8-2018

Rethinking Channel Protection Efforts: An Integration of Fluvial Geomorphology, Engineering, and Economics

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To the Graduate Council:

I am submitting herewith a dissertation written by Robert Ryan Woockman entitled "Rethinking Channel Protection Efforts: An Integration of Fluvial Geomorphology, Engineering, and Economics." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

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Rethinking Channel Protection Efforts: An Integration of Fluvial Geomorphology, Engineering, and Economics

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Robert Ryan Woockman

August 2018

Acknowledgements

I would like to express my gratitude to a number of people who have dedicated their time to progress this research.

Dr. John Schwartz has served as my advisor and has been a key resource in advancing research efforts. His expertise, perspective, and guidance have been invaluable and efforts to obtain funding instrumental. I would also like to express my gratitude to Dr. Christopher Clark, Dr. Jon Hathaway, and Dr. Athanasios Papanicolaou for their advice and willingness to serve as committee members. Their experience and broad knowledge base have been a great resource and helped shape the scope of this body of work and my personal perspective.

I would like to give thanks to the United States Geological Service (USGS). Without their funding support through the 104(b) program and the Tennessee Water Resources Research Center (TNWRRC), this research would not be possible.

I would like to recognize the efforts of Jackson Mohler, Andrew Veeman, Brandy Manka, Badal Mahalder, Adrian Gonzalez, Zachariah Zeiden, and Michael Walton. Through assistance in the field and/or laboratory, their contributions were extremely important to meeting research objectives. In particular, Jackson Mohler was fundamental in accomplishing a daunting fieldwork campaign.

I would like to acknowledge the love and encouragement of my parents. Their belief in me is unrivaled and always a boost in confidence.

Finally, I would like to express gratitude to my wife and daughter for their sacrifice and support. Without their commitment and love, this work would not have been possible. They made the long road shorter and brighter.

Abstract

In-stream channel degradation as a result of alterations to flow and/or sediment caused by urbanization can have detrimental ecological and socio-economic impacts. Although steps have been taken to minimize these impacts through stormwater regulatory efforts, there has been variance in effectiveness. As efforts have evolved to meet regulatory requirements and improve effectiveness, an awareness of the need for integrated watershed planning has developed. However, understanding of the linkage between in-channel sediment contributions, hydrogeomorphic setting, level of anthropogenic disturbance, and time dependent response remains limited. The rate channel forming work is performed, as result of increased surface runoff, is complex; therefore, incremental increases in flow do not necessarily lead to incremental changes in channel morphology. Rather specific geomorphic attributes and their spatial organizations dictate imbalances in hydraulic and mechanical disturbing/resisting forces over temporal patterns of flow.

In an attempt to address inefficiencies, a framework is proposed integrating stormwater related mitigation efforts ("channel protection"), related engineering practices, fluvial geomorphology, and economics in order to evaluate the outcomes of mitigating efforts and associated cost-effectiveness. This framework is supported by hydrological modeling and field surveys used to explore surrogate measures of eroding and resisting force with the intent to capture potential imbalances and define attributes that determine stability within the Ridge and Valley Province of Tennessee. In combination with these efforts, detailed in-situ flow monitoring was completed at three small stream systems to calibrate and validate coupled continuous simulation models of hillslope and in-channel processes. Models are utilized to explore response trajectory and efficacy of various mitigating suites.

This research contributes to a growing body of literature that suggests channel protection efforts and TMDL implementation plans (for purposes of sediment loading reduction) should incorporate stream system specific prevalent erosive processes, the mechanisms of those processes, and the geomorphic attributes that influence them to improve efficacy of efforts.

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Key Definitions

Best Management Practices (BMP): Any practice intended to mitigate negative impacts from stormwater runoff and/or improve stream system/reach condition (e.g. bank stabilization, stream restoration, stormwater control measure, etc.).

Effective Stream Power: Is a term utilized to describe the difference (or imbalance) between *driving and resisting* force. The difference being a function of geomorphic attributes dictating thresholds.

Effective Work Regimes: The cumulative work performed by effective stream power over time.

Low Impact Development (LID): Decentralized SCM applications incorporating infiltration and evapotranspiration.

Urban Hydromodification: Hydrologic alteration due to impervious surfaces leading to changes in patterns of streamflow and/or sediment dynamics.

Sediment Source Potential: A general description of the expected degree of geomorphic channel degradation that might occur as a result of urban hydromodification, assuming general geomorphic controls are held constant over time.

Surplus Stream Power: Is a term utilized to describe the increases in driving forces as a result of increased surface flows in the domains of magnitude, frequency, and duration.

Stormwater Control Measures (SCM): Any constructed structural or non-structural facility engineered to act as hydrologic control through management of stormwater runoff.

Introduction

The Problem

Geomorphic Channel Degradation

Hydrologic modification (hydromodification) is a major cause of non-point source (NPS) pollution in American waterways (USEPA 2002a). Hydromodification is often the result of alterations of land-use due to urbanization. Urbanization and associated impervious cover ultimately results in modifications to surface water flow regimes and sediment transport. Modifications to surface flow regimes and sediment transport can present significant problems for channel stability due to potential imbalances between eroding and resisting forces imposed on the system. Increases in volume of runoff, peak flow rate (Brater 1975), and the duration of flows (Booth and Jackson 1997) result in increased eroding flow potential where flows become concentrated if channel erosive resistance properties are insufficient to offset the increases in stream power, destabilizing channels. The geometry of a stream channel is determined through the long-term balancing of erosive forces generated by moving water and resistive forces of the channel bed and bank materials (Langbein and Leopold 1964; Knighton 1984). The interaction of these forces determines whether a channel will aggrade (accumulate sediment), degrade (erode sediment) or maintain equilibrium (Simon 1989; Simon and Downs 1995).

Destabilized channels and resulting contributions to sediment yield degrade ecological function and result in socio-economic impacts. External costs exist (Hardin 1968; Goetze 1987; Ostrom 2008) when hydromodification effects result in destruction of infrastructure, habitat alteration, increased water treatment costs, diminished reservoir capacities, and decreases in biodiversity. These inherent social costs provide the incentive for regulatory efforts directed at reducing impacts.

A Legacy of Uniform Prescriptions

Most regulatory efforts to date have focused on addressing the volume of surface runoff directly through uniform design standards segregated by phase of construction (e.g. developing and post development) and the area of disturbance. For the developing stage, a great deal of success has been achieved, likely attributed to the brief phase of disturbance. However, post construction channel protection efforts remain in a period of development.

Post construction channel protection design standards have historically lacked integration with the geomorphic processes of the stream channels they are intended to protect (Roesner, Bledsoe et al. 2001), which can lead to channel destabilization. This can be attributed to a lack of consideration for the work that flow events induce (MacRae 1993). Channel forming work is a function of temporal patterns of stormflows and a stream channel's erosive resistance. Temporal patterns of flow can be described in terms of magnitude, duration, and frequency. A stream channels morphology, boundary materials, bed material, supply conditions, and vegetation define its erosive resistance. Therefore, design standards intended to match certain magnitudes and/or frequencies often comes at the expense of increasing duration of work performing flows (Bledsoe and Watson 2001; Rohrer and Roesner 2006), for lack of consideration of these erosive resistance elements (MacRae 1996).

Uniform channel protection mandates have also failed to integrate geomorphic processes through not accounting for existing state (i.e. current channel form). For example, guidance is typically intended for all new or redevelopment with little consideration for the disturbance already existing within a watershed. Booth, Hartley et al. (2002) suggested that there is a distributed watershed and a non-disturbed watershed and that both should be expected to have varied strategies, *"Following the same strategy in all watersheds, developed and undeveloped alike, simply makes no sense".* The importance of considering the existing state of a reach and its larger stream system has been argued by others as well (Schumm, Harvey et al. 1984).

Cost-Effectiveness of Uniform Prescription

The annual social costs associated with stream degradation in North America have been approximated at 16 billion (Osterkamp, Heilman et al. 1998) as a result of the physical, chemical, and biological damage caused by excessive sedimentation in streams. Channel protection efforts focused on SCMs and mandated as uniform standards have been the preferred solution to address these damages resulting from urbanization. However, the question remains is this approach the most cost-effective option to protect stream channels. For that assumption to hold true, it would require that the cumulative improvements[1] resulting from SCMs would reduce the cumulative effects of imbalances of driving and resisting forces (both mechanical and hydraulic) throughout a stream system and thereby minimize channel destabilization, associated siltation, and habitat destruction. In combination, cost to mitigate externalities through SCMs would need to be generally consistent to avoid variance in preferred technologies as a result of changing economic circumstances. These necessary assumptions indicate specific constraints and highlight why scenarios continue to persist where uniform standards are unlikely to minimize the aggregate abatement costs of meeting a particular environmental objective (e.g., channel/habitat degradation resulting from increased impervious surfaces).

The Need

The critical need for research is to develop a watershed assessment framework that links implementation of SCMs, conservation, and stream restoration to achieve channel protection. This framework should provide MS4 managers a means to determine long-term and cost-effective watershed management strategies to successfully protect channels and enhance ecological health through restoration of habitat. Impaired streams on the 303(d) list benefit from Total Maximum Daily Load (TMDL) implementation plans, which require a watershed assessment that integrates implementation of both SCMs and stream restoration projects. However, there is limited research that incorporates fluvial geomorphic principles with engineering design in order to minimize costs associated with channel destabilization resulting from hydromodification.

In order to minimize costs a better understanding should be gained of how hydrogeomorphic setting and state influence the cost-effectiveness of mitigating practices[2]. Two critical components to advancing our understanding of this influence are: 1) how do channel erosive resistance elements influence thresholds of destabilization and 2) how do channel erosive resistance elements influence process rates. These findings can then be incorporated into process based planning tools to identify where channel form and process might burden other attempts to restore hydrologic processes (e.g. potential reaches in urban streams prone to excessive channel and bank erosion regardless of improved hydrologic conditions) or evaluate scenarios where

[1] The cumulative improvements, with respect to channel protection, would be a function of settling benefits, increasing infiltration/evapotranspiration, dampening surface flow peaks, and modifying the timing of hydrographs.
2 Practices would include conservation, stream/riparian/floodplain restoration activities, and SCMs.

design standards for hydrologic control measures cannot be met and are not the most effective use of funds. For example, even under the assumption SCMs and design standards are completely effective, MS4s are finding that underlying strata simply will not allow designers to meet infiltration standards and/or land requirements for retention make them unreasonable (Tillinghast, Hunt et al. 2012). In these scenarios, allowing in-lieu fee[3] options could create a scenario where capital expenditures, intended to restore natural erosive disturbance regimes and reduce sediment yield, could be used to greater effect elsewhere within the watershed.

Knowledge Gaps

1) There exists a need for clarification of sediment source potential (i.e. sources of excessive fine sediment loads) based on regionalized process-based tools and identification of drivers of susceptibility.

The importance of identifying specific geomorphic attributes to determine the fine sediment source potential and efficacy of mitigation measures is not necessarily a new concept. This is exemplified in a statement by Booth (1990) more than a decade ago, *"Recognition of incision susceptible terrain is clearly the most effective strategy for mitigation in urbanizing areas "*. However, research for the most part has failed to incorporate this perspective into process-based tools, for assessment at reach scale (Doyle, Harbor et al. 2000).

Work by Bledsoe, Stein et al. (2012) is a great step towards the research required for tailored BMP solutions, a decision framework is built supported by locally calibrated empirical based risk models. Yet the geomorphic conditions that were the backdrop for this research are not transferable to Ridge and Valley Province of Tennessee. Variation exists in all major drivers associated with potential destabilization. Hydrologically precipitation is distributed differently (e.g. Type I and IA storm, versus type II) and spatially cohesive soils, bedrock outcrops, and vegetation starkly contrast the semi-arid climate where Bledsoe, Stein et al. (2012) work was conducted.

The necessary research to improve urban watershed planning efforts to avoid channel destabilization is largely a regionalized effort. The scarcity of research in the Ridge and Valley

3 In-lieu fees could be redirected at appropriate stream/riparian/floodplain restoration activities, centralized SCMs and/or conservation within the stream system.

is highlighted by Berg, Burch et al. (2013),*"The majority of the available stream research has occurred in the Piedmont portion of the Bay watershed, limited research within the coastal plain, and* ***virtually none for the Ridge and Valley province or the Appalachian plateau****. The dearth of data from these important physiographic regions of the watershed reduces the Panel's confidence in applications in these areas"*. This report is the culmination of an extensive literature review on the ability of stream restoration projects to reduce sediment and nutrient delivery to the Chesapeake Bay. The statement identifies a significant need for additional research in the Ridge and Valley to improve approximation of urban stream channel contributions to sediment yields. Currently, supporting evidence is primarily limited to Maryland and Pennsylvania studies that are not published in peer reviewed journals and show a considerable range in approximated loadings.

2) A need exists to explore whether systematic variance among hydrogeomorphic settings would lead to more cost-effective approaches to channel protection.

Uniform standards have likely been preferred by managers over the years due to ease of enforcement and convenience in application at scale. These uniform prescriptions provide a means to address multiple issues with one practice. Some might argue, under certain conditions, their advantages outweigh their disadvantages (Kolstad 1987; Heyes and Simons 2010). Nevertheless, scenarios continue to persist where uniform standards are unlikely to minimize the aggregate abatement costs of meeting a particular environmental objective (e.g., channel/habitat degradation resulting from increased impervious surfaces). Under certain conditions, they may even lead to the adoption of mitigation measures with little or no corresponding environmental benefit if receiving stream systems hydrogeomorphic settings are ignored. Therefore, a critical need exists to determine if there are systematic variations in hydrogeomorphic settings that warrant modifications to channel protection strategies. This information should provide municipal separate storm sewer system (MS4) managers a means to determine long-term and cost-effective watershed management strategies to successfully protect channels and enhance ecological health through restoration of riparian and lotic habitats.

Research Questions

The central drivers determining response to urban hydromodification are still a point of discussion within literature (Bledsoe, Stein et al. 2012; Vietz, Sammonds et al. 2014) and vital to any effective regulation intended to avoid or minimize externalities associated with impacts of urban land-use modifications, along with, being instrumental to efforts to prioritize cost-effective mitigation efforts between SCMs, stream rehabilitation/restoration, and conservation. Therefore, the research needs and knowledge gaps discussed in the previous section led to the development of following primary research question:

Is cost-effectiveness of mitigation strategies, intended to mitigate geomorphic channel degradation in small stream systems, improved through consideration of hydrogeomorphic setting?

The following three research questions are components of answering the larger primary question. Each question is addressed through individual chapters, which are intended to constitute individual publications. Answering these questions is an instrumental step to advancing our understanding of the influence channel erosive resistance elements have on the efficacy of channel protection efforts in the Ridge and Valley Province of Tennessee and therefore the cost-effectiveness of associated mitigating efforts.

Research Question 1:

What geomorphic attributes of urbanizing and urban stream reaches influence the absence or presence of erosive processes within 2nd and 3rd order stream reaches of the Ridge and Valley Province of Tennessee?

Research Question 2:

Can the model platforms of SWMM & CONCEPTS be integrated successfully to represent "Effective Work Regimes" and the influence that SCMs and channel erosive resistance elements have on erosive regimes?

Research Question 3:

Does the cost-effective BMP suite, for the purposes of mitigating channel instability due to urbanization, systematically vary by hydrogeomorphic setting?

These research questions are intended to improve our understanding of the linkages between urbanization, stormwater management policy, stream channel morphology, and degradational response over a range of watershed conditions (i.e. urbanization) and restoration efforts.

Contributions

Many MS4s are currently considering how best to implement the new Phase II Stormwater NPDES requirements. The new regulation will require an increase in MS4s attention with respect to direct channel protection guidance. The information derived from this exploratory study should provide watershed managers with necessary parameters to create simplistic assessments of a stream reach's erosive resistance properties and inherent susceptibility to urban hydromodification. These geomorphic attributes and their spatial organization dictate imbalances in resisting force and eroding force over temporal patterns of flow. Therefore, the ability to spatially organize these features within their respective stream system informs assumptions about the degree of spatial propagation expected from the effects of hydromodification.

The ability to segregate streams into similar degrees of thresholds and response improves the efficacy of targeted mitigation efforts through approximation of impacts of land-use modifications, development of effective regulation to avoid or minimize externalities, and prioritization of mitigation efforts between stormwater control measures, conservation, and stream rehabilitation/restoration. Streams with similar erosive resistance properties should require similar suites of mitigation practices to restore and/or maintain a balance between eroding and resisting forces. This research should contribute to the body of knowledge necessary to identify those elements most influential in determining channel erosive resistance, and therefore improve the potential to derive solutions at the minimal cost with the greatest channel protection.

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Chapter 1

Influence of Urban Hydromodification and Channel Erosive Resistance Elements on Stream Morphology in the Southern Appalachian Region, USA.

Abstract

Erosion induced siltation and habitat alteration in urbanized/urbanizing stream systems is often associated with channel degradation due to urban hydromodification and can have detrimental ecological and socio-economic impacts. To mitigate these impacts the EPA has mandated development of sediment TMDLs and recommended implementation plans that include target load reductions from channel protection efforts. As efforts have evolved to meet regulatory requirements, an awareness of the need for integrated watershed planning has developed. However, understanding of the linkage between in-channel sediment contributions, geomorphic setting, level of anthropogenic disturbance, and time dependent response remains limited. Field surveys were conducted at 28 sites across the Ridge and Valley Province of Tennessee. Sites were characterized by degree of impervious cover, dominant soil texture, vegetation, bed particle distribution, valley setting, and proximity to natural/artificial grade control. Logistic regression was used to relate site characteristics to sites experiencing excess hydraulic erosion and presence of mass wasting processes. Measures of vegetation buffer, distance to grade control, particle size distribution, valley slope, and stream power all had a statistically significant effect on erosive processes. Various measures of the degree of urban hydromodification were not found to have a notable effect on probability. This research contributes to a growing body of literature that suggests channel protection efforts and TMDL implementation plans (for purposes of sediment loading reduction) should incorporate stream system specific prevalent erosive processes, the mechanisms of those processes, and the geomorphic attributes that influence them.

Introduction

Ecological degradation due to siltation and habitat alteration often correspond with urban and urbanizing channels due to development practices and associated impacts of hydromodification (USEPA 2002a). Since the 1990s, implementation of stormwater control measure (SCMs) efforts during construction activities have improved runoff quality, however, in-channel derived fine sediments have remained a problem following land development, due to modifications of surface runoff regimes, sediment transport regimes, and natural erosive process rates. Studies have indicated that sediments derived from in-channel can dominate sediment yields (Trimble 1997; Allmendinger, Pizzuto et al. 2007; Fraley, Miller et al. 2009). This is often due to channel enlargement, which has been the dominant response to urbanization (Hammer 1972; Booth 1990; Doll, Wise-Frederick et al. 2002; Chin 2006). Yet, it is important to note that not all research indicates enlargement and/or aggressive erosion as a primary response (Nelson, Smith et al. 2006; Annable, Watson et al. 2012). Whether a stream erodes excessively will be a function of the mode and magnitude of disturbance (i.e. land cover change), boundary conditions (Allen, Arnold et al. 2002; Bledsoe, Stein et al. 2012), and the erosive processes in play (Leopold 1973; Lawler 1995).

Streams are subject to a natural disturbance regime defined by the conveyance of water and sediment over time. The temporal patterns that make up disturbance regimes are the result of the interaction of these fluxes with the boundary materials and conditions of the channel. These regimes, over sufficiently long periods, can be assumed as steady state when quasi-equilibrium exists between eroding and resisting force. This is exemplified in form that is visually interpreted as representing a balance with the processes within the fluvial system (Leopold and Maddock 1953) during an appropriately long time scale (Schumm and Lichty 1965).

Hydrologic alteration (i.e. impervious cover) over time is a complex perturbation on fluvial systems representing both a ramped and pulse disturbance on abiotic and biotic properties of the system (Lake 2000). Urbanization modifies land cover through creating impervious surfaces. The cumulative effect results in a stream system with increased hydraulic efficiency and decreased hydrologic initial abstraction potential leading to additional surface flow. With particularly strong influences on higher frequency precipitation events (Hollis 1975).

Modifications to surface flow and sediment transport regimes can present significant problems for channel stability, due to potential imbalances between disturbing and resisting forces imposed on the system. Disturbing forces and resisting forces are influenced by controls on the system and include: climate, geology, land-use, basin physiography, base level, valley morphology, channel morphology, and boundary materials (Schumm 1977; Knighton 1984). Further segregation might include those which determine the processes of surface flow and sediment transport and those that determine specific hydraulic conditions relevant to thresholds (Schumm 1977). The latter would therefore include channel morphology, boundary material, and vegetation and represent elements functionally related to resisting forces. The interaction of these forces determines whether a channel will aggrade, degrade, or maintain equilibrium (Schumm, Harvey et al. 1984; Simon and Downs 1995), with thresholds and trajectories being governed by local boundary resistance (Booth 1990; Allen, Arnold et al. 2002; Simon and Rinaldi 2006; Bledsoe, Stein et al. 2012).

Channel evolution to urban hydromodification in single-thread channels is often described by a standard sequence of response: vertical degradation, vertical and lateral degradation, aggradation, and eventually restabilization at a lower base level incorporating a terraced floodplain (Simon 1989; Simon and Downs 1995). However, application of this model to urban streams assumes increases in impervious surfaces are synonymous with increases in transport capacity and there are no constraints on the system (i.e. completely alluvial without grade). Where vertical and/or lateral constraints on the reach/system and variations in mode or degree of disturbance exist, it can be assumed channel evolution may follow different trajectories (Cluer and Thorne 2014; Booth and Fischenich 2015).

In order to define imbalance most research has focused on importance of hydraulic-induced erosion utilizing various measures (e.g., excess discharge, shear stress, or stream power). The hydraulic component that represents the disturbing force has been well researched and approximations are often made with confidence ignoring variations resulting from work-energy over time (i.e. modifying channel boundaries). Yet, the determination of the resisting force, although well researched, remains difficult to assess. Variations in space (Daly, Fox et al. 2015a; Daly, Fox et al. 2015b) require a definition of scale and once it has been defined there is still the aspect of temporality (Wynn, Henderson et al. 2008), interaction effects (Hession, Pizzuto et al. 2003; Wynn and Mostaghimi 2006), shifts in influence along a continuum (Lawler 1995; Eaton and Church 2007), and/or relative distance to grade control (Bledsoe, Stein et al. 2012).

Understanding the balance between driving and resisting forces among channel reaches is key in the development of sediment TMDL implementation plans, which address destabilized streams impaired by siltation; plans consider how best to meet specified load allocations. The need to improve on TMDL plans has led to increased interest in stream restoration as a tool to meet load allocation (Berg, Burch et al. 2013) and as a compensatory mitigation in-lieu fee option where channel protection flows are not feasible. However, methods for determining the efficacy of these restoration projects as practices for sediment load reduction, or as alternatives to hydrologic controls are limited. Proposed methods often consider linear bank contributions, but there is little regard for natural versus unnatural rates or evolutionary state (i.e. sediment source potential as function of time).

Each stream system is unique with respect to its hydrology and geomorphic properties resulting in a unique dynamic interaction. Isolating the extremes through identification of a reaches sediment source potential (defined within context of space and time) and incorporating this perspective into the evaluation of stream restoration as a mitigation tool requires an understanding of imbalance between driving and resisting forces and associated erosive processes. These are important considerations for strategies intended to provide long-term and cost-effective channel protection and enhance ecological health through restoration of habitat (Ebersole, Liss et al. 1997; Schwartz 2016).

Therefore, to gain a better understanding of how urbanization impacts channel response we must have a complete understanding of how modifications to the magnitude, duration, and frequency of disturbing events manifest into modifications of erosive processes. It is relatively easy to model stream power in terms of land-use changes, but more difficult to assess channel factors that dominant erosive resistance to modification in terms of thresholds and rates of erosive processes. The objective of this research was to address this knowledge gap with specific focus on identifying elements of a channel that influence fine sediment contribution (i.e. excessive channel adjustment), within a study design that evaluated the presence of erosive processes along a gradient of urbanization in Ridge and Valley Province of Tennessee. In order to accomplish this objective, field surveys were conducted at 28 sites across the Ridge and Valley Province of Tennessee. Sites were characterized by degree of impervious cover, dominant soil texture, vegetation, bed particle distribution, valley setting, and proximity to natural/artificial grade control. Logistic regression was used to relate site characteristics to sites experiencing excess hydraulic erosion and presence of mass wasting processes.

Methods

Study Area

The study area lies within Region 8 of the ecological regions of North America. Region 8 consists of eastern temperate forests which cover a vast area of the eastern United States (CEC 1997). This region is distinguished by its dense and diverse temperate forest consisting primarily of deciduous and conifers (CEC 1997). The Level 2 ecoregion is Ozark, Ouachita-Appalachian Forests (Wiken, Nava et al. 2011). The level 3 ecoregion is identified as the Ridge and Valley (ER67) (Griffith, Omernick et al. 1997). The study area itself is delineated by the Tennessee state boundary to the north and south and bordered to the west by the Cumberland Mountains and Plateau and to the east by the Blue Ridge Mountains.

Much of ER67 consists of trellised drainage patterns, characterized by small streams draining the ridges (northeast-southwest trend) and connecting with higher order valley streams running parallel (Wiken, Nava et al. 2011). The terrain consists of ridges, rolling valleys, and low irregular hills (Wiken, Nava et al. 2011). Approximate elevation ranges from roughly 1159 meters in northeast corner of the state where streams drain higher elevation ridges to roughly 194 meters in the southwest corner of the state where the Tennessee River controls base level (NHDPlus 2012).

ER67 has diverse geological material: limestone, dolomite, shale, siltstone, sandstone, chert, mudstone, and marble (Wiken, Nava et al. 2011). Variation in weathering has created influential and diverse geological controls most pronounced in characteristic parallel ridges and valleys and also the karst topography. The dominant strata are Cambrian and Ordovician (Martin 1971). Vertical constraints on channel boundaries are common in the streams draining ridges and transitional zones connecting valley floors. Valley floors also are not exempt from a high frequency of bedrock exposure. Variance in weathering resistance of the various geologic strata has resulted in diverse topography, soil texture, structure, and depth and ultimately vegetation (Martin 1971). Common soils include Ultisols and Inceptisols with mesic to thermic soil temperature regimes. Soil moisture regimes characteristic of these soils are udic (Wiken, Nava et al. 2011). Textures within the study sites ranged from silt loam to more cohesive soils such as clay and silty clay's (NRCS 2017).

The Humid Subtropical Climate results in hot and humid summers and relatively mild winters. Precipitation totals and average temperatures generally decrease moving from the southern part of the region to the north. Chattanooga experiences average total rainfalls of 142 cm and an average temperature of 63 degrees Fahrenheit (NOAA 2015). Bristol experiences average total rainfall of approximately 99 cm and an average temperature of 59 degrees Fahrenheit (NOAA 2015). Summer storms are typically of short duration but intense and winter storms are characterized by large fronts with longer durations.

The mature deciduous forests have historically been poorly managed. As early as the late 1700's, poor management of land and timber was prevalent with both valley bottoms and associated hillslopes affected by harvesting of timber & land clearing activities. Steep ridges are still commonly dominated by forests and low relief valleys by pasture and cropland in rural areas (Homer, Dewitz et al. 2015). In urban and urbanizing settings there are varying degrees of developed land classes (Homer, Dewitz et al. 2015).

Site Selection & Characteristics

Research sites were selected from initial randomization of reaches from 2nd and 3rd order streams (Strahler 1957) delineated by the NHDPlusV2 dataset in ER67. Randomization was completed by zones generally encompassing the northwest, northeast, southwest, and southeast portions of the research zone (Figure 1.1). Randomization was further broken down into categories of degree of impervious surface cover to insure a gradient of impervious cover (the average value of impervious cover was 12%). Additional consideration included varying degree of response, degree of vegetation, and distance to grade control. Initial site selection was then screened based on: site accessibility, GIS analysis of reservoir controls on flow and sediment

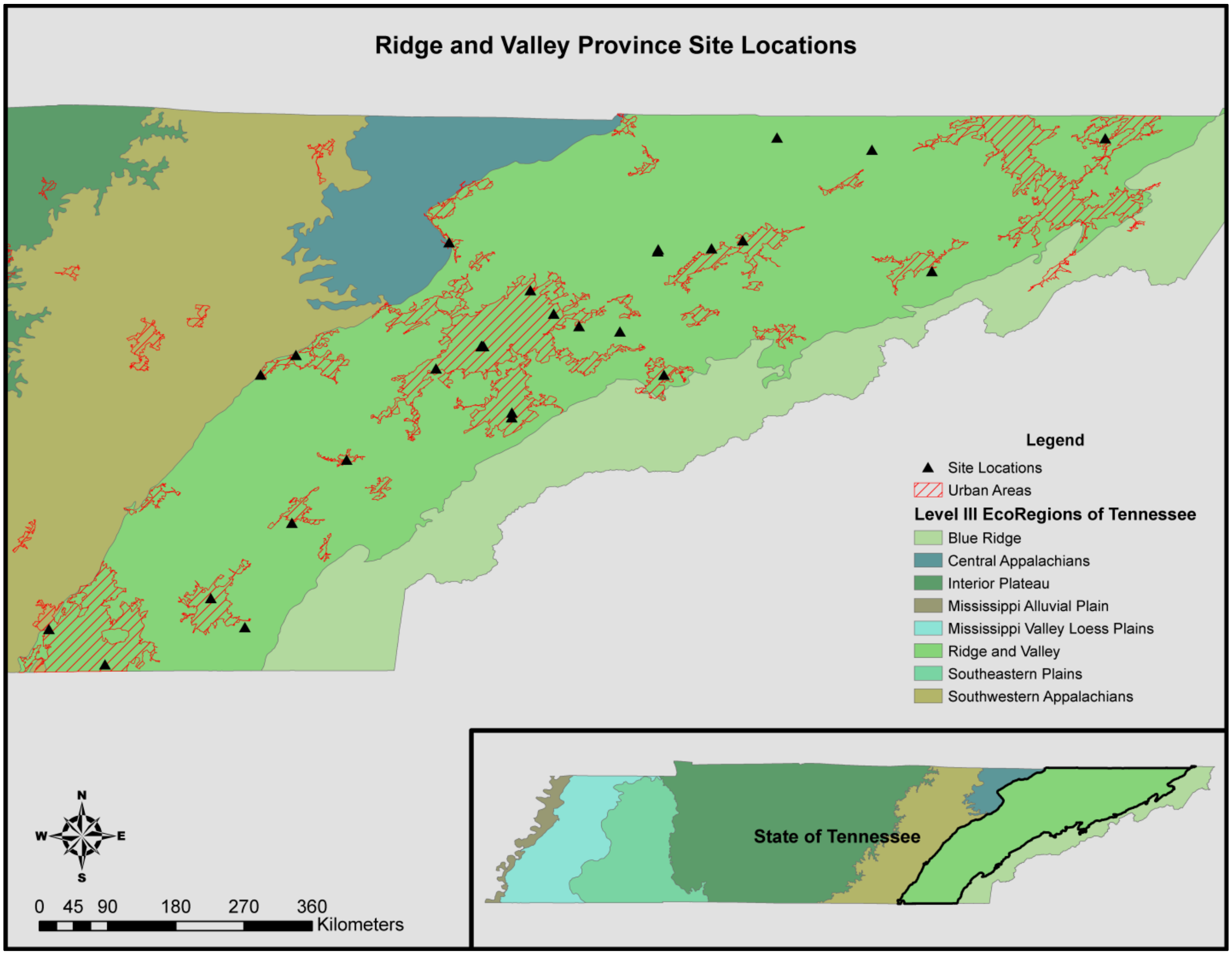

Figure 1.1. Site map for field based audit efforts.

regimes, and potential legacy impacts not associated with hydrologic alteration. Legacy impacts in urban/urbanizing streams are common and in order to avoid sites that have experienced significant alterations the TDEC ARAP (Tennessee Department of Environmental Conservation, Aquatic Resource Alteration Permit) database and historical orthoimagery were utilized. A total of 28 fluvial audits were completed. The general stream system and reach scale attributes can be seen in Table 1.1.

