grade control structures where the addition of small dams result in base level rise as sediment precipitates out in the still water of reservoirs causing sedimentation. A high concentration of millponds are scattered throughout the Northeast, many no longer serving a functional purpose and they pose an obstruction to fish migration. To address the problems associated with these millponds, dam removal has become more frequent [Shuman, 1995], especially in the Pacific Northwest, where the largest dam removal took place to enhance salmon migration [Stanley and Doyle, 2003]. However, when a dam removal project is completed, a large supply of legacy sediment is available to erosion. It can take decades for streams to return to equilibrium, as the large plug of sediment travels through the system [East et al., 2014]. Large hydropower dams also cause substantial, long term changes; the lack of sediment transport becomes more pronounced below large dams, where the channel and banks can be eroded as the river attempts to regain its equilibrium sediment concentration [Topping et al., 2000]. With enough time, even the largest reservoir may require dredging to remove sediment.

Mining and logging contribute significant changes to river systems. Forest logging can produce hydrological responses similar to urbanization, where large peak flows, along with increased surface runoff volume, lead to erosion. Mining can also have long lasting water quality impacts as acid mine discharge impairs a watershed for decades.

A common theme to the issues presented above is sediment. A variety of sources, such as agriculture, bank erosion, mining activities, and construction/urbanization, may contribute sediment to streams. Governments worldwide have recognized the need to address sediment, and have passes legislature calling for reductive measures. In the US, legislatives enacted the Clean Water Act in 1972. Originally, the CWA targeted point source pollution, such as wastewater treatment plants, but was later amended in 1987 to address non-point sources. Large scale restoration legislation is not limited to the United States. In the year 2000, the European Union issued the Water Framework Directive with the goal for all waterways to be in “good” chemical, ecological, and geomorphic condition by 2015 [Kallis, 2001]. Stream restoration is
increasingly seen as a method to reduce sediment in order to comply with these environmental regulations.

**History of Stream Restoration**

Stream restoration is a billion dollar a year industry in the US, and has been growing at an exponential rate [Bernhardt et al., 2005]. The restoration of streams can be executed for a variety of reasons from increasing fish habitat, to bank stabilization, and even mitigation banking [Thompson and Stull, 2002; Miller and Kochel, 2009; Doyle and Douglas Shields, 2012]. Projects like these are undertaken because natural forms or processes have been degraded, which now according to legislation warrant remediation or restoration. To address the potential myriad of sources that can degrade waterways, a truly multi-disciplinary approach must be utilized; this approach incorporates ecology, hydrology, and geomorphology [Wohl et al., 2005]. In the context of this thesis, stream restoration is defined as restoring or returning forms or processes that have become degraded or lost within the realms of ecology, hydrology, and geomorphology.

Historical stream restoration projects were designed primarily to enhance fish habitat due to overfishing before the Great Depression [Thompson and Stull, 2002]. Scientific evaluation of the structures occurred during the 1930’s, and within two years, a research team claimed fish populations were improved. Widespread implementation of the techniques was possible due to low-cost labor, and also government sponsored conservation projects led by the Civilian Conservation Corps [Thompson and Stull, 2002]. The addition of small drop structures created pools and aerated water. The structures were also implemented for grade control, to prevent degradation and erosion. However, the structures were not studied over the long term; many projects experienced problems shortly after construction, and very few maintained effectiveness twenty years post-construction [Thompson, 2002]. Government conservation efforts halted during World War II but resumed in the 1940’s thru 1960’s despite little to no changes in the design process [Thompson and Stull, 2002].

According to Thompson and Stull (2002), the modern era in stream restoration began with the growth of the environmental movement in the late 1960’s. Form-based restoration techniques, such as natural channel design, became popular during this time. Streams could be classified by the forms and shapes within their system, and then stable stream parameters could be looked up based a channel’s classification [Small and Doyle, 2012]. The classification of
restoration projects had mixed results; numerous failed projects weakened the public perception of stream restoration science. The failings can be attributed to oversimplification of the natural system, or that the fact that the contributing watershed has experienced significant changes and will no longer respond like its previous natural state [Small and Doyle, 2012].

The next school of thought centered on the restoration of geomorphic form, in particular, the riffle-pool morphology. The riffle-pool morphology is ideal habitat due to the heterogeneous nature of the calm, deep pools, and the shallow, fast riffles. Studies have shown that both macroinvertebrates and fish thrive in this type of morphology common in natural streams [Schwartz et al., 2014; Scrimgeour et al., 2014]. Again, project results comprise of both successful projects, but also some failures. Doyle and Douglas Shields (2012), have shown that macroinvertebrate populations in restored reaches never achieved the same population as those in natural channels. The notion of, “if you build it, they will come” has proven not to be true [Doyle and Douglas Shields, 2012]. However, this is not to say that riffle-pool morphology is not desirable, or to be included in stream restoration design; larger processes can override the effectiveness of site-scale measures [Lorenz and Feld, 2013]. The riffle-pool morphology is particularly useful due to the inherently stable maintenance mechanism of flow reversal: during high flow events, the riffles experience slow velocities and the pools experience high velocities, [Schwartz et al., 2014], yet there is still disagreement whether flow reversals occur [Jackson et al., 2015].

Today, there are current restoration projects around the US with different problems and goals for each geographic region. In the eastern US, the Chesapeake Bay Program is a multistate agreement to reduce pollutions delivered to the Bay. The program was created in 1983 and has expanded over the years. At its core are Watershed Implementation Plans, or WIP’s, which specify permissible nutrient and sediment loads are established for each state [Chesapeake Bay Program, 2012]. It is the responsibility of state and local governments to manage compliance efforts, commonly restoration techniques. The Chesapeake Bay Watershed features the highest density of stream restoration projects found anywhere in the country [Hassett et al., 2005]. In the Pacific Northwest, numerous restoration projects at performed to restore native salmon populations. Dams pose a barrier to spawning salmon, and fish ladders have mixed results. A common theme is dam removal, where the outdated dam is torn down and removed to reconnect the upstream and downstream watersheds. The largest dam removal project to date occurred in
the Elwha watershed, in Washington state, where the 32m (105ft) Elwha and 64m (210ft) Glines Canyon dam were removed to restore salmon migration [East et al., 2014]. Restoration efforts are not limited to the US; numerous large projects are undertaken in countries across the world like Australia and Great Britain [Fyirs et al., 2013; Smith et al., 2013]. There is a need for scientifically based restoration techniques to improve the practice of stream restoration [Wohl et al., 2005].

Types of Bank Erosion

Today, one of the most common components of stream restoration projects is bank stabilization [Bernhardt et al., 2005]. Banks can destabilize for a variety of reasons, and over different time scales, leading to bank erosion. Bank erosion can be the dominant sediment source in some watersheds, making it an important process. For example, a watershed in southern California receives over 67% of its total sediment from bank erosion [Trimble, 1997]. A survey of 15 watersheds in the glaciated Northeast found the median bank erosion to be 53% [Nagle et al., 2012]. Bank erosion requires knowledge of soil properties, erosion mechanisms, the effect of vegetation, and both surface and groundwater hydrology [Langendoen, 2000].

