Developing Strategies for Urban Channel Erosion Quantification in Upland Coastal Zone Streams: Final Report

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Prepared by:

Gene Yagow, W. Cully Hession, Tess Wynn, and Bethany Bezak
Virginia Tech Department of Biological Systems Engineering

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Project Personnel

Virginia Tech, Department of Biological Systems Engineering (BSE)

Gene Yagow, Research Scientist
W. Cully Hession, Associate Professor
Tess H. Wynn, Assistant Professor
Bethany Bezak, Research Associate

Project Sponsor Cooperators

Virginia Department of Environmental Quality (DEQ)

Laura B. McKay, Virginia Coastal Zone Management Manager
Shepard Moon Jr., Coastal Planner and Project Officer
Rachel Bullene, Grants Coordinator/Outreach Specialist
Virginia Witmer, Outreach Coordinator

Virginia Department of Conservation and Recreation (DCR)

Todd Janeski, Coastal NPS Program Manager

Advisory Committee Members

Mark Bennett, USGS
Louise Finger, VDGIF
Mike Flagg, Hanover County
Bob Kerr, Kerr Environmental Services Corp.
Tina Rayfield, DEQ
John Matthews, VDOT

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Chapter 1: Introduction

1.1. Background and Motivation

The overall project goal is to quantify sediment contributions due to channel enlargement of urban streams using a combination of the best available and most relevant modeling and field-based procedures. Currently, the State of Virginia is not accurately capturing the true volume of sediment that is affecting our rivers and streams. This project could position the State to better allocate the resources needed to address the true sources of sediment.

While considerable effort has been directed toward reducing erosion from agricultural and urban lands, a major source of sediment - streambank erosion - has received little attention. Studies have shown that sediment from streambanks can account for as much as 85% of watershed sediment yields (Simon et al., 2000). Because of the process complexity and the lack of physically-based algorithms to describe these processes, quantification of this source is often underestimated in current state accounting procedures both for state programs and for the regional Chesapeake Bay Program. This research provides a methodology to estimate sediment loading from stream channel degradation, as well as the most appropriate field-based monitoring techniques for future model calibration and verification.

1.2. Research Objectives

Objective 1: Review existing USGS, VDOT, and local government stream geometry data; and

Objective 2: Use a monitoring-based approach (with a statistically randomized procedure for site identification):

Tier 1: Space-for-time cross-sectional evaluation of 50 sites

Tier 2: Comparison of field-based channel erosion monitoring over a six-month period at each of the three major land uses, in each of the two physiographic provinces under Coastal Zone Management, with two replicates of each (12 sites total)

Tier 3: Selection of a subset of two Tier 2 sites for future detailed study (not to be conducted within this proposed workplan).

Under the field-based objectives, we will undertake two main activities aimed at better understanding the impact of urbanization on channel erosion: 1) collection of existing data to evaluate historic changes in streams due to increased urbanization; and, 2) a 3-tiered field study with linked GIS-based analysis to measure streams across a range of watershed conditions.

1.3. Modeling Objectives

Objective 1: To identify significant watershed characteristics related to channel erosion and associated nutrients;

Objective 2: To compare existing models on the basis of how well they represent these important characteristics;

Objective 3: To assess the ability of existing models to represent various types of BMPs that can affect runoff behavior, sediment transport, and instream sediment generation; and,

Objective 4: To assess modeling data needs and available data sources.

Chapter 2: Literature Review (Product #1)

2.1. Background

The United Nations (2005) predicts that the world's population from 2005 to 2050 will expand from 6.5 billion to 9.1 billion inhabitants. With such extreme population growth predictions, continued urbanization of the world is inevitable, increasing the impacts on aquatic ecosystems and degradation of rivers and streams. In the last half century, much research has been conducted to help us understand the influences humans have on river systems (Chin 2006; Gregory 2006). Specifically, a subset of this research has focused on alterations in watershed hydrology (Galster et al. 2006), which lead to channel enlargement (Hammer 1972; Cianfrani et al. 2006), and, in turn, to impacts on channel sediment dynamics (Wolman 1967).

2.2. Sediment as a Pollutant

At least 40 percent of the assessed waters in the U.S. are impacted to an extent that they do not meet state water quality standards (USEPA 2004). In the U.S., sediment is the second leading pollutant causing impairment of rivers and streams (USEPA 2002). Currently, more than $1 billion per year is expended for river and stream restoration in the U.S., with the improvement of water quality (or reduction in sediment) and improved aquatic habitat (reduced siltation) being among the most popular restoration goals (Bernhardt et al. 2005). While considerable effort has been directed toward reducing erosion from agricultural and urban lands, a potential major source of sediment, stream channel erosion, has received little attention.

The Federal Clean Water Act of 1972, section 303(d), requires states to submit a Total Maximum Daily Load (TMDL) Priority List (also called a 303(d) list) to the U.S. Environmental Protection Agency (USEPA) to address impaired waters within each state. A TMDL is the maximum quantity of a pollutant, from point, nonpoint, and natural background sources that a waterbody can accept while still maintaining water quality standards (VADEQ 2004). A state's 303(d) list must contain waters that do not meet its water quality standards. In Virginia, waterways are determined impaired when they cannot support at least one designated use (aquatic life, swimming, drinking water, fish and shellfish consumption), as assigned by the Virginia Department of Environmental Quality (VADEQ). TMDLs in Virginia are most commonly developed for bacteria, benthic, or nutrient impairments. In 2006, 8.9 percent of assessed Virginia rivers experienced benthic impairment, making it the fifth leading cause of impairment listed in the VADEQ 2006 303(d) Impaired Waters Report (VADEQ 2006).

The major causes of impairments are difficult to determine when multiple stressors impact a waterbody simultaneously. In an effort to identify the causes of biological impacts, the USEPA developed a Stressor Identification (SI) guide that establishes procedures for analysis of available evidence to determine the causes of biological impairments (USEPA 2000). In Virginia, the SI guide has been used to establish sediment as the most likely cause of most biological impairments within the State (Yagow 2007). Multiple parameters, such as bank stability, embeddedness, riparian vegetation, percent impervious cover and others, were used as evidence to distinguish sediment as the cause, apart from other biological stressors like ammonia, pH, nutrients, organic matter, temperature, and dissolved oxygen (Table 2.1). For this

reason, sediment TMDLs are frequently developed to address the biological impairments (Yagow 2007).

2.3. The Process of Erosion

Erosion is the natural process of soil weathering by water, wind, precipitation, gravity, and freeze-thaw action, where soil particles are detached and transported downslope. Erosion occurs at multiple scales and in many forms, including splash, sheet, rill, gully, and streambank erosion. While these are natural geologic processes, they are influenced by local and regional factors and can be accelerated by anthropogenic activities. The sediment that impacts waterways can originate from surface runoff from agricultural and urban landuses, anthropogenic activities like construction and channel modifications, and channel erosion (VADEQ 2006).

The process of streambank retreat, one form of degradation, is associated with either hydraulic action or mechanical failure. Within streams, hydraulic action includes a process where local scour of streambanks and undercutting causes the base of the banks to weaken, introducing entrained sediment into the water column. This process involves the combination of gravitational and hydraulic forces at the bed and bank toe (Thorne 1982; Simon et al. 2000). When hydraulic action at the interface of the water and bank boundary exceeds the critical shear stress of the bank material, soil entrainment occurs (Thorne 1982; Simon et al. 1999). Once significant local scour occurs, the force of gravity plays a critical role in the failure of the bank. In contrast, mechanical, or mass failure, involves the slumping of banks at a larger scale, resulting in large portions of soil being deposited into the stream channel. Unlike hydraulic action that occurs at the bed and bank toe, mechanical failure is initiated at the top of the bank.

2.3.1. Factors that Affect Channel Erosion

The complexity of channel erosion is simultaneously impacted by spatial and temporal variables, at regional and local scales, which influence the stability of stream channels (Thorne 1982). Both geomorphological and anthropogenic factors influence which erosional processes dominate in stream reaches (Couper and Maddock 2001), including landuse, vegetation, watershed size, geology or soils, stream slope, climate and season, and hydrology. Anthropogenically induced channel change is typically observed over a shorter time-scale than changes due to geomorphological influences (Couper and Maddock 2001).