Data Collection/Fluvial Audits

A host of variables representing critical components that may influence channel response to hydromodification were selected for observation and analysis. Variable selection efforts for the fluvial audits attempted to capture elements of a channel that described relevant controls, processes, and form affecting channel response/evolution to urban hydromodification. Variables were selected at three hierarchical scales (stream system, stream segment, and stream reach) and were recorded through either field techniques or desktop analysis. These spatial scales indirectly represent time scales of response and ultimately predict the potential capacity of a reach in question (Schumm and Lichty 1965; Frissell, Liss et al. 1986). The stream system spatial scale was delineated by the contributing basin upstream of the reaches audited. The stream segment scale is delineated by tributary junctions equal to or one order lower than the stream segment of interest. The reach scale is delineated by a length of approximately 18-20 CUWs (Channel Unit Widths).

Table 1.1: Stream system and reach characteristics for the 28 study sites in the Tennessee Ridge and Valley Province.

	Drainage Area (Km^2)	Watershed Slope (m/Km)[1]	Impervious Cover (%)[2]	Δ Impervious Cover (%)[3]	D50 Particle Diameter (mm)	Channel Slopes (m/m)
Minimum	3.4	1.3	0	0	2	0.0001
Median	14.2	9.4	9	1	14	0.0029
Mean	18.4	12.6	11	1	19	0.0036
Maximum	52.8	90.1	37	3	61	0.0129

1. Watershed Slope is based on 10 & 85 method.
2. Impervious Cover is based on 2011 NLCD database.
3. Δ Impervious Cover is based on difference between 2011 and 2001 NLCD databases.

Surveys were conducted following standard techniques and completed from December 2014 thru December 2015. Surveys included longitudinal profile, representative cross sectional geometries, distance to grade control, pebble counts, assessment of riparian buffer, soil texture sample, and rapid geomorphic assessments. Reach slope was delineated by riffle crests above and below the reach itself. Cross sections were sampled across riffles or in the situation where systems where step-pool samples were taken in the upper portion of the step. Recorded points were intended to describe characteristic cross-sectional area, bank height and angle, relevant terraces, and flood-plain connection for 1-D hydraulic methods. The distance to grade control (straight-line) was assessed with survey methods where feasible and in other situations with a Garmin GPSMap 62 (accuracy < 10 m). Pebble counts were conducted as ≥ 100 point samples (Wolman 1954) utilizing a gridded format and ϕ template along characteristic riffle. Particle size distributions were used to classify bed material and calculate incipient motion conditions.

Audits of the quality/quantity of vegetation were conducted at all sites. Analysis incorporated both width of influence and maturity of present vegetation with emphasis on deciduous vegetation. Reaches were segregated into sub-units to improve upon already subjective measures and determine a weighted average. Mature deciduous vegetation was identified as deciduous vegetation with an average trunk diameter of 30.5 cm or greater. The intent was to identify sites as those without deciduous vegetation, those with young deciduous vegetation, and those with mature deciduous vegetation. It was expected that utilizing a 30.5 cm diameter would roughly correlate with an average age of the vegetation of 25 or more years and be a surrogate for the depth of the rooting zone.

Soil texture was assessed both in the field (USDA 2014) and through desktop analysis of the SSurgo 2.2 database. The distribution of particles by size determines a given soils texture class. Soil texture class is often used to summarize the behavior of both physical properties and chemical properties of a soil (USDA 2014) and therefore can be used as a surrogate for a channel boundaries erosive resistance. Rapid Geomorphic Assessments (RGAs) were completed at all sites (Simon and Downs 1995). The resulting channel stability index (CSI) was utilized to provide an indication of stability and stage of channel evolution (Simon and Klimetz 2008).

Hydrology

Associated hydrological approximations of the 2-year return frequency discharge (Q_2) for sites were completed utilizing empirical relationships derived by the United States Geological Survey (USGS). For those sites with impervious cover greater than 4.7% USGS Tennessee Urban Regression Equations (URE) were utilized and for those equal to or less than 4.7% the USGS Regional Regression Equations (RRE) were utilized (Robbins 1984; Law and Tasker 2003). URE derived approximations are derived from contributing drainage area, impervious cover, and precipitation depth. RRE derived approximations are derived from drainage area, main channel slope, and a climate factor. Impervious cover was determined from the 2011 National Land Cover Database (NLCD). Precipitation depths for the 2 yr 24 hr event were approximated through NOAA atlas 14 point precipitation frequency estimates. The remaining exploratory variables were obtained from USGS StreamStats (Version 3) and listed in Table 1.3.

Hydraulics

Quantitative measures of hydraulic conditions and force balance were a function of collected morphological data and approximated hydrology. Measures of interest included critical flow (Q_c, flow conditions for incipient motion of bed material) and active channel discharge (Q_{tb}, defined by top of bank approximations). These conditions were identified through application of the USDA Forest Services WinXSPro 3.0 model and a VBA macro. WinXSPro 3.0 utilizes concepts of continuity through application of resistance equations to produce approximated flow rates relevant to hydraulic geometries (Hardy, Panja et al. 2005). The incremental output provides the necessary look-up tables to relate flow depth to values such as Q_c and Q_{tb}.

Q_c requires computation of critical hydraulic radius (R_{hc}). The method utilized in this study is outlined in Doyle, Harbor et al. (2000) through approximation of Eq. 1-1:

$$R_{hc} = \tau_c^*(\gamma_s - \gamma)D_{50}(\gamma S)^{-1} \qquad \text{Eq. 1-1}$$

Where τ_c^* is the dimensionless Shields parameter for entrainment of D_{50}, γ_s unit weight of sediment, and γ unit weight of water, D_{50} median bed material, and S channel slope.

It is possible to identify R_{hc} at a cross-section and then use it to identify Q_c through a hydraulic look-up table. Although, it is common to substitute depth for R_h, the decision was made not to substitute depth for R_h for the study sites. Many of the sites are influenced by lower width to depth ratios and this assumption was perceived to add a level of error that was avoidable.

Q_{tb} was determined by identifying an associated elevation in stationing data representative of the area considered to be the active channel prior to floodplain connection. This study utilized a method similar to Hawley, MacMannis et al. (2013) where the active channel is defined by point at which bank angle is <~ 15 degrees for a distance of 1 meter or greater. This decision was made to deal with subjectivity associated with bankfull observation in urban streams. Once, this elevation was determined the associated flow conditions were determined by the same procedure discussed to obtain Qc.

Flow conditions were translated to energy per unit width through application of Eq. 1-2:

$$\Omega = (\rho g \text{QS})/\text{w} \qquad \text{Eq. 1-2}$$

Where ρ is the density of water, g a gravitational constant, Q flow variable of interest, S channel slope, and w active channel width.

Statistical Analysis

A precursor to understating efficacy of stream restoration as a mitigating effort for sediment yield reduction requires consideration of those elements of a stream channel influencing erosive processes. Within ER67 there are three major bank erosion processes: subaerial, fluvial, and mass-wasting. By identifying the presence of erosive processes and relating presence to geomorphic attributes and degree of disturbance (i.e. hydrologic alteration), extrapolations of sediment contributions can be inferred, as well as, sediment source potential.

This research approached the matter through relating geomorphic attributes and degree of disturbance to observations of existing channel state. The study design involved identifying if elements of a channel had an effect on the probability that: 1) a site would be experiencing excess hydraulic erosion or 2) mass wasting processes.

Excess hydraulic erosion was classified as the “most impacted” 15 sites in terms of linear feet of streambank showing signs of hydraulic erosion. Natural rates of fluvial erosion are difficult to determine. In order to avoid issues with observational error and defining a stable versus unstable erosive rate, sites were grouped into one of two relative categories determined by the degree of fluvial erosion observed at a site (i.e. Group 1 may have had some degree of fluvial erosion present, but relatively less than Group 2 which was experiencing very discernable levels of fluvial erosion) (Table 1.2 & Figure 1.2). This method was deemed appropriate as inferences could then be generalized as to the fact that Group 2 would likely be deemed sources of sediment as compared to Group 1, allowing inference as to variables that may have an effect on membership in Group 2.

Sites were classified into two groups with respect to mass wasting processes (Table 1.2). Group 1 represents those sites that had no conclusive evidence of geotechnical failure. Group 2 were identified by those sites that had evidence of geotechnical failure. Evidence included presence of failure blocks (hydraulic erosion insufficient to remove entirety of failure block), irregular detachment faces along the bank faces (i.e. failure planes defined by scalloped banks), existing tension cracks, and/or slumped (incomplete failure) or tree fall (due to surcharge weight).

Effect of probability was analyzed through use of the logistic regression model (binary logit) utilizing maximum likelihood estimation (Newton Raphson) performed in SAS 9.4. Tests for significance were based on likelihood ratio using a χ^2 distribution and $\alpha < 0.05$. Diagnostics were graphed and visually inspected for influence.

As a conservative rule, type 2 error was favored over type 1. Therefore, tests were only reported if the original pool of observations provided sufficient evidence of significance (i.e. no outlier removal) and effect direction was not influenced by any one observation. The final list of variables along with description is provided in Table 1.3.

Table 1.2: A description of Logistic Regression Groupings.

Process	Group	n	Definition
Hydraulic Erosion	1	13	some degree of fluvial erosion may be observable, but relatively less than Group 2
	2	15	"most impacted" sites in terms of linear feet of streambank showing signs of hydraulic erosion
Mass Wasting	1	16	no conclusive evidence of geotechnical failure
	2	12	evidence of geotechnical failure

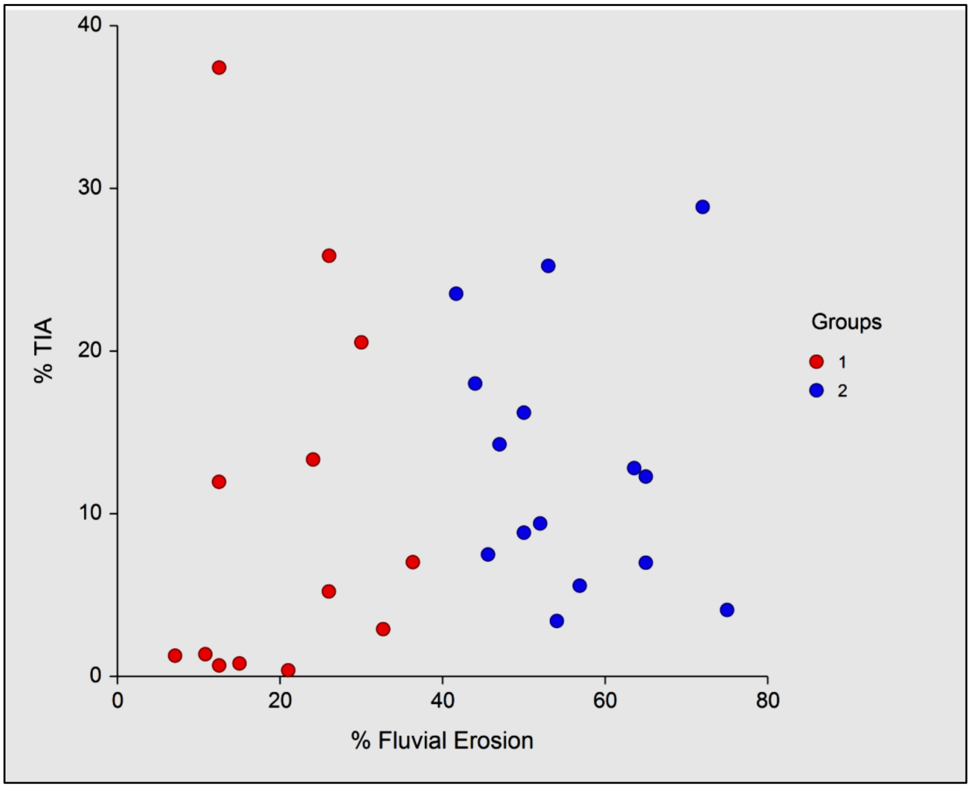

Figure 1.2. % Fluvial Erosion vs. % TIA with grouping for hydraulic erosion classes.

Table 1.3: Predictor variables considered for effect on probability of hydraulic erosion and presence of mass failure.

Predictor Variable	Description	Rationale
Ω_s	Approximated stream power relative to approximated pre-disturbance stream power utilizing valley slope and regional curves for width (McPherson 2011)	+
Δ TIA	Change in impervious cover from 2011 to 2001 utilizing NLCD	+
10_85	Change in elevation divided by length between points 10 and 85 percent of distance along main channel to basin divide (USGS StreamStats)	+,-
% TIA	NCLD 2011 impervious cover approximations	+
Ω_{tb}	Active channel stream power per unit width	+,-
Ω_{u2}	2 yr peak stream power per unit width	+,-
BDTG	Distance to grade / active channel unit width (Bledsoe, Stein et al. 2012)	-
D_{50}	Particle size that 50% of pebble count is equal to or less than	-
DA	Drainage Area	s
DD	Drainage Density	s
DDSG_DSR	Distance to grade control from downstream end of reach	-
ΔVz	Valley Slope*Distance to grade control	s
D_{WT}	Depth to water table at reach site based on soil map unit (SSurgo 2.2, dominant condition method)	-
FFdays	Frost-free days at reach site soil map unit (SSurgo 2.2, dominant condition method)	-,s
Flowpath	Longest distance to drainage divide (USGS StreamStats)	s
IR	Incision Ratio (Simon and Downs 1995)	+,-
n	Manning's N, Visual Assessment (Acrement et al., 1989)	+,-
Q_{c2}/Q_{tb}	Critical flow relative to the active channel flow	+,-
Q_{tb}/Q_{u2}	Active channel flow relative to the 2 yr peak flow	+,-
Q_{u2}/Q_{pre}	Approximated 2 yr peak flow relative to approximated pre-disturbance condition	+,-
%SC	% Silt-Clay at reach site based on soil map unit (SSurgo 2.2, Aggregation method: Weight Average 0-200 cm)	-
S_v	Valley Slope	+,-
S_vQ_{u2}	Power Index (Bledsoe and Watson 2001) using 2yr peak flows	+,-
VEC	Valley expansion or contraction coefficient at reach	s
VFP	% vegetated floodplain, observing 1 CUW, excluding maintained grasses	-
VFP_{MD}	% of floodplain with mature deciduous vegetation, observing 1 CUW	-
VWI	Valley width divided by active channel width	s
W/D	Active channel width relative to mean depth	+,-

+: Relates to driving force, -: Relates to resisting force, S: Relates to space/setting

Results

Resistance to Hydraulic Induced Erosion

Natural rates of fluvial erosion are difficult to determine unless long-term site surveys are available, and to avoid issues with both observational error and defining a stable versus unstable erosive rate, sites were assigned to one of the two relative groups. Membership in groups was determined by the degree of fluvial erosion observed at a site (Table 1.2). This method led to two classes of streams, those that are experiencing substantial fluvial erosion (Group 2) and those that may have some degree of fluvial erosion present, but could be considered minimal when compared to the other class (Group 1). This method was deemed appropriate as inferences could then be generalized as to the fact that Group 2 would likely be deemed sources of sediment when compared to Group 1 allowing inference as to the variables that may have an effect on membership in Group 2. The results from logistic regression (event=Group 2) are summarized in the following paragraphs.

A summary of variables having a statistically significant individual effect ($\alpha = 0.05$) on group membership are presented in Table 1.4. Based on these results vegetation, width/depth, and distance to grade control were deemed to have an individual effect on the probability of excessive fluvial erosion within the dataset, based on rejection of the null at a $\alpha < 0.05$. Prediction accuracy (i.e. sensitivity vs. specificity) did not have a biased to either group for any of the predictor variables. Specific details regarding definition of predictor variables can be seen in Table 1.3.

Within the study, four different variables were utilized to represent the degree of hydromodification: % TIA, Δ TIA, Q_{u2}/Q_{pre}, and Ω_s. None of these were deemed to have a statistically significant effect on the probability of group membership at $\alpha=0.05$. Yet, Δ TIA was most likely to have an effect ($p=0.11$).

Table 1.4: Significant results for analysis of individual effects on group membership (Group 2, fluvial erosion).

X1[a]	n	Effect	Likelihood Ratio χ^2	Pr > ChisSq	Sensitivity	Specificity
W/D	28	+	9.08	0.0026	73%	69%
VFP_{MD}	28	+	5.40	0.0202	67%	69%
BDTG	28	-	5.93	0.0149	60%	54%
DDSG_DSR	28	-	4.57	0.0326	60%	62%
VFP	28	+	3.87	0.0493	60%	69%

+: Odds of group membership (Group 2) decrease as variable scale increases.
-: Odds of group membership (Group 2) increase as variable scale increases.
a: Descriptions of each variable can be reviewed in Table 1.3.

Resistance to Mass Wasting Processes

A logistic regression analysis was run to predict the presence of mass-failure events at a stream reach using a number of predictor variables that were indicative of imbalances in driving and resisting forces, as well as, spatial position (Table 1.3). A number of tests of the full model when compared against a constant only model were significant ($\alpha < 0.05$), indicating that a number of variables potentially have an effect on the probability of mass failure events (Table 1.5). Measures of vegetation, particle size distribution, valley slope, and stream power indicated a reduction in the likelihood of mass failure presence, as scale increased. Proximity to grade control both standardized and unstandardized indicated an increased likelihood of mass failure presence, as scale increased.

Hydromodification predictor variables (% TIA, Δ TIA, Q_{u2}/Q_{pre}, and Ω_s) again were not statistically significant at $\alpha<0.05$. As with the tests performed for fluvial erosion, Δ TIA had the greatest chance of having an effect on presence of mass wasting (p=0.23).

The probability of mass wasting has been shown to have a positive correlation with bank height and angle. Therefore, the decision was made to run the analysis a second time removing sites with immediate grade control (n=10). When sites were removed with immediate grade control, modeling results indicated decreased probability for S_v (p=0.12), Ω_{u2} (p=0.08), and S_vQ_{u2} (p=0.39) ($\alpha = 0.05$, n=18). Notably, though the chance that Δ TIA had a measureable effect did improve (p=0.07).

Table 1.5: Significant results from analysis of individual effects on group membership in Group 2 (mass wasting).

X1[a]	n	Effect	Likelihood Ratio χ^2	Pr > ChisSq	Sensitivity	Specificity
VFP	28	+	12.73	0.0004	58.3	81.3
VFP_{MD}	28	+	9.58	0.0020	75.0	75.0
D_{50}	26	+	8.18	0.0042	54.5	60.0
DDSG_DSR	28	-	7.16	0.0075	58.3	87.5
W/D	28	+	6.73	0.0095	75.0	75.0
BDTG	28	-	5.37	0.0204	33.0	81.0
S_v	28	+	4.54	0.0332	33.0	62.5
S_vQu2	28	+	4.43	0.0352	41.7	62.5
Ωu2	28	+	4.36	0.0368	66.7	75.0

+: Odds of group membership (Group 2) decrease as variable scale increases.
-: Odds of group membership (Group 2) increase as variable scale increases.
a: Descriptions of each variable can be reviewed in Table 1.3.

Discussion

In an effort to elucidate the relationship between geomorphic attributes and in-channel contributions to fine-sediment yield resulting from urbanization, this study identified 28 2nd and 3rd order stream reaches in Ridge and Valley Province of Tennessee spanning a gradient of hydrologic alteration (Table 1.1). Hydrogeomorphic characteristics of the stream reach expected to be instrumental in response to urban hydromodification were then either qualitatively or quantitatively described (Table 1.3). These measures were then tested through logistic regression modeling to identify the influence on presence of erosive processes. The following section entails a discussion of the results of this study with emphasis on why certain variables were more influential statistically by highlighting their relation to erosive processes. As well, the discussion includes implications for managing in-channel contributions to siltation in light of these findings and others.

Channel Erosive Resistance Elements Influence on Urban Channel Geomorphic Response in the Ridge and Valley

Riparian Vegetation

The results of this study indicate vegetation has an effect on both resistance to fluvial entrainment and presence of mass wasting at a site. This is in agreement with a large body of literature which suggests: vegetation has the potential to increase flow resistance, decrease soil erosion due to entrainment, increase geotechnical properties, and improve drainage of bank soils (Thorne 1990).

Channel boundary resistance to erosion can be generalized by two categories: mechanical strength and erosional strength. Mechanical strength represents the geotechnical properties of the streambank soil and erosional strength represents a soils resistance to fluvial entrainment (Papanicolaou 2001). Vegetation can improve mechanical strength through addition of root reinforcement, which is a function of tensile strength, areal density and root distortion under loading (Simon and Collison 2002). Vegetation can also influence bank hydrology through pore water pressures and matrix suction. Typically, this influence is a function of interception and evapotranspiration rates relative to vegetative types.

Hey and Thorne (1986) identified bank vegetation as major control on the width of stable stream channels in quasi-equilibrium with hydrologic regime. Millar and Quick (1998) showed that vegetation can increase bank critical shear stress by up to three times that of bare soil. Papanicolaou (2001) indicated similar results for mechanical strength approximating roots could provide as much as an order of magnitude increase in mechanical strength. This effect is illustrated in Figure 1.3 and demonstrates how vegetation may overwhelm soil influences on resistance to hydraulic erosion[4].

Other arguments for why vegetation appears to be a major control would include its influence on subaerial processes. Subaerial processes are the result of temporal changes in climate that influence streambank soil moisture conditions (Wynn, Henderson et al. 2008) and the physical state of the moisture (Thorne 1990). The modifications to soil properties can be considered

[4] Figure 1.3 depicts that threshold bank conditions in the active channel, at the Back Creek site, would be drastically changed due to the effect of mature vegetation. Indicating that additional frequency and duration of eroding flows due to urbanization may be mitigated by vegetation based on Millar and Quick (1998) findings.

preparatory processes which weaken the streambank soils for fluvial erosion (Wolman 1959; Leopold 1973; Lawler 1993), but can also act as the erosive agent themselves (Couper and Maddock 2001). Vegetation impacts both thermal regimes and the hydrology of river banks and therefore a plausible argument exists for its influence on subaerial induced erosion because of hydrologic alteration. This has implications for urban hydromodification due to its effect on the frequency of channelized surface flow as a result of high probability precipitation events (Hollis 1975). This is an important finding; as many channel protection design standards ignore frequency of shearing events in favor of magnitude and/or duration of eroding flows.

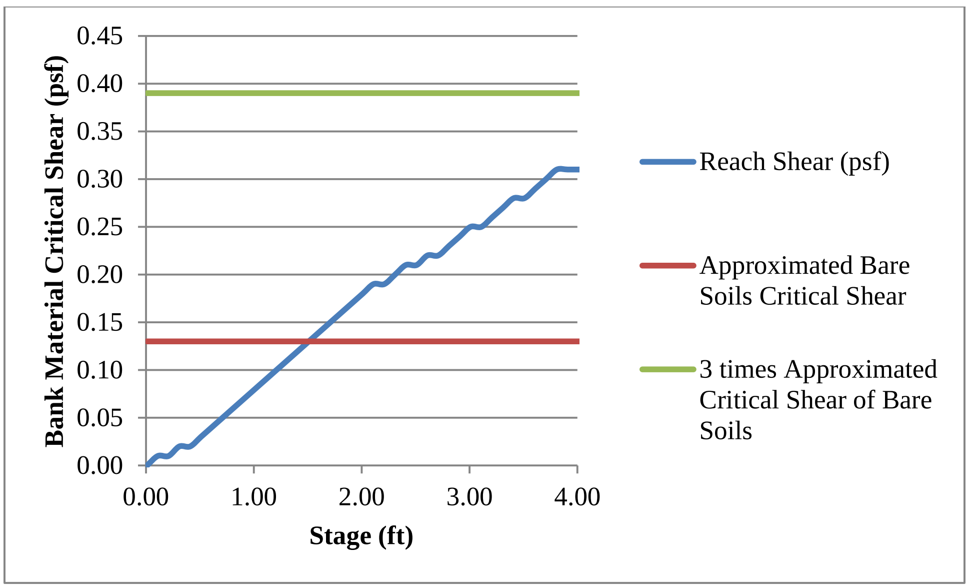

Figure 1.3. Graph depicts that threshold bank conditions in the active channel, with and without the effect of mature vegetation, at the Back Creek site.

Proximity to Grade Control

Incision is systematic bed level lowering in a reach, segment, or stream system caused by the process of degradation (Mackin 1948). Modifications to the surface flow regime create conditions of excess transport capacity relative to sediment supply and a system will adjust accordingly with incision being one of many potential outcomes (Simon and Rinaldi 2006). It is common in alluvial depositional settings for incision to precede lateral retreat of the banks (Schumm, Harvey et al. 1984; Simon, 1995). Incision and fluvial erosion of the bank toe often are precursors, which progress bank morphology towards critical bank height. These coupled mechanisms of vertical and lateral retreat result in channel degradation of a "non-linear asymptotic nature" (Simon and Rinaldi 2006).

Vertically, grade control has the potential to stabilize the bed preventing upward migration of a knickpoint or knickzone. Laterally, grade control has the potential to: 1) prevent streambanks from reaching critical height thresholds, 2) actually reduce bank heights through sediment deposition, and 3) provide reduction of shear stress and basal cleanout due to potential backwater effects (Watson and Biedenharn 1999). Ultimately, the frequency of grade control relative to channel slope, erosional strength, and mechanical strength has a strong influence on the degree of incision and progression of channel evolution (Langendoen, Simon et al. 2000). Examples of natural grade controls include beaver dams, large woody debri jams, bedrock outcrops, and boulder/cobble distributions in excess of transport capacity. Artificial examples include weirs, bridges, culverts, sills (Watson and Biedenharn 1999), and armoured beds (Bravard, Kondolf et al. 1999). Therefore, in urban drainages, the potential for vertical control tends to increase with development, but lateral protections generally are decreased through riparian vegetation disturbances.

The results of this study indicate distance to grade control (natural or artificial) has an effect on both the resistance of streambank material to fluvial entrainment and presence of mass wasting at a site. These results add to a growing body of literature that indicates vertical controls within a system can have significant impact on geomorphic processes within urban systems (Bledsoe, Stein et al. 2012; Hawley, MacMannis et al. 2013) and should be included in assessments of reach susceptibility (Bledsoe, Stein et al. 2012) and channel evolution (Booth and Fischenich 2015).

Geomorphic Setting

The initial findings of this study indicate that probability of mass-failure decreases with an increasing D_{50} which are expected, but a decreasing probability with increasing transport capacity (assessed by S_v, Ω_{u2}, and S_vQ_{u2}) is less intuitive and requires additional discussion.

A transport limiting condition exists when only lower frequency storms have the necessary transport capacity to move materials. A supply limiting condition exists when higher probability storms are capable of entraining materials. These conditions vary spatially and are determined by geomorphic attributes of the stream system and reach, demonstrated by the concept of Process Domain (Montgomery 1999). If surplus stream power derived from impervious cover is insufficient to create supply-limited conditions (excess shear) then bed material provides vertical protection (under the assumption this conditions is dominant over a sufficiently long period). Valley slope and confinement are often descriptors of Process Domains and correlate with bed material transport conditions (Figure 1.4). As well, the potential for bedrock control tends to correlate with higher S_v and D_{50} and lower valley width index ratios (Figure 1.4) providing explanation of why there is correlation between decreased probabilities of mass wasting and increased energy surrogates.

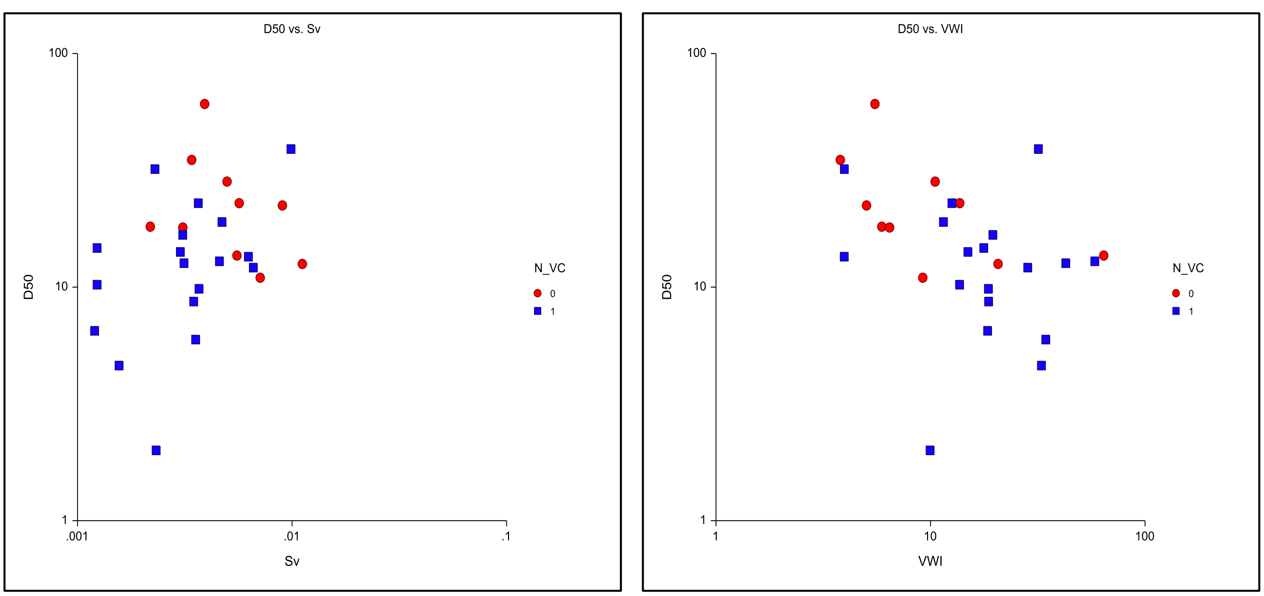

Figure 1.4. D_{50} vs. Valley Slope & Valley Width Index. N_VC Groups represent vertical control or not (0: vertically controlled site).

When logistic regression modeling was repeated with immediate grade control sites removed (n=10) the variables S_v, Ω_{u2}, S_vQ_{u2} were all deemed insignificant (p=0.12, 0.08, 0.39) based on $\alpha=0.05$ (n=18). Notably, an effect from Δ TIA became more likely (p=0.07, n=18). This could be attributed to a decrease in sample size, yet is theoretically sound. Urbanization's impact on surface flow regimes is not linear in nature. Impacts are most pronounced within higher probability events (events that would normally be infiltrated). The influence decreases as the probability of a given precipitation event decreases (Hollis 1975).

Process Domains have been used to describe variation in disturbance regimes associated with climate and topology interaction. Embedded within the concept is how energy is distributed across the riverine landscape through a disturbance regime and how the landscape evolves in response. Higher energy reaches are likely less sensitive to shifts in higher frequency storms as they tend to be supply limited. In contrast, lower energy reaches are more susceptible to shifts in higher frequency storms and therefore more susceptible to increases in urbanization. Therefore, it is suggested Process Domains should be instrumental in defining susceptibility to modifications to surface flow disturbance regimes and incorporated into planning.

Identifying Zones of High Sediment Source Potential

Understanding when and where mass failure processes will occur is critical to any integrated watershed planning that seeks to minimize sediment yield; as mass wasting is commonly considered the greatest contributor to excess sediment loads generated from in-channel erosion processes (Simon and Rinaldi 2006; Sutarto, Papanicolaou et al. 2014). Mass wasting is not a continuous process, but rather episodic and sometimes a drastic contribution to sediment supply determined by a unique set of conditions. Those conditions include thresholds for bank height and bank angle relative to cohesion, specific weight, and angle of friction (Osman and Thorne 1988).