Bank erosion is characterized into five main types, each with its own erosional mechanism and relevant parameters. The material and the specific setting in the landscape determine the type of erosion that occurs. Rotational bank failure takes place in cohesive banks with shallow slope angles [Langendoen, 2000]. In this case, a portion of a layer of the bank fails, but tends to rotate backward as it slides [Laury, 1971]. The second type is planar failure, which occurs in cohesive banks with steep slopes (streambank failure). Planar failure is another mass wasting process like rotational failure, but due to the steep slope, the mass of sediment simply slides down the bank at the planar failure surface [Langendoen, 2000]. The third type of bank erosion is cantilever failure. Cantilever failure is common when a layer of cohesive material is on top of a layer of non-cohesive material [Simon et al., 2000]. The non-cohesive soil preferentially erodes while the cohesive fraction remains, resulting in an undercut bank. Once the cohesive materials can no longer support their weight, tension cracks develop, and the slap falls into the channel [Langendoen, 2000]. The fourth type of bank erosion is seepage erosion, also called piping or sapping erosion. This kind of erosion occurs when the exfiltration of
groundwater into a channel causes erosion of small conduits or tunnels [Langendoen, 2000]. The tunnels then can either collapse, or eroded material can clog the conduit, which causes pore water pressure to build until there is a bank failure [Hagerty, 1991]. Seepage erosion is poorly understood, yet its importance is increasing as the interactions between groundwater and erosion are studied [Fox and Wilson, 2010]. The final type of erosion is fluvial erosion. This type is most common and can occur anytime the material is wet. In this process, the water in the channel shears off soil particles, which become entrained in the fluid flow. This process is gradual, but occurs whenever the critical shear stress of the material is exceeded [Langendoen, 2000]. Fig 1 below depicts the different types of erosion where a) represents rotational failure, b) depicts planar failure, c) illustrates cantilever failure, and d) shows seepage erosion.

Fig 1: Different types of bank erosion. Source: [Langendoen, 2000]
**Bank Erosion Monitoring**

Different measurement methods exist for monitoring bank erosion. The simplest and most common is erosion pins. Erosion pins have a history due to simple installation and ease of use [Palmer et al., 2014]. The pins are stakes of metal, which are driven in the study area; the distance from the bank surface to the end of the pin are measured. Several pins spread over a zone can be used to predict the volume of sediment eroded. One downside to this method is that the bank is physically disturbed by the installation of the pins, which some may argue will affect the soil strength parameters [Hooke, 1979]. Another downside is a lack of real-time information. Scientists must physically measure the pin to record erosion, which makes short time interval measurements tedious to record.

The next method is surveying. Through cross section surveying, it is possible to determine the erosion of both the bank as well as channel bottom. This approach can require either a transit, laser level, or total station to measure each point. The resolution of the survey is dependent on permissible time. A weakness of this method is the time intensive nature needed to obtain high-resolution data and complex bank shapes, such as overhangs, which may be impractical to capture.

The next bank erosion method is photo-electronic erosion pins. Photo-electronic erosion pins are erosion pins in which the sensor can determine the length of the pin that is exposed. Since physical measurement is no longer required, it is possible to record measurements quasi-continuously [Lawler, 1991]. However, the same downside of disturbing the bank still exists, as the pin physically has to be driven into the bank.

The third method is a recent advancement, terrestrial laser scanning (TLS). With TLS, it is possible to obtain a high-resolution (10^7 point / bank face) point cloud of the bank surface [Rinaldi and Darby, 2007]. The advantage of 3D high-resolution data is the resulting detailed analysis that becomes possible with it. The comparison of the same study area from different time periods allows the volume of erosion and spatial patterns of erosion to be determined [Milan et al., 2007]. Common drawback to TLS are the expensive hardware, slow data collection, and ample computer resources to process the high-resolution data.

The final method is structure-from-motion or SfM. SfM was established as a photogrammetry technique in the 1980’s, but was not widely utilized due to limitations in data processing [Koenderink and van Doorn, 1991]. Despite the limitations, there have been bank
erosion applications during the analog age of SfM [Barker et al., 1997]. Recent advances in software and computer processing have resulted in several automated SfM software packages; a widely used example is Agisoft photoscan [Mertes et al., 2014]. Recently, SfM has been applied to a variety of geoscience applications, including bank erosion [Westoby et al., 2012]. Through SfM, a computer algorithm generates a TLS quality point cloud from a series of overlapping photos. With this method, the fieldwork consists of taking a series of pictures; the model can be built through computer processing. The exported point cloud has similar accuracy and density as TLS, yet does not require the expensive equipment. With this method continuous data collection is still not possible, yet it is more practical to collect data at more frequency greater than TLS. Each collection method has its unique strengths and weaknesses, and a perfect measurement technique does not exist, rather a combination of techniques could be utilized to link time scales and resolution for bank erosion.

**Bank Erosion Modeling**

Bank erosion modeling is an important topic since it is a critical component of channel stability analysis and stream restoration projects. Modeling requires knowledge of erosion mechanisms, combined with soil properties. Rinaldi and Nardi (2013) have reviewed modeling efforts of river bank erosion, and their applications to coupled simulations. Many different models exist, and they each have their unique tradeoffs.

BSTEM is a specific bank erosion model which accounts for bank erosion along with sediment transport of the channel bed material [Simon and Pollen, 2006]. One unique feature is the addition of the RipRoot module, which adjusts the effective cohesion of the soil due to vegetation [Simon et al., 2011]. The physically based model requires detailed soil parameters such as critical shear stress, cohesion, erodibility and others, yet there are limitations. In the current form, it is only possible to simulate the changes at a single cross section. The hydrology parameters are specified for each time step, it is not possible to input a hydrograph. Landscape position is not taken into account, i.e. land use is not considered.

CONCEPTS is a model developed by the USDA, National Sedimentation Laboratory [Langendoen, 2000]. This model simulates bank erosion and sediment transport similarly to BSTEM, yet it is structured to run multiple cross sections within a reach. The simulation is based on non-equilibrium sediment transport, which allows precipitation of excess sediment to simulate
aggradation accurately. Hydraulic routing is performed by 1D unsteady flow, which does not fully capture the turbulent flow of complex bank shapes, yet requires less computation time. Static groundwater level is used to adjust soil strength parameters leading to simulations that are more accurate; however, groundwater simulations are not dynamic. Similar to BSTEM, simulations require several specific soil strength parameters.

One major limitation of detailed, physically-based models is the uncertainty of soil parameterization. While there are numerous empirical and laboratory experiments performed to determine relationships between soil parameters, there is an inherent variability of properties, even from a specific soil at a specific site [Parker et al., 2008]. Sutarto et al. (2014) found that certain parameters varied by orders of magnitude at a single location. The problem of soil variability is widespread, and is not addressed in current modeling efforts of fluvial systems.

**Soil Parameters, Testing, and Theory**

A primary parameter of interest for erosion is critical shear stress, or the amount of shear stress required to move a single grain of sediment. Similarly, incipient motion is defined as the minimum shear stress needed to move a single particle, or the largest particle size that can be moved by a given shear stress. From the definitions above, there is difficulty in declaring when this condition occurs. Some researchers argue that incipient motion is met when a single particle moves. However, in turbulent flow conditions, particles may erode sooner than expected. For example, the turbulence from an eddy could create an impulse, which exerts enough force to move a particle, while the rest of the bed remains motionless. Declaring when cohesive sediment starts eroding is even more difficult due to the smaller particle size [L. A. Clark and T. M. Wynn, 2005]. The differences between cohesive and non-cohesive sediment prove to be significant with cohesive sediments increasing the complexity.