Because soils respond directly to fluctuations in temperature, level of moisture, vegetation density, and anthropogenic changes, soil composition, at a local scale, is a fundamental parameter that impacts channel erosion (FISRWG 1998). Soils are typically classified as cohesive or granular. Cohesive soils, composed of silt and clay particles, are characterized by a diffuse double layer at the particle surface created by a negative charge of the clay surface and a positive charge from cations within the soil. This characteristic leads to a strong affinity with water and charged surfaces, giving cohesive soils the ability to attract ions to its structure. Granular soils, composed of sands and gravels, do not exhibit diffuse double layer characteristics and have a higher porosity than cohesive soils (FISRWG 1998). These intrinsic differences cause these two types of soils to react considerably differently to changes in watershed hydrology and landuse and when exposed to in-stream, hydraulic factors. “Erosivity of cohesive soils is affected by the chemical composition of the soil, the soil water, and the stream, among other factors” (FISRWG 1998). Cohesive soils exhibit higher shear strength than granular soils and therefore can resist erosion by hydraulic action (Osman and Thorne

1988). Soil moisture content, bulk unit weight, friction angle, and apparent cohesion are relevant parameters to consider when measuring streambank erosion because they influence the erodibility of the soil (Simon et al. 2000).

Also at a local scale, the type and condition of the riparian vegetation can influence the morphological characteristics of channels and their resistance to erosion (FISRWG 1998; Trimble 2004). The hydrologic and mechanical properties of riparian vegetation impact streambank stability (Thorne 1982). Simon and Collison (2002) found that the spatial density and tensile strength of roots within the riparian zone increase soil strength. In addition, the presence of large woody debris (LWD), contributed to channels from forested riparian zones, can cause aggradation or degradation of channels and changes in channel pattern (Piegay and Gurnell 1997) and evolution (Brooks and Brierley 2002). Some research suggests that total sediment loads, calculated from sediments budgets (FISRWG 1998), can be effectively controlled with the management of riparian vegetation (Trimble 2004). While some disagreement exists whether forested or unforested reaches have larger cross-sectional areas, studies have shown that the type and density of vegetation impact channel morphology (Simon and Collison 2002; Hession et at. 2003; Trimble 2004).

Regionally, seasonal and climate variations within a watershed affect hydrology by driving the quantity, intensity, and frequency of precipitation. These factors can influence the shape of a watershed's hydrograph. Bledsoe (2002) found that the duration of flow events has a much larger impact on bank erosion than the intensity or peak discharge of flow events. With longer duration events, soils are in a saturated condition for a longer time and, therefore, more susceptible to erosion (Simon et al.

2000). Seasonal changes also initiate variations in soil response. The seasonal effects on streambank erosion have been documented within the U.S., United Kingdom, Scotland, and Australia (DeWolfe 2004; Table 2.2). Many studies have provided evidence of the greatest erosion occurring during winter (Wolman 1959; Hooke 1979; Lawler 1993; Prosser et al. 2000). In winter, moderate flow events can have a considerably larger influence on channel erosion, bank retreat, and channel migration, than during other seasons, producing higher sediment yields due to freeze-thaw action (Simon et al. 2000).

2.3.2. Consequences of Channel Erosion

The consequences of accelerated sedimentation of streams from erosion can be economically and environmentally detrimental. Drinking water supplies are directly impacted when sedimentation fills reservoirs and increases treatment costs because of taste and odor problems (USEPA 1999). Flooding can be initiated through reduced storage capacity of water bodies due to sedimentation. Channel erosion can cause potentially valuable, large areas of land to be removed as streams migrate laterally, longitudinally, and vertically (Wolman 1967; Hammer 1972; Trimble 1997). Excess sediment increases turbidity and sedimentation, affecting recreational uses (FISRWG 1998), and alters channel form, disrupting navigation of waterways (USEPA 1999). The quality of fisheries is impaired (USEPA 1999) and the diversity of fish communities is reduced (Waters 1995) because excess sediment impacts the habitat and biological processes of aquatic species. Channel form alteration and reduced habitat complexity occur when rearing pools are filled and bed substrate becomes embedded, altering fish spawning habitats (Waters 1995; FISRWG 1998). The biological impacts of excess

sediment include clogging fish gills and affecting embryonic development (FISRWG 1998).

2.3.3. Quantifying Channel Erosion

Estimates of channel erosion can vary considerably. Studies have shown that channel enlargement can account for 70 percent to 80 percent of total watershed sediment yields (Allmendinger et al. 2007). Sediment from streambanks alone can account for as much as 85 percent of watershed sediment yields (Simon et al. 2000). A summary of reported, global streambank retreat rates can range from 0-7.26 m/year (DeWolfe 2004; Table 2.3). Because of the process complexity and the lack of physically-based algorithms to describe these processes, quantification of streambanks as a source of sediment is often either under- or over-estimated, or simply unaccounted for (Hession et al. 2000) in state and regional accounting procedures, such as the Chesapeake Bay Program. Correctly estimating sediment loading from channel erosion is crucial for the development and successful implementation of TMDLs. Improved quantification of this source could help to inform statewide nonpoint source programs through improved modeling capabilities and lead to more cost-effective management solutions.

2.4. Urbanization Effects on Rivers

2.4.1. Physical, Biological and Chemical Impacts

For decades, the correlation between urbanization and channel degradation of river systems has been investigated (Wolman 1967; Leopold 1968; Hammer 1972; Klein 1979; Booth 1991; Schueler 1994; Booth and Jackson 1997; Pizzuto et al. 2000; Booth et al. 2002; Hession et al. 2003) to better understand the impacts of urbanization on the

physical, biological, and chemical characteristics of stream ecosystems. The level of watershed urbanization is commonly linked to the changes in hydrology that induce channel alterations (Hammer 1972; Booth 1991; Booth and Jackson 1997; Cianfrani et al. 2006). Watershed hydrology is modified by increased infrastructure and imperviousness, causing urban river systems to experience higher peak flows and volumes than rural areas because of increased runoff (Wolman 1967; Hammer 1972; MacRae 1997). Urbanized streams enlarge because of reduced sediment supply and an increase in the magnitude and frequency of storm events (Trimble 1997; Galster et al. 2006; Colosimo and Wilcock 2007). As urban streams enlarge they experience fewer out of bank flow events where flow enters the floodplain (Colosimo and Wilcock 2007). Additionally, imperviousness reduces groundwater recharge due to decreased infiltration (Galster et al. 2006) and groundwater contributions to river systems during periods of low flow (Finkenbine et al. 2000).

Biotic integrity has been observed to decline with increased watershed impervious cover (Wang et al. 1997). At approximately 10 percent impervious cover, the quality of fish habitat degrades, aquatic ecosystem health declines (Booth and Jackson 1997), and the diversity of fish species decreases (Klein 1979). Aquatic habitat is impacted when the geomorphology of streams is simplified as pools are filled (Booth 1991; Pizzuto et al. 2000) and bed substrate is embedded with fine grain sediment (FISRWG 1998).

Water quality decreases from sediment and other pollutants due to increased runoff from urban areas. Pollutant loads in urban runoff from metals and other contaminants, such as organic carbon, zinc, and iron, have been found to be

considerably higher during storm events than during baseflow (Characklis and Wiesner 1997). Runoff from suburban lawns can transport nutrients, like nitrogen and phosphorus, and other chemicals into channels where the pollutants are incorporated into the bed or wash load (FISRWG 1998). Surface water temperatures increase as urban activity alters the external drivers of stream temperature – heat load and flow regime (Poole and Berman 2001). Increases in water temperature initiate decreases in dissolved oxygen, increases in fish metabolic rates, and changes in chemical processes (FISRWG 1998).

2.4.2. Dynamic Equilibrium

Streams are constantly changing to accommodate fluctuations in system inputs, such as water discharge, channel slope, sediment discharge, and sediment size. As one system input fluctuates, the other variables will adjust accordingly to maintain a balance within the system. This balance is often called dynamic equilibrium (FISRWG 1998). When hydraulics, hydrology, and sediment loads are affected by urbanization, the balance between key variables such as water discharge (Q_w), channel slope (S), sediment discharge (Q_s), and sediment particle size (D_{50}), is impacted (Lane 1955). Lane (1955) proposed the following relationship between these parameters to understand the process of dynamic equilibrium (Figure 2.1), where the sediment size and discharge must balance the water discharge and channel slope.

$$Q_s \times D_{50} \propto Q_w \times S \tag{1}$$

When alterations of a river's natural system affect the dynamic equilibrium between water and sediment supply, reach and watershed-scale effects can occur. Channel slope and form will change to accommodate the sediment discharge and

particle size distribution from the watershed (Wolman 1967). As urbanization disrupts the stability between system inputs, channels should, theoretically, change to create a new dynamic equilibrium until all parameters are balanced, typically causing alterations to the geomorphology (Leopold 1968; Hammer 1972; Booth and Jackson 1997; Pizzuto et al. 2000). This process occurs in alluvial channels that have the ability to adjust to changing system variables; however, non-alluvial channels, like streams dominated by bedrock and concrete channels, are unable to maintain Lane's (1955) balance (FISRWG 1998). While Lane's balance (1955) can be used to make qualitative predictions, quantitative predictions require more complex equations (FISRWG 1998).