Incision and fluvial erosion of the bank toe are often precursors, which progress bank morphology towards critical bank height. If thresholds of bank angle and height are sufficient, destabilization typically will progress through saturation of bank soils, loss of matric suction, generation of positive pore-water pressures, and then followed by a loss of confining hydrostatic pressure on the trailing arm of the hydrograph (Simon, Curini et al. 2000). Therefore, rates of destabilization are influenced by controls on infiltration rates, seepage mechanics, and potential failure planes and would include soils and riparian vegetation (Abernethy and Rutherfurd 1998; Abernethy and Rutherfurd 2000; Simon and Collison 2002; Simon, Pollen et al. 2006) as well as vertical controls (both artificial and natural).

Vegetation when coupled with grade control has the potential to create a zone of minimal sediment source potential when exposed to urbanized surface flow regimes. A physically based model is provided in Figure 1.5 to demonstrate the effect. In Figure 1.5 distances A and B are not to scale, but represent the distance of the stream channel that is subject to mass wasting processes (i.e. critical bank height is less than actual bank height). The assumptions associated with the depiction are overly simplified when compared to urban stream channels, but when assuming similar soils characteristics, stratification of soils, saturation dynamics, and consistent hydraulic/sediment conditions through the reach, one can assume that the linear distance of stream where $H_c < H$ would be greater for section A than B. With the same assumptions, it is possible to infer Reach C, representing a length of stream with a high frequency of grade control (either bedrock or artificial), might not experience mass wasting.

The inferred model is based on the concept that at any given equivalent bank height the factor of safety (Langendoen, Simon et al. 1999) for section A will be less than section B. This simplified model demonstrates that riparian vegetation can influence whether mass wasting processes occur in the event of incision by providing added mechanical and erosive strength to the boundary material. Yet, it is critical that this vegetation coincide with grade control to avoid incision below the root mass zone. When grade control (or threshold channel conditions) co-exist with a floodplain connection occurring at higher flood frequency intervals, it is reasonable to assume that vegetation plays an instrumental role in bank sediment delivery. The degree of this role will be a function of effect on frictional resistance, modification of near bank stress, and interaction with shear strength. Therefore, reaches should have lower sediment source potentials then those with grade and without vegetation (i.e. high vertical resistance to erosion and low lateral resistance) or those lacking grade control and riparian buffers (low vertical/lateral resistance).

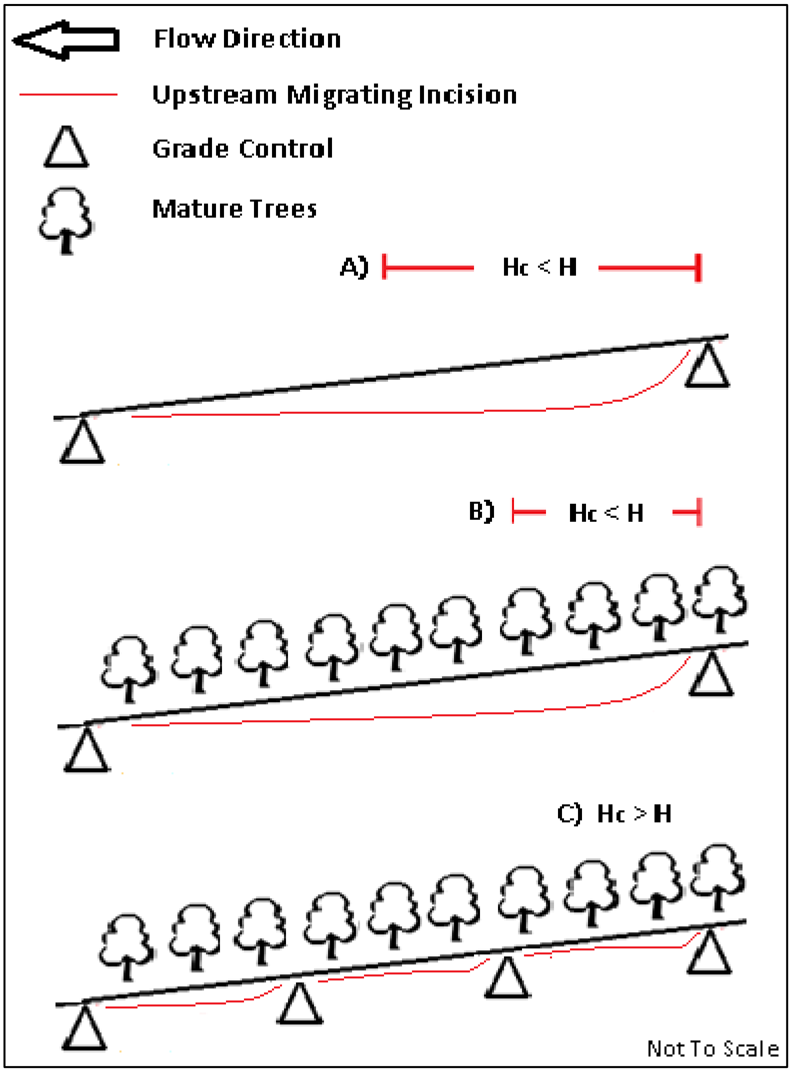

Figure 1.5. A diagram depicting the influence vegetation in combination with grade control may have on potential for mass wasting. Distance A and B represent areas where $H_c < H$. Reach C represents a reach with high frequency of grade control (bedrock or artificial) where $H_c > H$.

Response Through Accelerated Meandering vs Enlargement (Incision and Widening)

The original channel evolution models (Schumm, Harvey et al. 1984; Simon and Hupp 1987) are often utilized to describe urban channel response to hydromodification through standard sequence of response: vertical degradation, vertical and lateral degradation, aggradation, and eventual restabilization at a lower base level incorporating a terraced floodplain. Yet, this sequence of response may be overly simplified for the purpose. Demonstrated by more recent work that expands application through inclusion of vertical and/or lateral constraints, variations in mode or degree of disturbance, and variance in response (Hawley, Bledsoe et al. 2012; Cluer and Thorne 2014; Booth and Fischenich 2015). Observations made during the field study would further support the importance of these revisions; but, also suggest the need for further refinement.

Through field observations, it became increasingly clear that a measurable amount of fine sediment was derived from streambanks within reaches not necessarily undergoing incision and/or widening phases typical of evolutionary models. Within the Stream Evolution Model (SEM) described by Cluer and Thorne (2014), the observed reaches are likely best described as stage 3s (vertically arrested) and stage 7 (laterally active) channels. However, these channels are presented with the following characteristic conditions:

$$3s: Qs_{in} \sim Qs_{out}, H > H_c$$

$$7: Qs_{in} \geq Qs_{out}, H << H_c$$

where, Qs is sediment discharge in and out, H is bank height, and H_c is the critical bank height for mass wasting to occur. Yet, these conditions do not adequately describe conditions observed. First, a number of sites exhibited signs of previous incision, but possessed lateral bars without cutlines (i.e. eroded faces along the depositional form), mature vegetation at base level, and isolated fluvial erosion around macro turbulent (e.g., vegetation, LWD, and bed form) structure. As well, bank heights were not an excess of critical and mass wasting was not an active process nor could it be inferred as pre-requisite to existing state. So, these streams might better be defined by the following existing conditions:

$$3s^*: Qss_{in} \leq Qss_{out}, Qsb_{in} \geq Qsb_{out}, H \leq H_c$$

where, Q_{ss} is suspended load and Q_{sb} bed load.

Second, sites were also observed to have accelerated meandering processes exhibiting conditions of mass-wasting in outside bends. These sites might best be described by the stage 7 channel; however, bank heights in the outside bends were sufficiently in excess of critical geotechnical thresholds (often the result disturbed riparian buffers). Cluer and Thorne (2014) indicate renewed retreat along the outer margins of the channel, but do not necessarily clearly identify the process. This is likely to avoid confusion with changing process along a continuum (Lawler 1995) as opposed to an oversight. Therefore, conditions observed due to urban hydromodification might better be represented by the following:

$$7^*: Qss_{in} \leq Qs_{out}, Qsb_{in} \sim Qsb_{out}, H << H_c \text{ (inside bank)}, H > H_c \text{ (outside bank)}$$

An important distinction, as mass wasting is typically inferred to be the largest source of sediment contribution among erosive processes. These sites (7*) seemed to persist in valley segments within maintained tracts for utilities, greenway systems, urban farms, neighborhoods, and agricultural zones.

These observations along with the findings within the data set suggest four things. First, within the context of the geomorphic setting studied by this research, significant contributions of fine sediments (from 2^{nd} and 3^{rd} order streams) may result from planform channel response and the degree of response will be influenced by frequency of grade control (both artificial and natural) and presence of riparian buffer.

Second, in situations where lateral planform changes (i.e. slope reductions through meandering processes) are predominate as opposed to enlargement of channels (i.e. incision and widening or widening) shifts in the frequency of surface flows may be as important as duration or magnitude of eroding flows. Table 1.6 highlights how modifications to surface flow disturbance regimes might increase rates of fine sediment contributions (i.e. siltation) and Table 1.7 highlights how erosive resistance elements might influence those erosive processes. When this information is considered in light of the concept of process dominance (Lawler 1995) and coupled with urban channel evolution models a more mechanistic understanding is obtained allowing better inferences as to imbalances in natural versus excessive rates of fine sediment yields.

Table 1.6: Anticipated effect on erosive process rates or thresholds as a result of shifts in surface flow disturbance regime resulting from urbanization.

Erosive Process	Magnitude	Frequency	Duration
Subaerial Erosion		x	
Fluvial Erosion	x	x	x
Mass Wasting		x	

x. represents directly influenced by that domain of surface flow regime

Table 1.7: Table indicates whether erosive processes are influenced by erosive resistance element.

Elements	Subaerial Erosion	Fluvial Erosion	Mass Wasting
Vegetation	x	x	x
Grade Control		x	x

x. represents dominate influence on the mechanics of erosive process

Third, in situations where retention/detention based SCMs are the primary BMP utilized to avoid in-channel contributions to siltation and riparian buffer management is ignored, siltation conditions may persist regardless of mitigating efforts.

Finally, most channel and stream evolution models tend to infer a feedback exists along a generally alluvial continuum of heterogeneous boundary materials with a pre-existing state of quasi-equilibrium. However, these assumptions are inappropriate in many urban settings, as a result, of legacy impacts to channel form, boundary resistance, and existence of geomorphic controls (both artificial and natural) which all tend to increase along a gradient of urbanization. This suggests that mitigating siltation, resulting from in-channel contributions, requires a process based approach focused on how changes in the magnitude, duration, and frequency of Q and Q_s influence both cohesive and non-cohesive mechanics of detachment and transport.

Limitations & Considerations

Although in this study riparian vegetation has been demonstrated to decrease the probability of erosive processes along a gradient of urbanization, the findings must be considered in light of the fact vegetative influence will vary significantly. Riparian vegetation can help to mitigate the impacts of subaerial erosive processes, provide mechanical and fluvial support, improve habitat conditions (Orzetti, Jones et al. 2010) , and provide nutrient and phosphorus reductions (Barling and Moore 1994). However, vegetative influence varies by community composition indicating variance in influence both temporally and spatially. Community composition is dictated by climate and geology therefore vegetative influence is likely to be more dramatic in humid climates when compared to semi-arid climates (Bledsoe, Stein et al. 2012), and the potential to override sedimentary influences (Anderson, Bledsoe et al. 2004) would respond accordingly. As well, erosive process dominance varies spatially within watersheds (Lawler 1995) and vegetative influence on erosive resistance varies by channel scale (Abernethy and Rutherfurd 1998). Therefore, considering removal of vegetation is synonymous with stream restoration activities, we must be cautious and as to when, where, and how channel intervention might influence this dynamic over periods longer than typical monitoring periods.

Another consideration, in light of the benefits discussed for channel protection of both artificial and natural grade control, is its inability to influence other biologic and geomorphic processes. Sediment transport for example likely will still be significantly influenced by urbanization as result of modified hydrology and hydraulics. This may manifest in decreases in sediment supply or increases in the frequency of bed load movement. Therefore, consideration of the benefits of stability must be considered in light of shifts in other processes that may affect ecological function and integrity. Hawley, MacMannis et al. (2013) demonstrated that although vertical controls provide protection and decrease channel instability within a spatial domain, modifications to habitat units may still be sufficient to impact macroinvertebrate community assemblages as a result of life history requirements.

Consideration should also be given to our current approach to channel protection. Research is still inconclusive as to what levels of siltation are within ecological thresholds. With some regulations considering scale requirements (Berg, Burch et al. 2013) and few TMDL implementation plans considering riparian buffers as a means of sediment reduction (from in-channel contributions), we may be avoiding a significant source of sediment contributions when aggregated over an entire stream system. As localized variation in resistance properties (due to the removal of vegetation) could provide a significant source of sediment in ER67 streams when considered in aggregate.

As well, by only considering those reaches that are mid phases of most channel evolution models (e.g. incision and widening phases) we are ignoring where meandering processes (lateral adjustments) may be increased as a result of modifications to the frequency of effective erosive flows. Within the context of ER67, many stream system channels have been impacted by vegetation removal or channel form modifications. Using vegetation removal as an example and excess shear as the accounting unit, this could be equivalent to significant increases in impervious cover (Figure 1.3).

Summary & Conclusions

The Ridge and Valley's, 2nd and 3rd order, dendritic and trellised stream systems appear to have been an ideal setting to demonstrate the importance of assessing geomorphic setting as well as geomorphic attributes when considering geomorphic channel response to urbanization**.** As the frequency of bedrock exposure is high and the climate is supportive of deciduous and herbaceous vegetation in combination with cohesive soils, providing a unique geomorphic template of both vegetated and non-vegetated alluvial and threshold reaches along a gradient of urbanization.

This study demonstrated vegetation, grade control, and geomorphic setting are fundamental controls on erosive processes in the Ridge and Valley of East Tennessee. Vegetation impacts rates and thresholds of subaerial, fluvial, and mass-wasting. Grade control influences degree of vertical hydraulic erosion thereby controlling channel evolution and lateral erosive processes. Spatial position and/or geomorphic setting are linked to concepts of transport/supply limited conditions and therefore are controls on the time dependent response to surface flows, indicating how a reach might respond to variations in flood magnitude, frequency, and duration or disruptions to sediment transport dynamics resulting from land-use change.

These findings demonstrate the value of conserving riparian buffers especially when coupled with grade control. Riparian buffers are likely to provide the greatest geomorphic benefit when those buffers are spatial linked to grade control. This benefit was demonstrated through introduction of a simplified model for assessing potential sediment source potential when channel evolution is expected.

Additionally, this study may have inadvertently demonstrated the importance of shifts in frequency of flows. Probability of fluvial erosion and mass-wasting processes did not necessarily relate to higher levels of energy within ER67 streams. Therefore, it could be inferred in a setting with cohesive sediments and disturbed riparian buffers timing of flows (i.e. frequency) may need to be considered in conjunction with duration and magnitude of flows, as increased rates of subaerial processes and mass-wasting processes can occur with relatively small increases in surplus stream power. Indicating that infiltration and evapotranspiration processes may be a better alternative than matching peak flows or utilizing flow duration control standards (relative to bed material conditions) for the purposes of channel protection.

These findings should be considered in light of larger considerations within watershed planning (e.g. water quality, etc.), but nonetheless demonstrate the need to integrate mitigation efforts (both SCMs and in-channel intervention) for the purposes of channel protection and reduction of sediment yields. As well as clarifying erosive processes, the mechanisms of those processes, and the geomorphic attributes that influence them.

With the ultimate goal being to manage the effects of urban hydrologic alteration, focus should therefore emphasize re-equilibrium of processes through integrated watershed management plans. This approach would hopefully allow managers to evaluate the strategic value of various reaches both for conservation and restoration, as well as, evaluate when form might burden other attempts to restore process (i.e. rehabilitation of hydrology).

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Chapter 2

Coupling Hydrology, Hydraulics, and Channel Evolution to Evaluate Channel Protection Efforts: A Case Study in the Southern Appalachian Region, USA.

Abstract

Channel protection efforts in urban watersheds are intended to mitigate the impacts of siltation and habitat destruction resulting from urban hydromodification. Although some success has been achieved through implementation of stormwater control measures (SCMs), scenarios still occur where mitigating efforts do little to avoid effects, often attributed to current regulation lacking an integrated systems approach. More specifically, few agencies mandate incorporating stream geomorphic attributes into watershed/channel protection guidance and Total Maximum Daily Load (TMDL) implementation plans for fine sediment. The purpose of this paper is to demonstrate a unique approach linking hillslope hydrology and channel processes for the purposes of evaluating efforts to mitigate channel degradation in urban stream reaches. Topographic surveys at three stream sites in combination with in-situ monitoring were conducted for three stream systems (2^{nd} and 3^{rd} order) in the Ridge and Valley Province of Tennessee. These data are utilized to construct non-dynamically coupled hydrologic, hydraulic, and channel evolution models and then used to explore channel response trajectories to urbanization and treatments through continuous simulation modeling (SWMM and CONCEPTS). Simulated scenarios include variation in SCMs in order to evaluate the protection from channel erosion under different hydrogeomorphic settings. Results indicated that hydrogeomorphic setting was a fundamental control on determining treatment effectiveness and associated trajectories of channel response to urbanization. Results also indicated low impact development (LID) treatment was generally more effective than regional detention at mitigating the geomorphic effects of impervious surfaces. These findings have direct application to improving channel protection design standards, stormwater and stream compensatory mitigation programs, and valuing TMDL siltation credits. Because of unique hydrological responses from urbanization modeling scenarios associated with catchment characteristics, it suggests channel protection requires a comprehensive watershed planning process that includes geomorphic attributes.

Introduction

Ecological degradation due to siltation and habitat alteration tends to coincide with urban and urbanizing channels, commonly attributed to urban hydromodification (USEPA 2002a). Urban hydromodification is often the result of alterations of land-use due to development practices, which modify excess rainfall regimes leading to increased surface runoff and disruption of natural sediment delivery and transport regimes. Modifications to surface flow regimes and sediment transport can lead to significant in-channel contributions of fine sediments (and associated nutrients), due to imbalances between eroding and resisting forces imposed on the stream system over time.

Studies have indicated that sediments derived from in-channel sources can be a significant portion of sediment loads (Trimble 1997; Allmendinger, Pizzuto et al. 2007; Fraley, Miller et al. 2009). This is often attributed to channel enlargement, which appears to be a predominant response to urbanization (Hammer 1972; Booth 1990; Doll, Wise-Frederick et al. 2002; Chin 2006). Yet, not all research indicates enlargement as a primary impact (Nelson, Smith et al. 2006; Annable, Watson et al. 2012). Whether a stream responds will be a function of the mode and magnitude of disturbance (i.e. land cover change), boundary conditions (Allen, Arnold et al. 2002; Bledsoe, Stein et al. 2012; Booth and Fischenich 2015), the erosive processes in play (Leopold 1973; Lawler 1995), and geomorphic setting (Utz and Hilderbrand 2011).

Many municipalities, in the US and other regions globally (Ashley, Jones et al. 2007; Grove, Bilotta et al. 2015), are now faced with how to mitigate the effects of hydromodification manifesting in increased sediment loads from in-channel contributions and habitat degradation. Most regulatory efforts to date have focused on addressing the peak discharge and/or volume of surface runoff directly through mandating implementation of stormwater control measures (SCMs) designed to generally uniform standards, often referred to as “channel protection” flows. However, there is growing understanding that mitigation cannot be accomplished through SCMs alone (Berg, Burch et al. 2013). Therefore, targeted stream rehabilitation/restoration efforts in combination with SCMs may be required to improve “channel protection” efforts. However, understanding when and where mixed efforts are appropriate requires an understanding of channel erosive resistance elements (i.e. influential geomorphic attributes) that define a reaches sediment source potential. Therefore, a critical research need exists to classify channel erosive resistance elements within the context of hydromodification disturbance regimes to improve how urban streams can be better managed.

The objectives of this research were to integrate processes that determine surface runoff with channel erosive processes to account for the dynamic nature of geomorphic channel response; and to provide a better understanding of what constitutes effective "channel protection" efforts. Topographic surveys in combination with in-situ monitoring were conducted at three stream sites in the Ridge and Valley Province of Tennessee. These data are utilized to construct loosely coupled hydrologic, hydraulic, and channel evolution models. The coupled platform (SWMM[5] and CONCEPTS[6]) offers a physically based integrated model, providing approximation of interactions between driving force and resisting forces. Simulated scenarios include variation in SCM treatments to allow comparison of "relative response" and evaluate the afforded protection from channel erosion. Discussion includes a review of results, fundamental controls on dynamics, and implications for channel protection efforts.

Methods

Study Area

The study area lies within Region 8 of the ecological regions of North America. Region 8 consists of eastern temperate forests which cover a vast area of the eastern United States (CEC 1997). The region is distinguished by its dense and diverse temperate forest consisting of primarily deciduous and conifers (CEC 1997). The Level 2 ecoregion is Ozark, Ouachita-Appalachian Forests (Wiken, Nava et al. 2011). The level 3 ecoregion is identified as the Ridge and Valley (ER67) (Griffith, Omernick et al. 1997) and in Tennessee is bordered to the west by the Cumberland Mountain/Plateau and to the east by the Blue Ridge Mountains. Much of ER67 consists of trellised drainage patterns, characterized by small streams draining the ridges (northeast-southwest trend) and connecting with higher order valley streams within terrain

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5 EPA SWMM (EPA, 2008) is a physically based dynamic rainfall-runoff simulation model with the capability to address either design storm precipitation events or historical rainfall data through CSM (Huber and Dickinson 1988). SWMM was developed by the USEPA in the 1970s and continues to this day to be the most widely used stormwater management model for planning SCMs within urban drainages.

6 CONCEPTS (Conservational Channel Evolution and Pollutant Transport System) was developed by the USDA in the 1990s to simulate channel evolution (Langendoen, Simon et al. 1999). The model incorporates one-dimensional (1-D) unsteady flow (described by the Saint-Venant equations), graded sediment transport, and bank erosion processes (both fluvial and geotechnical processes).

consisting of ridges, rolling valleys, and low irregular hills (Wiken, Nava et al. 2011). The humid subtropical climate results in hot and humid summers and relatively mild winters. Summer storms are typically of short duration but intense and winter storms are characterized by large fronts with longer durations.

ER67 has diverse geological material: limestone, dolomite, shale, siltstone, sandstone, chert, mudstone, and marble (Wiken, Nava et al. 2011). Variation in weathering has created influential and diverse geological features (karst topography as well as characteristic parallel ridges/valleys). Vertical constraints on channel boundaries are common in the streams draining ridges and in transitional zones connecting valley floors. However, valley floors are not necessarily exempt from a high frequency of bedrock exposure. Variance in weathering resistance of the various geologic strata has resulted in diverse topography, soil texture, structure, and depth and ultimately vegetation (Martin 1971).

The mature deciduous forests have historically been poorly managed. As early as the late 1700's, poor management of land and timber was prevalent with both valley bottoms and associated hillslopes impacted by harvesting of timber & land clearing activities. Steep ridges are still commonly dominated by forests and low relief valleys by pasture and cropland in rural areas. In urban and urbanizing settings, there are varying degrees of developed land classes (Homer, Dewitz et al. 2015).

Watersheds

Three watersheds were identified for this study they were Cedar Springs, Little Turkey Creek, and Pistol Creek (Figure 2.1, Figure 2.2, and Table 2.1). The Cedar Springs Creek site has a contributing basin of 8.5 km^2 and an average slope of 14.8 m/km. Cedar Springs provides a site that is vertically susceptible to down-cutting. There is no immediate downstream grade control and bed material supply is dominated by alluvial very fine gravel. Riparian vegetation is deciduous forest, with a maturity approximated at greater than twenty years. There are some areas that do see maintenance by landowners and in these areas the mature deciduous vegetation can be considered sparse but continuous. The valley setting is unconfined and floodplain connection allows ample hydrological storage once made.

The Little Turkey Creek watershed is 11.6 km^2 and has an average slope of 7.3 m/km. Bedrock outcrops dominate the vertical profile of the Little Turkey Creek reach and the larger stream system as whole. The alluvial bed material is coarse gravel. The reach boarders a greenway, but maintenance respects a riparian buffer in some places as much as a channel unit width along the left bank. The right bank is controlled by property owners and does have some devegetated sections resulting from landowner maintenance. Yet as a whole, the riparian vegetation along the reach is primarily a continuous mature mixed hardwood with understory of thick privet and honeysuckle. Of interesting note, some hydraulic features exist anchored by bedrock outcrops vertically and by sycamores (acting as hard-points) in the lateral direction. These features provide a unique area of energy dissipation. Floodplain connection, much like the other reaches, allows ample storage once breached.

The Pistol Creek watershed is 16.1 km^2 and has an average slope of 5.6 m/km. The Pistol Creek site is influenced by an artificial grade control in the lower reach and bedrock outcrops within the encompassing stream segment. The bed material is alluvial coarse gravel. Riparian vegetation at the site is significantly disturbed bordering a greenway that is aggressively maintained. The right bank is largely devoid of a riparian buffer, although some pockets of invasive vegetation (privet and honeysuckle bush) and the occasional mature hardwood (likely left for aesthetics) do exist. The left bank vegetation is somewhat improved as bank vegetation dominates (deciduous trees with invasive understory) over sparse pockets of maintained grasses in the immediate bank area. The valley setting is unconfined and floodplain connection allows ample storage once made.

Table 2.1: Research stream system characteristics.

Site	Latitude & Longitude	Drainage Area (km^2)	10 & 85 Method Slope (m/km)	Valley Slope (m/m)	Stream Order	% TIA	% Developed
Cedar Springs	35.416114° -84.617807°	8.5	14.8	0.0023	2	4%	21%
Little Turkey Creek	35.863228° -84.200178°	11.6	7.3	0.0050	2	21%	81%
Pistol Creek	35.735604° -83.980498°	16.1	5.6	0.0037	3	15%	63%

Note: 10 & 85 Method Slope is the approximated slope between 10 % and 85% of the stream length to basin divide (USGS 2012).

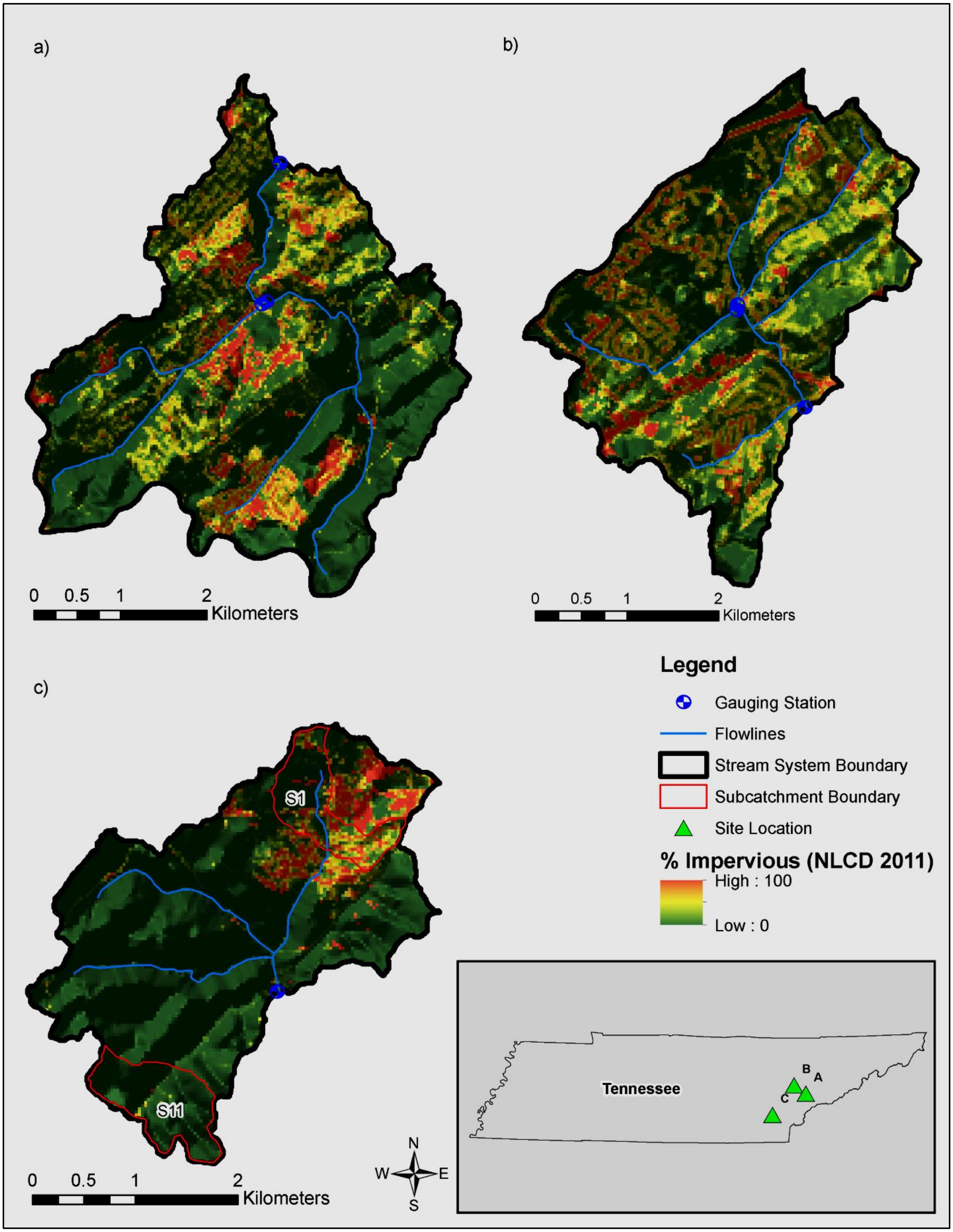

Figure 2.1. a) Pistol Creek watershed in Maryville, TN b) Little Turkey Creek watershed in Farragut, TN c) Cedar Springs Creek in Athens, TN.

Figure 2.2. Research site photographs: top photo is Cedar Springs, middle photo is Little Turkey Creek and bottom photo is Pistol Creek. Photographed by the author in 2013.

Coupled Models

Characterization of Stream System Hydrology

Contributing basins were delineated with the PCSWMM watershed delineation tool (PCSWMM 2017) with a targeted discretization level of 80.9 hectare (200 acres). A break down showing average and number of delineated subcatchments is seen in Table 2.2. Initial conveyance network structure was also determined with the assistance of PCSWMMs watershed delineation tool (PCSWMM 2017) utilizing the NED database and then validated through use of NHDPlus V2 flowlines, orthoimagery, and USGS topographic maps. Conveyance network channel geometries in SWMM models were approximated through application of regional curves (McPherson 2011). Additional model parameters regarding soils and landuse were approximated through PCSWMMs GIS Based Area Weighting Tool (PCSWMM 2017) utilizing the SSurgo 2.2 and NLCD databases.

Rainfall and flow monitoring equipment were installed at each of the study sites. Data were monitored during a period spanning March 2014 thru February 2016. Storms across a range of precipitation intensity and depth and distributed in different seasons were selected from the data set and utilized to calibrate the SWMM runoff block thru PCSWMMs SRTC calibration tool (PCSWMM 2017). Calibration involved refinement of uncertain watershed characteristics (e.g., catchment width, depression storage, and infiltration model parameters). Calibrated models were then utilized to simulate 25 year periods (01/01/1985 – 12/31/2009) of hydrology utilizing a historical precipitation record for existing conditions, disturbed conditions (i.e. increased impervious surfaces), and treated conditions (i.e. implementation of SCMs). Modeled results were then utilized as input upstream boundary conditions in CONCEPTS to run continuous simulation models and allow channel erosion analysis.

Treatment methods included two types of SCMs: regional detention and bioretention basins. Regional detention facilities were implemented in each of the subcatchments and calibrated to match site specific estimates of peak flows for the 2 year 24 hour storm (Bonnin, Martin et al. 2006). Implementation of decentralized LID treatments were implemented through calibrating the # of bioretention basins in each subcatchment necessary to capture and infiltrate all runoff from effective impervious surfaces for the 1” storm (2.54 cm). Bioretention facilities were identical in nature other than storage layer seepage rates which were approximated based on average native soils for each specific subcatchment (Table 2.3). Table 2.2 provides details regarding total number of facilities utilized in each subcatchment of the three research stream systems.