The study of non-cohesive sediment is the basis of bedload transport in river channel morphology. Three types of forces act on a non-cohesive particle: particle weight, contract forces, and fluid forces [Julien, 2002]. In a static channel, particle weight and contact forces are constant, while the fluid forces vary by the flow rate, depth, and turbulence. The shield’s diagram was the first attempt to plot the boundary between movement and non-movement of particles. The original diagram has been widely used, even recently, though other’s have offered improvements and added more data points for the curve [Miller et al., 1977; Buffington and
Montgomery, 1997]. One study shows the impulse of turbulent flow can provide enough force to mobilize sediment, even when the time-averaged shear stress is below the threshold for incipient motion [Diplas et al., 2008].

The erosion of cohesive particles is much more complex than non-cohesive particles. Due to their small size, the intermolecular forces of cohesion become dominant. Cohesive forces can be quite strong, and even become greater than gravitational forces. Undercut banks lead to different erosional processes, like mass failure, where an overhanging block of sediment can fall in the channel because the cohesive forces can no longer overcome gravity. Static factors such as organic matter, compaction, and temperature affect the erosion of the cohesive fraction, but also dynamic factors such as water content and pore water pressure [Salem et al., 2014; Sang et al., 2015]. The interrelatedness of all these processes is poorly understood.

Smerdon and Beasley (1961) developed empirical equations relating critical shear stress to percent clay, dispersion ratio, plasticity index, and mean particle size. Different studies have shown that these empirical equations do not hold up well, yet they continue to be used because they are simple and a more accurate solution has not been found [Mallison, 2008; Weidner, 2012]. The Smerdon and Beasley studies were based on a flume in a laboratory environment with homogenized, prepared soils. While careful preparation produces better relationships with predicting parameters, the predictions are only good for each specific soil prepared in that manner.

Due to the complexity of estimating parameters, and the difficulty in lab testing, a standard practice has become to measure properties in the field. The Submerged Jet Test Device (JET) is commonly used to determine the critical shear stress and erodibility of different soils in situ. The JET test device produces a jet of water, which scours the surface of the soil. Based on the depth of the scour hole and duration of the test, the critical shear stress and erodibility can be determined [Blaisdell et al., 1981; Hanson and Simon, 2001]. Despite growing use, the submerged jet test device does not consistently agree with either laboratory flume experiments or empirical equations [Mallison, 2008; Weidner, 2012]. A possible cause of the disagreement could lie in the manner the jet test data is collected. Traditionally, only the depth of scour hole and duration were used; research has shown that the shape of the scour hole has an effect on the predicted parameters. A Computation Fluid Dynamic study has demonstrated that the applied
shear stress for a narrow hole is not the same for a wider hole [Weidner et al., 2012]. Several lab and field studies have come to this conclusion as well [Weidner, 2012; Ghaneeizad et al., 2014].

Compounding the complexity of predicting and measuring cohesive soil parameters is the significant natural variability in parameters. There is a known inherent variability for a single soil in a single location, the measured variance in parameters can be orders of magnitude [Parker et al., 2008; Daly et al., 2015]. In addition to the inherent variability, roots from vegetation can further affect soil strength and erosion parameters [Pollen-Bankhead and Simon, 2010]. The effect of vegetation on soil properties is not static. The effect of water content on critical shear stress dynamically changes to affect the root reinforcement of streambanks [Pollen, 2007]. Overall, the natural variability is a significant uncertainty further compounded by vegetation. Due to considerable variation and uncertainties, the study of cohesive soils is an ongoing research area. Efforts have been made to determine bounding equations to provide a region for which expected values might fall [Briaud, 2013]. As cohesive soil theory advances, improved equations should allow more accurate parameter estimation, but at the present time, predictive soil strength equations have not improved markedly since the work of Smerdon and Beasley.
Research Areas and Methodology

Introduction

This study comprises of field and lab work in addition to data analysis. A field site was chosen where a stream was relocated for a highway mitigation project. Niezgoda (2004) collected bed material as well as cross section survey measurements. The geomorphic model FLUVIAL-12 (Chang, 1998) was used to predict future channel changes. The Niezgoda study survey data allowed the comparison of cross section surveys from 2004 with those measured in 2014. The comparison enabled assessment of trends in erosion and deposition. Soil samples from the field site were processed in a lab to determine the size distribution and Atterberg limits. The measured soil parameters were compared to those estimated from the Soil Survey Geographic Database (SSURGO), to determine the suitability of regional parameterization. Additionally, a database of submerged jet test and soil properties were compared to erosion properties determined by SSURGO and empirical equations.

Site Description

Oliver Run is a second order stream with a watershed area of 8.368 km². The perennial cobble bed stream is located in the Ridge and Valley Province of Pennsylvania [Niezgoda, 2004]. In 2003, the Pennsylvania Department of Transportation relocated the stream due to the construction of US Route 322. The final channel was constructed as a high sinuosity, type C [Rosgen, 1994; Niezgoda, 2004]. The reach longitudinal profile has a slope of 1.7%, with the \( D_{50} \) of the bed material falling within the gravel particle size. As part of the relocation project, natural riffle-pool morphology was mimicked; the designed channel included four riffles and three pools, with a pool-to-pool spacing of approximately six times the bankful width [Niezgoda, 2004]. Several in-stream structures were incorporated into the design, with rock vanes at the head and tail of riffles for the purpose of grade control. Root wads and rock linings were used to reinforce the outside of meander bends to reduce erosion [Niezgoda, 2004]. J-hooks were incorporated into a riffle to reduce near-bank velocity. In the time that has elapsed since construction, some structures were altered by high flow events. Despite minor changes in morphology, the reach continues to evolve without signs of rapid degradation. Floodplain vegetation was cleared for construction, and during the post-construction monitoring, little
vegetation growth was observed; however, over the next ten years, woody vegetation has established itself along the channel and throughout the floodplain. Fig 2 below shows the watershed location within Centre County Pennsylvania, the designated stream use from Chapter 93 of the Pennsylvania Code for water quality standards, and the site of the surveyed study reach [PA DEP, 2014].

Fig 2: Watershed overview map [Data Sources: PA DEP (2014), PennDOT(2016), ESRI(2015)]

The Oliver Run watershed is located within the Bald Eagle Creek watershed. The elevation in Oliver Run’s watershed varies from 324m to 701m. The larger watershed contains a variety of different land uses with the majority consisting of deciduous forest; there are some smaller agricultural areas as well as limited developed spaces. The geology consists primarily of sandstone formations; karst is not present in the watershed, despite formations found in the lower elevation valleys. Fig 3 below summarizes this information.
Fig 3: Oliver Run watershed characteristics [Data Sources: PA DCNR(2007), PA DCNR(2001), US Department of Interior(2015)]

Fieldwork

Six field surveys were performed, from 2003 to 2004, for the Niezgoda (2004) study. For this study, two additional surveys were performed, one in December, 2014 and another in December, 2015. Five representative cross sections and a longitudinal profile of the channel thalweg comprised each survey. For the December surveys, a Topcom GPT 3005W Total Station was used along with a Bluetooth data logger. In addition to the surveys, a pebble count was performed in May of 2014, according to the Wolman (1954) method. Like the prior study, pool
bed material was measured separately from riffle bed material to allow comparison to the previous study. To characterize bank and floodplain materials, five soil samples were taken as shown below in Fig 4. Left and right overbanks were sampled for the relocation reach, as well as immediately downstream, so that the constructed fill could be compared to the natural soil type in the area. Table 1 below characterizes the different soil samples.