2.4.3. Channel Evolution Models

Bank erosion, channel incision, and channel enlargement, can occur in urban streams as part of the process of regaining dynamic equilibrium. Channel evolution models (CEM), models used to describe the processes of channel enlargement, have been developed from observations of channel response to changes in sediment supply and transport (Bledsoe et al. 2002). A CEM proposed by Schumm (1984; Figure 2.2) describes the degradation of channels through five stages involving bank erosion, channel incision, and enlargement. Schumm's model (1984) also categorizes each stage by the relationship of the bank height (h), to the critical bank height (h_c), defined as the bank height at which bank instability is initiated. The stages of Schumm's (1984) CEM are as follows: A) changes occur in the stable channel system, the initial channel condition begins to incise, increasing the depth of the channel ($h < h_c$; Stage I); B) the bed degrades and bank instability initiates ($h > h_c$; Stage II); C) the bed begins to aggrade and the channel banks are unstable ($h > h_c$; Stage III); D) aggradation

continues, and bank stability increases ($h \approx h_c$; Stage IV); and E) aggradation slows until the channel reaches a new 'stable' equilibrium based on the new system inputs ($h < h_c$; Stage V). Other CEMs propose similar stages of stream response to watershed alterations (Lane 1955; Wolman 1967; Leopold 1973; Simon 1989). The CEM developed by Wolman (1967; Figure 2.3) describes the evolution of channel condition relative to sediment yield and landuse. These CEMs have allowed the process of channel change to be more easily documented in the field, making it possible to predict channel forms and processes (Bledsoe et al. 2002).

The State of Virginia has implemented a process of assessing the condition of streams called the Unified Stream Methodology (USM; USACE and VADEQ 2007). The USM outlines procedures for evaluating channel condition, riparian buffer, in-stream habitat, and channel alteration individually, then compiling all the factors into a single reach condition index (RCI). Using principles similar to other CEMs, the channel condition is assessed "…to determine the current condition of the channel cross-section, as it relates to [the] evolutionary process, and to make a correlation to the current state of stream stability" (USACE and VADEQ 2007). The relationship between channel evolution and USM channel condition is shown in Figure 2.4. The channel condition for the stream reach can be categorized as optimal, suboptimal, marginal, poor, or severe by visual observation of the stream's geomorphology including "channel incision, access to the original or recently created floodplains, channel widening, channel depositional features, rooting depth compared to streambed elevation, streambank vegetative protection, and streambank erosion" (Table 2.4; USACE and VADEQ 2007).

2.4.4. Quantifying Channel Enlargement

Urban streams generally enlarge in cross-sectional dimensions (width, depth, area) to maintain dynamic equilibrium (Hammer 1972; Pizzuto et al. 2000; Hession et al. 2003). Channel enlargement has been linked to watershed urbanization or Total Impervious Area (TIA; Hammer 1972; Morisawa and LaFlure 1979; MacRae and DeAndrea 1999; Hession et al. 2003; Cianfrani et al. 2006) and is commonly used to quantify channel impacts because of the relationship between land use change and hydrology. Impervious surfaces can be connected or disconnected from drainage systems. TIA includes both connected and disconnected impervious surfaces and is frequently used to measure imperviousness because of data availability (CWP 2003). Another method of measuring urbanization is Effective Impervious Area (EIA), which includes only connected impervious surfaces (Sutherland 1995; Booth et al. 2002); however, it can be difficult to obtain accurate data to compute EIA (Cianfrani et al. 2006).

Channel enlargement can be quantified by calculating an enlargement ratio (*ER*)

$$ER = \frac{X_{post}}{X_{pre}} \tag{2}$$

where *ER*=enlargement ratio; X_{post}=any channel measure (such as bankfull cross-sectional depth, width, or area) in the disturbed or post condition; and X_{pre}=the same channel measure for the typical, non-urban channel obtained from a regional curve. Regional curves, empirical relationships that relate channel dimensions to watershed drainage area, have been developed for mostly non-urban (rural and forested) watersheds by many states for various physiographic regions, such as the Coastal Plain and Piedmont (Cinotto 2003; Krstolic and Chaplin 2007).

Other empirical relationships have been developed to understand the connection between channel enlargement and urbanization (CWP 2003). MacRae and DeAndrea (1999) developed a relationship between TIA and the "ultimate" enlargement ratio (ER_{ult}), defined as the channel enlargement occurring once the channel has established a new steady state

$$ER_{ult} = 0.00135 * (TIA)^2 + 0.0167 * (TIA) + 1.0 \quad (3)$$

where ER_{ult}=ultimate enlargement ratio; and *TIA*=total impervious area.

Most studies of the impacts of urbanization on river morphology have relied on space-for-time substitution methods (Wolman 1967; Hammer 1972; Klein 1979; Pizzuto et al. 2000; Booth et al. 2002; Hession et al. 2003; McBride and Booth 2005). In such cases, river reaches with varying degrees of watershed urbanization are compared (while accounting for differences in watershed size) to infer the changes that occur due to increased urbanization. Although space-for-time substitution techniques are valuable and frequently employed, there are some limitations with the method and results need to be evaluated carefully (Ebisemiju 1991; Gregory et al. 1992; Colosimo and Wilcock 2007). This method requires other watershed variables, such as vegetation, watershed size and slope, soils, and hydrology, to be the same or to be assumed negligible, which is rarely the case (Wolman 1967; Wolman and Schick 1967; Leopold 1973).

Because of the time and expense required, direct observation of geomorphic processes through time by repetitive measurement rarely occurs, but is incredibly valuable and powerful (Trimble 1997; Leopold et al. 2005). Morphological changes are quantified through monumenting field sites and performing repeated measurements over-time. From this method, a sediment budget can be developed, quantifying the

changes in storage with time. Trimble (1997) established a sediment budget by monumenting and resurveying 196 stream cross-sections in the San Diego Creek watershed. He concluded that stream channel erosion can be a substantial contributor to total sediment yields. Leopold et al. (2005) documented the impact of increasing watershed urbanization in Watts Branch, Rockville, Maryland with repeated cross-sectional surveys from 1953-1994. Over this time period, changes in streamflow, streambed material, and watershed development were also monitored. In the first two decades, Leopold et al. (2005) observed decreases in cross-sectional areas due to sediment deposition; however, in the following decades, during considerable urbanization within the watershed, the channel width increased significantly.

Without long-term, continuous measurement and monitoring of changes in hydrology, sediment transport, and channel morphology, it is difficult to establish sediment budgets. Few studies have accomplished this, with the exception of Allmendinger et al. (2007), where a tiered approach was used to calculate the sediment budgets for a watershed. A schematic of the process is presented in Figure 2.5. Beginning upstream with the first-order tributaries, Allmendinger et al. (2007) calculated sediment budgets by accounting for upland sediment production and sediment production due to channel enlargement. Upland sediment production was estimated with an equation from Yorke and Herb (1978)

$$Log Y_x = 0.059C \quad 0.047 \tag{4}$$

where Y_x=suspended sediment yield (tons/year); and C=percentage of land under construction.

The sediment production due to enlargement was estimated by using surveyed data for the study area to develop empirical models. The sediment budget for the main channel, downstream of the tributaries, included the input of net sediment supply from the tributaries, sediment production for channel enlargement, and floodplain storage. The same method for estimating sediment production from channel enlargement for the tributaries was used for the main channel. Sediment from floodplain storage was calculated by taking cores on the floodplain of the channel, to estimate the thickness of the soil above tree roots. The overall main channel budget then was used to calculate the watershed sediment budget (Allmendinger et al. 2007).

With the investigation of sediment budgets, like those documented by Allmendinger et al. (2007) and Trimble (1997), we have gained a greater understanding of the relationship between urbanization and channel enlargement. However, while this area has begun to receive focus and funding, many questions remain concerning the period of channel adjustment due to urbanization and whether channels attain a different, but 'stable' geometry (Chin 2006; Gregory 2006). Because the evolution of urbanizing streams over time is difficult to observe, it is rarely documented. Understanding these processes, however, is essential to develop predictive models for managing sediment as a nonpoint source pollutant.