Table 2.2: Subcatchment delineation and treatment details.

Site	# of Delineated Subcatchments	Average Contributing Drainage Area per Subcatchment (hectare)	# of Regional Detention Facilities	# of Bioretention Basins for 10% TIA increase	# of Bioretention Basins for 25% TIA increase
Cedar Springs	11	75	11	564	1398
Little Turkey Creek	15	72	15	774	1913
Pistol Creek	22	74	22	1189	2914

Table 2.3: Summary of bioretention basin parameters used in long term simulations.

Layer	Description of Parameter	Parameter Value
Surface	Ponding Depth (cm)	15.24
Soil	Soil Thickness (cm)	60.96
	Porosity (volume fraction)	0.2
	Field capacity (volume fraction)	0.19
	Soil Conductivity (cm/hr)	1.27
	Suction Head (cm)	8.89
Storage	Storage Height (cm)	60.96
	Storage Void Ratio (voids/solids)	0.4
	Seepage Rate	K_{sat} of native soils

Characterization of Stream Corridor

Hydraulic Routing

Hydraulic routing in CONCEPTS is performed through means of 1-D numerical methods, utilizing the Saint Venant equations (Langendoen 2000). Therefore, interval cross-sections are necessary that capture representative channel and floodplain topography. Flow resistance is implemented through an approximation of Manning's n, which can vary between floodplain, bank, and active channel. Surveys were conducted following industry standard techniques and completed between March and June in 2014. Surveys included representative cross sectional geometries and longitudinal profiles. Recorded points characterized cross-sectional area, bank height/angle, relevant terraces, and floodplain. Implementation of Manning's n values involved initial approximation following methods of Arcement and Schneider (1989) and then further refinement thru calibration between observed and simulated stages. *A loop-rating curve* was utilized for the downstream boundary condition (Langendoen 2000). Calibrated hydraulics were then coupled with output hydrology from PCSWMM simulations and implemented in CSM modeling efforts.

Sediment Routing

CONCEPTS simulates both sediment transport and bed adjustment thru time, incorporating bed material stratigraphy (both cohesive and non-cohesive materials) and grain size distribution. Material influx can be determined through measured, calculated, or fractional transport conditions (Langendoen 2000).

Pebble counts were conducted as ≥ 100 point samples (Wolman 1954) utilizing a gridded format and ϕ template along characteristic riffle to characterize particle size distributions (PSDs) of surface layer. To incorporate fine sediment distributions (distributions less than 2 mm) on the bed, interpolations were made utilizing data representative of average conditions for ER67 streams in Tennessee from Williams (2005). PSDs are utilized to classify bed material and calculate fractional transport conditions thru a modified SEDTRA model in CONCEPTS (Langendoen 2000). To model influx, fraction of transport capacity was utilized. Supply limited conditions were assumed for fines (< 0.5 mm) and transport limited conditions assumed for medium sands (0.5 mm) and greater.

Stream Bank Erosion

CONCEPTS models lateral adjustment through incorporating physical processes involved with bank retreat; these include both fluvial erosion and mass failure processes (Langendoen 2000). Input data include bank material stratigraphy, grain size distributions, bulk density, and hydraulic/mechanical resistance to erosion. Hydraulic resistance parameters include critical shear (τ_c) and the erodibility coefficient (k_d). Mechanical resistance parameters include cohesion (c), friction angle (ϕ), and suction angle (γ_s).

Soil properties at each site were characterized through a combination of in-situ methods, laboratory methods, and reference to existing literature (Table 2.4). A submerged jet device was utilized to measure in-situ critical shear (τ_c) and the erodibility coefficient (k_d) (Simon, Thomas et al. 2010; Al-Madhhachi, Hanson et al. 2013). In-situ soil probes in combination with geotechnical laboratory analyses was utilized to approximate unit weight, texture, and distribution (Standard 2007). The variable c was approximated as three orders of magnitude greater than τ_c following findings of Sutarto, Papanicolaou et al. (2014) and ϕ and γ_s assumed based on textures of lab samples following Selby (1982).

Table 2.4: Average conditions for bank soil parameters used in CONCEPTS models.

Site	Bulk Density (kg/m^3)	τ_c (Pa)	k_d (m/s/Pa)	C (Pa)	ϕ (◦)	γ_s (◦)
Cedar Springs	1326	9.6	7.20E-07	9600	29	15
Little Turkey Creek	1313	6.1	2.15E-06	6100	29	15
Pistol Creek	1445	7.1	1.17E-06	7100	29	15

Implementation of Simulated Hydrogeomorphic Conditions

To evaluate the efficacy of mitigation suites and the influence of erosive resistance parameters, SWMM and CONCEPTS are non-dynamically coupled to integrate hillslope processes with in-channel processes. SWMM provides assessment of existing and future hydrologic state allowing comparison of rainfall-runoff relationships. Future hydrologic state includes implementation of SCMs (centralized and decentralized) allowing assessment of hydrologic controls as mitigating efforts to reduce in-channel destabilization. CONCEPTS provides assessment of in-channel erosional processes to include fluvial erosion, mass wasting, and sediment transport at a reach scale (Langendoen, Simon et al. 1999; Langendoen, Simon et al. 2000; Langendoen 2011) across the three sites that represent unique geomorphic settings (e.g., Little Turkey Creek – high frequency of grade control).

Table 2.5 provides a summary of the model simulations implemented for each reach of the three study streams. Emphasis was not placed on specifically tailoring a suite to a watershed, but rather representing variance in treatment/practice. Since, the intent of this research was to determine if channel erosive resistance elements dictate variance in efficacy of various mitigating suites, a definitive optimized solution for each watershed was perceived as an unnecessary step. Rather, scenarios were selected to represent the extremes of mitigating suites to allow comparison of "relative response" and evaluate the afforded protection from channel erosion provided by various mitigating suites within geomorphic setting constraints.

The scenarios listed in Table 2.5 were run as standard, worst case, and an adjusted bedload supply condition. The standard model contains the average observed characteristics on-site. The worst case scenario (-WC) represents the 90% confidence interval (CI) for t-distribution means based on observed site data (i.e. minimum τ_c and maximum k_d CI's for each site). Worst case cohesion values were adjusted accordingly as an order of 3 relative to τ_c and all other values were held constant. The bedload supply version (-B) represents modified fraction of transport capacity (Qs upstream boundary condition) values. These values were adjusted to roughly decrease incoming sediment loads by 50% relative to the standard model.

Table 2.5: Table of Simulated Hydrologic and Geomorphic Conditions

Scenario	PCSWMM	Hydrologic Alteration	Hydrologic Controls (Treatment)	CONCEPTS
1.0	Existing Condition	na	na	Existing Condition
1.0-b	Existing Condition	na	na	Modified Bedload Conditions
1.0-WC	Existing Condition	na	na	Modified Boundary Conditions
1.1	Post Condition 1	10% increase in TIA	na	Existing Condition
1.1-b	Post Condition 1	10% increase in TIA	na	Modified Bedload Conditions
1.1-WC	Post Condition 1	10% increase in TIA	na	Modified Boundary Conditions
1.1.1	Post Condition 1.1	10% increase in TIA	Regional Detention	Existing Condition
1.1.1-b	Post Condition 1.1	10% increase in TIA	Regional Detention	Modified Bedload Conditions
1.1.1-WC	Post Condition 1.1	10% increase in TIA	Regional Detention	Modified Boundary Conditions
1.1.2	Post Condition 1.2	10% increase in TIA	LIDs	Existing Condition
1.1.2-b	Post Condition 1.2	10% increase in TIA	LIDs	Modified Bedload Conditions
1.1.2-WC	Post Condition 1.2	10% increase in TIA	LIDs	Modified Boundary Conditions
1.2	Post Condition 2	25 % increase in TIA	na	Existing Condition
1.2-b	Post Condition 2	25 % increase in TIA	na	Modified Bedload Conditions
1.2-WC	Post Condition 2	25 % increase in TIA	na	Modified Boundary Conditions
1.2.1	Post Condition 2.1	25 % increase in TIA	Regional Detention	Existing Condition
1.2.1-b	Post Condition 2.1	25 % increase in TIA	Regional Detention	Modified Bedload Conditions
1.2.1-WC	Post Condition 2.1	25 % increase in TIA	Regional Detention	Modified Boundary Conditions
1.2.2	Post Condition 2.2	25 % increase in TIA	LIDs	Existing Condition
1.2.2-b	Post Condition 2.2	25 % increase in TIA	LIDs	Modified Bedload Conditions
1.2.2-WC	Post Condition 2.2	25 % increase in TIA	LIDs	Modified Boundary Conditions

*Identifiers are used to show stream system and then scenario (e.g., CS_1.0 - Cedar Springs standard conditions)
*The inclusion of -WC represents modification to fluvial/mechanical resistance parameters
*The inclusion of -B represents modification to sediment supply boundary conditions

Data Processing & Analysis

In order to quantify channel adjustments data were sampled at three roughly equally spaced cross-sections within the reach (i.e. the sampled cross-sections generally represented stationing equivalent to ¼, ½, and ¾ of the total stationing along the thalweg alignment). Data were sampled at cross-sections by identifying initial WSE for the active channel flow area. Active channel is defined as the existing flow area immediately prior to floodplain connection. A VBA script was then utilized to sample the 25 year 15 min time-series for observations of the selected WSE elevation and associated hydraulic parameters (e.g., velocity, flow area, etc.) at each of the designated XS. This effort provided necessary data to construct the following metrics: change in active channel flow area (ΔFA), relative change in active flow area (RΔFA), and a modified relative change in active flow area (R_2ΔFA).

Change in Active Channel Flow Area (ΔFA)

Modifications were measured through analysis of change in active channel flow area. ΔFA was measured at designated XS's and then summed to represent the net change in flow area for the reach. It is expected that the ΔFA is a rough approximation of the work performed on the channel boundaries or lack thereof and direct measure of instabilities when compared to existing state simulation. As well, this measure captures interaction effects and mechanical processes on the streambanks that are not only a function of flow, but timing and antecedent condition as well.

Relative Change in Flow Area (RΔFA)

The relative change in flow area (RΔFA) was also used. RΔFA describes the ΔFA of a given simulation relative to the existing state model (e.g., CSM-1.0). This metric was intended to provide further understanding of patterns of change as a function of treatment. Equation 2-1 defines RΔFA.

$$R\Delta FA = \frac{\Delta FA_{1.\#}}{\Delta FA_{1.0}} \qquad \text{Eq. 2-1}$$

Relative Change in Flow Area for Varied Geomorphic Attributes (R_2ΔFA)

The relative change in flow area for varied geomorphic attributes (R_2ΔFA) was also used. R_2ΔFA describes the net change in flow area relative to the comparable average geomorphic conditions model (e.g., a comparison between 1.0 and 1.0-WC or 1.0 and 1.0-b). Therefore, a value of 1 would represent equivalent change. This metric was intended to provide further understanding of patterns of change as a function of modified geomorphic attributes (e.g., worst case scenario model or modified bedload boundary conditions). The formula below defines $R_2\Delta FA$.

$$R_2\Delta FA = \frac{\Delta FA_{CSM-1.\#-(WC\ or\ b)}}{\Delta FA_{CSM-1.\#}} \qquad \text{Eq. 2-2}$$

Results

SCMs

In each of three stream systems TIA was increased from existing conditions by 10% and 25%. Additions of TIA were applied at the subcatchment level to make a generally spatially uniform increase. For example, if a subcatchment had a TIA of 4% as an existing condition the post condition was 14% (with application of the 10% increase). This translated to increased frequency, duration, and magnitude of surface runoff in response to increased TIA in all three stream systems, demonstrated by the flow duration curve (FDC) in Figure 2.3.

Treatment had little effect on runoff behavior from less frequent precipitation events. Figure 2.3 demonstrates consistent peak flow values for a given duration at the Pistol Creek site, regardless of type. The pattern observed in Figure 2.3 was observed for all three stream systems. LID treatment (PC_1.1.2 and PC_1.2.2) had measureable effect on higher frequency reoccurrence intervals; demonstrated by lower durations for a given flow value when compared to post conditions without treatment (PC_1.1 and PC_1.2) and with regional detention as treatment (PC_1.1.1 and PC_1.1.2). This general pattern of influence was also observed across all three stream systems. These results indicate that regional detention was less effective at treating more frequent precipitation events in terms of surface runoff.

The lack of performance in regional detention (PC_1.1.2 and PC_1.2.2) treatment effects on mitigating stream system scale peak flows is demonstrated by a nearly consistent FDC when compared to the post condition models without treatment (PC_1.1 and PC_1.2) (Figure 2.3). This pattern was observed in all three stream systems and appears to be a function of spatial scale. For instance, the Cedar Springs subcatchment S11 representing 8.7% of the contributing area (approximately 0.75 km^2) of the Cedar Springs basin indicates regional detention treatment has a direct influence on the 2 yr 24 hr storm peak (Figure 2.4) by matching existing conditions peak flow. Yet, at the basin outlet effect is lost (Figure 2.5). This same pattern was not observed for the 1" storm for the LID treatment during calibration. For example, Figure 2.6 and Figure 2.7 demonstrated that there is no apparent scaling effect. These results support other research findings which have indicated detention facilities have a loss of effect at scale on watershed-wide peak flows (Emerson, Welty et al. 2005). The implications that this has for in-channel erosive processes will be demonstrated in later sections.

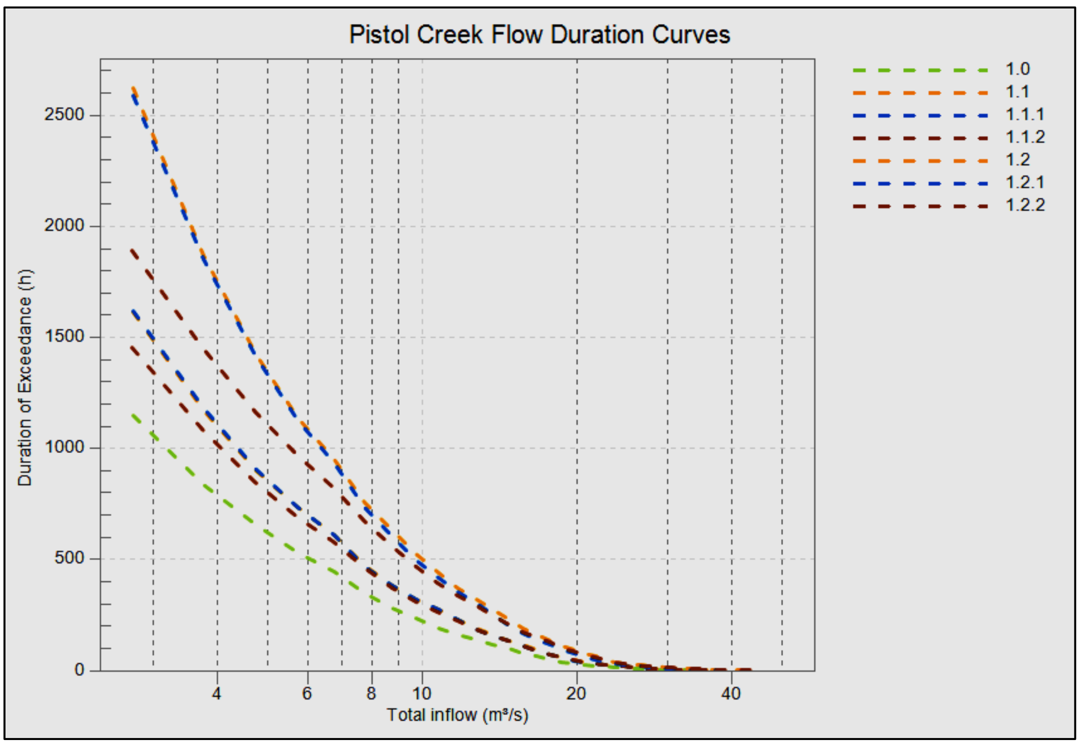

Figure 2.3. Flow duration curves for Pistol Creek simulation including existing condition, post condition, and both post treatment conditions (Table 2.5).

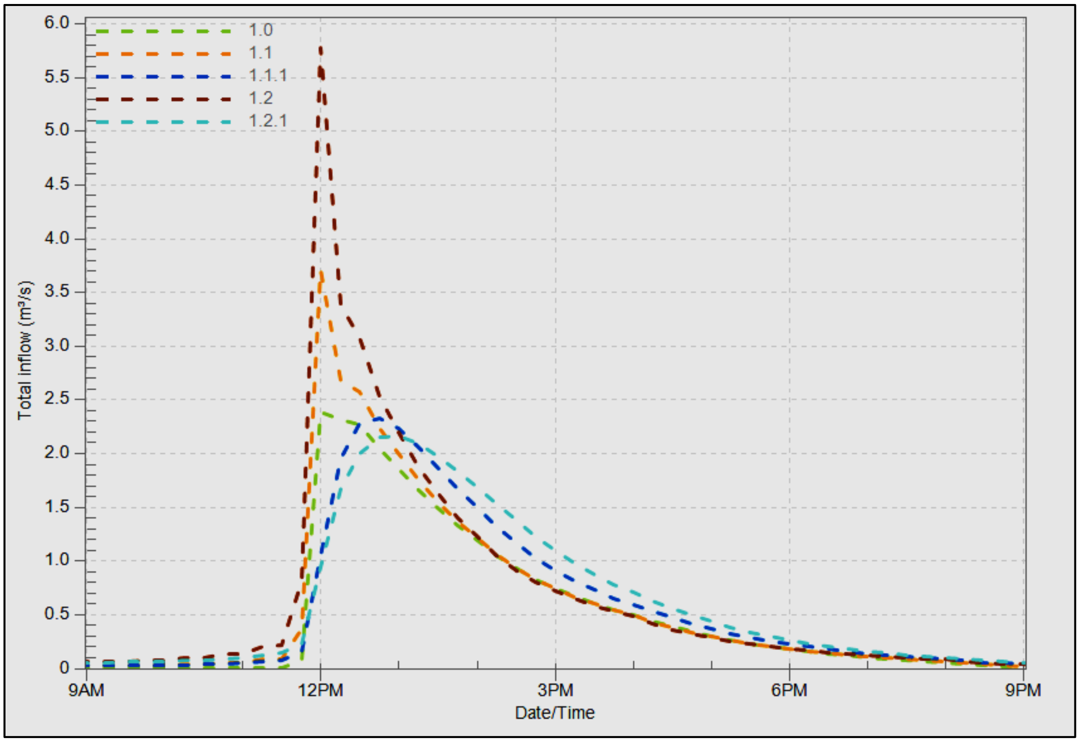

Figure 2.4. Hydrograph of surface runoff from subcatchment S11 in the Cedar Springs stream system. Graph shows the influence of regional detention treatment. Simulations can be referenced in Table 2.5.

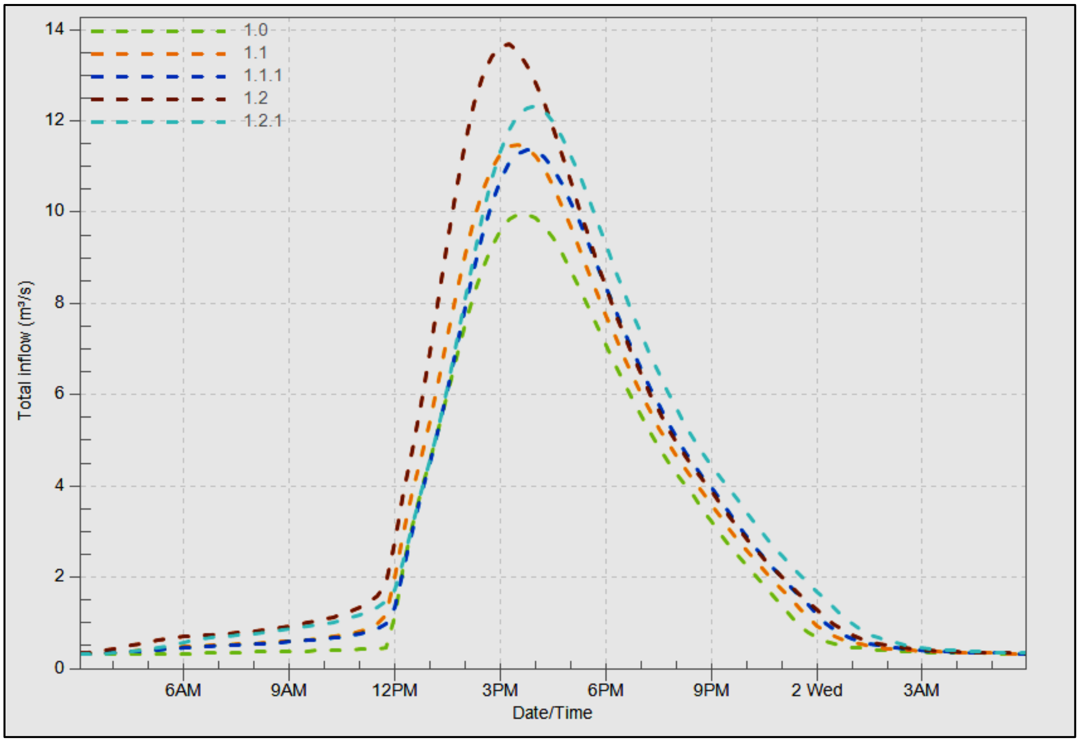

Figure 2.5. Hydrograph of surface runoff from Cedar Springs stream system. Graph shows the influence of regional detention treatment at stream system scale. Simulations can be referenced in Table 2.5.

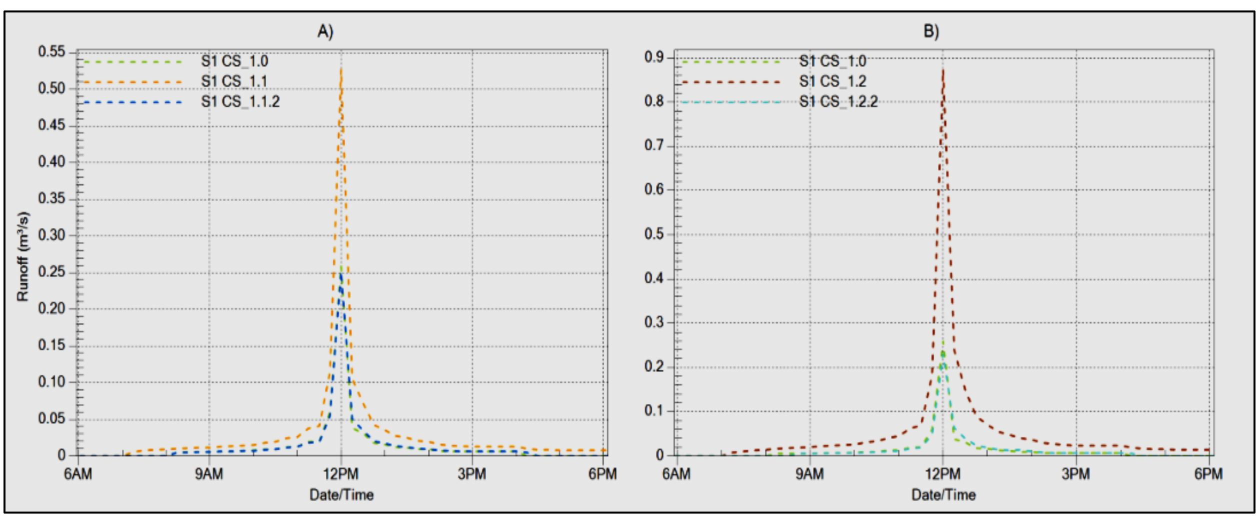

Figure 2.6. 1" storm runoff from subcatchment S1 in the Cedar Springs stream system. A) represents a 10% increase in the stream system and B) represents a 25% increase in the stream system. Simulations can be referenced in Table 2.5.

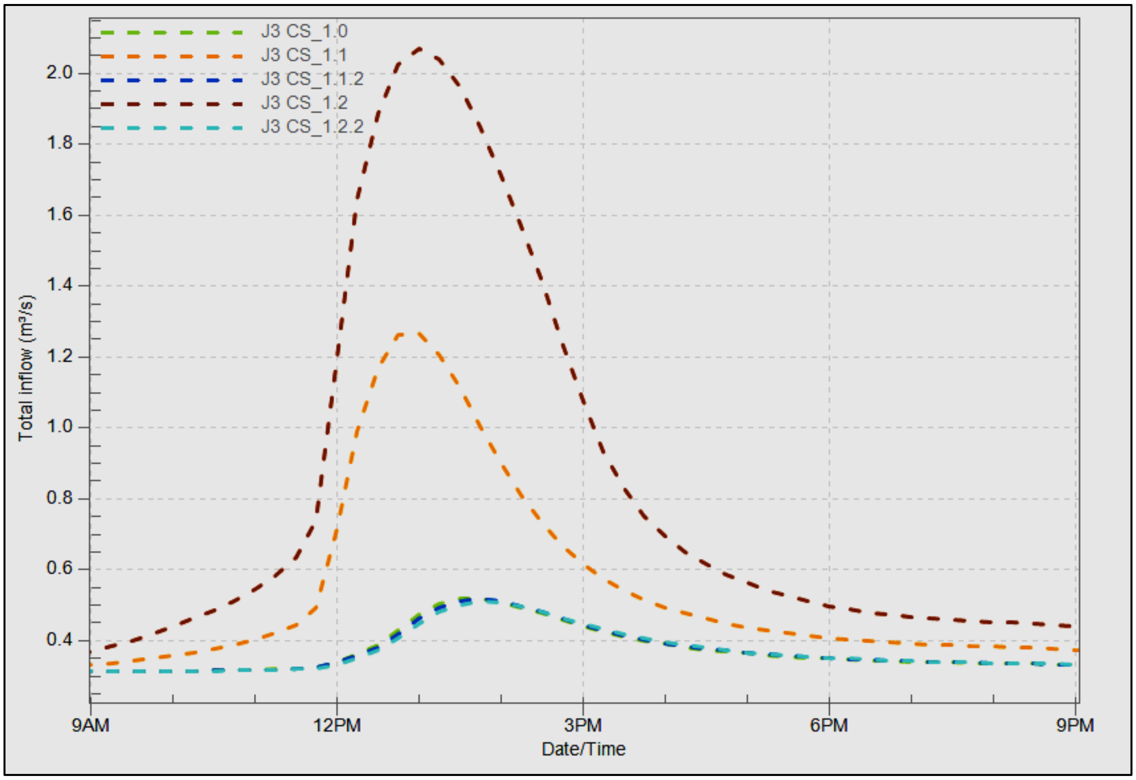

Figure 2.7. 1" storm runoff at the outlet of the Cedar Springs catchment. Simulations can be referenced in Table 2.5.

Response to Increasing Impervious Cover

The change in unit stream power for all seven standard (i.e. average conditions) long-term simulations was documented at a characteristic riffle at each of the three sites (Figure 2.8) to demonstrate general conditions with respect energy. Little Turkey Creek has the greatest rate of potential energy expenditure per unit weight of all three sites. Alternatively, Cedar Springs has the lowest rate of potential energy expenditure per unit weight. These observations are consistent regardless of degree of impervious surface or treatment and should be considered a general description of the relative available energy at the sites.

Figure 2.9 demonstrates that under average geomorphic conditions all three sites responded to increases in impervious cover to some degree through channel enlargement. Yet, a unit increase in impervious cover did not necessarily translate into equivalent channel enlargement for all three sites. Rather, Cedar Springs experienced a more dramatic channel enlargement associated with increasing impervious cover during long-term simulations.

However, this variation in response was not attributable to additional energy at Cedar Springs when compared to the other two sites as one might expect. This is demonstrated by Figure 2.10 which indicates that Cedar Springs had the lowest energy setting of the three study sites, but nonetheless experienced the greatest channel enlargement. Rather, it is likely explained by the fact that Cedar Springs favors a transport limited condition for bed material (gradation favoring very fine gravels to very coarse sand), in combination with a supply limited condition for bank materials and a lack of grade control. This combination leads to incision without an arresting grade-control undermining stability afforded by vegetation and leading to onset of cantilever failures. Therefore, these conditions make it uniquely sensitive to modifications in hydrologic regime as modifications to surface runoff translate directly to channel forming work due to imbalances in driving and resisting forces.

Figure 2.8. Approximated Unit Stream Power (USP) during long-term simulations for all standard scenarios (modified boundary and bedload conditions not included). Simulations can be referenced in Table 2.5.

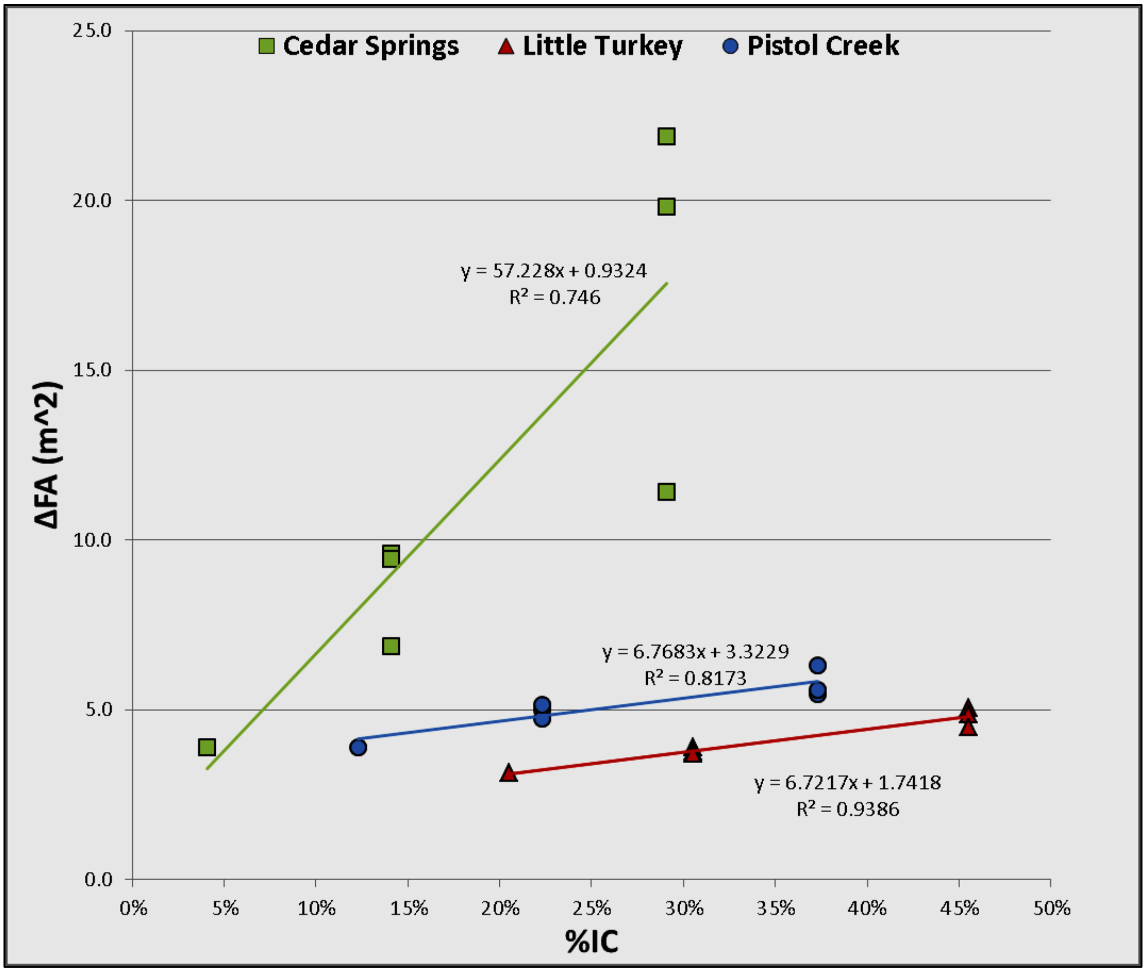

Figure 2.9. Graph of % Impervious Cover vs.ΔFA for the standard models for each site.