Table 1: Soil Sample Descriptions

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Location #</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Constructed</td>
<td>River right, at the restoration site. Top layer rocky fill</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Constructed</td>
<td>Same location, second layer compacted clay</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Natural</td>
<td>River right, natural, 2” organic layer on top. Water seeping in the bottom, leaf litter</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Natural</td>
<td>River left, natural, 1-2” organic layer with leaf litter</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>Constructed</td>
<td>River left the site, no organic layer. Stopped at thick imbricated rock layer</td>
</tr>
</tbody>
</table>
Laboratory Analysis

The five soil samples taken in the field were processed to determine the size distributions, Atterberg limits, and ultimately the USCS Soil Classification. The #10 sieve separated the coarse fraction from the fine fraction. Next, the coarse fraction was washed to remove residual fines. Residual fines were added to the initially separated fines and oven dried with the washed, coarse fraction. Once dry, soil was run through a set of standard sieve sizes to determine the size distribution for each sample. Next, the fine fraction was combined and mixed to determine the Atterberg limits according to ATSM Standard D4318–05. Once the Atterberg limits and size distribution curves were determined, the soils were classified into the USCS system according to ASTM Standard D2487-11.
Bank Erosion Model Selection (CONCEPTS)

For this study, the physically based bank erosion model, Conservative Channel Evolution and Pollutant Transport System (CONCEPTS), was selected. A physically based model was chosen so that processes are modeled in a mechanistic manner; this way, the model has parameters of physical significance and can be measured. This particular model was selected for a variety of reasons. First, cohesive and non-cohesive sediments are distinguished, and each has corresponding erosion and deposition governing equations [Langendoen, 2000]. Another reason is that the model has the potential to be integrated into a hydrologic model. CONCEPTS requires hydrologic inputs such as groundwater level and an input hydrograph for the modeled reach; a hydrologic model could supply these, and then coupled hydrologic-bank erosion model has the possibility accurately capture dynamic erosional phenomena. Several studies have demonstrated the merits of coupled model simulations, and as the cost of high-performance computing decreases, it is expected that they become more prevalent [Wang et al., 2007; Mao et al., 2010; He, 2012; Kim et al., 2013].

CONCEPTS Conceptual Framework

The CONCEPTS computer model was developed by the US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory (NSL) in Oxford, Mississippi. The model simulates open channel hydraulics, sediment transport and channel morphology [Langendoen, 2000].

Hydraulics are calculated by a 1D diffusive wave equation, which combine the continuity equation with the Saint Venant equations and simplifying by removing inertial terms. The model is set up to accept different hydraulic structures such as culverts or bridge crossings, but for this study, no structures were simulated.

Sediment transport is addressed in a multilayer method where bedload is distinguished from suspended load, as seen in Fig. 5.
In application, a non-equilibrium approach is applied for non-cohesive bed material; where the erosion or deposition rate is proportional to the difference between the sediment transport capacity and sediment transport rate. For cohesive material, the [Parchure and Mehta, 1985] approximation was used for erosion, and the Krone (1962) formulation for deposition. Three different methods were used to determine the sediment transport capacity, Laursen (1958) for silt size class, Yang (1973) for sand size classes, and Meyer-Peter and Müller (1948) for gravel size classes. Error! Reference source not found. Table 2 below, shows the different size classes distinguished in CONCEPTS and the resulting transport equation.
Table 2: Sediment size fractions and corresponding transport equations. Source: [Langendoen, 2000]

<table>
<thead>
<tr>
<th>Size class</th>
<th>Upper bound (mm)</th>
<th>Representative diameter (mm)</th>
<th>Description</th>
<th>Transport equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.010</td>
<td>-</td>
<td>clay - very fine silt</td>
<td>Wash load</td>
</tr>
<tr>
<td>2</td>
<td>0.025</td>
<td>0.016</td>
<td>fine - medium silt</td>
<td>Laursen</td>
</tr>
<tr>
<td>3</td>
<td>0.065</td>
<td>0.040</td>
<td>medium - coarse silt</td>
<td>Laursen</td>
</tr>
<tr>
<td>4</td>
<td>0.250</td>
<td>0.127</td>
<td>fine sand</td>
<td>Laursen</td>
</tr>
<tr>
<td>5</td>
<td>0.841</td>
<td>0.458</td>
<td>medium - coarse sand</td>
<td>Yang</td>
</tr>
<tr>
<td>6</td>
<td>2.000</td>
<td>1.297</td>
<td>very coarse sand</td>
<td>Yang</td>
</tr>
<tr>
<td>7</td>
<td>3.364</td>
<td>2.594</td>
<td>very fine gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>8</td>
<td>5.656</td>
<td>4.362</td>
<td>fine gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>9</td>
<td>9.514</td>
<td>7.336</td>
<td>fine gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>10</td>
<td>16.000</td>
<td>12.338</td>
<td>medium gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>11</td>
<td>26.909</td>
<td>20.749</td>
<td>coarse gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>12</td>
<td>38.055</td>
<td>32.000</td>
<td>coarse gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
<tr>
<td>13</td>
<td>50.000</td>
<td>43.713</td>
<td>very coarse gravel</td>
<td>Meyer-Peter &amp; Mueller</td>
</tr>
</tbody>
</table>

Channel morphology or bank erosion and channel widening can be categorized into two different classes, fluvial erosion, and mass failure processes. Fluvial erosion of cohesive soils is determined by an excess shear stress approach [Ariathurai and Arulanandan, 1978]. While mass processes are addressed with a factor of safety approach. Planar and cantilever failure are simulated by determining the ratio of resistive forces to gravitational forces.