2.4.5. Phases of Urbanization

Wolman (1967) documented the connection between specific watershed alterations and changes in channel morphology with a CEM linking the cycle of land use changes, channel behavior, and sediment yield (Figure 2.3). Wolman (1967) discussed the process of urbanization with associated channel conditions occurring in three stages:

A) a stable, equilibrium condition on land and within the channel (Stage I); B) a construction phase where land is exposed and channel aggradation occurs (Stage II); and C) new urban landscape with enlarged channel (Stage III). He proposed that the quantity of sediment supplied to channels from the watershed varies during these stages. In particular, Stage II is marked by a significant spike in sediment yield (Bledsoe 2002; Colosimo and Wilcock 2007), followed by a decrease in Stage III, as urbanization increases (Wolman 1967).

Many studies have provided evidence of a dramatic increase in sediment production at the beginning phase of urbanization, during active development (Wolman 1967; Bledsoe 2002; Leopold et al. 2005; Colosimo and Wilcock 2007). Sediment yields during construction can be two times greater than pre-construction yields (Wolman 1967). However, few studies have focused on quantification of sediment loading once active development has ceased. Because the quantity of sediment can vary substantially over this time, understanding the age of watershed urbanization can be an important parameter. With the development of CEMs, channel size should be considered relative to the age of urbanization (Hammer 1972).

In a recent review of urbanization impacts on rivers worldwide, Chin (2006) presented a conceptual model (Figure 2.6) of the general phases of urbanization with associated channel process changes, channel conditions, and morphological adjustments. Chin (2006) describes the following effects as process variables that impact the river system: sediment production/yield (S); imperviousness (I); hydrological (H); morphological (M); and physical and biological degradation (D). The sediment production curve, based on Wolman (1967), is the foundation of Chin's model,

characterized by increased sediment due to active construction, which can cause net aggradation and channel-size reduction initially (Figure 2.6). Following active construction, sediment production decreases (Wolman 1967; Wolman and Schick 1967), inducing net channel erosion and enlargement as well as morphological change (Chin 2006). An increase in imperviousness causes hydrological effects, changes in channel morphology, and biological degradation in streams (Chin 2006).

The morphological response curve shown in Figure 2.6 is similar to the rate law proposed by Graf (1977; Figure 2.7), which suggests that a geomorphic system subjected to disruption (e.g. urbanization) goes through 4 stages: A) *steady state* - prior to disruption, the system is in stable state with minor variations about a mean; B) *reaction time* – after the disruption, new conditions are internalized, but no major changes occur; C) *relaxation time* - after disruption, the system adjusts to new conditions over time; and D) *new steady state* – the system has reached a new, dynamically-stable condition with variations around a mean. When analyzing urban impacts on channel erosion, the dependent variable could represent a channel enlargement ratio (Hammer 1972), channel capacity (area), or channel width.

In general, most studies have reported changes in channel capacity, width, and depth due to urbanization, but did not discuss the changes relative to the age of development (Chin 2006), with the exception of Hammer (1972). He documented that as the age of imperviousness increases, channel size increases, until age 30 when the effects of urbanization begin to diminish. Knowledge of the relaxation times and the new steady-state condition can be a useful predictive tool in the assessment of environmental impacts from human activities (Graf 1977) and can inform stream

restoration projects in urban watersheds. However, even though much research has been conducted over the years (Chin 2006), we still do not know how long it will take for the adjustment process to occur before a new steady-state condition is reached (Gregory et al. 1992; Gregory 2006). The ability to quantify the amount of change that will occur and the rate at which the adjustments will occur, is essential for assessing and managing sediment as a nonpoint source pollutant.

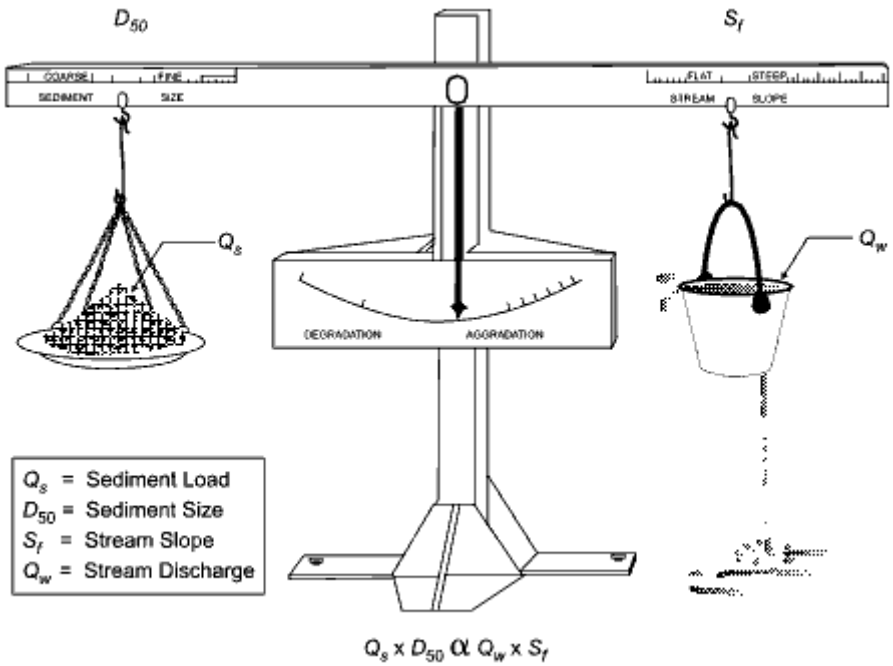

Figure 2.1. Schematic of Lane's balance between water discharge (Q_w), channel slope (S), sediment discharge (Q_s), and sediment particle size (D_{50}) (Lane 1955)

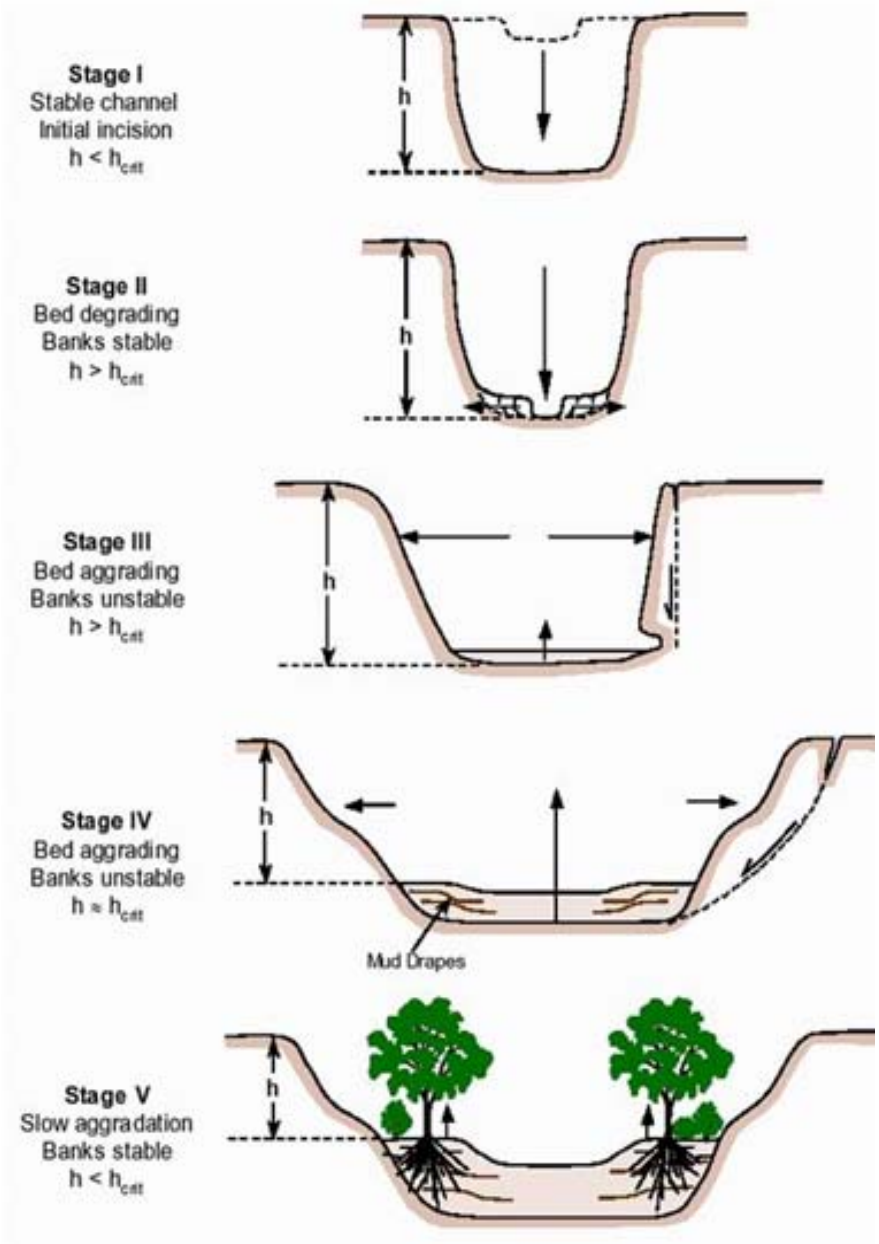

Figure 2.2. The cycle of land use changes, sediment yield, and channel behavior (Schumm 1984)