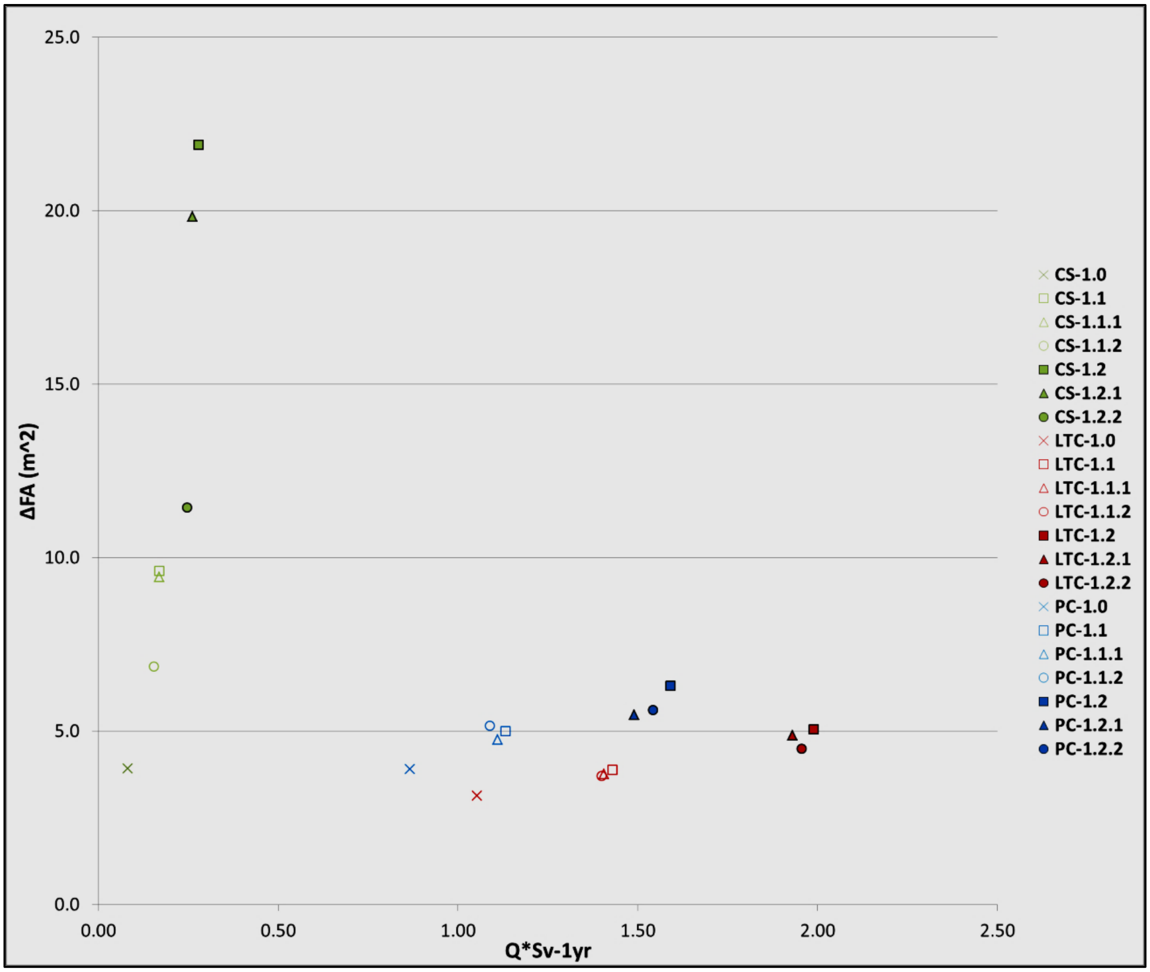

Figure 2.10. Q*S_v vs ΔFA for standard simulations across the research sites.

Response to SCM Treatments

Treatment of increases in impervious cover involved both regional detention and bioretention applications. Case study results indicated influence of treatment generally declined with increasing impervious cover, was rarely completely effective, and varied between case study sites (Figure 2.11) regardless of treatment method. However, results also indicated bioretention was generally more effective at reducing channel enlargement when compared to detention facilities.

Effects of SCMs on channel enlargement were most observable at the Cedar Springs research site. Variance in effectiveness of treatment was likely attributable to a combination of geomorphic attributes and variance in effect on hydrologic regime, as discussed in previous sections. However, even though SCMs reduced channel enlargement; enlargement relative to the existing condition still occurred. For example, when Cedar Springs saw an increase of 25% impervious cover the site still experienced significant enlargement (5 times that of existing conditions for regional detention (1.2.1) and 3 times for bioretention (1.2.2)) (Figure 2.11).

Responses to treatment for Pistol and Little Turkey were suppressed when compared to Cedar Springs (i.e. there is very little variation in ΔFA regardless of treatment). Yet, this may be more of a function of the fact that response was suppressed even without treatment of impervious cover (simulations 1.1 and 1.2). Suppressed response is likely attributable to variations in erosive thresholds as a result of variation in geomorphic setting at the different sites (e.g., grade control, bed material, existing channel state, etc.) and indicates the importance of setting on response to urban hydromodification.

Response to Modified Geomorphic Attributes

In conjunction with standard models, two additional models were included that represented an approximate worst case scenario (-WC) for both fluvial/mechanical resistance parameters and one where the incoming bedload was reduced by half of the approximated standard model conditions (-b). These long-term simulations were performed to gather further understanding of sensitivity to geomorphic attributes.

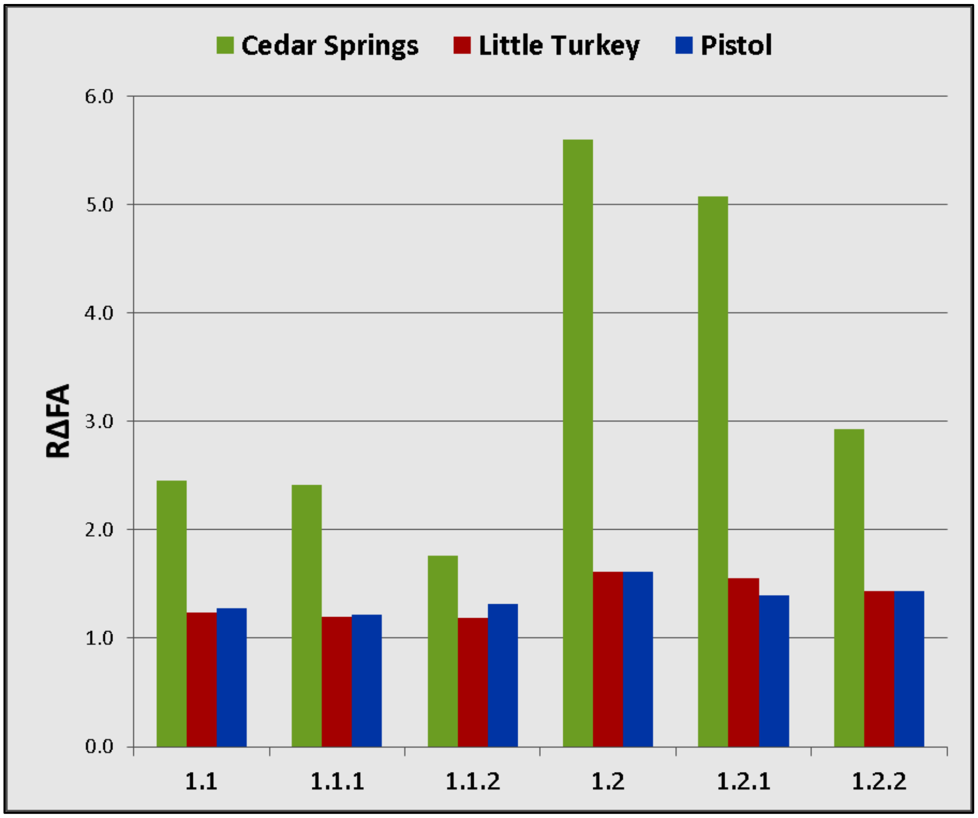

Figure 2.11. Chart reflecting the relative net Δ in flow area for all simulations. (RΔFA = Post Condition/Existing Condition Sims)

Of note, Little Turkey and Pistol Creek were both sensitive to modified approximations of fluvial/mechanical resistance parameters, documented through $R_2\Delta FA$ and seen in Figure 2.12. However, the enlargement at Little Turkey was most dramatic. For example, at LTC enlargement on average is as much as 4 to 5 times the equivalent standard conditions model. This is likely attributable to LTC having the highest valley gradient of the sites and the largest variance in observed hydraulic resistance parameters (i.e. τ_c and k_d). Therefore, these –WC scenarios represented simulations with significant imbalances between driving and resisting forces.

More specifically, lateral boundaries had minimal resistance to hydraulic and mechanical related erosive processes. These conditions might be equivalent to a site experiencing significant devegetation of the riverbanks. In this state, regardless of hydrologic regime, erosive process thresholds and rates would have been modified. For example, a lowered τ_c resulting in a lower fluvial erosion threshold and an increased k_d resulting in an increased erodibility. In combination, with these outcomes temporal effects of subaerial processes will have been amplified further reducing τ_c and k_d[7]. As well, mechanical resistance will have been influenced leading to lower critical bank heights and resulting in the onset of mass-wasting sooner due to increased rates and magnitudes of fluvial erosion and lower critical bank heights.

Reductions of incoming sediment supply had less of an effect on channel enlargement. Most models resulted in $R_2\Delta FA$ values near unity with minimal variance and no obvious trends. Cedar Springs did appear to have a reduced degree of channel enlargement for the reduced bedload model. For example, Cedar Springs had an average $R_2\Delta FA$ of 0.8 indicating a lower degree of channel enlargement when compared to the standard model. Yet, these observations were likely within the inherent error associated with modeling efforts and it was difficult to draw substantive conclusions from these results that could be extrapolated to other sites.

[7] Subaerial processes are not at this time incorporated into the CONCEPTS model and therefore the associated discussion is only intended to exemplify the potential effects of subaerial processes on these parameters.

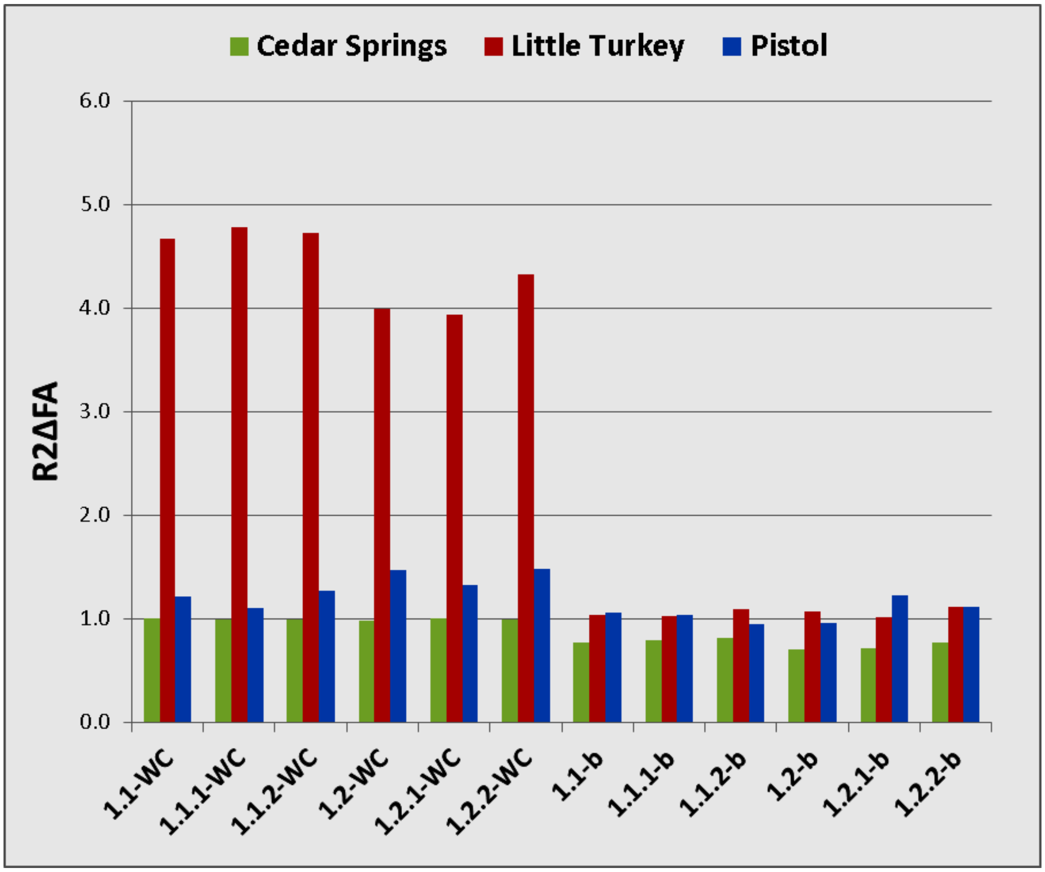

Figure 2.12. Bar Chart of $R_2\Delta FA$ comparing worst case and modified bedload scenarios to average condition scenarios.

Discussion

Surplus Stream Power, Effective Stream Power and Erosion

The long-term simulations performed in this research resulted in a number of observations requiring further discussion. The most notable of these observations are listed below:

- Treatments, regardless of type, do not appear to be completely effective at restoring hydrologic patterns in terms of the magnitude, frequency, and duration of surface flows within case study stream systems.
- LID treatments were more successful at mitigating the effects of impervious surfaces in terms of duration and frequency for higher return interval storms.
- Both increases in impervious surfaces and treatments to mitigate appear to have a varying degree of effect relative to the geomorphic setting with which they interact.
- Increases in impervious surfaces did not correlate to a uniform destabilization of reaches and there appeared to be no threshold effect at any of the reaches related to increases in impervious surfaces.
- Sensitivity to increased surface runoff is not unique to completely alluvial reaches, but rather bedrock controlled reaches are potentially susceptible to channel enlargement when lateral boundary erosive resistance is modified.
- Channel enlargement appeared to be far more sensitive to approximated geomorphic parameters associated with physical thresholds and rates than increases in impervious surfaces within the case study stream systems.

Summarizing these findings is a difficult task and one fraught with the possibility of oversimplification. Nonetheless, these steps are necessary to understand the implications of these findings and be able to identify the context, in which, these case study findings might be extrapolated. Ultimately, it is suggested that many of these results can be attributed to the different hydrogeomorphic settings and the erosive processes those settings impose; which translate to variation in how flow induced energy is expended.

Even though each study stream system saw generally uniform increases in “surplus stream power”[8] this did not translate into similar patterns of energy expenditure termed “effective stream power”[9]. Effective stream power is a function of the geomorphic setting/controls and the variance in associated attributes over time. Table 2.6 documents some of the more influential attributes that determine the magnitude, frequency, and duration of effective stream power.

Effective stream power incorporates both the increased surface flows due to urbanization and the geomorphic setting, providing a process-based conceptual framework. This process-based conceptual framework helps to highlight that sensitivity is not only a function of the alluvial nature of the reach. Rather, gross imbalances in driving and resisting force can translate into channel enlargement in non-alluvial (i.e. bedrock controlled) reaches. These areas, where valley slopes are significant and supply-limited conditions tend to persist, are especially prone to riparian buffer modification.

For instance, Cedar Springs demonstrated the traditional exponential decay pattern expected of channel degradation and experienced the largest ΔFA for the standard scenario. In contrast, Little Turkey Creek experiences minimal response for the standard scenario, but a significantly greater response under modified lateral boundary condition simulations (-WC) (Figure 2.11 and Figure 2.12). The ensuing channel enlargement resulting from reduced erosive resistance of the boundaries is amplified by the local valley gradient leading to significant channel forming work as a result of the effective stream power. These simulations are representative of an outcome where riparian vegetation removal might have occurred and demonstrates the need to consider in-channel erosive processes within the context of effective versus surplus stream power. This is a hypothetical situation, but none-the-less highlights the influence hydrogeomorphic setting has on erosive processes and therefore the domains where surplus stream power will be erosive in nature. In this light, more effective strategies will likely result as a by-product of taking a process-based approach to channel protection.

8 The term “Surplus Stream Power” is being utilized to describe the increases in driving forces as a result of increased surface flows in the domains of magnitude, frequency, and duration.
9 The term “Effective Stream Power” is being utilized to describe the difference between driving and resisting force. The difference being a function of geomorphic attributes.

Table 2.6: Influential geomorphic attributes related to the magnitude, frequency, and duration of effective stream power.

Geomorphic Attributes	**Related Literature**
Local valley width and gradient	(Grant and Swanson 1995; Lawler 1995; Van den Berg 1995; Montgomery 1999)
Sediment supply gradation (e.g., sand dominated vs cobble dominated) and condition (e.g., supply/transport limited)	(Buffington and Montgomery 1999; Simon and Rinaldi 2006; Bledsoe, Stein et al. 2012)
Proximity to grade control and frequency of	(Watson and Biedenharn 1999; Langendoen, Simon et al. 2000; Bledsoe, Stein et al. 2012; Hawley, MacMannis et al. 2013)
Near bank vegetation community and maturity	(Dunaway, Swanson et al. 1994; Millar and Quick 1998; Simon and Collison 2002; Wynn and Mostaghimi 2006; Polvi, Wohl et al. 2014)
Bank materials and stratification	(Hooke 1979; Thorne and Tovey 1981; Dunaway, Swanson et al. 1994; Julian and Torres 2006; Wynn and Mostaghimi 2006; Sutarto, Papanicolaou et al. 2014)
Local groundwater dynamics	(Simon, Curini et al. 2000; Fox and Wilson 2010)
Existing channel form (i.e. evolutionary state)	(Simon 1989; ASCE 1998a)

Note: The list of referenced material is not meant to be comprehensive.

It is important to note though these arguments are not intended to negate the impacts of modifications of hydrology. Influences on riparian communities, biota, and associated biological processes are of paramount importance and should be considered in conjunction with geomorphic stability within restoration management planning time frames. Simply, the discussion is intended to highlight the importance of hydrogeomorphic setting and stress the need for a process-based framework that incorporates in-channel processes to maximize effectiveness of channel protections efforts manifesting in hillslope measures (SCMs), channel restoration, and/or conservation.

Modification to Sediment Supply

It has been theorized by some (Stein and Bledsoe 2013) that FDC (flow duration control) is an improvement to peak flow matching, but may still not be sufficient to avoid channel destabilization when sediment supply is severely disrupted. The scenarios that were simulated (1.0-b, 1.1-b, 1.1.1-b, 1.1.2-b, 1.2-b, 1.2.1-b, and 1.2.2-b) in this study did not necessarily indicate a potential change in stability as result of decreased sediment supply whether treated or untreated (Figure 2.12). Each of the sites saw no measurable effect where it would be prudent to draw conclusions from. The metric $R_2\Delta FA$ indicated that for all sites values were near unity (Figure 2.12), indicating that halving incoming load had little to no effect on channel destabilization.

Although, this case study data suggests sediment supply has minimal influence on channel destabilization (at least at these sites) it is important to remember that many geomorphic processes are threshold based and complex. Therefore, the reduction in supply may have been insufficient to trigger a site specific geomorphic threshold response. As well, these sites represent a range of conditions but aren't a sufficient sample to draw definitive conclusions from regarding bedload supply influence on response to impervious surfaces. This in combination with the many assumptions that accompany the associated hydrologic, hydraulic, bedload, and channel evolution models associated with this effort, necessitate that inference be kept to a minimum as the hypothesis has strong theoretical support. Rather, the results simply indicate that this area warrants further research as many SCMs have strong influence on sediment supply conditions.

Implication for Channel Protection Efforts

Municipalities throughout the country are now faced with how to mitigate the effects of hydromodification manifesting in increased sediment loads from in-channel contributions and degraded ecological integrity. At a basic level, this involves restoring hydrology to the pre-disturbed condition and most efforts have centered on "channel protection flows" intended to restore less erosive flow regime through implementation of SCMs. Yet, even with the stormwater community making great strides to incorporate fluvial geomorphic processes, there is growing understanding that mitigation cannot be accomplished through SCMs alone and integrated planning (SCMs and channel restoration practices) is a necessity (Berg, Burch et al. 2013) to achieve both short-term and long-term objectives.

This realization is likely the result of failing to accept that the stream systems under consideration for protection and/or restoration are rarely in a pre-existing reference condition (Walter and Merritts 2008; Cluer and Thorne 2014). Therefore, restoration of hydrology is not equivalent to a restoration of hydraulics and sediment transport dynamics as a result of legacy impacts on riverine floodplains and channels. The failure to incorporate this reality has resulted in channel protection efforts which could be improved by incorporating a more comprehensive process based approach which accounts for setting and evolutionary state to better understand the dominant erosive processes (Lawler 1995).

For example, hydrologic controls as a retrofit that do not consider geomorphic processes relative to setting and evolutionary state have the potential to prolong adverse conditions and therefore habitat recovery. Conditions generated from destabilization are well understood and discussed throughout this paper, but assuming one agrees with general tenants of the SEM model (Cluer and Thorne 2014) delaying evolution of a currently incised or incising stream (arguably the common form in urban systems) may extend periods of limiting ecological integrity if channel restoration activities aren't considered in conjunction. In contrast, channel restoration activities without consideration for contributing drainage hydrology, water quality, and evolutionary state will likely have similar outcomes for restored reaches.

As an additional example, where low gradient receiving channels have degraded near bank vegetation and canopy cover, subaerial erosion is likely a significant process (Wynn and Mostaghimi 2006; Wynn, Henderson et al. 2008). Therefore, frequency of high probabilities events may be as much a concern as the duration of eroding flows. This is also likely a concern for higher gradient lower order streams where this process can be the dominate form of erosion (Yumoto, Ogata et al. 2006). Assuming these concerns are valid, it implies the potential need for channel interventions and/or increased value of infiltration as opposed to retention/detention. More importantly, it provides evidence that integrated process-based approach could provide the foundation for more effective management of channel protection. For instance, it may be more effective to improve channel form and boundary resistance then to offset reduced erosive resistance (reduced hydraulic and mechanical resistance as a result of disturbed riparian vegetation) through the use of SCMs. Ultimately, management will be charged with determining where form may burden other attempts to restore hydrologic processes and stream function, but this work helps frame a template for that analysis.

Summary & Conclusions

The coupling of SWMM and CONCEPTS provided an original approach to evaluating the impacts of hydromodification. Although SWMM and CONCEPTS have both been used to evaluate hydromodification impacts, stream restoration structures, and SCM influence, the coupling of these dynamic models is an original approach to integrated management of urban stream systems. This approach provides a framework founded in physical descriptions of the relevant processes and a sound theoretical background. Therefore, this case study served as an opportunity to both explore the mechanics of integration and evaluate channel evolution in response to hydromodification through a process based framework. Nevertheless, although a coupled model at the catchment scale provides critical information regarding the management of energy in urban streams it is understood that it would be unreasonable to perform this time intensive strategy at each watershed. Rather, expectations are that the information derived from this study provides a general framework that can be applied and, at the watershed management level, determinations can be made regarding when and where these methods are appropriate.

In conjunction, with demonstrating the value of coupling hydrologic, hydraulic, and channel evolution models there were several interesting observations derived from this case study. First, increases in impervious surfaces did not correlate to a uniform destabilization of case study stream reaches. Second, SCM treatment was not completely effective at restoring hydrologic patterns or avoiding geomorphic change at the case study sites which represented 2^{nd} and 3^{rd}

order stream systems and effectiveness varied relative to hydrogeomorphic setting. Third, decentralized LID treatment was generally more effective than regional detention at mitigating the geomorphic effects of impervious surfaces. Fourth, sensitivity to increased surface runoff is not unique to completely alluvial reaches, but rather bedrock controlled reaches are potentially susceptible to channel enlargement when lateral boundary erosive resistance is modified. Finally, channel enlargement appeared to be more sensitive to approximated geomorphic parameters associated with physical thresholds and rates than increases in impervious surfaces within the case study stream systems.

In closing, the coupling of models incorporates the time dependent response of a number of hydrologic, hydraulic, and fluvial geomorphic processes. Yet, each have inherent assumptions incorporated that add some degree of uncertainty. Therefore, it is important to note that this research represents relative truths as opposed to absolute truths and expert judgment must be utilized to extrapolate these findings outside the context of this study. Nonetheless, it demonstrates the need for urban watershed planning and the importance of geomorphic process to provide a better assessment foundation to guide successful channel protection efforts and reach-scale stream restoration projects.

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Chapter 3

Towards Cost-Effective Mitigation Strategies for Channel Protection

Abstract

In-stream geomorphic channel degradation, as a result of urban hydromodification, can have detrimental ecological and socio-economic impacts. Although steps have been taken to minimize these impacts through stormwater regulatory efforts, regulation has historically focused on discharge and been mandated through uniform control measures without consideration for hydrogeomorphic context. Although implementation of such uniform regulations offers many conveniences for agencies, there are drawbacks as their effectiveness can have significant variance between stream systems they are intended to protect. Ineffectiveness has been attributed to not integrating regulatory guidance and watershed management strategies based on local stream system hydrologic and morphologic attributes. In an attempt to address inefficiencies, a framework is proposed integrating stormwater related mitigation efforts ("channel protection"), related engineering practices, fluvial geomorphology, and economics in order to evaluate the outcomes of restoration mitigation and associated cost-effectiveness. Concepts of marginal abatement cost and environmental damage are utilized in conjunction with the impervious cover model (ICM) and additional research to demonstrate that economic inefficiencies may exist as a result of systematic variation in hydrogeomorphic thresholds and processes. Therefore, the cost-effectiveness of mitigation plans would likely improve by incorporating existing degree of stream system hydrologic alteration, hydrogeomorphic setting, and evolutionary state of receiving channel network. Incorporating variation in these parameters through watershed assessment, planning, and compensatory mitigation should improve management through application of tailored practices (e.g., stream restoration/rehabilitation vs storm water control measures (SCMs), regional retention vs low impact development (LIDs), etc.) decreasing impact of hydromodification and therefore improving the cost-effectiveness of mitigating efforts.

Introduction

Hydromodification associated with urbanization is a major cause of non-point source (NPS) pollution in waterways nationally (USEPA 2002a). Urban hydromodification, resulting from increased impervious cover (IC), leads to loss of infiltration potential within urbanizing watersheds; a loss of infiltration potential results in modifications to surface water flow regimes and sediment transport. These modifications can present significant problems for channel stability due to potential imbalances between eroding and resisting forces[10] imposed on the system. Increases in volume of runoff, peak flow rate (Brater 1975), duration of flows (Booth and Jackson 1997), and frequency of flows results in increased eroding flow potential (where flows become concentrated if channel erosive resistance properties are insufficient to offset the increases in stream power) and destabilized channels. Destabilized channels and the resulting contributions to sediment yield degrade ecological function (Schueler, Fraley-McNeal et al. 2009; Fitzgerald, Bowden et al. 2012; Cluer and Thorne 2014) and result in socio-economic impacts (Osterkamp, Heilman et al. 1998; Berg, Burch et al. 2013; Hill, Kolka et al. 2013).

Most regulatory efforts, directed at channel protection, to date have focused on addressing the peak discharge and/or volume of surface runoff directly through the imposition of generally uniform design standards for stormwater control measures (SCMs[11]). Yet, design standards have historically lacked integration with the geomorphic processes of the stream channels they are intended to protect (Roesner, Bledsoe et al. 2001) and consideration for the existing geomorphic state (Schumm, Harvey et al. 1984; Booth, Hartley et al. 2002). Uniform standards have been preferred by the regulatory community over the years due to ease of enforcement and convenience in application at scale. These uniform prescriptions have been considered a means to address multiple issues with one practice and some might argue under certain conditions their advantages outweigh their disadvantages (Kolstad 1987; Heyes and Simons 2010). Nevertheless, scenarios continue to persist where uniform standards are unlikely to minimize the aggregate costs of meeting the environmental objective (i.e. avoiding channel/habitat degradation

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10 The geometry of a stream channel is determined through the long-term balancing of erosive forces generated by moving water and resistive forces of the channel bed and bank materials (Langbein and Leopold 1964; Knighton 1984). The interaction of these forces determines whether a channel will aggrade (accumulate sediment), degrade (erode sediment) or maintain equilibrium (Simon 1989; Simon and Downs 1995).

[11] SCMs (e.g., detention ponds, wet ponds, bioretention cells/basins, green-roofs, etc.) are an attempt to restore post-urbanized hydrologic conditions to a more natural or pre-disturbance state.

resulting from increased impervious surfaces). In extreme circumstances, they may even lead to the adoption of mitigation measures with little or no corresponding environmental benefit.

A critical need for effective water quality management with a focus on instream fine sediment is the development of a watershed assessment framework that links design and implementation of SCMs and stream restoration practices to achieve channel protection through emphasis on rebalancing both hydrologic and fluvial geomorphic processes. This framework could provide municipal separate storm sewer system (MS4) managers a means to determine long-term and cost-effective watershed management strategies to successfully protect channels and enhance ecological health through restoration of riparian and aquatic habitats. However, there is limited research incorporating geomorphic principles, engineering design, and economics to identify the most cost-effective strategies for mitigating the environmental damage associated with channel destabilization as a result of hydromodification.

This article introduces a new watershed management framework by integrating fluvial geomorphic and economic concepts with engineering practice to evaluate mitigation efforts. Concepts of marginal abatement cost (MAC) and marginal environmental damage (MED) are utilized in conjunction with the impervious cover model (ICM) and additional research to demonstrate economic inefficiencies in terms of cost-effectiveness. The goal of this article is to highlight what the author perceives as generally systematic variation in hydrogeomorphic response that could be addressed through tailored practices (e.g., stream restoration/rehabilitation vs SCMs, regional retention vs low impact development (LIDs), etc.) decreasing the impact of hydromodification and improving the cost-effectiveness of mitigating efforts.

Integrated Channel Protection Strategies

The Need for Integrated Channel Protection Efforts

The annual social costs associated with soil erosion in North American watersheds has been estimated to exceed $16 billion as a result of the physical, chemical, and biological damage caused by excessive sedimentation in streams (Osterkamp, Heilman et al. 1998). Studies have indicated that sediments derived from channel erosion can be a significant portion of sediment loads (Trimble 1997; Allmendinger, Pizzuto et al. 2007; Fraley, Miller et al. 2009). The excessive channel erosion is often attributed to channel enlargement, which appears to be a dominant response to urbanization (Hammer 1972; Booth 1990; Doll, Wise-Frederick et al. 2002; Chin 2006). Yet, systematic variance in stream channel evolutionary response to urbanization can be expected (Utz and Hilderbrand 2011; Bledsoe, Stein et al. 2012).

Regulatory efforts directed at channel protection and associated siltation are intended to avoid channel and aquatic habitat degradation. To date, most efforts have focused on universally mandated upland hydrologic controls (e.g., SCMs) to mitigate additional surface runoff from impervious surfaces and avoid in-channel impacts. However, SCM effectiveness is variable by treatment type and influent quantity and quality per storm event. As well, hydrologic processes vary spatially per SCM placement on the landscape (e.g., depth to water table, soil hydraulic conductivity, etc.), receiving stream channel processes are threshold-based, and form and sediment dynamics are often already modified.

In combination with these issues, many of the practices available to rehabilitate stormflow hydrology do not necessarily address other geomorphic processes inherent to natural disturbance regimes (e.g., LWD/sediment supply and transport) and in some situations interfere with these processes, which are critical to maintain or improve ecological integrity. Therefore, SCMs and stream restoration practices occur where these mitigating efforts do little to avoid channel/habitat degradation, often attributed to current regulation lacking an integrated systems watershed approach (i.e. historically regulations have failed to incorporate the geomorphic setting/processes of the stream channels they are intended to protect (MacRae 1993; Bledsoe and Watson 2001; Roesner, Bledsoe et al. 2001; Rohrer and Roesner 2006)).