The bank erosion model CONCEPTS requires various cross sections, soil, and bed material characteristics for simulation. Table 3 shows the summary of the data needed as well as suggested collection and estimation methods Error! Reference source not found.. The Soil parameterization method listed under Bank Material Data is described in the next section.
Table 3: CONCEPTS data requirements

<table>
<thead>
<tr>
<th>Variables</th>
<th>Collection / Estimation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross Section Data</strong></td>
<td></td>
</tr>
<tr>
<td>River Station</td>
<td>ArcMap or Survey</td>
</tr>
<tr>
<td>Cross Section Geometry</td>
<td>Survey</td>
</tr>
<tr>
<td>Top and toe of bank nodes</td>
<td>Survey</td>
</tr>
<tr>
<td>Groundwater elevation</td>
<td>Measured or Estimated or Modeled</td>
</tr>
<tr>
<td>Bedrock elevation</td>
<td>Geologic Maps</td>
</tr>
<tr>
<td>Manning's coefficients</td>
<td>Look up based on vegetation and channel conditions</td>
</tr>
<tr>
<td>Bed material profile</td>
<td>Pebble Count</td>
</tr>
<tr>
<td>Left bank soil profile</td>
<td>Soil Sampling or Estimated</td>
</tr>
<tr>
<td>Right bank soil profile</td>
<td>Soil Sampling or Estimated</td>
</tr>
<tr>
<td><strong>Bed Material Data</strong></td>
<td></td>
</tr>
<tr>
<td>Particle density</td>
<td>Sample or Estimate</td>
</tr>
<tr>
<td>Porosity</td>
<td>Sample or Estimate</td>
</tr>
<tr>
<td>Size Distribution Curve</td>
<td>Pebble Count</td>
</tr>
<tr>
<td><strong>Bank Material Data</strong></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Particle density</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Porosity</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Permeability</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Critical Shear Stress</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Erodibility</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Cohesion</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Friction angle</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Suction angle</td>
<td>Soil Parameterization</td>
</tr>
<tr>
<td>Size Distribution Curve</td>
<td>Sieve Analysis / Soil Parameterization</td>
</tr>
</tbody>
</table>
Regional Parameterization Framework

Parametrization of physically-based models prove to be challenging, especially when attempting to model large areas [Kumar et al., 2013]. To aid in large-scale parameterization of soil properties, a novel regional parameterization is proposed below. Empirical equations were researched from available literature to estimate soil strength and erosion properties based on attributes available from the national SSURGO soil database [Smerdon and Beasley, 1961; Hanson and Simon, 2001]. On the XY plane, SSURGO data is discretized by the Map Unit Key (MUKEY), a numeric code from which further properties can be attributed. For a single MUKEY, there can be several components, each designated by their unique component code; within each component, there can be several horizons. Fig 6 below depicts this hierarchy.

![SSURGO Hierarchy](image)

Fig 6: SSURGO Hierarchy

The classification of SSURGO is important because parameters of interest, such size distribution and percent clay, vary on the horizon level, yet spatially it is not possible to differentiate differences at the MUKEY level. The primary horizon of a given MUKEY is distinguished in the tables. To simplify the analysis, the primary horizon was used for all comparisons to reduce the number of soil property values for a given MUKEY. The final parameterization method allows values to be determined for SSURGO soil types. Table 4 below summarizes the parameterization method.
Table 4: Soil Parameterization Equations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units Used in CONCEPTS</th>
<th>Equation/Value</th>
<th>Source/Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Shear Stress</td>
<td>Pa</td>
<td>$\tau_c = 0.0103 \times 100.0182(P_c)$ where $\tau_c = \text{lbs/ft}^2$ $P_c = % \text{ clay}$ OR $\tau_c = 0.0034(I_{w})^{0.84}$ where $I_w = \text{plasticity index}$</td>
<td>[Smerdon and Beasley, 1961]</td>
</tr>
<tr>
<td>Permeability</td>
<td>1/s</td>
<td>Bank height / conductivity</td>
<td></td>
</tr>
<tr>
<td>Erodibility</td>
<td>m/(s Pa)</td>
<td>$k_d = 0.2 \times \tau_c^{-0.5}$</td>
<td>[Hanson and Simon, 2001]</td>
</tr>
<tr>
<td>Suction Angle</td>
<td>degrees</td>
<td>Estimate between 12 and 15</td>
<td></td>
</tr>
<tr>
<td>Bulk Density</td>
<td>kg/m³</td>
<td>Direct from SSURGO</td>
<td></td>
</tr>
<tr>
<td>Particle Density</td>
<td>kg/m³</td>
<td>particle density = bulk density / (1 - porosity)</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>dimensionless</td>
<td>Direct from SSURGO</td>
<td></td>
</tr>
</tbody>
</table>

**Database Introduction**

An additional component of this study utilized a mini submerged jet test database, graciously contributed by Eddy Langendoen, of the US Department of Agriculture, National Sedimentation Laboratory. The database consists of soil erosion parameters derived from mini submerged jet tests as well as measured soil properties at the test locations. In addition to the Oliver Run site comparison with SSURGO, this database will allow comparison of SSURGO estimated parameters with measured bank soil parameters on a larger scale, which is crucial to evaluate the efficacy of a regional soil parameterization method. The main properties of interest are critical shear stress, $D_{50}$, percent clay, bulk density, and particle size distribution information.
Sample sites are located in five states as well as different physiographic provinces. Fig 7 shows the spatial distribution.

Fig 7: Soil Database Sampling Locations [Data Sources: ESRI(2015), USGS(2002)]
Results & Discussion

Oliver Run Design & Morphology

The Oliver Run stream restoration project features several large rock structures. The purpose of these structures, or hard points, is to prevent erosion at specific areas of the channel. One example is the outside of a meander bend where high shear stress is expected. Another is at the base of a riffle before a pool; this structure prevents vertical erosion and helps maintain the riffle-pool morphology. To predict future changes, the Niezgoda study used the geomorphic model FLUVIAL-12. Fig 8 shows the initial longitudinal profile from 2003, the simulated thalweg ten years in the future, and the actual thalweg after 11 years of erosional processes.

![Simulated and observed longitudinal profile changes](image)

Fig 8: Simulated and observed longitudinal profile changes

The figure shows several trends; some of the pools are aggrading with sediment, while some of the riffles are degrading, and several points experience no changes at all.
Field Surveys

Part of the Niezgoda (2004) study involved surveying five cross sections of Oliver Run for 1.5 years post-construction. To evaluate how the channel is changing, this study revisited the Oliver Run site to perform the same survey ten years after completion. Fig 9 shows the longitudinal profile. The figure shows that there have been small changes over the past eleven years. Some of the riffles are degrading, while the pools are aggrading, but overall, there have been minimal changes.

Fig 9: Longitudinal profile of relocated section of Oliver Run

Fig 10 shows channel widening of the banks. This particular cross section occurs at a meander where the curving channel produces secondary circulation, which may have contributed to the erosion. One-dimensional hydraulic models are unable to resolve secondary circulation since it is a two-dimensional hydraulic problem.
Fig 10: Changes in cross section 2

Fig 11 shows small vertical adjustment of the streambed with little changes to the bank. From this study it is unclear what this adjustment is due to.

Fig 11: Changes in cross section 4
The boundary shear stress was examined to help explain the observed changes. The Niezgoda study calculated the boundary shear stress at each cross section during each survey. Fig 12 depicts the boundary shear stress at each cross section compared with HEC-RAS simulated channel shear stress for a bankful flow. Note the lines are only to connect the data points and do not represent continuous data.

![Variation in Boundary Shear Stress Along Reach](image)

**Fig 12:** Oliver run boundary shear stress

The figure shows small variations in measured boundary shear stress between each cross-section, but the HEC-RAS simulated values show an interesting trend. Cross section 1, which experienced substantial changes post-construction, featured the highest simulated channel shear stress of the five studied. Cross section 2, where the channel widening occurred, had the second largest simulated shear stress. Cross section 4, where the thalweg eroded, had the third largest simulated shear stress. On the opposite end of the spectrum, cross section 3, which had the lowest shear stress, is experiencing deposition in the pool.
Bed Material Sampling

The channel bed material was sampled in 2004 as well as 2015. Significant changes in bed material are indicative of changing sediment and flow regimes. The Wohlman method was used to determine the size distribution of bed material. Two samples were taken at both the riffle and pool morphology, and then averaged to obtain a representative riffle and pool distribution, which was compared with the Niezgoda study. Fig 13 and Fig. 14 show very little change in the bed material size distribution.