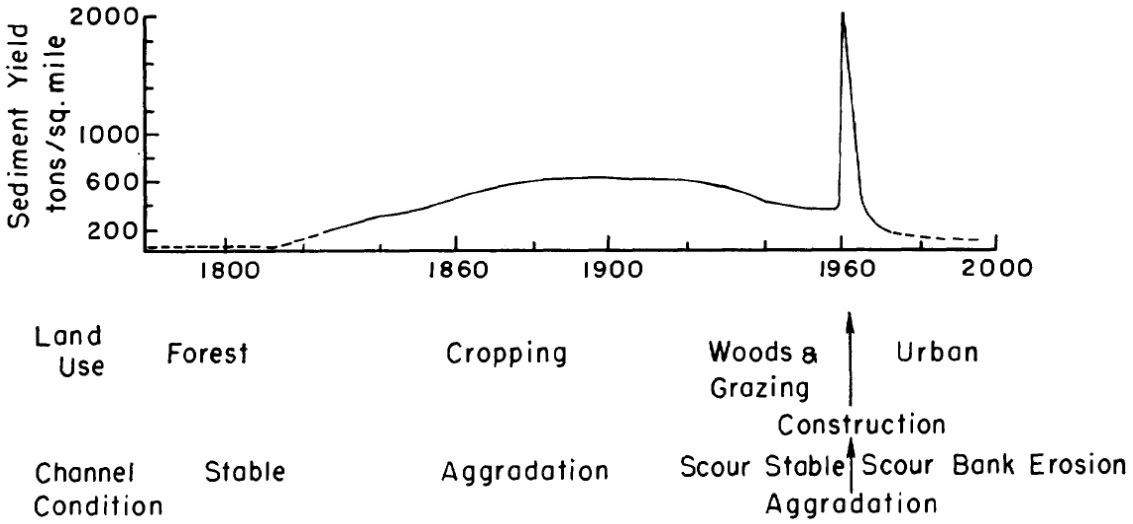

Figure 2.3. The cycle of land use changes, sediment yield, and channel behavior (Wolman 1967)

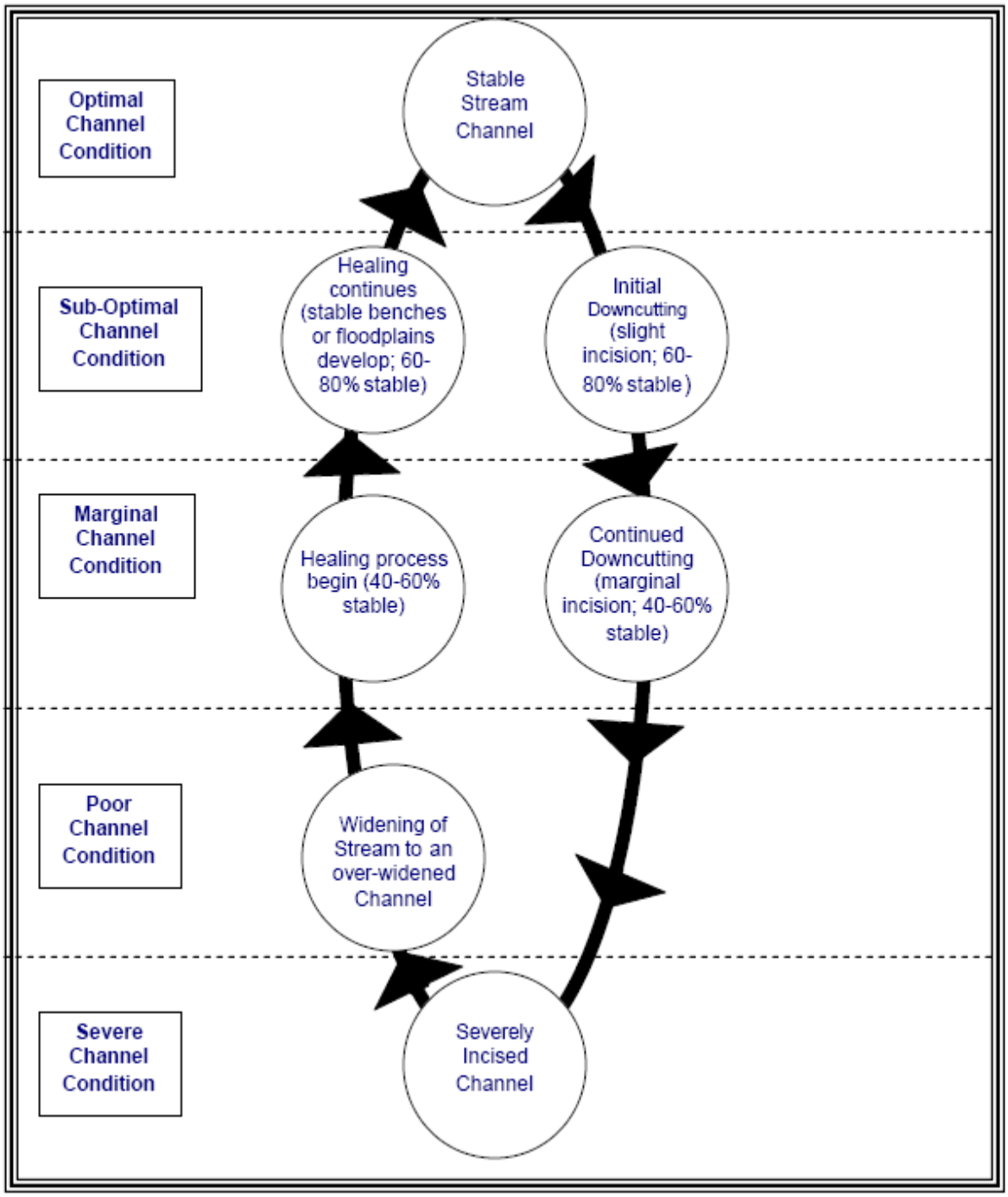

Figure 2.4. Schematic showing the relationship between the channel evolution and USM channel condition (USACE and VADEQ 2007)