Tillinghast et al. (2012) provides an example of how regulations mandating SCMs can be ineffective at protecting geomorphic stability. In this case study, designed SCMs were not sufficient to reach a geomorphically stable condition, based on the authors' proposed metrics. Their results suggest that uniform regulations requiring new development and/or retrofit SCMs may be an inefficient use of mitigating funds under certain hydrologic and geomorphic conditions, indicating a degree of flexibility in regulations may be necessary to improve the cost-effectiveness of channel protection efforts. This flexibility is likely best administered through stream system-based compensatory mitigation programs[12] which should provide more cost-effective alternatives for funds.

Environmental Damages, Abatement and the Impervious Cover Model

MAC in general, measures the cost of reducing an additional unit of pollution. MED can be considered the environmental damage associated with an additional unit of pollution. MAC can be expected to rise as more pollution is reduced and more cost-effective technologies/practices and land become exhausted. MED can be considered to increase as the quantity of pollution increases. Figure 3.1 is an idealized representation of this concept depicting the relationship between pollution and marginal abatement/damage represented through cost. Yet in reality, these curves can be complex. Damages, for example, may be a function of thresholds and non-linear response to unit increase (Maler and Wyzga 1976). Complex and systematic variation in damage functions is likely the case for channel degradation based on the former discussion and the ICM conceptual model presented in Schueler, Fraley-McNeal et al. (2009). The primary tenet of the ICM is that indicators of urban stream health and function are inversely related to the degree of imperviousness in a watershed and research has also demonstrated that variance in stream channel evolutionary response to urbanization can be expected (Utz and Hilderbrand 2011; Bledsoe, Stein et al. 2012).

Two distinct aspects of the Schueler, Fraley-McNeal et al. (2009) ICM model are the proposed classes of stream quality which have varied gradients of response associated with the degree of imperviousness and the cone effect which highlights variance in response among classes (Figure 3.2). Stream quality classes are generally categorized as 0-10% IC (sensitive), 10%-25% IC (impacted), 25%-60% IC (degraded/non-supporting), and 60%+ IC (Urban Drainage) with impact becoming increasingly certain as imperviousness increases. The classes indirectly represent the chemical, biological, and physical state of the impacted watersheds and imperviousness ultimately is a surrogate measure of pollution representing the associated modification to water quality, habitat, and channel degradation that occurs in conjunction with

[12] The term compensatory mitigation program is utilized to refer to any program intended to allow compensation for a development action and associated negative effects. In the specific situation highlighted, it would allow for an alternative to mandated channel protection design standards due to the inability to avoid negative in-stream consequences.

urbanization. Therefore, it is proposed that in many ways the ICM (Figure 3.2) can be translated to a rough depiction of an aggregate damage function at the stream system scale.

Nonetheless, there is difficulty when utilizing imperviousness as a surrogate measure for pollution as it should likely possess a physical linkage to energy (at least in terms of channel protection). As well, the regulatory community would not necessarily want to reduce or prevent a unit of imperviousness, but rather the associated impacts on stream system hydrology and hydraulics which manifest as an environmental "stressor" due modification of natural disturbance regimes. A stream system corridor is naturally exposed to a disturbance regime that influences both geomorphic processes and form. Surplus stream power as described in Woockman, Schwartz et al. (2018) is a function of modification (i.e. additional surface runoff) to this regime in the domains of magnitude, duration, and frequency. Surplus stream power becomes effective stream power when there is an imbalance in driving and resisting forces as a result of increased surface flows. Effective stream power is a function of geomorphic setting and present evolutionary state (Woockman, Schwartz et al. 2018).

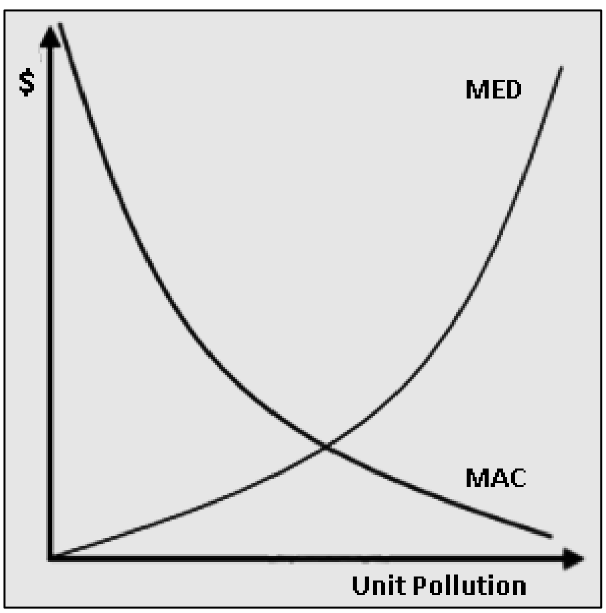

Figure 3.1. Conceptual model of marginal cost of abatement per unit of pollutant and the marginal damage of increasing pollutant emissions.

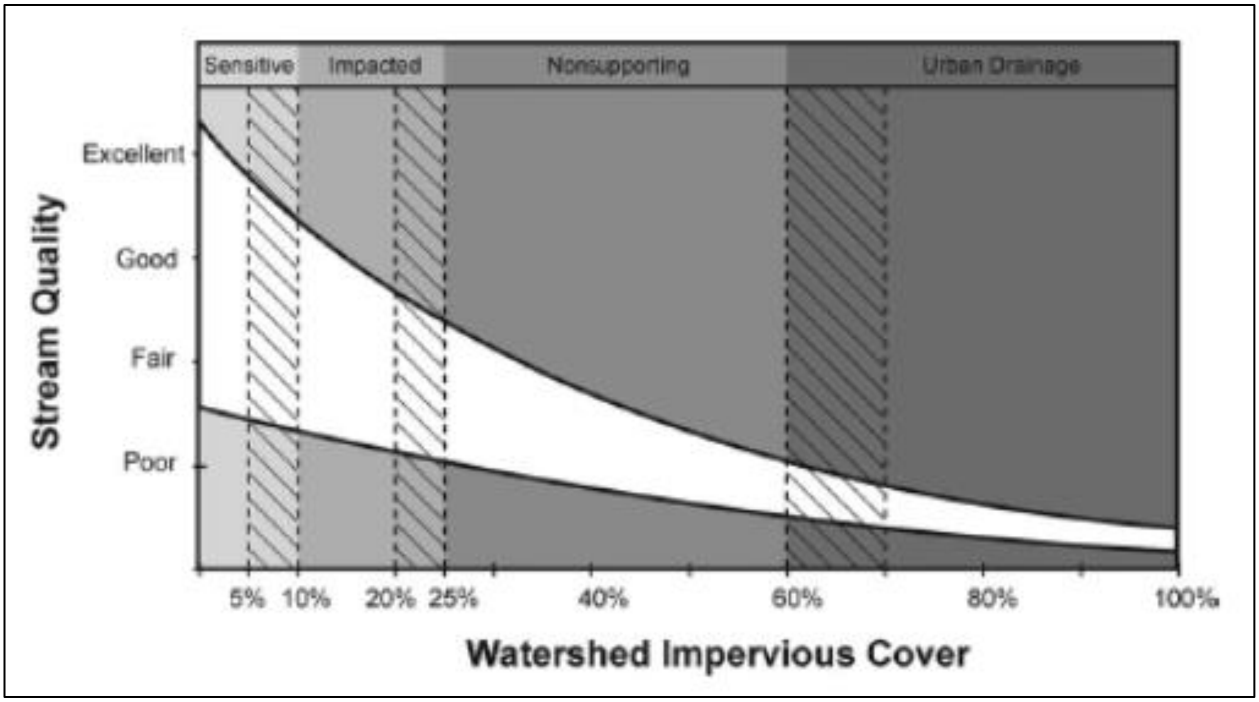

Figure 3.2. A depiction of the reformulated impervious cover model.

Source: Schueler, T. R., L. Fraley-McNeal and K. Cappiella, 2009. Is impervious cover still important? Review of recent research. Journal of Hydrologic Engineering 14:309-315.

Therefore, the surrogate pollutant in the case of channel degradation could be described as the surplus stream power associated with impervious cover that results in additional energy directed at in-channel erosion and degradation of habitat due to additional surface runoff and gravity. Thus, we can abate pollution (surplus stream power that becomes erosive) not only by reducing surface runoff associated with imperviousness (e.g., through installation of SCMs), but also through other actions (e.g., improving vegetation conditions of the riparian corridor thereby improving channel erosive resistance characteristics). Systematic differences in the effects of surplus stream power, in combination with discussed aspects of the ICM, imply that effectiveness of practices will vary systematically and inherently so will the associated MAC as a function of hydrogeomorphic setting and state.

For example, consider MAC static and not a function of time (i.e. managers will face the same costs 10 years from now as they do today). Also, consider that we ignore spatial variation in costs and assume two stream systems identical other than the degree of current imperviousness. A stream system that is 70% impervious will have a different MAC function as opposed to one that is 15% impervious. If we attempt to reduce the effects of imperviousness (i.e. move from 70% - 69% imperviousness in terms of hydrology) in the stream system with 70% imperviousness the assortment of practices available for treatment will be diminished (i.e. increased technology costs) as a result of land constraints and the cost for a unit of land increased. If we attempt to reduce the effects of imperviousness (i.e. move from 15% - 14% imperviousness in terms of hydrology) in the stream system with 15% imperviousness, we likely will have a larger assortment of available practices (e.g., regional retention/wetland ponds) and land costs will be less. As well, the marginal damage reduction relative to a unit of abatement in the 70% watershed would be small, generally demonstrated by the ICM, when compared to the 15% watershed as a result of geomorphic and ecological thresholds, and the non-linear nature of response. This would also be true if we consider the same two watersheds and avoidance of future emissions (i.e. from 70% to 71% and from 15% to 16%).

The broad conclusions one can draw from utilizing the ICM as a predictive tool regarding the damages associated with channel/habitat degradation and costs of abatement are:

- current state of imperviousness[13] influences the marginal costs of abatement (e.g., land and available practices being influential);
- environmental damages associated with increasing imperviousness is only broadly correlated with existing degree of imperviousness (i.e. a reasonable portion of variance in stream quality is unexplained by hydrologic alteration in the form of impervious cover alone and variance might be further explained by incorporating hydrogeomorphic setting);
- policy requiring uniform control is unlikely to be cost-minimizing;
- higher levels of control are likely to be economically rational[14] in areas of low imperviousness; and

[13] Interpreting the current state of imperviousness should incorporate the degree of connectivity to receiving stream system through the concept of effective imperviousness (Vietz, Sammonds et al. 2014; Epps and Hathaway 2018).
[14] It is important to acknowledge that uncertainty in response at lower levels of imperviousness introduces possible performance issues. Therefore, higher levels of control are likely only justified if uncertainty in performance of mitigating measures can be reduced through watershed planning efforts and associated implementation based on those efforts.

- there appears to exist a definitive scenario where invested capital to abate a unit of imperviousness would provide little or no reductions in damage (e.g., 60%+).

These conclusions along with other research (Booth and Jackson 1997; Bledsoe, Stein et al. 2012; Tillinghast, Hunt et al. 2012; Booth and Fischenich 2015; Hawley and Vietz 2016; Woockman and Schwartz 2018; Woockman, Schwartz et al. 2018) suggest that current channel protection efforts in the form of uniform standards are unlikely to be cost-minimizing in terms of channel protection. In the opinion of the author, more cost-effective strategies could be obtained by accounting for what is perceived as generally systematic variation in hydrogeomorphic processes. This systematic variation could be accounted for through clarifying the existing degree of hydrologic alteration, identifying geomorphic setting through classification, determining evolutionary state of the receiving channels, and tailoring practice accordingly (e.g., stream restoration/rehabilitation vs SCMs, regional retention vs LIDs, etc.). The tailored suite of practices derived from this integrated management strategy could generally be guided by the classes proposed by Schueler, Fraley-McNeal et al. (2009); classifications schemes that incorporate geomorphic attributes, evolutionary state, and habitat function (Frissell, Liss et al. 1986; Bledsoe, Stein et al. 2012; Cluer and Thorne 2014; Booth and Fischenich 2015); and an economic framework (Table 3.1).

Economic Classification of Stream Reaches

In moving toward integrated management of channel degradation, managers could benefit from identifying discernable variance in channel geomorphic response to increased surface flows among reaches. This segregation should represent distinct classes which relate to consequences. In the context of moving *toward* cost-effectiveness, this segregation would correlate to discernable variations in abatement cost functions and/or damage functions relative to channel degradation caused by urbanization. An optimal segregation of stream reaches should define an applicable spatial domain and differentiate the many possible trajectories of response a stream might experience.

Table 3.1: ICM translation to marginal abatement cost and environmental damage framework.

Degree of Imperviousness	**Class**	**MAC**	**MED**
0-10%	Sensitive	• Land and Infrastructure Cost low • Full suite of practices available	• Threshold effect may exist, but environmental damage gradient significant potentially if breached
10%-25%	Impacted	• Land costs are more expensive, but improved compared to higher levels of imperviousness • Most practices should still be an option	• Environmental damage gradient significant
25%-60%	Degraded/non-supporting	• Land and Infrastructure Costs are significant • Some practices may be available that are not available in 60%+	• Environmental damage gradient decreasing
60%+	Urban Drainage	• Land and infrastructure costs may be significant making cheaper treatment technology economically impracticable. • Incremental unit of abatement is attainable, but there is no direct correlation with reduction in damage	• Environmental Damage is close to constant and there may be limited if no marginal environmental damage based on ICM model

Ultimately, any physically related term moves us closer to understanding the imbalances in channel driving and resisting forces, but it is recommended that it should incorporate both characteristic cross-sectional geometry and boundary resistance in combination with reach level geomorphic controls and therefore may very well require a qualitative description; as parameters used to describe boundary resistance have been shown to be highly variable in space (Daly, Fox et al. 2015a; Daly, Fox et al. 2015b; Mahalder, Schwartz et al. 2017) and time (Wynn, Henderson et al. 2008), influenced by interaction effects (Hession, Pizzuto et al. 2003; Wynn and Mostaghimi 2006), and mechanistically complex (Papanicolaou, Wilson et al. 2017). Nevertheless, some of the primary factors for consideration in application are:

- Identifying factors that determine regional streams absorptive capacity (threshold response) and response trajectories within a hierarchical framework that has biological/ecological and geomorphic context;
- Segregating reach types defined by regionally specific erosive resistance characteristics (vertical and lateral stability elements);
- Assessing uncertainty in erosive resistance parameterization, how those translate to process thresholds and rates, and ultimately interpretable output[15]; and
- Conceptualizing geomorphic adjustment pathways (per Stream/Channel Evolution Models) for segregated reaches in light of treatment effect on recovery or rate of response to mitigating effort (e.g., are we prolonging less ecologically desirable forms (Cluer and Thorne 2014) as a result of retro-fits).

These considerations, proposed to influence an optimal segregation, highlight the need to identify elements that easily differentiate the physical relationship between pollutant and environmental damage. Therefore, as a watershed approach (i.e. integrated management approach), segregation should likely involve the *spatial organization* of the geomorphic elements listed in Table 3.2 at the reach scale, but considered within the context of hierarchal position (Frissell, Liss et al. 1986), process domain (Montgomery 1999), and relevant dominant erosive processes (Lawler 1995). In this context, regional variations in critical elements should become more discernable (e.g., variation in vegetative community as a result of difference in climate,

[15] If the bounds of uncertainty significantly overlap then little is gained by segregation (e.g., soil characteristics in a highly vegetated reach).

Table 3.2: Instrumental reach scale geomorphic attributes

Dominant Geomorphic Attributes Predictive of Erosive Process Rates and Thresholds	Related Literature
Local valley width and gradient	(Grant and Swanson 1995; Lawler 1995; Van den Berg 1995; Montgomery 1999)
Sediment supply gradation (e.g., sand dominated vs cobble dominated) and condition (e.g., supply/transport limited)	(Buffington and Montgomery 1999; Simon and Rinaldi 2006; Bledsoe, Stein et al. 2012)
Proximity to grade control and frequency of	(Watson and Biedenharn 1999; Langendoen, Simon et al. 2000; Bledsoe, Stein et al. 2012; Hawley, MacMannis et al. 2013)
Near bank vegetation community and maturity	(Dunaway, Swanson et al. 1994; Millar and Quick 1998; Simon and Collison 2002; Wynn and Mostaghimi 2006; Polvi, Wohl et al. 2014)
Bank materials and stratification	(Hooke 1979; Thorne and Tovey 1981; Dunaway, Swanson et al. 1994; Julian and Torres 2006; Wynn and Mostaghimi 2006; Sutarto, Papanicolaou et al. 2014)
Local groundwater dynamics	(Simon, Curini et al. 2000; Fox and Wilson 2010)
Existing channel form (i.e. evolutionary state)	(Simon 1989; ASCE 1998a)

Note: The list of related literature is not intended to be comprehensive.

resulting in reduced importance of near bank vegetation on channel stability (Bledsoe, Stein et al. 2012)) and more easily incorporated into management plans. As well, other considerations affecting reach specific ecological importance (e.g., habitat patch dynamics) and/or potential for degradation (e.g., situations where form might burden other attempts to restore process) can better be assessed. The spatiotemporal changes in structure, function, and dynamics of the stream ecosystem are inherently tied to hydrogeomorphic processes and ecological integrity (Schwartz 2016) and are important for the purposes of valuing effectiveness of hillslope measures, channel restoration, and/or conservation.

Conceptual Framework for Implementation

An integrated approach to channel protection, as discussed through incorporation of hydrogeomorphic setting, could benefit from implementation of some form of compensatory mitigation. Even under the assumption there is little to no trade-off value between SCMs and in-channel restoration measures, MS4s are still finding that underlying strata and/or water table simply will not allow designers to meet infiltration standards and/or land requirements for retention make them unreasonable (Tillinghast, Hunt et al. 2012). In these situations, in-lieu fees options would create a scenario where capital expenditures, intended for channel protection efforts, could be invested with a greater return on investment elsewhere within the watershed in the form of targeted SCMs, stream/floodplain restoration, or conservation easements.

An in-lieu fee program for stormwater management (generalized in Table 3.3) utilizing some modification of a trust fund style approach[16] mentioned in Doyle and Shields (2012) and incorporating concepts discussed in previous sections, would likely provide many benefits. It is beyond the scope of this paper to go into great detail, but generally this approach would provide more flexibility in actions. It would allow larger projects creating the possibility for compounding benefits (Doyle and Shields 2012) and avoid economic incentive and social forces shaping morphology and site selection (Doyle, Singh et al. 2015) within the context of in-channel (stream restoration) efforts. It would avoid some of the difficulties inherent in developing "functional lift" criteria for stream restoration banking and permittee-responsible approaches. It would reduce the need to specifically define credit values per load reductions for

[16] Administration of funds generated from in-lieu fees are likely best guided by a multidisciplinary team of local experts involved in stream system scale planning and implementation efforts.

Table 3.3: Example of proposed generalized approach for stormwater compensatory mitigation.

Hydrologic Scenario	**Regulatory Approach**
New Development & Re-development[a]	• Option 1 - match existing hydrologic regime (magnitude, duration, and frequency)[b] through natural process (i.e. infiltration and evapotranspiration) • Option 2 - match existing hydrologic regime through retention/detention of surface runoff in terms of magnitude and duration. Pay in-lieu fee relative to frequency disturbance. • Option 3 - pay in-lieu fee equivalent to variation in pre vs post hydrologic regime.
Existing Impervious Cover	• Pay tax based on existing degree of hydrologic alteration

a. If re-development opted to match existing regime tax burden consequence would still exist.
b. Incorporating magnitude, duration, and frequency should account for spatial implications and effect of position on hydrograph domains.

instream measures without an evolutionary context (Berg, Burch et al. 2013). Additionally, it would potentially provide funds to remove unnatural flow structures impacting fluvial processes and conserve high value (habitat patches) areas/reaches already functioning properly. Also, within specific accounting years, if metrics of evaluation from monitoring efforts are favorable and surplus funds are available there is the option of returning surplus funds in the form of some sort of subsidy.

As a final point, it would provide the necessary funds to work from a more holistic integrated approach (incorporating SCMs, stream restoration, and conservation); incorporating stream system hydrology, geomorphology, and ecological function allowing identification of projects that have inherently greater value based on considerations discussed in previous sections. Figure 3.3 is an idealized depiction of the general process involving implementation of discussed concepts using only sensitive stream systems as an example and although the flow chart is simplified it highlights that an integral part of implementation requires assessment and stream system scale planning efforts.

In certain situations, it may very well become clear that investing fees within the stream system are unlikely to result in a positive return on those mitigation funds. Unfortunately, many of the practices available to rehabilitate hydrology, hydraulics, and form do not necessarily address other processes that are inherent to a natural disturbance regime (e.g., sediment supply/transport, LWD supply/transport, etc.) or improve stream function, both of which are required for ecological integrity. Therefore, it is reasonable to assume that at some point ecological integrity and a natural system is no longer attainable within constraints of the system (Ebersole, Liss et al. 1997) and the available technologies/practices, arguably already demonstrated in the ICM model. Nevertheless, the appropriate application will likely vary as a result of a number of considerations including: hydrogeomorphic setting, existing channel state, existing water quality, economics, and stakeholder goals.

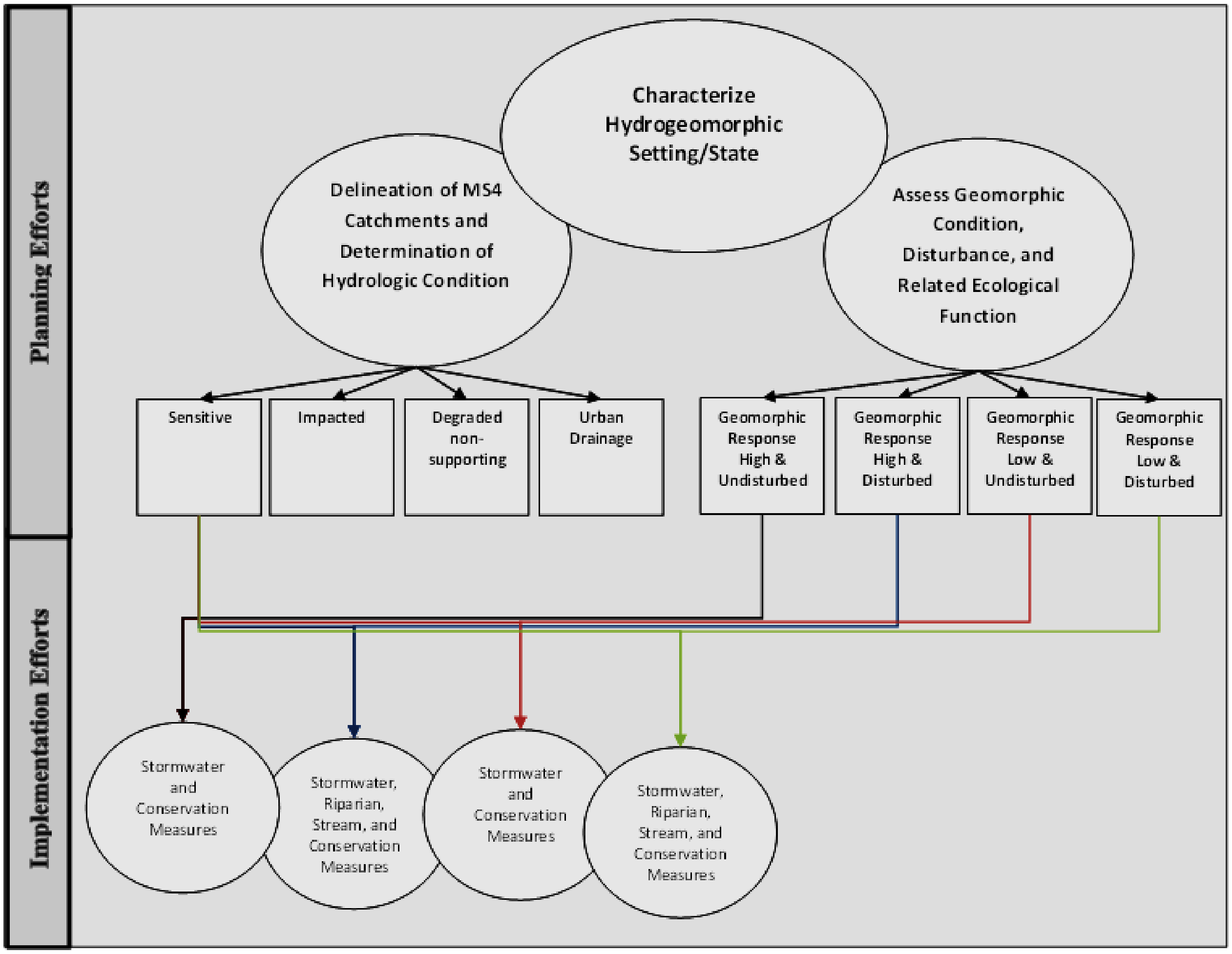

Figure 3.3. A simplified conceptual overview for improving selection of integrated mitigation suites in urbanized and urbanizing streams.

Closing Summary

Many MS4s have moved forward with new guidelines for channel protection and are working towards watershed plans that allow them to meet proposed TMDLs for siltation (that include crediting in-channel measures such as bank stabilization and stream restoration/rehabilitation) in order to meet ecological targets and remove streams from the 303(d) list. Plans should incorporate effective mandates that prevent channel degradation, manage water quality, and effectively implement mitigation funds. However, this is done with minimal supporting evidence of the benefits for various mitigation efforts within the context of their geomorphic setting and often lacks consideration for time-dependent response. Whether a result of convenience or practicality, it is the opinion of the author that efficacy of mitigation strategies would be improved by integrating modifications of hydrology with geomorphic attributes providing a sound basis for causal relationships and ultimately more cost-effective mitigation efforts.

This article has discussed a framework integrating stormwater related mitigation efforts ("channel protection"), engineering practices, fluvial geomorphology, and economics in order to evaluate the outcomes of restoration mitigation and associated cost-effectiveness. Concepts of MAC and MED are discussed and utilized in conjunction with the ICM model and additional research to demonstrate that economic inefficiencies may exist as a result of systematic variation in hydrogeomorphic processes. Therefore, the cost-effectiveness of mitigation plans would likely improve by incorporating attributes that distinguish this variation. Attributes suggested include existing degree of stream system hydrologic alteration, hydrogeomorphic setting, and evolutionary state of receiving channel network. Incorporating this information would allow management to address variation through tailored practices (e.g., stream restoration/rehabilitation vs SCMs, regional retention vs LIDs, etc.) decreasing impact of hydromodification and therefore improving cost-effectiveness and reducing external costs (Hardin 1968).

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Summary and Closing Remarks

Summary

The work summarized in this dissertation involves an assessment of the influence hydrogeomorphic setting has on cost-effectiveness of channel protection efforts within 2nd and 3rd order stream reaches of the Ridge and Valley Province of Tennessee. The preceding chapters included: 1) a field based study to identify geomorphic attributes (of urbanizing and urban stream reaches) which influence the absence or presence of erosive processes, 2) a case study of three stream systems where coupled hydrologic, hydraulic, and channel evolution models were utilized to evaluate the influence that SCMs and channel erosive resistance elements have on channel geomorphic evolution through long-term simulation, and 3) a proposed framework for the purposes of evaluating the cost-effectiveness of channel protection efforts intended to mitigate channel instability due to urbanization.

Chapter One demonstrated that vegetation, grade control, and geomorphic setting are instrumental controls on erosive processes in the Ridge and Valley of Tennessee. Vegetation impacts rates and thresholds of subaerial, fluvial, and mass-wasting processes. Grade control influences the degree of vertical hydraulic erosion thereby controlling channel evolution and associated lateral erosive processes. Spatial position and/or geomorphic setting are linked to concepts of transport/supply limited conditions and therefore are controls on the time dependent response to surface flows, indicating how a reach might respond to variations in flood magnitude, frequency, and duration or disruptions to sediment transport dynamics resulting from land-use change. These findings demonstrate the value of conserving riparian buffers especially when coupled with grade control. Riparian buffers are likely to provide the greatest geomorphic benefit when those buffers are spatial linked to grade control.

Additionally, this study may have inadvertently demonstrated the importance of shifts in frequency of flows. Findings indicated that the probability of fluvial erosion and mass-wasting processes did not necessarily relate to higher levels of stream power regardless of degree of urban hydromodification. Therefore, it could be inferred that timing of flows (i.e. frequency) may play a significant role in channel destabilization in urbanizing systems, as rates of subaerial processes and mass-wasting processes are prone to frequent surface flow events (especially when boundary materials do not have supportive vegetation). Indicating infiltration and evapotranspiration processes may be a better alternative (in certain settings) than matching peak flows or utilizing flow duration control standards (relative to bed material conditions) for the purposes of channel protection.

Chapter Two provided an original approach to evaluating the impacts of hydromodification by loosely coupling SWMM and CONCEPTS. The associated case study served as an opportunity to both explore the mechanics of integration and evaluate channel evolution in response to hydromodification through a process based framework. Expectations are that the information derived from this study provides a general framework that can be applied and, at the watershed management level, determinations can be made regarding when and where these methods are appropriate.

In conjunction with demonstrating the value of coupling hydrologic, hydraulic, and channel evolution models, there were several interesting observations derived from the case study. First, increases in impervious surfaces did not result in uniform destabilization of case study stream reaches. Second, SCM treatment was not completely effective at restoring stream system scale hydrologic patterns or avoiding geomorphic change at the case study sites and effectiveness varied relative to hydrogeomorphic setting. Third, decentralized LID treatment was generally more effective than regional detention at mitigating the geomorphic effects of impervious surfaces at the stream system scale. Fourth, sensitivity to increased surface runoff is not unique to completely alluvial reaches, but rather bedrock controlled reaches are potentially susceptible to channel enlargement when lateral boundary erosive resistance is modified. Finally, channel enlargement appeared to be more sensitive to approximated geomorphic parameters associated with physical thresholds and rates than increases in impervious surfaces within the stream reaches studied.

Chapter Three discussed a framework integrating stormwater related mitigation efforts (“channel protection”) in the context of engineering practices, fluvial geomorphology, and economics in order to evaluate the outcomes of restoration mitigation and associated cost-effectiveness. Concepts of marginal costs of abatement and marginal environmental damage are discussed and utilized in conjunction with the ICM model, as well as, additional research to demonstrate that the relationship between investment and return is not guaranteed to be constant and/or continuous in nature as a result of systematic variation in hydrogeomorphic processes. Therefore, the cost-effectiveness of mitigation plans would likely be improved by incorporating attributes that distinguish this variation. Attributes suggested included existing degree of stream system hydrologic alteration, hydrogeomorphic setting, and evolutionary state of receiving channel network.

Observations from the Field and Implications for Channel Protection Efforts

Many of the existing approaches to mitigation of geomorphic channel degradation that incorporate fluvial geomorphology are focused on principles of quasi-equilibrium concepts (Langbein and Leopold 1964). However, applications of these concepts are being applied to streams already disturbed or not in a quasi-equilibrium state (even at very low levels of urban development). Urban streams with legacy impacts affecting form and process are not outliers. Rather, field observations of East Tennessee streams would indicate that legacy alterations are more likely the average condition then an anomaly. Local hydraulic conditions are influenced by change in surface flow disturbance regimes, but hydraulic conditions are also a function of channel alterations that exist at a site and within the larger stream system.

Disturbance to hydraulics and sediment transport are characterized by channel constrictions, legacy channel alterations, rip-rap protection, bridges, and low head dams to name a few. These alterations modify both the timing and magnitude of the driving force of water as well as sediment and debri (e.g. LWD) supply/transport. All of which can have dramatic local effects and propagate impacts, both upstream and downstream, leading to highly disturbed streams at even low levels of urban development; destabilizing outright or increasing susceptibility to destabilization from hydrologic alteration.