Fig 13: Riffle bed material size distribution

Fig. 14: Pool bed material size distribution
The minimal changes in the bed material of riffles and pools leads to the conclusion that the channel is not experiencing large changes, such as aggradation or degradation.

One of the largest changes at the Oliver Run site since construction has been the establishment of vegetation. Woody vegetation further reinforces bank and prevents erosion. Fig 9 displays that the pools have slightly aggraded, while some of the riffles have degraded. Fig 10 shows the lateral channel widening occurring at cross section 2.

In the ten years since construction, there have been small changes, but no indication of large changes. The small changes include channel widening seen at cross section 2, thalweg erosion seen at cross section 4, and pool deposition seen at cross sections 3 and 5. There are minimal changes in both the riffle and pool particle size distributions. Based on the measured boundary shear stress, the small changes would be hard to predict, whereas the HEC-RAS simulated channel shear stress for bankful flow is more indicative of the measured changes. Despite the limitations of a 1-D hydraulic model, HEC-RAS performed well, and the model results compare well with the measured changes.

**Comparison between Measured and SSURGO estimated Soil Properties**

To develop a regional soil parameterization method for physically based models, first the accuracy of SSURGO must be determined. The accuracy comparison included two different analysis scales, the reach scale at the Oliver Run site, as well as a regional level, which features data from different states. SSURGO estimated values were compared against measured values to evaluate the accuracy of SSURGO estimates.

**Oliver Run Soil Sampling and Analysis**

Fig 4 shows only one MUKEY in the SSURGO database for the Oliver Run study site. Five soil samples were taken in the field, the size distribution and Atterberg Limits were determined through lab analysis. Fig 15 shows the measured particle size distributions, and Fig 16 shows the SSURGO estimated particle size distributions. Since there are several components and horizons for the single MUKEY, all were graphed to see if any were a good match with measured data.
Fig 15: Measured Oliver run soil particle size distributions

Fig 16: SSURGO estimated particle size distribution for SSURGO horizons at Oliver run site
The figures show that the SSURGO estimates are too fine, which would affect the values of percent clay, \( D_{50} \), and ultimately, their applications in empirical equations. Table 5 summarizes the Atterberg limits, \( D_{50} \), and USCS soil classification for the soils found at the Oliver Run site, while Table 6 reviews the SSURGO estimates at the Oliver Run site.

Table 5: Oliver run measured properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>LL</th>
<th>PL</th>
<th>PI</th>
<th>( D_{50} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.9</td>
<td>24.8</td>
<td>3.0</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>18.6</td>
<td>16.7</td>
<td>1.9</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>29.9</td>
<td>24.1</td>
<td>5.8</td>
<td>0.11</td>
</tr>
<tr>
<td>4</td>
<td>30.4</td>
<td>24.6</td>
<td>5.8</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>34.3</td>
<td>28.4</td>
<td>5.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 5: Oliver run measured properties

<table>
<thead>
<tr>
<th>Horizon</th>
<th>LL</th>
<th>PL</th>
<th>PI</th>
<th>( D_{50} )</th>
<th>USCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>69</td>
<td>30</td>
<td>22</td>
<td>8</td>
<td>0.16</td>
<td>SM</td>
</tr>
<tr>
<td>70</td>
<td>30</td>
<td>18.5</td>
<td>11.5</td>
<td>0.02</td>
<td>SM</td>
</tr>
<tr>
<td>71</td>
<td>30</td>
<td>18.5</td>
<td>11.5</td>
<td>0.01</td>
<td>CL-ML</td>
</tr>
<tr>
<td>65</td>
<td>35</td>
<td>21</td>
<td>14</td>
<td>0.01</td>
<td>CL</td>
</tr>
<tr>
<td>66</td>
<td>35</td>
<td>21</td>
<td>14</td>
<td>0.01</td>
<td>CL</td>
</tr>
<tr>
<td>67</td>
<td>35</td>
<td>28</td>
<td>7</td>
<td>0.01</td>
<td>ML</td>
</tr>
<tr>
<td>62</td>
<td>27.5</td>
<td>22</td>
<td>5.5</td>
<td>0.05</td>
<td>SM</td>
</tr>
<tr>
<td>64</td>
<td>27.5</td>
<td>22</td>
<td>5.5</td>
<td>0.02</td>
<td>SM</td>
</tr>
</tbody>
</table>

A possible source of this error for the SSURGO estimates could be the lack of distinguishing fill from native soil. The SSURGO map only shows native, undisturbed soils. Any modifications or amendments to the soil are not shown. With the proximity of streams to roads, and the history of channel modifications, current streambank soils can be significantly different than the native soils. At the reach scale, SSURGO does not accurately estimate soil parameters for streambank soils.

**Database Comparison of Properties**

Next, SSURGO estimates were compared on the regional basis. Of the many different soil properties, three were selected. The three properties chosen are \( D_{50} \), percent clay, and bulk density. Those properties were chosen because of the immediate applications of \( D_{50} \) and percent
clay in existing empirical equations; bulk density was selected because critical shear stress can be affected by it. Fig 17 shows a lack of strong agreement between measured and predicted values of $D_{50}$.

For a range of measured values, there is little variation in predicted values. Based on the $D_{50}$ comparison, it is not recommended to use SSURGO to estimate $D_{50}$ for streambank soils.

The next property examined was percent clay. Fig 18 shows there is little relationship between measured and predicted percent clay.
The figure shows large scatter with no discernable trends. Based on the percent clay correlation, it is not recommended to use SSURGO to estimate percent clay for stream bank soils. The last property examined was bulk density. Fig 19 shows the comparison between measured and predicted percent clay.
Of the three different properties, bulk density was the best match; however, percent clay and $D_{50}$ are more useful than the bulk density in empirical equations.

This work shows that at the current time, SSURGO does not provide an accurate representation for streambank soils, at both a site or national scale. Possible reasons for this discrepancy include a lack of updated soils due to disturbance or fill, and a fundamental inaccuracy in capturing detail at the fine scale required for erosional processes. For the application of large scale, physically based erosion models, a new dataset needs to be developed, since current options are not applicable for this type of modeling.
**Evaluation of Empirical Equations**

The next section of this study evaluated the accuracy of existing empirical equations. The two equations evaluated were developed by Smerdon and Beasley (1961); they estimate critical shear stress as a function of percent clay and D$_{50}$. This analysis of empirical equations utilizes the dataset provided by Eddy Langendoen. The critical shear stress derived from a submerged jet test device will provide the in-situ measured streambank critical shear stress. The histogram of the measured critical shear stress values is shown below in Fig 20.

![Histogram of Measured Critical Shear Stress Values](Data Source: Langendoen)

**Fig 20:** Histogram of measured critical shear stress values [Data Source: Langendoen]

The figure shows a large range of measured critical shear stress values with some very large (>50 Pa) values. The Smerdon and Beasley equation evaluated was based on percent clay show in

**Error! Reference source not found.**

$$\tau_c = 0.4993 \times 10^{0.0182 \times P_c}$$  

(Equation 1)

where $\tau_c$ = pascals, and $P_c$ is soil percent clay.
Fig 21 graphs the ratio of predicted to measured critical shear stress versus percent clay.