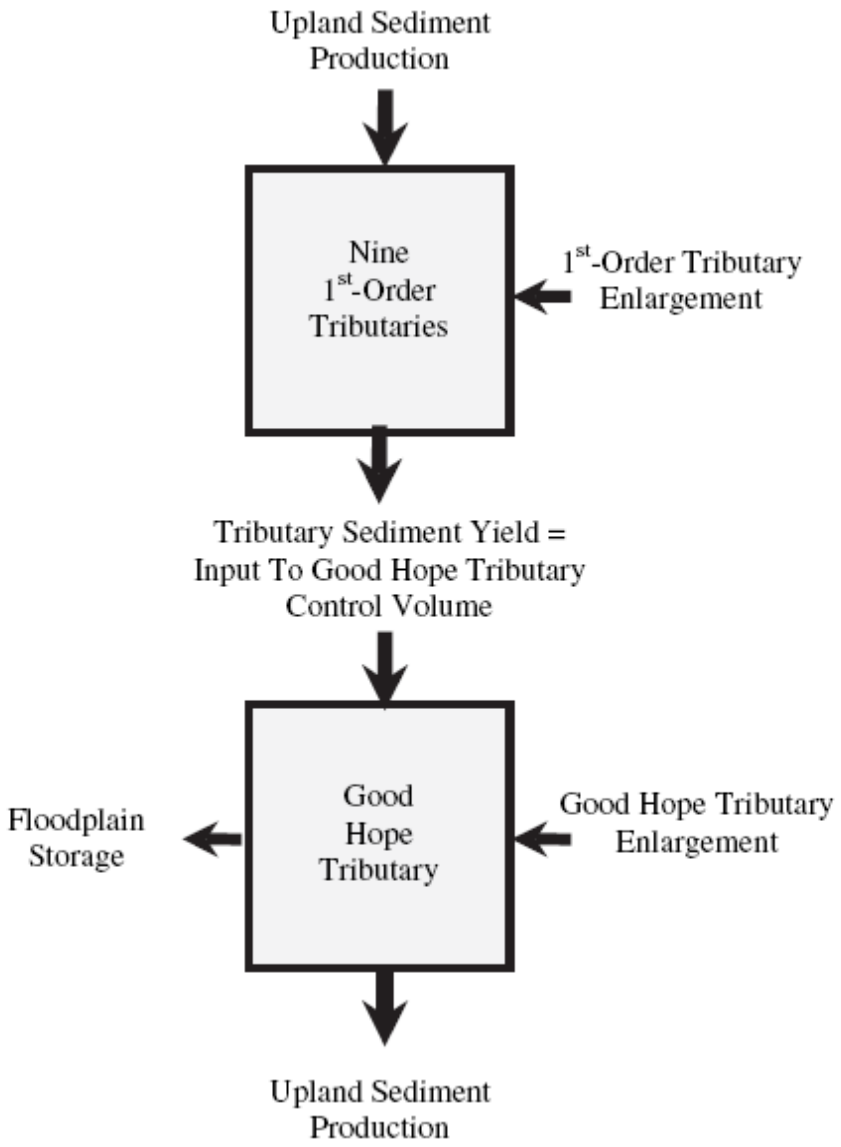

Figure 2.5. Schematic of two-phase sediment budget illustrating control volumes and sediment sources and storage areas (Allmendinger et al. 2007)

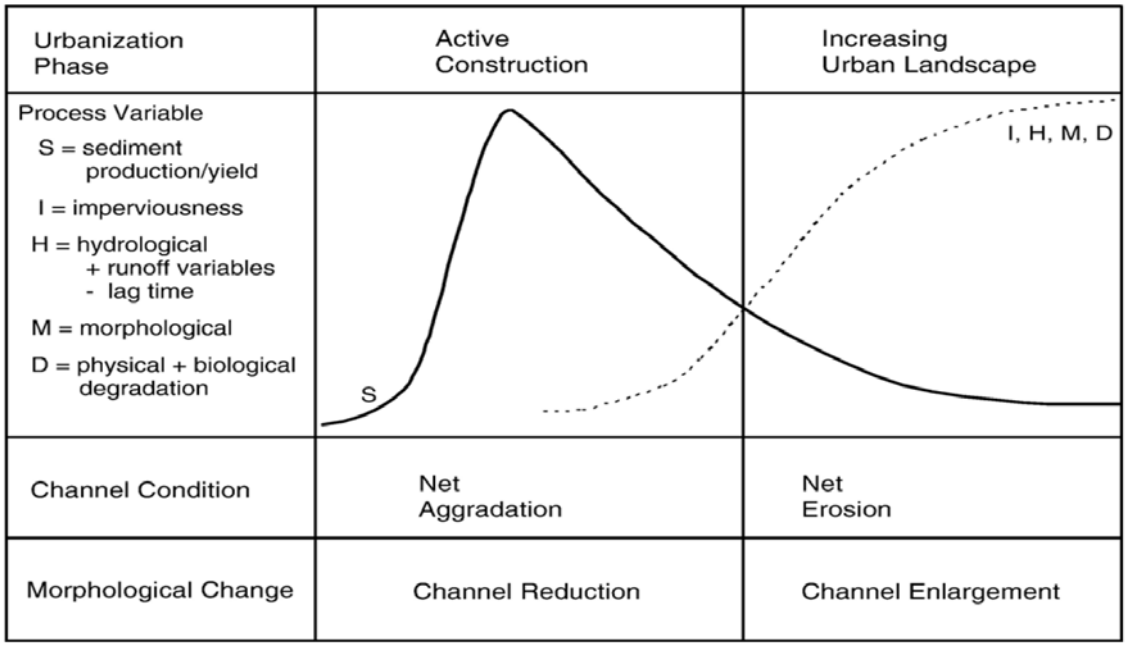

Figure 2.6. Urbanization phases based on process variables, channel condition, and morphological change (Chin 2006)

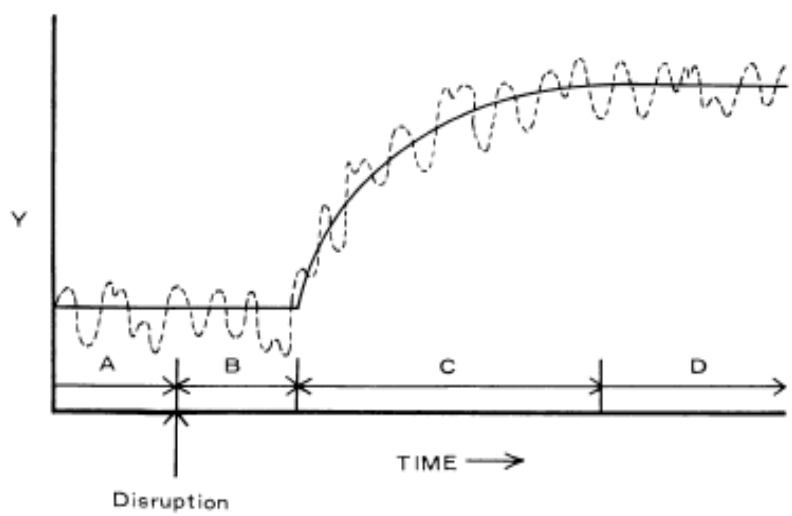

Figure 2.7. Rate law for geomorphic systems subjected to disturbance (Graf 1977)

Table 2.1. Data types used as evidence to establish sediment as the most likely cause of biological impairments within Virginia (summarized by Yagow 2007)

Type of evidence	Description
% haptobenthos	Percentage of a benthic macroinvertebrate sample composed of clingers and sprawlers that require a clean, coarse, firm substrate. Low numbers may indicate heavy sedimentation (Smith and Voshell, 1997).
Presence of silt intolerant fish species	Grazing species, such as central stonerollers, do not inhabit heavily silted streams, as they require hard surfaces from which to scrape algae and the availability of pebbled substrate for forming spawning nests.
RBP II habitat metrics	Each metric rated from 0-20: with 0-5 indicating poor habitat, 6-10 marginal habitat, 11-15 sub-optimal habitat, and 16-20 optimal habitat (Barbour et al., 1999).
Bank stability	Evaluates the condition of stream banks for signs of erosion.
Embeddedness	Evaluates the extent to which rocks are covered with silt, sand, or mud on the stream bottom.
Epifaunal substrate	The variety of natural structures and features available for refuge or feeding, and as sites for spawning and nursery functions.
Riparian vegetation	The extent, type, and degree of vegetation coverage within the riparian zone.
Sediment deposition	Evaluates the amount of sediment accumulated in pools and deposited in point bars. Large amounts tend to indicate an unstable and changing environment.
Channel alterations	Evaluates large-scale changes in the shape and sinuosity of the stream channel usually associated with increased scouring.
Total habitat score	An aggregate score from 10 metrics, each with a maximum score of 20; optimal range is 160-200.
Ambient TSS	Monitored total suspended solids (TSS) data generally collected during baseflow conditions on a bi-weekly or monthly basis.
Runoff TSS	Monitored stormflow data that would be more representative of nonpoint source (NPS) runoff contributions of sediment.
PS TSS	Point source (PS) discharger effluent sampled concentrations as part of NPDES permit compliance monitoring.
Upstream monitoring	Where available, this data can help isolate or delimit potential major sediment sources.

Table 2.1 (continued). Data types used as evidence to establish sediment as the most likely cause of biological impairments within Virginia (summarized by Yagow 2007)

Type of evidence	Description
Relative bed stability	A procedure to measure the likelihood of changes in stream bed composition due to upstream hydrological changes. Can be used to separate human-induced from natural sediment problems (Kaufmann et al., 1999). Logarithm of RBS (LRBS) < -1 indicates excessive sedimentation, and > 1 indicates a sediment starved stream.
Impervious area %	Estimated from landuse and aerial imagery – high percentages are associated with faster runoff response and larger storm peaks.
Upstream sediment TMDLs	Downstream sediment problems are often related to sediment problems farther upstream that may propagate downstream, even though surface runoff from the immediate segment produces minimal sediment loading.
Biennial state NPS sediment rating	These simulated sediment load ratings may provide supplemental support for sediment and potential source areas that are not evident in available monitored data.
High resolution aerial imagery	1:400 or better imagery allows viewing areas not readily accessible by roads and can save time by identifying a limited number of specific areas requiring ground-truthing during watershed visits.
Impairment severity	RBP II rating categories based on the chosen suite of metrics and a reference non-impaired site. Ratings are NI – non-impaired, SI – slightly impaired, MI – moderately impaired, and VI – severely impaired.