Ignoring these existing state conditions has implications as degraded existing geomorphic states (e.g. incising channels) represent a condition where form and process are not imbalance. Rather, form is driving processes and ultimately may hinder other attempts to restore process (i.e. rehabilitation of hydrology). Therefore, understanding the implications of urbanization on ER67 streams should be improved by taking a process based approach with consideration for how modifications to hydrology and hydraulics manifest into modifications of potential capacity (Frissell, Liss et al. 1986) of reaches.

Contributions

Many MS4s have moved forward with new guidelines for channel protection and are working towards watershed plans that allow them to meet proposed TMDLs for siltation that include crediting in-channel measures (stream restoration/rehabilitation) in order to meet ecological targets and remove streams from the 303(d) list. Plans should incorporate effective mandates that prevent channel degradation, manage water quality, and cost-effectively implement mitigation funds. However, this is done with minimal supporting evidence of the benefits for various mitigation efforts within the context of their geomorphic setting and often lacks consideration for time-dependent response.

The information derived from this exploratory study will hopefully improve these scenarios as it should provide watershed managers with the necessary parameters to create simplistic assessments of a stream reach's erosive resistance properties and inherent susceptibility to hydromodification. As fluvial geomorphic units are defined (hydrogeomorphic setting and relevant erosive processes) within the context of response to urbanization a better understanding of the implications of urbanization should be gained and can be applied across a larger spatial scale in terms of sediment transport and flow.

The ability to spatially organize geomorphic units within their respective stream system informs assumptions about the degree of spatial propagation expected from the effects of hydromodification. The ability to segregate streams into similar degrees of thresholds and response improves the efficacy of targeted mitigation efforts through approximation of impacts of land-use modifications, development of effective regulation to avoid or minimize externalities, and prioritization of mitigation efforts between stormwater control measures, conservation[17], and stream rehabilitation; which should improve the potential to derive solutions at the minimal cost with the greatest channel protection.

The findings, opinions, and framework associated with this work has focused on channel protection efforts, however it should be considered in light of larger considerations within

[17] It is hoped that this work has also articulated the value of "mature" riparian vegetation and therefore conservation. For instance, Rutherfurd (2007) indicates, "*Root density is also significantly affected by the maturity of the n vegetation, with total biomass even after decades of regrowth being only ~50% of that of mature vegetation.*" Along with its stabilizing effects, riparian vegetation improves habitat conditions and provides nutrient and phosphorus reductions (Barling and Moore 1994).

watershed planning (e.g. water quality, etc.)[18]. As well, extrapolations of these findings outside Tennessee Ridge and Valley streams should be done with caution. Nonetheless, it is hoped that efforts throughout the work to stress the importance of clarifying erosive processes, the mechanisms of those processes, and the geomorphic settings/attributes that influence them has provided a basis to make the appropriate extrapolations.

[18] For example, even though grade control may afford additional channel protection it doesn't necessarily mitigate other processes related to hydrologic disturbance regime. Hawley, MacMannis et al. (2013) demonstrated that although vertical controls provide protection and decrease channel instability modifications to habitat units instrumental to macroinvertebrate life history requirements may still be impacted.

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Appendix

Literature Review

Background

Urban Hydromodification

Impacts of urban development on watershed processes include modifications to site water balance, surface flow, interflow, groundwater recharge, sediment delivery, and transport (O'Driscoll, Clinton et al. 2010). These modifications or alterations can result in the degradation of wetland, riparian, and stream habitats. As well as, increased social costs as a result of destruction of infrastructure, loss of property, and diminished water quality (Osterkamp, Heilman et al. 1998). Anthropogenic modifications to stream systems that result in changes to channel form, flow regime, and/or sediment transport regimes can be described as hydromodification. This may be the result of hydrologic alteration of the landscape or alteration of stream system units that convey flow.

Hydrologic alteration, within this work, will refer to modifications of site or catchment scale properties that result in changes to interception, infiltration, evapotranspiration, and/or hydraulic efficiency as a result of increased impervious surfaces. These modifications can be expected to lead to a potential change in the magnitude, frequency, and/or duration of runoff and sediment transport events (Sauer 1983; Robbins 1984; Bledsoe and Watson 2001).

Channel alteration, within this work, will be considered any direct anthropogenic intervention in channel form, riparian zone, or hydraulic efficiency. Alternatively, it is suggested this is best described as site scale intervention that influences site specific flow and sediment processes. This may be the result of channel straightening, infrastructure, or modifications to stream frictional resistance. Examples include in-channel weirs, rip-rap lined banks and channels, constricted floodplains, and removal of riparian vegetation. Therefore, channel alterations may influence the forces that drive sediment detachment (e.g., stream power) and/or those forces that resist detachment (e.g., total cohesion).

Although impacts of hydromodification can include physical, chemical, and biologic changes, the chemical and biological impacts are beyond the scope of this research. This research holds the tenet that channel stability is one of many required conditions for biologic integrity and a necessary requirement for the reduction of pollution derived from excess sedimentation. Studies by Trimble (1997) and Simon (2008) have shown that sediments derived from channel boundaries can represent a significant source to sediment yield as a result of anthropogenic disturbance.

Degradation, Surface Runoff, & Hydraulic Efficiency

In order to determine thresholds of stream channel degradation to hydrologic alteration one must utilize a surrogate measure that incorporates the influence urbanizing land-use practices have on both the volume of surface runoff and the hydraulic efficiency of the affected stream system. A number of surrogates have been considered through the years to represent the impacts and how they correlate to destabilization (Hammer 1972; Booth and Jackson 1997; O'Driscoll, Soban et al. 2009). Measures have included development characteristics (e.g. residential versus commercial), roadways, total impervious area (TIA), and effective impervious area (EIA) to name a few. Of these surrogate measures of hydrologic alteration, most discussion has persisted around which measures best represent the degree of hydraulic connectivity.

Hammer (1972) was an important step to documenting the importance of hydraulic connectivity attempting to relate response to a number of various measures. Yet, later research has seemed to focus on the importance of EIA (effective generally referring to directly connected impervious cover (IC)) as opposed to the less resolute surrogate TIA (Vietz, Sammonds et al. 2014). However, the debate to some extent remains, with only marginal improvements in prediction of response, the impractically of obtaining such measures may deem them inappropriate depending on the scope of the study as TIA is arguably a surrogate for EIA and typically a less subjective measure.

Aside from the focusing on the inherent differences in surrogate measures, a general theme has been thresholds of response are generally documented at 10% or greater IC (Booth and Jackson 1997; Chin 2006; O'Driscoll, Soban et al. 2009). Response though cannot be assumed as linear in nature or uniform as a function of scale (Fitzgerald, Bowden et al. 2012). The later possibly being the result of dilution effects or a shift in processes (Lawler 1995).

Alterations of Flow Regime

Urbanization impacts flow regime through decreased interception, decreased infiltration, decreased evapotranspiration, and improved hydraulic efficiency. These effects on hydrologic regime can be significant. Research has correlated alteration in flow estimates to increased hydraulic efficiency (represented by either impervious area (IA) or Basin Development Factor (BDF)) and documented increased magnitudes as a result of urbanization (Sauer 1983; Robbins 1984). In these studies IA represented what many later studies term TIA.

Bledsoe and Watson (2001) documented two-fold increase in peak discharges in Tennessee with as little as 10 % TIA (Figure A.1). Significant alterations to the frequency and duration of flows have also been identified, with a great deal of modification occurring in the small and moderate flows (Booth 1990; Bledsoe and Watson 2001; Hawley and Bledsoe 2011).

What is critical for the purposes of channel protection flows is when, where, and how these modifications to flow regime manifest into an erosive flow regime and influence transport capacity. This has led some researchers to suggest that rather than design criteria matching flow based metrics, alternative measures may offer more effective mitigation of the effects of hydrologic alteration (MacRae 1993; MacRae 1996; Booth and Jackson 1997; Palhegyi 2009; Tillinghast, Hunt et al. 2011).

Alteration of Sediment Regime

In natural undisturbed stream systems, the sediment regime at a given point in the channelized network is the result of a number of integrated processes. Sediments may be derived from hillslope processes (e.g., rainfall impact & sheet flow) or processes unique to channelized flow (e.g., fluvial erosion & mass failure). When urbanization occurs, there is often a disruption to the integrated nature of these processes. For example, detention facilities may exist as sediment sinks with one point at which their associated channelized flows are discharged deprived of sediment loads that in a natural setting would possess entrained sediments derived in rills or gullies.

As well, urban streams often flow from natural to hardened sections of reaches and have artificial macro turbulent structures dispersed through the fluvial system that disrupt natural transport or supply. Riprap and/or concrete may be interspersed decreasing the boundary supply of coarse sediments or changing the distribution of particles available for transport (Grable and Harden 2006). Weirs and bridges may create additional frictional resistance in channels; creating backwaters zones and areas where transport capacity is decreased, providing sediment sinks.

Contrasting these isolated regions in the system, frequency of transport capable flows are often increased through natural sections, resulting in supply limited conditions and vertical degradation of stream channels (a potential bountiful area of research for the future as technology for bedload monitoring continues to improve).

There are two primary periods in which urbanization impacts sediment supply. First, is when sediment supply is typically increased because of poor land-management practices during development. Second, are those impacts that occur following development to hardscapes. The second phase often results in increases in stream power due to improved hydraulic efficiency associated with development. This has been shown to increase in-channel contributions of sediments (Trimble 1997), but doesn't necessarily correlate to increased yields of bed material (Annable, Watson et al. 2012) . An extensive review by Chin (2006) showed these phases were common in supporting literature associated with urbanizing systems.

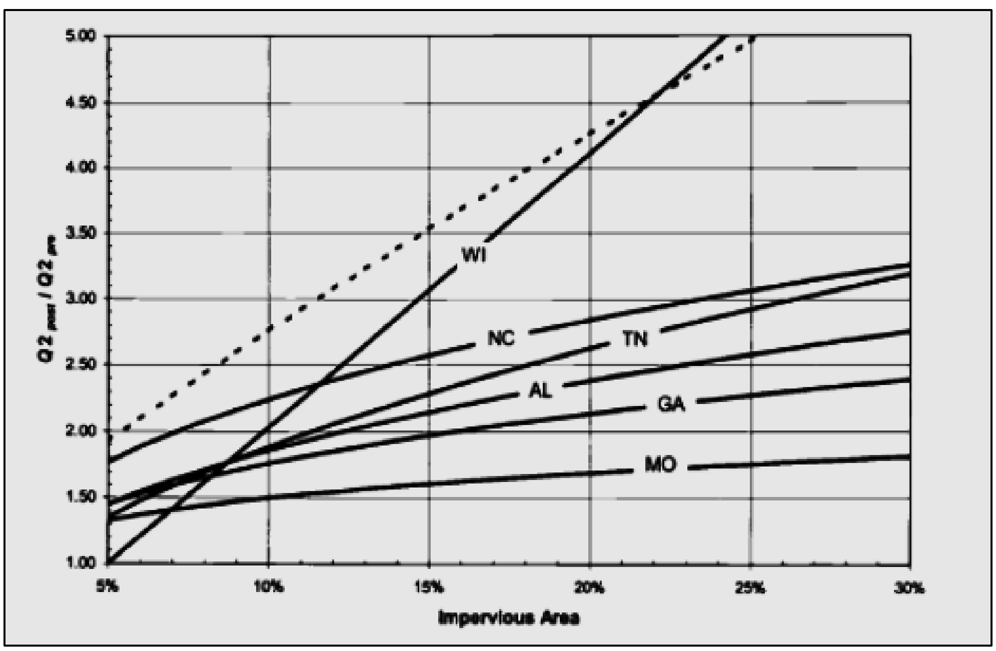

Figure A.1. Graph represents the ratio of median annual flood (urbanizing watershed vs. rural watershed) as a function of impervious area. Approximations are based on USGS Flood Regression Equations and watershed area is assumed to equal 20 km2 for six states. The dashed line represents the relationship developed using NURP data.

Source: Bledsoe, B. P. and C. C. Watson, 2001. Effects of Urbanization on Channel Instability1. JAWRA Journal of the American Water Resources Association 37:255-270.

Increased fine-sediment yield, as a result of in-channel contributions, is synonymous with channel enlargement. Channel enlargement has been suggested by many to be the predominant response to urbanization because of modifications to erosive flow regimes (Hammer 1972; Booth 1990; Doll, Wise-Frederick et al. 2002; Chin 2006). Yet, it is important to note that not all research indicates enlargement and/or aggressive erosion as a primary impact of hydromodification (Nelson, Smith et al. 2006; Annable, Watson et al. 2012). Whether a stream vertical degrades, lateral degrades, or both will be a function of boundary conditions (Allen, Arnold et al. 2002; Bledsoe, Stein et al. 2012) and the erosive processes in play (Leopold 1973; Lawler 1995).

Channel Erosive Resistance

Erosive Processes

Sub-aerial

Subaerial processes are the result of temporal changes in climate that influence streambank soil moisture conditions (Wynn, Henderson et al. 2008) and the physical state of the moisture (Thorne 1990). The modifications to soil properties can be considered preparatory processes which weaken the streambank soils for fluvial erosion (Wolman 1959; Leopold 1973; Lawler 1993), but can also act as the erosive agent themselves (Couper and Maddock 2001). Over the years it has become more apparent that subaerial process, in combination with other erosive processes, play a significant role in bank morphology (Couper 2003). Although erosion due to subaerial events can be considered of low magnitude events are frequent (Couper and Maddock 2001), reducing streambank resistance to erosive flows (Lawler 1993; Prosser, Hughes et al. 2000; Yumoto, Ogata et al. 2006; Wynn, Henderson et al. 2008). Yumoto, Ogata et al. (2006) found that subaerial erosion produced 20 – 60% of annual sediment yields from a small mountain stream in central Japan. In some headwater reaches subaerial processes can be a necessary precursor to fluvial entrainment (Prosser, Hughes et al. 2000). This is an important finding; as channel protection flows designed to reduce the number of shearing events may be ineffective if erodibility approximations ignore subaerial influence.

Streambank subaerial processes consist of four basic processes wetting, drying, freezing and thawing. The interaction of these processes combine to become cyclical agents of erosion themselves or induce a decrease in erodibility and to some degree a decrease in mechanical strength of the bank soils (Papanicolaou, Dey et al. 2006). Wetting and drying typically act in conjunction. The wetting process results in increased streambank soil moisture content typically induced by flows, groundwater rise, and/or infiltration of precipitation. Desiccation is often the second phase of this cycle. Desiccation occurs when soil moisture is reduced leading to soil cracking and exfoliation (Wynn, Henderson et al. 2008). Desiccation creates a ped fabric where cohesive strength is greater within peds than between them (Thorne 1990) and aggregates are formed. Green, Beavis et al. (1999) found that wasting of clayey aggregates (10-40 mm diameter) following desiccation was a significant source of bank erosion in tributaries of the Namoi River, Australia.

Freeze-thaw affects soils at or near the freezing front of the soil (Papanicolaou, Dey et al. 2006) through a decrease in bulk density and a decrease in cohesive strength of the impacted layer (Bullock, Nelson et al. 1988). Freeze-thaw susceptibility is expected to be influenced by soil texture as soils with higher silt-clay content typically have a greater plasticity and therefore a greater swelling and shrinkage potential (Couper 2003). Streambank soils in ER67 commonly have high silt and clay contents and are exposed to freeze-thaw cycles throughout the winter months. Streambanks soils are exposed to freezing temperatures at night followed by warming during daytime hours, due to either direct sunlight or a rise in temperatures (Wynn, Henderson et al. 2008).

Fluvial Erosion

Fluvial Erosion of Non-cohesive Materials

Fluvial erosion represents the entrainment of particles or aggregates from the bed and banks of fluvial systems by forces generated from water flowing downhill. The concept of tractive force and shear force is often used to describe detachment and transport relative to a channel's flow regime and is a common engineering tool for the design of a stable channel (Lane 1955). For non-cohesive soils and alluvial bed materials, Shields' diagram is often used to represent the critical shear stress necessary to entrain a characteristic particle size (Shields, Ott et al. 1936;

Yalin and Karahan 1979). Yet, other methods have been successful in characterizing incipient motion as well (Yang 1973).

Entrainment or transport is expected when tractive forces as a result of flows overcome resisting forces. The determination of the effective force responsible for detachment is usually described by some measure of excess velocity, discharge, shear, or stream power. Calculations in alluvial materials typically involve an assumption of a characteristic grain size and the associated submerged weight of the grain. The effective tractive force over time, or possibly better termed "eroding force", can be related to the stream system or reach wide conditions of transport or supply limited.

Fluvial Erosion of Cohesive Materials

While fluvial erosion of non-cohesive soils is often governed by gravitational forces and soil parameters, entrainment of cohesive soils is governed by both physical and chemical forces (Arulanandan, Gillogley et al. 1980). A common model used to predict the erosion rate ($\boldsymbol{\mathcal{E}}$) of cohesive streambanks is the excess shear stress equation. Regularly this relationship is defined by the magnitude of erosive force (τ) versus resisting force (τ_c) and a coefficient value (K_d) representing a rate of erodibility (Partheniades 1965; Arulanandan, Gillogley et al. 1980; Osman and Thorne 1988; Hanson 1990a; Hanson 1990b; Hanson and Cook 1997). The model in its basic form can be expressed as ($\boldsymbol{a}$ is commonly assumed as 1):

$$\boldsymbol{\mathcal{E} = k_d(\tau - \tau_c)^a} \qquad \text{Eq. A-1}$$

Although reasonable estimates of hydrodynamic forces are attainable values, resisting force parameter estimates are difficult to determine for cohesive soils (Clark and Wynn 2007). With factors such as particle size and distribution, nature of electrochemical bonding, organic matter content, stress history, pH, and moisture content influencing parameter estimates (Arulanandan, Gillogley et al. 1980; ASCE 1998a; Simon and Collison 2001; Wynn, Henderson et al. 2008). As well, parameter estimates are not static through space (Daly, Fox et al. 2015) or over time (Wynn, Henderson et al. 2008).

Research performed by Wynn and Mostaghimi (2006) exemplify this variance. Individual site erodibility varied from 0.2 cm^3/N-s to 13.1 cm^3/N-s and critical shear stress values ranged from 0 Pa to 21.9 Pa; while at-a-site erodibility varied by one order of magnitude and critical shear values varied by as much as four orders of magnitude, the variance attributed to subaerial processes. Included in this complexity is interaction effects of variables, such as variation in soil horizon attributes (Sutarto, Papanicolaou et al. 2014), secondary currents (Papanicolaou, Elhakeem et al. 2007), and soil texture and vegetation combinations (Dunaway, Swanson et al. 1994).

Sediment derived from in-channel fluvial erosion is typically considered to represent a lower bound with respect to mass wasting processes (Sutarto, Papanicolaou et al. 2014). However, fluvial erosion is often a prerequisite process for mass wasting through increases in bank height and angle (ASCE 1998a) as result of incision.

Incision

Incision is systematic bed level lowering in a reach, segment, or stream system caused by the process of degradation (Mackin 1948). It can be described by concepts of equilibrium proposed by (Lane 1954) applicable to alluvial channels (Eq. A-2):

$$Q_s d \propto Q_w S \qquad \text{Eq. A-2}$$

Where Q_s is bed material load, d is characteristic particle diameter, Q_w is the water discharge and S is the reach slope. When conditions of excess transport capacity exist relative to sediment supply a system will adjust accordingly and incision is one of many potential outcomes (Simon and Rinaldi 2006). Simon and Rinaldi (2006) further adds clarity to the concept of incision with the following statement, "*the defining characteristic of incised channels is that they contain flows of greater recurrence intervals than non-incised channels in similar hydrologic settings*." Therefore, incision is a condition that is present when a channel contains a portion of the erosive flow regime that would be expected to make floodplain connection in a similar reach that is stable.

There are many different causes of incision. Of importance to this study are anthropogenic causes that increase the magnitude, duration, or frequency of erosive flows and/or decrease bed material supplied to the channel. These disturbances affect available stream power or change erosional resistance in a manner that creates an excess stream power greater than the pre-disturbed state (Simon and Rinaldi 2006). Anthropogenic causes may include development that increases impervious surfaces within a watershed or channel alterations that increase channel slope, reduce frictional resistance, or disrupt sediment transport. A more encompassing review of causes of channel incision can be found in (Schumm 1999).

Usually when a channel experiences vertical degradation there is a systematic base level lowering, followed by widening (Schumm, Harvey et al. 1984; Simon, 1995). Incision and fluvial erosion of the bank toe often are precursors, which progress bank morphology towards critical bank height. These coupled mechanisms of vertical and lateral retreat result in channel degradation of a "non-linear asymptotic nature" (Simon and Rinaldi 2006), that ultimately leads to an expansion that is generally proportional to the imbalance in stream power associated with a disturbance. Yet, if the right combination of slope and boundary erosive resistance exists, expansion can be disproportional to the magnitude of increased flows that initiated the expansion (Booth 1990). Simon and Rinaldi (2006) indicated that boundary materials were a significant predictor of the relative magnitude of channel expansion, with similar disturbances resulting in varied degrees of expansion as a function of boundary materials.

Mass Wasting

Mass wasting is an erosive process that can contribute greatly to downstream sediment yield. Incision and fluvial erosion of the bank toe often are precursors for mass wasting potential, which progress bank morphology towards critical bank height (Little, Thorne et al. 1982). When shearing resistance (resisting force) is no longer greater than the gravitational forces (driving forces) imposed by the soil block, critical bank height (threshold for failure) has been exceeded. The ratio of resisting force to driving force, is often defined by the "factor of safety" (Langendoen, Simon et al. 1999).

Resisting force is controlled by frictional resistance, cohesion, and potentially hydrostatic confining pressure (dependent on stage) and is often aggregated as the total cohesion of the soil materials. Gravitational forces are typically determined by saturated soil unit weight (Simon, Curini et al. 1999) relative to the slip plane. When gravitational forces exceed resisting forces, the mass will fail along some slip plane.

Mass wasting is not a continuous process, but rather a sudden and sometimes drastic contribution to sediment supply determined by a unique set of conditions. Those conditions include thresholds for bank height and bank angle relative to cohesion, specific weight, and angle of friction (Osman and Thorne 1988) . Incision and fluvial erosion of the bank toe often are precursors, which progress bank morphology towards critical bank height. Once thresholds of angle and height are sufficient, conditions of destabilization typically progress through saturation of soils during precipitating event, loss of matric suction, generation of positive pore-water pressures, and the absence of confining hydrostatic pressure on the trailing arm of the hydrograph (Simon, Curini et al. 2000). Rates of destabilization therefore are influenced by controls on infiltration rates, seepage mechanics, and potential failure planes and would include soils and riparian vegetation (Abernethy and Rutherfurd 1998; Abernethy and Rutherfurd 2000; Simon and Collison 2002; Simon, Pollen et al. 2006).

Bank failures can be identified generally by five major types: shallow, cantilever, planar/slab, rotational, and sapping. The four types of failure most common to cohesive soils and likely to occur in ER67 are cantilever, planar/slab, rotational and seepage. Each of these failure types represent different mechanics of failure. Mechanics are a function of the soils, stratification of soils, vegetation, bank morphology, and saturation dynamics.

Cantilever failures are common when variation in erodibility exists among soil horizons or is a result of riparian vegetation influence. Riparian vegetation can provide sufficient variation in erodibility and tensile strength to create a cantilever block in the immediate vicinity of the root mat (ASCE 1998a). Failure usually occurs along a vertical plane.

Planar/Slab type failures are common where steep bank angles exist. This type of failure is common in cohesive soils where deep tension cracks form. Planar/Slab is commonly described as an intact block failing along a linear type failure plane sometimes toppling into the stream.

Rotational failures are common among stream banks where bank heights are significant but bank angles are lower. Failure planes are usually curved and represent a slide or slumping type failure. Sapping is common in streambanks of contrasting permeability and usually occurs where a lower soil horizon is less permeable resulting in seepage forces that create conditions necessary for destabilization (Simon, Curini et al. 1999; Fox and Wilson 2010).

Understanding when and where mass failure processes will occur is critical to any integrated watershed planning that seeks to minimize sediment yield; as mass wasting is commonly considered the greatest contributor to excess sediment loads generated from in-channel erosion processes (Sutarto, Papanicolaou et al. 2014). Within the context of this research, mass wasting processes represent one of three major bank erosion processes. By identifying the presence are potential for erosive processes, extrapolations of sediment source potential can be inferred. Sediment source potentials would therefore provide the extremes of susceptibility and allow more effective management of sediment yield.

Erosive Resistance Elements

Resistance properties in Ridge and Valley are extremely diverse. Bedrock, vegetation, cohesive soils, and very sudden and drastic changes in topology provide a wide spectrum of force vs resistance relationships.

Vertical Erosive Resistance Elements

Grade Control

ER67 channel evolution is significantly influenced by both natural grade controls (bedrock exposures) and artificial grade controls**.** The presence of grade control has the potential to prevent bed level lowering through fixing the slope in the immediate vicinity of the grade control, as well as, provide bank protection to streambanks in the immediate vicinity through a number of mechanisms. Grade control influence on erosive processes is likely best categorized through influence in the vertical and lateral dimensions.

Vertically grade control has the potential to stabilize the bed preventing upward migration of a knickpoint or knickzone. It is common in alluvial depositional settings for incision to precede lateral retreat of the banks (Schumm, Harvey et al. 1984; Simon, 1995). Laterally, grade controls have the potential to: 1) prevent streambanks from reaching critical height thresholds, 2) actually reduce bank heights through sediment deposition 3) and provide reduction of shear stress and basal cleanout due to potential backwater effects (Watson and Biedenharn 1999).

Ultimately, the frequency of grade control relative to channel slope, erosional strength, and mechanical strength has a strong influence on the degree of incision and progression of evolution (Langendoen, Simon et al. 2000). It's importance is exemplified in research performed by Hawley, Bledsoe et al. (2012), "*Self-stabilized reaches without a proximate grade control structure were rare, both during field reconnaissance and in our dataset (2 of 33 reaches, 3 of 83 sites)*" and later included in a framework to assess southern California streams susceptibility to hydromodification (Bledsoe, Stein et al. 2012). Grable and Harden (2006) suggested that grade controls (artificial and natural) were a significant factor leading to non-linear response to urbanization in 2nd Creek a ER67 stream, but no formal measures were taken to confirm these suggestions.

Examples of natural grade controls include beaver dams, large woody debri jams, bedrock outcrops, and boulder/cobble distributions in excess of transport capacity. Artificial examples include weirs, bridges, culverts, sills (Watson and Biedenharn 1999), and armoured beds (Bravard, Kondolf et al. 1999). In either situation, it is important to consider time scale and the geomorphic setting of a stream in question before assumptions are made about longevity of protection afforded relative to the control; as undermining and flanking of structures is an important consideration with both classes.

Although SCMs have the potential to prevent incision, it is important to note these structures do this through the function of controlling process rates. If geomorphic thresholds have been breached then they only theoretically control the rate of incision. Artificial and natural grade controls have the potential to prevent incision within a longer time scale.

Transport Limited Condition

Einstein (1964) proposed two general conditions on sediment yield at a cross-section. The first is the sediment must have been derived from upstream of the cross-section and somewhere within the stream system. The second was that the sediment was transported by flow from point of detachment to the cross-section. Einstein (1964) further suggested that these conditions create a time dependent response through two controls: transport capacity and sediment supply (Julien 2010).

A transport limiting condition exists when only lower frequency storms have the necessary transport capacity to move materials. A coarse surface layer on riverbeds is termed “the armour” and armoured beds are an example of a transport limited condition with respect to bed material. This layer often protects a more mobile substratum that would be entrained during more probable flow events had “the armour” not been present, resulting in a transport limited condition (Reid, Bathurst et al. 1997). A supply limiting condition exists when most high probability storms of a flow regime are capable of entraining materials.

Lateral Resistance Elements

Riparian Vegetation

Riparian vegetation has a significant impact on the rate of work performed on channel boundaries and the ultimate stable morphology (Hey and Thorne 1986), because vegetation influences the mechanics and process rates of erosion. Vegetation has the potential to increase flow resistance, decrease soil erosion due to entrainment, increase geotechnical properties, and improve drainage of bank soils (Thorne 1990). Therefore, vegetation can be considered an element that influences a channels erosive resistance.

For the purposes of researching streambank erosion and channel evolution, vegetation is often distinguished as either herbaceous or deciduous vegetation. Herbaceous vegetation can be considered non-woody species such as grasses and groundcovers. Deciduous vegetation includes woody tree species and large brush. These two categories appear to be sufficient to capture the variance in root mat characteristics (Wynn, Mostaghimi et al. 2004). As well, they appear to capture a sufficient variance in hydrologic and mechanical strength (Simon and Collison 2002; Simon, Pollen et al. 2006) that help define resisting force characteristics of a streambank.

Vegetation has been documented to affect the hydraulic strength, mechanical strength, and hydrology of streambanks. Millar and Quick (1998) showed that vegetation can increase bank critical shear stress by up to three times that of bare soil. Vegetation can improve mechanical strength through addition of root reinforcement, which is a function of tensile strength, areal density and root distortion under loading (Simon and Collison 2002). However, it is important to note gains in mechanical strength are not a guarantee as there is potential negative impacts through surcharge (Thorne 1990). Vegetation can also influence bank hydrology through pore water pressures and matrix suction. Typically, this influence is a function of interception and evapotranspiration rates relative to vegetative types. Research by Simon and Collison (2002) documents the importance of this influence showing positive impacts, but also indicating potential for negative impacts through increased infiltration.

Vegetation represents a control on erosion and therefore influences imbalances between driving and resisting erosive forces. Analysis of existing literature indicates that riparian vegetation type, density, area, and maturity are the critical components necessary to characterize the influence vegetation has on both bank hydrology and mechanical strength. Yet, this must be considered within a spatial domain. Erosive process dominance varies spatially within watersheds (Lawler 1995) and previous research has suggested vegetative influence on erosive resistance varies by channel scale (Abernethy and Rutherfurd 1998).

Cohesive Soils

In non-cohesive soils, bank erosion is generally controlled by gravitational forces determined by the physical composition of bank materials. In cohesive soils, bank erosion and failure mechanisms are influenced by the physical and chemical composition of bank material (Lawler, Thorne et al. 1997). A soil's resistance to erosion can be generalized by two categories: mechanical strength and erosional strength. Mechanical strength represents the geotechnical properties of the streambank soil and erosional strength represents a soils resistance to fluvial entrainment (Papanicolaou 2001). Both categories of strength are influenced by soil texture, clay mineralogy, and chemistry of pore and eroding fluids, which determine the inter-particle forces of attraction and repulsion (Arulanandan, Gillogley et al. 1980).

The distribution of particles by size determines a given soils texture class (Figure A.2). Soil texture class is often used to summarize the behavior of both physical properties and chemical properties of a soil (Burt 2009) and therefore can be used as a surrogate for a channel boundaries erosive resistance. Increasing silt-clay content has been shown to correlate with increased erosional strength and mechanical strength (Thorne and Tovey 1981), but indicates a higher susceptibility to subaerial processes (Couper 2003). Julian and Torres (2006) suggested a relation between % silt-clay and τ_c.

Other research has had success relating bulk density as a predictor variable of K_d and τ_c, which incorporates soil texture, organic matter, and root density (Wynn and Mostaghimi 2006). These findings speak to the importance of interaction effects between the soil matrix and local vegetation and their dependence on each other with respect to erosive resistance (Wolman 1959; Dunaway, Swanson et al. 1994).