![Comparison of %Clay to Accuracy of Smerdon Empirical Equation](image)

**Fig 21: Evaluation of Smerdon and Beasley (1961) percent clay empirical equation [Data Source: Langendoen]**

The figure shows when critical shear stress is estimated as a function of percent clay, the equation underestimates the critical shear stress, with a few exceptions. Fig 22 further shows this conclusion, where the measured values are plotted along with the curve of estimated values as a function of percent clay.
Fig 22: Critical shear stress as a function of percent clay [Data Source: Langendoen]

The second Smerdon and Beasley (1961) equation is a function of $D_{50}$ shown below in:

$$\tau_c = 3.54 \times 10^{-28.1 D_{50}}$$  \hspace{1cm} (Equation 2)

where $\tau_c = \text{pascals}$, and $D_{50}$ is the median particle size in mm.

Fig 23 graphs the ratio of predicted to measured critical shear stress versus $D_{50}$. 

---

Comparison of Smerdon Empirical Equation

- Measured Values [Source: Langendoen]
- Predicted Values

Critical Shear Stress [Pa]

Percent Clay

0 5 10 15 20 25 30 35 40 45 50

0 20 40 60 80 100 120
Fig 23: Evaluation of Smerdon and Beasley (1961) $D_{50}$ empirical equation [Data Source: Langendoen]

As shown in the figure, the second empirical equation overestimates the critical shear stress, since the values are greater than a ratio of one. The overestimation trend can also be seen in Fig 24, where the measured values are compared to the estimated curve as a function of $D_{50}$.
This study found that the Smerdon and Beasley (1961) equations are not good predictors of critical shear stress at either a site or regional scale. Both equations varied considerably, with one equation overestimating, and the other equation underestimating critical shear stress. To see if any trends could be uncovered, the samples were further discretized by physiographic province. Fig 25 plots the ratio of predicted to measured critical shear stress as a function of physiographic province using the percent clay Smerdon and Beasley equation.

Fig 24: Critical shear stress as a function of $D_{50}$ [Data Source: Langendoen]
This analysis found that the Smerdon and Beasley equations are poor predictors of critical shear stress. The single input variable equations are simple to use, yet lack the ability accurately predict critical shear stress since it is a function of several different properties. An example of a recent attempt is by (Julian and Torres, 2006), who produced a third order polynomial predicting critical shear stress as a function of silt-clay percentage and erosion rate, shown below in

\[ \tau_c = 0.1 + 0.1779(SC) + 0.0028(SC)^2 - 2.54E - 5(SC)^3 \] 

(Equation 3)

where \( \tau_c \) = pascals, SC is the silt-clay (<0.063mm) content, and E is the erodibility rate (cm/s).

A unique part of the Julian and Torres equation is the addition of a vegetation coefficient to compensate for the effect of vegetation. The Julian and Torres equation was compared to the Smerdon and Beasley equations in this study, but it was found to have poor predictive power. Other efforts include (Wang, 2013), which is a function of fine sediment and water content, shown below as Equation 4:
\[ \tau_{*c} = 8.46 - 27.76 \times w + 73.69 \times P_c + 83.22 (w \times P_c) \]  
(Equation 4)

where \( \tau_{*c} \) is the Shields parameter, \( w \) is the water content (in decimal form), and \( P_c \) is the percentage of clay in the soil (in decimal form).

Even with the addition of water content, the Wang equation still has scatter in the results and does not fully predict all of the natural variation. Due to the scatter from the original work, Equation 4 was not included in the study, but remains an option for others seeking a different empirical equation. At this time, an equation that accurately predicts critical shear stress was not found. Without a venerable predictive equation, expensive field and lab tests remain the only viable option to definitively determine critical shear stress. This limitation prevents large-scale modeling of erosional processes.

**Improvements to Soil Parameterization**

The previous section highlights the limitations of existing empirical equations. This section focuses on methods to improve predictive soil property equations. First, a correlation analysis of the measured soil properties found in submerged jet test dataset showed that none of the selected parameters has a strong correlation with critical shear stress. The parameters included in the analysis were critical shear stress (\( \tau_c \)), percent sand, percent silt, percent clay, \( D_{50} \), and bulk density. Table 7 summarizes the correlation coefficients.

**Table 7: Soil property correlation coefficients**

<table>
<thead>
<tr>
<th>( \tau_c )</th>
<th>%sand</th>
<th>%silt</th>
<th>%clay</th>
<th>( D_{50} )</th>
<th>bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_c )</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%sand</td>
<td>-0.0828</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%silt</td>
<td>-0.03529</td>
<td>-0.87411</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%clay</td>
<td>0.135241</td>
<td>-0.71228</td>
<td>0.458314</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( D_{50} )</td>
<td>0.016361</td>
<td>0.223501</td>
<td>-0.51289</td>
<td>-0.29879</td>
<td>1</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.163986</td>
<td>0.140478</td>
<td>-0.09387</td>
<td>-0.16972</td>
<td>0.124687</td>
</tr>
</tbody>
</table>

Since the table shows that none of the soil properties has a close correlation coefficient, there cannot be an expectation to produce an accurate empirical equation based on these parameters alone.
Many others have shown that the critical shear stress off cohesive sediments are difficult to predict because it is based on different soil properties that are hard to measure. Existing empirical equations do not predict critical shear stress due those different soil properties. In Jean-Louise Briaud’s work, he proposes two power functions that act as bounding equations, providing a region of possible values [Briaud et al., 2004; Briaud, 2013]. Equation 5 acts as the lower limit, graphed as equation 1, while Equation 6 acts as the upper limit, graphed as equation 2:

\[
\tau_c = 0.05(D_{50})^{-0.4} \quad \text{(Equation 5)}
\]

\[
\tau_c = 0.006(D_{50})^{-2} \quad \text{(Equation 6)}
\]

where \(\tau_c\) = pascals and \(D_{50}\) is the median particle size in mm.

Briaud developed the curves by fitting data measured from the Erosion Function Apparatus. The Erosion Function Apparatus erodes the soil by water flowing horizontally across the soil and shearing off particles. The dataset used in this study utilized a mini-jet device, which erodes soil from a vertical impinging jet. Fig 26 graphs equations 5 and 6 as a function of \(D_{50}\).
The figure shows that the data falls roughly in the region of the second equation, but over half of it is outside of the overlapping region. One interesting trend is that the data has the same approximate slope as the first equation, Briaud Equation 1. The exponent of the second equation is the same as the data (-0.4), but the coefficient varies widely. The different coefficient may be due to the difference of measurement devices. To explore the trend, Fig 27 shows Briaud Equation 1 along with an adjusted equation where the coefficient is changed to six, reflecting the average coefficient for the data.
From this work, it is proposed that the critical shear stress of cohesive sediments for the data set follows a power law relationship where the exponent is -0.4. With this power law relationship, the coefficient then becomes a combination of vegetation, climate, and site specific soil properties. The power law relationship is a new finding and further will need to be done to determine the coefficient relationships; however, this relationship could lead to large-scale estimates, which have practical uses in modeling erosion.