Table 2.2. Seasonal effects on streambank erosion (summarized by DeWolfe 2004)

Author(s) / location of study	Seasonal effect reported
Wolman (1959) / Maryland	Little erosion in summer, 85 percent between December and March
Hooke (1979) / England	Majority of erosion to occurred between September and March
Lawler (1993) / England	Nearly all erosion between November and April
Trimble (1994) / Tennessee	Major scour occurred after two large discharge events following long period of winter precipitation
Stott (1997) / Scotland	~50 percent erosion between January and March, <12 percent between July and September
Lawler et al. (1999) / England	Erosion particularly active between January and early March, minimal between April and September
Prosser et al. (2000) / Australia	Majority of erosion in winter

Table 2.3. Reported global streambank erosion rates for various geographic regions and drainage areas (summarized by DeWolfe 2004)

River and location	Drainage area (km^2)	Average rate of streambank retreat (m/year)	Duration of study (years)	Source
Watts Branch (MD)	9.6	0.12-0.17	2	Wolman (1959)
Mississippi (LA)	$>10^6$	4.5	17	Stanley et al. (1966)
Axe River Exe River (Devon, England)	288 620	0.15-0.46 0.62-1.18	2	Hooke (1980)
Ohio River (KY)	-	0-1.5	1	Hagerty et al. (1981)
Narrator Brook (England)	4.75	<0.03	1.6	Murgatroyd and Ternan (1983)
River Ilston (Wales)	7-13	0.04-0.31	2	Lawler (1986)
Western Canada	Various	0.57-7.26	21-33	Nanson and Hickin (1986)
Des Moines East Nishnabotna (IA)	1129-2314 32320-36360	2.1-3.2 2.4-3.7	6-8	Odgaard (1987)
Kirkton Glens (Scotland)	<7.7	0.016-0.076	37	Stott et al. (1986)
Monachyle Glen Kirkton Glen (Scotland)	7.7 6.85	0.059 0.047	1.25	Stott (1997)
Mooki River (Australia)	>100	0.33	2	Green et al. (1999)
Swale-Ouse River System (England)	3315 km^2 System	0.0827-0.441	19	Lawler et al. (1999)
Ripple Creek (Tasmania)	46	0.013	1.2	Prosser et al. (2000)

Table 2.4. USM riparian buffer categories (USACE and VADEQ 2007)

Category	Description
Optimal	Tree stratum (dbh > 3 inches) present, with > 60% tree canopy cover. Wetlands located within the riparian areas are scored as optimal.
Suboptimal	*High Suboptimal*: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and containing both herbaceous and shrub layers or a non-maintained understory. *Low Suboptimal*: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and a maintained understory. Recent cutover (dense vegetation).
Marginal	*High Marginal*: Non-maintained, dense herbaceous vegetation with either a shrub layer or a tree layer (dbh > 3 inches) present, with <30% tree canopy cover. *Low Marginal*: Non-maintained, dense herbaceous vegetation, riparian areas lacking shrub and tree stratum, areas of hay production, and ponds or open water areas. If trees are present, tree stratum (dbh >3 inches) present, with <30% tree canopy cover with maintained understory.
Poor	*High Poor*: Lawns, mowed, and maintained areas, nurseries; no-till cropland; actively grazed pasture, sparsely vegetated non-maintained area, recently seeded and stabilized, or other comparable condition. *Low Poor*: Impervious surfaces, mine spoil lands, denuded surfaces, row crops, active feed lots, trails, or other comparable conditions.

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Chapter 3: Research Methods

3.1. Site Selection

To quantify the impact of urbanization on channel erosion, 50 study sites were selected on 1st- through 3rd-order streams. The following criteria were used to select the study sites:

- All study sites were located within the non-tidal portion of the CZM Area (**Error! Reference source not found.**);
- All study sites were in headwater streams with small watersheds (less than 100 km^2) on 1st- through 3rd-order streams;
- Half of the study sites (25) were located within the Coastal Plain physiographic region and half were located in the Piedmont physiographic region;
- Sites were selected from stations identified by the VADEQ probabilistic monitoring (ProbMon) program, when possible. These sites are stream and river locations throughout Virginia that were randomly selected as representative of channels of various sizes in different geographic regions (VADEQ 2008). Additional sites were selected, as needed, from the VADEQ's 2006 Water Quality Monitoring Stations (WqMon; VADEQ 2006); and,
- Study sites were selected to represent a gradient of urbanization in their watersheds.

A geographic information system (GIS; ArcGIS 9.2, ESRI, Redlands, CA) was used to assist in the study site selection. The GIS procedures were as follows: 1) Virginia state and county boundary data layers were obtained from the U.S. Geological Society (USGS) National Map Seamless Server (Seamless; USGS 2007) and imported into the GIS; 2) the geographic coordinates (latitude and longitude) for each site (ProbMon and WqMon) were imported into the GIS; 3) the CZM Area was clipped from the Virginia State boundary; 4) ProbMon sites (from the original VADEQ ProbMon set) outside the

CZM boundary were eliminated; 5) of the remaining sites, those with stream order greater than 3rd were eliminated; 6) to ensure independence, if more than one site was located on the same stream (for example up or downstream of each other), the duplicate sites were eliminated from the original ProbMon set; 7) the boundaries for the physiographic regions of Virginia were obtained and imported into GIS; 8) of the remaining possible sample locations, 50 were selected within the CZM Area, 25 within each of Virginia's Piedmont and Coastal Plain physiographic regions (Figure 3.2). Each site was located on a 1st- through 3rd-order stream, was non-tidal, and was located in a separate watershed to ensure independence.

3.2. Field Methods

3.2.1. Tier 1

At each study site, a reach 10-20 bankfull-widths in length was selected. Each reach contained a riffle-pool (Montgomery and Buffington 1998) bed morphology sequence of at least three riffles and three pools. An effort was made to select a reach that was accessible and without apparent direct geomorphologic and hydraulic effects from bridges, culverts, livestock, beaver dams, and human other alterations.

Each reach was surveyed during summer 2007 with a laser level (LaserMark-LMH Series, CST/berger, Watska, IL), metric surveying rod, and metric survey tapes. Surveys included a single cross-sectional survey at a riffle and a longitudinal profile. The riffle, located at approximately the middle of the reach, was selected to survey as the cross-sectional riffle, ensuring that both a pool and riffle were upstream and downstream, and within the study reach. The riffle cross section was monumented, perpendicular to the channel, with rebar pins driven vertically into the floodplain

(Harrelson et al. 1994). A surveying tape was extended horizontally across the channel, beginning at the left pin (facing downstream). The cross-sectional riffle survey included measuring the distance along the surveying tape and the elevation of the surveying rod of all major features and slope breaks. Where no break in slope was evident, the maximum distance between points was 0.5 m. The location of each point was given one of the following classifications: ground at left and right rebar (LPIN, RPIN), left and right top of bank (LTOB, RTOB), left and right bankfull (LBF, RBF), left and right water surface (LWS, RWS), ground surface (G), channel bottom (BTM), and thalweg (TH). A bankfull elevation for each cross section was identified using field indicators including vegetation changes, point-bar elevations, topographic changes, and evidence of streambank erosion and scour (Leopold 1994). If the identified left and right bankfull measurements were dissimilar, then the most appropriate bankfull elevation was selected and identified in the field notes.

A survey of the longitudinal profile was conducted to obtain the channel and water-surface slope. A surveying tape was placed along the thalweg, beginning at the top of the riffle, upstream of the riffle cross section, and extending to the top of the riffle, downstream of the riffle cross section. The longitudinal survey included measuring the distance along the surveying tape and the bed elevation and water depth at the following points: top of riffle (upstream of cross section); deep point in pool (between upstream riffle and cross section riffle); top of riffle (at cross section); deep point in pool (between cross section riffle and downstream riffle); and top of riffle (downstream of cross section).