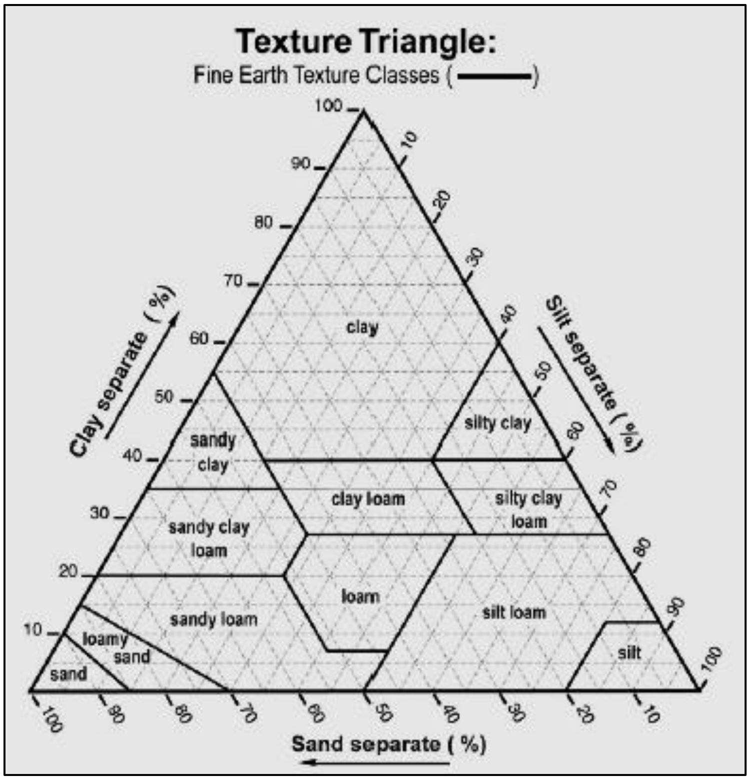

Figure A.2. Texture Triangle utilized to determine texture by percentage of sand, silt, and clay.

Source: Burt, R., 2009. Soil survey field and laboratory methods manual. National Soil Survey Center, Natural Resources Conservation Service, US Department of Agriculture.

Channel Protection Flows

Stormwater Control Measures

Stormwater Control Measures (SCMs) are designed systems intended to reduce the volume of surface runoff (as a function of time) and in certain situations provide treatment of stormwater. The reduction of the volume of runoff occurs through detention, retention, infiltration, and/or evapotranspiration of surface runoff. Detention simply detains the surface flows during precipitation events through storage of inflows for a period determined by the rate of inflow and some design outflow standard. Retention performs this same function, however, the change in storage as a function of time includes losses due to infiltration and evapotranspiration. Arguably, detention may also see losses of this nature but they are not intended design criteria. Retention design offers additional water quality benefits, when compared to detention. Yet, these benefits have varying degrees of performance influenced by design and underlying strata. The additional water quality benefits do provide potential reductions of externalities, but including these considerations is beyond the scope of this study.

To accomplish the intentions of detention and retention, SCMs may vary significantly in scale, configurations, and design (Vietz, Walsh et al. 2015). Generally though, SCMs can be broken down into structural (e.g. wetponds & wetlands) and non-structural applications that are de-centralized (Tillinghast, Hunt et al. 2012; Fletcher, Shuster et al. 2014). The decentralized applications are synonymous with the term Low Impact Development (LIDs) and include measures such as green roofs, rainwater harvesting, permeable pavement, and rain gardens (Tillinghast, Hunt et al. 2012).

Channel Protection Design Criteria

Design standards have typically focused on matching peak flows of a pre-existing condition. The pre-existing condition assumes a non-developed state and usually the 2 and/or 10-year re-occurrence interval storm. For the last 20 years or so, this method has been the predominate standard. Yet, channel degradation has persisted attributed to increased durations of eroding flows as a function of detention (Roesner, Bledsoe et al. 2001). Where duration of eroding flows persist in excess of pre-disturbed work regimes, there is a change in the effective work performed on channel boundaries and therefore channel instability can be expected (MacRae

1993; MacRae 1996). These oversights are typically attributed to a lack of consideration for the geomorphic properties of a receiving channel (Booth 1990).

More recent volume based design criteria include retention and infiltration/evapotranspiration of certain recurrence interval storms. These guidelines do have promise as they still offer the convenience of implementation unique to uniform design criteria and the added benefits of water quality. However, these types of measures are not always practical. Underlying strata may create scenarios where infiltration is not possible and/or necessary retention volumes may be impractical (Tillinghast, Hunt et al. 2012) creating excessive economic costs relative to reductions in externalities. As well, in the case of redevelopment they do little to protect stream reaches that are already destabilized.

Alternatives to volume based design standards have been suggested for the design of SCMs. These include concepts that attempt to integrate geomorphic processes of sediment detachment and transport with the transport capacity of the outflow discharge. MacRae (1993) was one of the first to suggest considering erosive flow regimes in SCM design as a means to insure stability in streams. He proposed the use of an effective work index. Other authors have suggested these concepts are prerequisites to insure the stability of streams as well (Bledsoe and Watson 2001; Palhegyi 2004; Palhegyi 2009).

Efforts that are more recent have included design standards intended to match reference conditions for bedload transport through empirical relation. Tillinghast, Hunt et al. (2011) proposed matching measures such as allowable annual erosional hour standard (AAEH) and allowable volume of eroded bedload (AV). However, these empirically derived standards are based in an analog approach and only account for work performed on alluvial non-cohesive materials. The downfalls of the analog approach are highlighted in the lack of performance for mature urbanized watersheds, where the calculated critical discharge varied by roughly 50% to that of the empirically derived critical discharge. Only considering bed load movement provides no consideration for the resistance of lateral boundary materials and contrasts research by MacRae (1996). Either way, it is interesting to note that there was limited success implementing these measures in highly urbanized systems and the author suggested the efforts could be all together impractical (Tillinghast, Hunt et al. 2012).

Coupled Catchment Modeling

EPA Storm Water Management Model (SWMM)

The SWMM platform is one of the few models that currently allow modeling of pollutant fate and transport while at the same time providing the ability to influence pollutant fate transport through the application of SCMs, including Low Impact Development (LIDs). SWMM is physically-based dynamic rainfall-runoff simulation model with the capability to address either design storm precipitation events or historical rainfall data through continuous simulation modeling (Huber and Dickinson 1988). SWMM has two primary components consisting of a runoff component and a routing component. The runoff component is addressed through its hydrology block, which consists of rain gauges, subcatchments, aquifers, snow packs, unit hydrographs, and LID controls. The routing component is addressed through its hydraulics block, which consists of nodes and links. The nodes consist of junctions, outfalls, dividers, and storage units. The links consist of conduits, pumps, orifices, weirs, and outlets. The interaction of these components, dictate the rainfall-runoff relationship for a modeled watershed.

Conservational Channel Evolution and Pollutant Transport System Model (CONCEPTS)

The CONCEPTS (Conservational Channel Evolution and Pollutant Transport System) model developed by the USDA is a 1-D hydraulic and channel erosion model that includes fluvial erosion, bank mass failure from geotechnical processes, and sediment transport. This model in conjunction with output from a coupled SWMM model, representing a contributing catchment, has the potential to describe the dynamic interaction of hillslope processes and in-channel processes through continuous simulation modeling (CSM).

Initial field validations of the CONCEPTS model were done by Langendoen, Simon et al. (1999). This article documents the use of the CONCEPTS to simulate scour and fill of the channel bed and streambank erosional processes. Langendoen, Simon et al. (1999) includes discussion of the math behind the bank stability algorithm used to evaluate the effect of surface water and pore-water pressures on the bank factor of safety and that automatically searches for the slip surface that produces the smallest factor of safety. They also apply CONCEPTS to field data showing that the bank-stability algorithm accurately (they might have been loose with this conclusion) predicts the timing and dimensions of failure at their site location.

Langendoen, Simon et al. (2000) report modeling efforts utilizing CONCEPTS as well. Modeling objectives were to evaluate the ability of alternative types and placements of mitigation measures to prevent channel instability and evaluate the effects of hydromodification on channel stability. This article exemplifies the benefits of in-channel process-based model to evaluate receiving channel impacts as opposed to statistically based models based on surrogate measures. Langendoen, Simon et al. (2000) found that at the research site critical shear stress values varied significantly through the reach. CONCEPTS is capable of modeling cross-section specific critical shear stress thresholds providing more resolution of reach susceptibility and the influence of point specific estimates on reach scale outcomes.

Langendoen (2011) summarized three different studies that utilized CONCEPTS to represent various in-stream restoration measures representing the models potential for modeling variations in channel erosive resistance. As well, it explored long-term stability of newly constructed channels, the impact of bank protection measures on both sediment loads and streambed composition, and finally the effectiveness of various vegetation strategies.

Conceptual Model for the Fluvial System

Detachment and Entrainment in Stream Systems

The primary driving force for erosion in a watershed is determined by hydrologic interaction with both the environment and geological setting. This interaction results in lowering of relief over time through the detachment, entrainment, and eventual deposition of sediment downstream. The forces that drive detachment and transport of sediment vary relative to position within the contributing stream system. The most distinct break in erosional processes within a catchment is between in-channel and what constitutes hillslope. However, variation has been noted even within in-channel erosional processes (Lawler 1995) assuming it is an appropriately large stream system. This section will briefly describe processes of detachment and transport along a continuum from hillslope to channelized flow. For further review of variation in in-channel processes, please see section "*Erosive Processes*".

Interrill erosion is driven primarily through detachment of surface aggregates by rainfall impact and then transported by entrainment in sheet flow from non-abstracted rainfall (Ellison 1947). Yet, surface sheet flow at this stage is typically insufficient to produce detachment due to shearing. In a forested setting, this process is hindered through interception by canopy and additional protection provided by surface organic matter. In a rural /agriculture setting, this process can be a significant contributor to sediment yields without application of appropriate agricultural BMPs. In an urbanized or urbanizing system, this process is representative of impervious surfaces and roads where build-up and wash-off is a contributor to yields. As well as, construction phase projects with exposed soils similar to agricultural settings.

At the point where surface sheet flows begin concentrating, rills form. The increase in depth of flow, due to concentration of flow, typically reduces the power density of rainfall impact and detachment typically no longer occurs due to rainfall impact in the rill. In rills, detachment is a function of shear force, headwall cutting, and sidewall sloughing. Transport in rills is primarily due to entrainment (Haan, Barfield et al. 1994). Rilling would also constitute hillslope processes and so the settings described in the previous paragraph would be appropriate for rilling. However, it is important to note landscape units of impervious cover do not allow for concentration and detachment as a function of shear force. Therefore, this process is largely lacking in heavily urbanized systems.

Moving along the continuum, we reach gullying or channelized flow and what will be referred to as in-channel erosional processes. The fundamental principles of detachment and transport are the same as rill erosional processes. However, the variation and interdependence of controlling factors increases exponentially (Haan, Barfield et al. 1994).

Time Scales and Spatial Scales

If intention is to mitigate the effects of flow regimes on channel destabilization resulting from urbanization, it is necessary to establish cause. As Schumm and Lichty (1965) very clearly define, *"The distinction of cause and effect among geomorphic variables varies with the size of a landscape and with time"* . Therefore, through defining or landscape units and the time span of consideration we can identify what controls we have on our system and how that may influence both our processes at play and the form they are responding to, or determining.

The time scale probably most appropriate to this study is equivalent to the definition provided by Mackin (1948) of a graded stream. Here we are unconcerned with variation around the graded state. Rather, we are interested in disturbances that are deviations from this state. It is expected erosion of a reach is a natural condition, but enlargement of a channel as response to urbanization would be a deviation of state, providing considerably larger sediment yields.

Defining the landscape unit is important as it defines the time scale of response. As well, where this landscape unit is within a continuum determines important aspects of the larger processes of Q and Q_s and how those interact with the landscape unit to determine the natural disturbance regime (Montgomery 1999). Also, it is descriptive of more specific erosive processes that may occur and potentially dominate (Lawler 1995). Understanding these components are important elements of any research because they provide a conceptual foundation for reasonable assumptions about legacy effects or historical states, "potential capacity" for response, and future developmental state (Ebersole, Liss et al. 1997).

For the purposes of this study, focus will be on stream system response within the stream reach unit. This unit is generally delineated by a stream section of equivalent slope with similar boundary materials and vegetation. Research suggests that response times within this unit are generally on the order of 10 – 100 years and provide a scale capable of determining anthropogenic influence (Frissell, Liss et al. 1986).

Environmental Controls, Processes and Form

Controls

Dynamic interaction with atmospheric processes and land result in geomorphic processes. These geomorphic processes are dictated by certain controls on the system in question. The system as previously discussed is determined by its spatial extent and positioning within a larger continuum. Generally speaking, controls determine processes and form relative to the fluvial unit. For the stream reach unit controls include climate, geology, land-use, basin physiography, base level, valley morphology, channel morphology, and boundary materials (Schumm 1977; Knighton 1984). Further segregation might include those which determine the processes of surface flow and sediment transport and those that determine specific hydraulic conditions relevant to thresholds (Schumm 1977). The later would therefore include channel morphology, boundary material, and vegetation and represent resisting forces and the former driving forces. Therefore, controls could be considered analogues to forces acting on the system.

Fluvial Processes

The physical interaction between climate and the watershed ultimately result in a number of exogenic processes. Yet, many are beyond the scope of this research. Of particular interest to this study is how fluvial processes are modified as a result of human interactions with the formerly mentioned controls on the fluvial system. Therefore, it is important to define which fluvial processes are relevant and what potential other processes might be influenced as a result.

The spatially distributed difference in process rates result in sediment detachment, transport and/or deposition. The magnitude of these processes within a defined control volume define conditions of an aggradation zone (depositional), transportation zone (stable), or degradation zone (eroding). For the purposes of this research the control volume could be considered a stream reach, therefore: an aggrading reach is defined as one experiencing storage of sediments, a stable reach is one experiencing neither storage or loss, and degrading reach is one experience progressive loss (Schumm 1963). In the event of the later additional erosional processes are important. These include sub-aerial and mass wasting and much like fluvial processes rates are influenced by controls on the system and spatial positioning within the system (Lawler 1995) (Figure A.3). It is important to note that a degrading state is not isolated to unstable stream systems. Rather, degradation and the processes responsible are instrumental to the denudation that occurs in a stream system during longer erosional cycles (Schumm and Lichty 1965).

Form

A stable channel by definition represents a balance between form and process; the stream is in a quasi-equilibrium state with the processes of streamflow and sediment transport. Over an extended period, the stream channel morphology is able to adequately convey Q and Q_s without significant work being performed on the channel boundaries. Therefore, energy expenditure is primarily accomplished through work performed by viscous shear and turbulence, friction at the interface with the channel, and in transporting the supplied sediment load. This physical description of processes in balance with form has been supported through statistical relations termed “hydraulic geometries” (Leopold and Maddock 1953) and many theories have followed attempting to impose some governing law or laws (Langbein and Leopold 1964; Singh 2003) that result in balance. However, it is important to note, the degree of local variance that may be present in these predictive relations. Lane and Richards (1997) statement highlights these

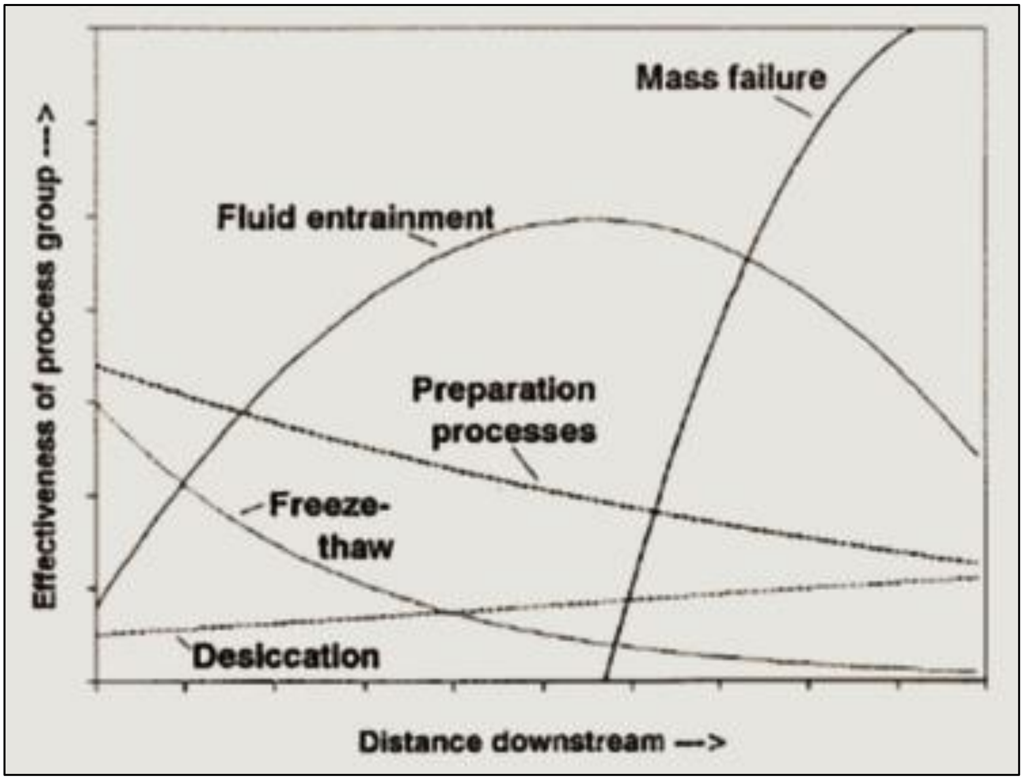

Figure A.3. Conceptual model for downstream change in bank erosion processes.

Source: Lawler, D., 1995. The impact of scale on the processes of channel-side sediment supply: a conceptual model. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences* **226**:175-186.

necessary considerations, "*These are power laws in which the seductive quality of the trend may disguise order-of-magnitude local variability*."

Erosive Disturbance Regimes

Urban hydrologic alteration is a complex perturbation on fluvial systems representing both a ramped and pulse disturbance (Lake 2000) on both abiotic and biotic properties of the system. Streams are subject to a natural disturbance regime defined by the conveyance of water and sediment over time. The temporal patterns that make up disturbance regimes are the result of the interaction of these fluxes with the boundary materials and conditions of the channel. As discussed previously, it is believed that these regimes, over sufficiently long periods, can be assumed as steady state and ultimately a quasi-equilibrium between eroding and resisting force exists within a natural undisturbed state. This is exemplified in form that is visual interpreted as representing a balance with the processes within the fluvial system (Leopold and Maddock 1953) during an appropriately long time scale (Schumm and Lichty 1965).

Hydrologic alteration coincides with alterations to the flux of water through a fluvial unit. So, by nature there is a shift in the disturbance regime associated with fluxes of flow. However, modifications to the disturbance regime of flow do not guarantee a perturbation in the sediment transport disturbance regime. This regime has the added requirement on processes, of thresholds. Therefore, it is not prudent to assume that a shift in flow regime is synonymous with a shift in the sediment transport disturbance regime.

Theory of Minimum Stream Power

Stream power and the theory of minimum energy dissipation have been strongly supported through research. Multiple studies have identified strong correlations between unit stream power in various forms and sediment detachment, transport, and eventual form (Yang 1972; Yang 1973; Chang 1979; Van den Berg 1995). In Simon and Rinaldi (2006), numerous examples are given of temporal trends in channel adjustment after disturbance. The adjustment process appears to follow a pattern of minimization of the following: the rate of energy dissipation and the ability of the river to transport bed-material sediment. This response can be described as a non-linear decay function that becomes asymptotic and ideally reaches a minimum variance (Simon and Rinaldi 2006) with relative magnitude a function of both hydrologic and hydraulic controls on the system.

Although many alternatives to this theory exist that attempt to conceptualize governing principles which determine the many stable forms we observe in fluvial systems and there relation to driving force (Singh 2003), the concept of "Minimization of Stream Power" is uniquely adaptable to measuring the magnitude of deviation from natural disturbance regimes. It provides the theoretical underpinnings for approximation of a trajectory of response when anthropogenic influences result in modifications to the controls on the system. These qualities will provide the necessary foundation to advance the conversation of channel erosive resistance elements and its application to energy management in urban systems.

A central tenet of this research is that the time derivative of channel erosive resistance elements is minimal when compared to the influence that those elements have on the processes that determine effective stream power as a function of time. More clearly, modification of effective stream power through time will be significant when compared to environmental changes in channel erosive resistance elements (environmental changes not including anthropogenic influenced modifications). It is important to note that although the time derivative of channel erosive resistance will be assumed constant, the spatial derivative cannot be neglected and will be the central focus of this research.

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Chapter 1 Statistical Data

Table A.1: Data for Logistic Regression analysis

Site	Identifier	Latitude	Longitude	FE	MW
Back Creek	BA1	36.52942	-82.26225	2	2
Black Creek	BC1	35.84540	-84.70851	1	1
Buffalo Creek	BUS	36.20795	-83.55691	1	1
Buffalo Creek	BDS	36.20205	-83.55876	1	1
Caney Creek	CC1	35.90214	-84.60616	2	2
Cedar Springs	CS	35.41611	-84.61781	2	2
Fillauer Branch	FB1	35.19820	-84.85262	1	2
Fisher Creek	FC1	36.49646	-82.93790	1	1
Greasy Rock Creek	GRU	36.53144	-83.21309	1	1
Havley Springs Branch	HSB	36.23381	-83.31192	2	2
Holley Creek	HC1	36.14503	-82.76466	2	1
Little Turkey Creek	LTCDS	35.86323	-84.20018	1	1
Loves Creek	LC1	36.02185	-83.85942	2	1
Mackey Branch	MB1	35.00622	-85.15893	2	1
Middle Creek	MI1	35.84489	-83.54044	1	2
Mountain Creek	MO1	35.10851	-85.32102	2	2
North Fork	NF1	36.08946	-83.92742	2	1
Panther Creek	PAN	36.21058	-83.40264	1	1
Pistol Creek	PCUS2	35.72160	-83.98104	2	2
Pistol Creek	PCDS	35.73560	-83.98050	2	2
Right Fork Coal	RFCC	36.22845	-84.16261	1	1
South Chestuee Creek	SCC	35.11380	-84.75375	1	1
SwanPond Creek	SP1	35.98588	-83.78628	2	2
Sweetwater Creek	SW1	35.59861	-84.45945	2	2
Ten Mile Creek Trib 2	TMCT2	35.92793	-84.06290	1	1
Ten Mile Creek	TMC	35.92753	-84.06953	2	2
Ten Mile Creek Trib 1	TMCT1	35.92905	-84.06758	2	1
Tuckahoe	TUC	35.97020	-83.66792	1	1

Table A.1 (continued)

Identifier	Ω_{u2} (Watts/m^2)	Ω_{tb} (Watts/m^2)	S_vQ_{u2} (m$^{1.5}$/s$^{0.5}$)	FFdays (d)	DA (km^2)	10_85 (m/km)	DD	Q_{u2}/Q_{pre}
BA1	27.5	7.7	0.011	189	30.8	13.4	0.9	1.0
BC1	122.9	41.2	0.013	217	15.9	32.8	0.7	2.1
BUS	84.9	14.6	0.020	155	12.1	15.4	0.9	1.0
BDS	222.4	43.0	0.049	155	47.3	12.0	0.8	1.0
CC1	46.2	8.6	0.017	217	17.8	10.1	0.9	1.9
CS	9.6	3.4	0.007	190	8.6	14.7	0.9	1.0
FB1	174.1	16.9	0.026	190	10.6	7.3	1.1	3.0
FC1	32.2	22.5	0.014	176	28.0	6.9	0.8	1.0
GRU	131.8	26.3	0.026	176	6.5	90.1	1.0	1.0
HSB	59.8	0.9	0.014	181	13.3	7.5	0.8	1.5
HC1	128.4	36.3	0.027	176	12.9	10.1	0.8	1.4
LTCDS	101.7	7.1	0.024	195	11.6	7.3	1.2	2.4
LC1	251.9	28.0	0.019	195	10.7	11.0	1.0	2.5
MB1	67.6	7.0	0.036	205	22.3	8.2	1.0	2.0
MI1	17.3	1.8	0.014	169	30.0	4.1	0.5	1.0
MO1	22.3	6.0	0.015	205	14.1	12.2	0.6	1.6
NF1	86.5	26.0	0.022	195	5.1	20.4	1.2	1.9
PAN	171.5	10.7	0.051	176	14.2	8.2	0.5	2.0
PCUS2	182.4	64.3	0.019	160	7.6	6.8	0.9	1.6
PCDS	53.7	8.9	0.016	160	16.1	5.6	1.1	1.5
RFCC	92.1	11.5	0.020	207	14.1	11.5	0.9	1.5
SCC	51.2	11.1	0.008	190	15.7	8.5	0.8	1.0
SP1	43.5	12.0	0.010	195	10.8	11.6	1.1	1.0
SW1	24.5	4.3	0.009	193	52.8	1.2	0.9	1.0
TMCT2	2.8	0.0	0.004	195	3.3	11.2	1.4	2.9
TMC	22.4	0.6	0.007	195	15.6	11.3	0.9	2.6
TMCT1	63.5	0.6	0.006	195	11.8	11.9	0.7	2.5
TUC	83.1	69.2	0.013	195	25.0	5.3	1.3	1.0

Table A.1 (continued)

Identifier	VWI	VEC	S_v (m/m)	BDTG	ΔVz (m)	DDSG_DSR (m)	SC (%)	DtoWT (cm)
BA1	18.7	2.4	0.00348	41.2	1.1	314.9	86.3	15
BC1	4.0	0.2	0.00229	18.6	0.5	217.3	62.3	76
BUS	4.0	0.1	0.00626	11.6	0.5	81.4	77.3	201
BDS	5.0	-0.4	0.00901	0.0	0.0	0.0	77.3	201
CC1	42.7	0.2	0.00313	23.2	0.8	260.6	57.3	168
CS	10.0	-0.2	0.00232	63.7	1.2	509.9	57.7	51
FB1	58.3	0.0	0.00458	11.1	0.4	83.5	81	76
FC1	3.8	0.3	0.00340	0.0	0.0	0.0	57.2	201
GRU	31.8	0.1	0.00988	11.5	0.7	74.4	79.7	69
HSB	34.5	0.5	0.00355	104.3	1.0	293.2	79.2	201
HC1	9.2	-0.1	0.00710	0.0	0.0	0.0	91.9	69
LTCDS	10.5	0.5	0.00497	0.0	0.0	0.0	93	61
LC1	5.5	0.9	0.00391	0.0	0.0	0.0	93	61
MB1	64.2	0.8	0.00553	0.0	0.0	0.0	78	31
MI1	18.6	0.7	0.00368	23.3	1.0	260.3	54.6	107
MO1	14.9	2.8	0.00301	18.5	0.6	194.2	76.1	46
NF1	28.4	0.3	0.00660	58.6	2.7	405.1	54.6	129
PAN	20.6	1.0	0.01116	0.0	0.0	0.0	79.9	76
PCUS2	13.7	0.1	0.00567	0.0	0.0	0.0	91.8	69
PCDS	12.6	0.0	0.00365	9.1	0.2	57.9	91.8	69
RFCC	11.5	0.3	0.00471	8.7	0.3	60.3	73.8	61
SCC	5.9	0.2	0.00218	0.0	0.0	0.0	93.3	15
SP1	19.5	0.6	0.00309	38.6	0.8	271.3	93.6	30
SW1	32.9	0.2	0.00156	4.8	0.1	40.5	91.7	31
TMCT2	18.5	-0.5	0.00120	22.0	0.1	86.6	93.6	30
TMC	13.7	0.3	0.00123	20.4	0.2	129.3	93.6	30
TMCT1	17.7	-0.2	0.00123	29.4	0.1	118.9	93.6	30
TUC	6.4	0.1	0.00309	0.0	0.0	0.0	93	61

Table A.1 (continued)

Identifier	D_{50} (mm)	n	Flowpath (m)	Q_{c2}/Q_{tb}	Q_{tb}/Q_{u2}	W/D	IR
BA1	8.7	0.070	11022	0.2	0.3	9	0.2
BC1	32.0	0.049	8599	0.5	0.3	13	0.1
BUS	13.5	0.041	7192	0.4	0.2	18	0.6
BDS	22.4	0.044	12396	0.3	0.2	16	0.4
CC1	12.7	0.060	7438	0.3	0.2	14	0.2
CS	2.0	0.040	3405	0.1	0.4	10	0.2
FB1	12.9	0.064	6941	0.2	0.1	11	0.1
FC1	35.0	0.049	8586	1.0	0.7	14	0.1
GRU	39.0	0.086	3891	0.5	0.2	18	0.1
HSB	6.0	0.077	7502	1.0	0.0	6	0.2
HC1	11.0	0.063	8820	0.0	0.3	11	0.3
LTCDS	28.3	0.083	4718	1.0	0.1	8	0.1
LC1	60.8	0.040	5496	1.0	0.1	16	0.3
MB1	13.7	0.053	9743	1.0	0.1	8	0.2
MI1	9.8	0.071	15249	1.0	0.1	15	0.1
MO1	14.1	0.053	7694	1.0	0.3	9	0.1
NF1	12.1	0.065	4899	0.0	0.3	9	0.1
PAN	12.6	0.085	9464	0.2	0.1	8	0.2
PCUS2	22.9	0.070	5215	1.0	0.4	8	0.3
PCDS	22.9	0.054	7533	1.0	0.2	6	0.2
RFCC	19.0	0.065	7182	0.6	0.1	12	0.4
SCC	18.1	0.053	8791	0.6	0.2	13	0.3
SP1	16.7	0.075	6788	0.4	0.3	10	0.2
SW1	4.6	0.041	22909	0.3	0.2	8	0.3
TMCT2	6.5	0.059	3575	1.0	0.0	10	0.3
TMC	10.2	0.060	6428	1.0	0.0	8	0.1
TMCT1	14.7	0.055	6182	1.0	0.0	11	0.5
TUC	18.0	0.040	19134	1.0	0.8	13	0.1

Table A.1 (continued)

Identifier	% TIA	Δ TIA	VFP	VFP_{MD}
BA1	6%	1%	0%	0%
BC1	13%	0%	100%	100%
BUS	1%	0%	95%	75%
BDS	1%	0%	86%	71%
CC1	9%	0%	2%	3%
CS	4%	1%	80%	65%
FB1	26%	2%	11%	0%
FC1	0%	0%	88%	88%
GRU	3%	0%	81%	52%
HSB	16%	1%	0%	0%
HC1	18%	1%	100%	11%
LTCDS	21%	3%	75%	50%
LC1	24%	2%	6%	3%
MB1	13%	2%	100%	71%
MI1	5%	3%	60%	10%
MO1	7%	1%	40%	10%
NF1	14%	2%	83%	13%
PAN	12%	3%	89%	70%
PCUS2	9%	2%	53%	25%
PCDS	12%	3%	25%	10%
RFCC	7%	0%	31%	15%
SCC	1%	0%	100%	100%
SP1	8%	2%	60%	55%
SW1	3%	1%	1%	0%
TMCT2	37%	1%	100%	45%
TMC	29%	2%	75%	50%
TMCT1	25%	2%	100%	90%
TUC	1%	0%	55%	50%

Vita

Robert Woockman was born in Anaheim, CA in 1980. His family later moved to Cumming, GA where he graduated high school in 1998. Following his high school graduation, he attended the University of Georgia and graduated with a Bachelor of Business Administration in Finance in December 2002. He spent the next eight years in the residential lending field. While that field did not end up suiting him, both the degree and work experience provided him with a strong foundation in economics and finance. In 2010, he made the decision to change career paths. In August of 2011, he was awarded a graduate research assistantship by the Department of Civil and Environmental Engineering at the University of Tennessee. In December 2012, he received a Master of Science degree in Civil Engineering. In 2013, Mr. Woockman received an additional research assistantship from the Department of Civil and Environmental Engineering to pursue his Doctor of Philosophy degree. In the summer of 2018, he completed the requirements for the Doctor of Philosophy in Civil Engineering from the University of Tennessee, Knoxville. Robert now resides in Boise, ID where he works on large-scale habitat restoration projects to benefit ESA listed salmonids.