**Conclusions**

Sediment is a natural component of our landscape; yet when the landscape is modified, it can become a pollutant. Urbanization and changing land use are direct anthropogenic changes, while changing climate and more frequent higher intensity storms are indirect anthropogenic or
natural changes. The changing land use and climate affect the hydrology, which then influences the hydraulics. Hydraulics then affect the channel erosion and sediment transport processes. As our landscape continues to change, streams and rivers will continue to change. Stream restoration and bank stabilization projects reconfigure channels with the goal of no net erosion or deposition. Engineers use different hydrologic, hydraulic, and erosion models in the design process of restoration projects. Parameterization of these models requires time, effort and money.

To aid model parameterization, this study set out to determine if a combination of SSURGO soils data and empirical equations are viable methods to develop a large scale soil parameterization method for erosion models. This study was first time that SSURGO data and the Smerdon and Beasley (1961) equations were evaluated within a region, as well as across different regions within the United States. The study also shows that SSURGO data is not accurate for predicting soil parameters of streambanks at either a site scale, or at locations throughout the continental United States. The differences could be due to the highly modified nature of rivers, and the fact that fill or disturbed areas are not denoted within SSURGO. This discrepancy could lead to large differences between predicted and measured properties. A second possible explanation is the natural variability of soils. Studies have shown that streambank properties are highly variable, even at a single location [Parker et al., 2008]. Vegetation further complicates the situation since it can greatly affect soil properties [Labbe et al., 2011; Polvi et al., 2014].

Another area of this study focused on evaluating existing empirical equations used to prediction critical shear stress. Smerdon and Beasley (1961), Julian and Torres (2006), and Wang (2013) offer potential empirical equations. This study shows that the two of the Smerdon and Beasley (1961) empirical equations did not explain the variation in the data at either a site, or regional scale. There is significant scatter in all cases. The properties of cohesive soils are dependent on many factors that are not incorporated in these equations, some of which are dynamic and change temporally, such as water content [Pollen, 2007]. The response of soil properties by different parameters is largely unknown. The creation of general equations while omitting some of the dependent soil properties leads to overfitting of available data, thus significantly reducing the predictive power across, and within different regions. For large scale erosion modeling, the current knowledge gap includes accurate empirical equations to predict properties of cohesive soils, as well as available datasets that accurately describe real life soil
conditions. Because of this gap in available knowledge, advanced physically based erosion models such as CONCEPTS, are difficult to use because of the required input data.

When comparing the measured data with the bounding equations proposed by Briaud (2013), it was discovered that the measured data appeared to follow the Briaud Equation 1 with an exponent of -0.4, despite different measurement techniques. To add to the existing knowledge of cohesive sediments, it is proposed that the critical shear stress follows a power law relationship, where the exponent is -0.4. The coefficient of the power law relationship is a function of climate, land use, vegetation, and site-specific conditions. Further work is required to research methods of determining the coefficient.

The results of this research show that SSURGO data does not accurately describe stream bank soil properties. Additionally, empirical equations tested in this study were shown to be poor predictors of critical shear stress. At the present time, the best method of determining soil properties for erosion studies is by in-situ soil testing, with lab testing samples a close second. The final finding is the power law relationship of critical shear stress; this provides a new research area, which could help with large-scale determination of critical shear stress.
Bibliography


Wang, W. B. (2013), Effects of physical properties and rheological characteristics on critical shear stress of fine sediments, Georgia Institute of Technology.


## Appendix A: Research Timeline

August 2014 – June 2016

<table>
<thead>
<tr>
<th>Event or Activity</th>
<th>Fall 2014</th>
<th>Spring 2015</th>
<th>Fall 2016</th>
<th>Spring 2016</th>
<th>Summer 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research literature to define problem</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Survey field site</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collect soil samples and perform lab analysis</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Begin writing proposal / thesis components</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Select committee members</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present research proposal to committee and modify as needed</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analyze regional dataset</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Synthesize results</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Finish writing thesis and submit drafts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Complete final thesis defense</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Prepare manuscripts for publication, graduation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
### Appendix B: Program of Study (MS)

<table>
<thead>
<tr>
<th>Fall 2014</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Course/Deliverable</strong></td>
<td><strong>Requirement Fulfilled</strong></td>
</tr>
<tr>
<td>CE 561 (3)</td>
<td>3 Credits designated CE</td>
</tr>
<tr>
<td>CE 497B (3)</td>
<td>3 Credits designated CE</td>
</tr>
<tr>
<td>GEOSC 548 (3)</td>
<td>3 Graduate Level Credits</td>
</tr>
<tr>
<td>Complete SARI Online Modules</td>
<td>PSU Graduate School Requirement</td>
</tr>
<tr>
<td><strong>Spring 2015</strong></td>
<td></td>
</tr>
<tr>
<td>CE 564 (3)</td>
<td>3 Credits designated CE</td>
</tr>
<tr>
<td>CE 555 (3)</td>
<td>3 Credits designated CE</td>
</tr>
<tr>
<td>CE 600 (3)</td>
<td>CE M.S. Research Requirement</td>
</tr>
<tr>
<td>Finalize Thesis with Advisor</td>
<td></td>
</tr>
<tr>
<td><strong>Summer 2015</strong></td>
<td></td>
</tr>
<tr>
<td>Start Literature Review</td>
<td></td>
</tr>
<tr>
<td><strong>Fall 2015</strong></td>
<td></td>
</tr>
<tr>
<td>ABE 500 (3)</td>
<td>3 Graduate Level Credits</td>
</tr>
<tr>
<td>ENGR 597B (3)</td>
<td>3 Graduate Level Credits</td>
</tr>
<tr>
<td>ERM 450 (3)</td>
<td>Elective</td>
</tr>
<tr>
<td>Submit Plan of Study for Approval</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Recommend Faculty Members to Serve on Committee</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Submit Proposal to Advisory Committee</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Meet with Advisory Committee for Proposal Approval</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Prepare First Draft of Thesis</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td><strong>Spring 2016</strong></td>
<td></td>
</tr>
<tr>
<td>CE 596 (3)</td>
<td>3 Graduate Level Credits</td>
</tr>
<tr>
<td>CE 548 (3)</td>
<td>3 Graduate Level Credits</td>
</tr>
<tr>
<td>CE 600 (3)</td>
<td>CE M.S. Research Requirement</td>
</tr>
<tr>
<td>Schedule Thesis Defense</td>
<td>CE M.S. Research Requirement</td>
</tr>
<tr>
<td><strong>Summer 2016</strong></td>
<td></td>
</tr>
<tr>
<td>Submit Intent to Graduate</td>
<td>PSU Graduate School Requirement</td>
</tr>
<tr>
<td>Pay Thesis Fee</td>
<td>PSU Graduate School Requirement</td>
</tr>
<tr>
<td>Submit Draft Copy of Thesis to Adviser</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Complete Thesis Defense</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Submit Copy of Thesis to Graduate School</td>
<td>CE M.S. Requirement</td>
</tr>
<tr>
<td>Finish Any Other Requirements Prior to Graduation</td>
<td>CE M.S. Requirement</td>
</tr>
</tbody>
</table>