The coordinates of each riffle cross-section location were recorded with a handheld GPS (GPS 76, Garmin, Olathe, KS), with 3-m accuracy, to document the location for GIS analysis and future monitoring. The riparian-zone condition was assessed using the following categories from the Virginia Unified Stream Methodology (USACE and VADEQ 2007): optimal, suboptimal high, suboptimal low, marginal high, marginal low, poor high, and poor low (**Error! Reference source not found.**). The riparian zone for the full length of the study reach (10-20 bankfull-widths in length) was evaluated, considering the conditions on the left and right banks, including invasive species, tree canopy cover, and understory.

3.2.2. Tier 2

A subset of 12 Tier 1 sites was selected for more detailed analyses (six in each physiographic region). Within each physiographic region we selected two stream reaches within rural, relatively unimpacted watersheds, two in watersheds with older urban developments (> 30 yrs), and two in watersheds with newer urban development (< 10 yrs). Within these 12 Tier 2 study streams, we selected study reaches consisting of two riffle-pool sequences, which encompassed the reaches surveyed as part of Tier 1. In fall 2007, detailed surveys were conducted for these stream reaches (including two riffle and two pool cross-section surveys), as well as pebble counts and habitat assessments (Virginia Unified Stream Methodology; USACE and VADEQ 2007). Within each of these study reaches two cross sections (at riffles) were permanently monumented with rebar driven into the floodplain on opposite banks. In spring 2008 we resurveyed the monumented cross sections and collected streambank soil samples. The composite soil sample for each site was compiled with samples taken at random

locations along the streambanks within each reach. These samples were analyzed for total nitrogen, total phosphorus, and particle-size distribution.

3.3. GIS Analysis

GIS was used to perform spatial analysis of the upstream watershed contributing to each study site, including determining watershed size, geology, percent impervious cover, and phase of urbanization, among other characteristics. Initially, the watershed for each site was delineated using a 30-m resolution Digital Elevation Model (DEM) obtained from Seamless (USGS 2007). From these data, the total watershed area above each study reach was calculated using the Spatial Analyst Hydrology Tools in GIS.

Digital percent impervious cover data were obtained from Woods Hole Research Center (Woods Hole 2007) to calculate watershed-level urbanization statistics for each site (Table 3.2). The following digital land cover data at 30-m resolution were collected for the CZM area: percent impervious cover for 1990; percent impervious cover for 2000; and the change in percent impervious cover from 1990 to 2000. Using GIS, statistics for each dataset were generated for each delineated watershed. This analysis provided multiple datasets with information on watershed impervious cover (1990 and 2000) and watershed age (Table 3.2). To analyze the impact of recent urbanization on channel enlargement, a ratio of change in percent impervious cover from 1990 to 2000 by percent impervious cover for 2000 (Percent Impervious Cover Ratio, PICR) was calculated for each watershed.

A digital dataset of the Bureau of Transportation Statistics (BTS) roads was obtained from Seamless (Table 3.2; USGS 2007). Using the BTS roads dataset, the number of road crossings over streams within each watershed was determined to provide another factor describing the level of urbanization impacting each study site (McBride and Booth 2005).

A digital dataset of the 1993 geologic map of Virginia (Virginia Department of Mines, Minerals, and Energy 1993) was obtained from Seamless (Table 3.2; USGS 2007). This source was used to classify each watershed by the predominant age of rock: Cretaceous, Triassic, Metamorphic and Igneous intrusives, Granite and Gneiss, and Tertiary (Figure 3.3).

After developing these independent variables, they were used in the data analysis to assess relationships between the independent, watershed-scale variables and the dependent, measured instream variables.

3.4. Data Analysis

The overall goal of this project was to assess and quantify sediment contributions due to channel enlargement (erosion) of first- through third-order urban streams in the Coastal Zone Management (CZM) Area of Virginia. This goal was achieved by developing relationships between channel enlargement and upstream watershed condition.

The first objective towards meeting this goal was to measure morphological features of streams in watersheds with varying levels and ages of urbanization in two physiographic regions, the Coastal Plan and Piedmont, of Virginia. This objective was

achieved by calculating values of key parameters from the field data collected in summer 2007. The surveyed riffle cross sections provided the following dependent parameters describing channel morphology:

- Bankfull cross-sectional width (WBF);
- Bankfull cross-sectional mean depth (DBF);
- Bankfull cross-sectional area (ABF);
- Bankfull cross-sectional wetted perimeter (PBF);
- Bankfull cross-sectional hydraulic radius (RBF);
- Bankfull cross-sectional width to depth ratio (WDR);
- Flood-prone width (WFP);
- Enlargement ratio for cross-sectional area (ERA);
- Enlargement ratio for cross-sectional width (ERW); and
- Enlargement ratio for cross-sectional depth (ERD);

The W_{FP} was calculated as the width of the floodplain at two times the $D_{BF,}$ and the entrenchment ratio (E_R) was calculated as W_{FP} divided by W_{BF} (Rosgen 1996). The enlargement ratios (ER) for cross-sectional parameters (ER_A, ER_W, and ER_D) were calculated to quantify channel change relative to stable, non-impacted streams by comparing the measured bankfull cross-sectional parameter to the bankfull parameter from the regional curves. Enlargement ratios were computed as the ratio of our measured estimate of the channel characteristic in question over the estimated parameter value from the regional curve for a stream with the same watershed size. Regional curves were obtained for the Coastal Plain (Virginia and Maryland; Krstolic and Chaplin 2007) and the Piedmont (Pennsylvania and Maryland; Cinotto 2003) physiographic regions to provide information on the non-disturbed, non-urban condition of streams within each region.

The longitudinal profile provided the following dependent parameters:

- Channel bed slope (SB);
- Water surface slope (SWS);
- Maximum residual pool depth (DPR); and
- Maximum pool water depth (DPW).

The D_{PR} was calculated as the elevation of the riffle crest (downstream of the pool) minus the D_{PW} (Lisle 1987).

To see if there is a significant difference in the morphological features of streams between physiographic regions, the Wilcoxon Rank Sum Test (the nonparametric equivalent of the two sample, unpaired t-test) was used to test if the difference in means was significant for each measured reach parameter for two independent, nonparametric groups (Coastal Plain versus Piedmont) using JMP (version 7.0; SAS Institute Inc., Cary, NC). To reduce error associated with varying watershed sizes, ABF was normalized by dividing by the watershed area before performing the test, and WBF, DBF, PBF, RBF, WFP, and DPR were normalized by dividing by the square root of the watershed area. To confirm the test results on the measured reach parameters, the same analysis was performed on the collected Coastal Plain and Piedmont regional curve data (Krstolic and Chaplin 2007; Cinotto 2003).

The second objective was to develop relationships between watershed urbanization characteristics (TIA and age) and channel enlargement. To meet this objective, the age and level of urbanization relative to channel enlargement sediment production were analyzed using JMP. The Shapiro-Wilk test for normality was performed on each independent and dependent variable. A summary of all independent

and dependent variables analyzed is provided in Table 3.3. All of the variables indicated that the null hypothesis of normality should be rejected ($p < 0.05$); therefore, the data was assumed nonparametric.

To determine correlation between all variables (independent and dependent), the Spearman correlation coefficient (nonparametric) was calculated. This analysis was performed on three site groups of data (coastal plain sites, Coastal Plain; piedmont sites, Piedmont; all sites combined, All). For each site group, the non-correlated independent variables were combined, yielding 2 unique combinations of non-correlated independent variables for All (A1, A2), three for Coastal Plain (C1, C2, C3), and three for Piedmont (P1, P2, P3) (Table 3.4). Stepwise multiple linear regression was performed for each unique combination of non-correlated independent variables (A1, A2, C1, C2, C3, P1, P2, P3) against each dependent variable. For this analysis all variables were log-transformed. To validate each significant model, the PRESS statistic was computed and a plot of the predicted versus residual values was analyzed for any trends in the data.

The third objective was to estimate sediment loading due to channel enlargement for use in statewide Nonpoint Source Pollution (NPS) assessment and management. This objective was addressed by estimating sediment loading due to channel enlargement at each of the study sites and by developing relationships between landuse variables such as watershed size, percent impervious, and age. The difference in bankfull, cross-sectional area of the measured, current condition to the bankfull, cross-sectional area from the regional curve was calculated for each site, similar to the approach used by Allmendinger et al. (2007). Then, the change in cross-sectional area

was multiplied by 1 m length of the stream, to provide an estimate of the volume of sediment contributed to the stream due to enlargement per 1 m of stream.

Figure 3.1. Map of the Virginia counties included in the Coastal Zone Management Area (VADEQ 2007)

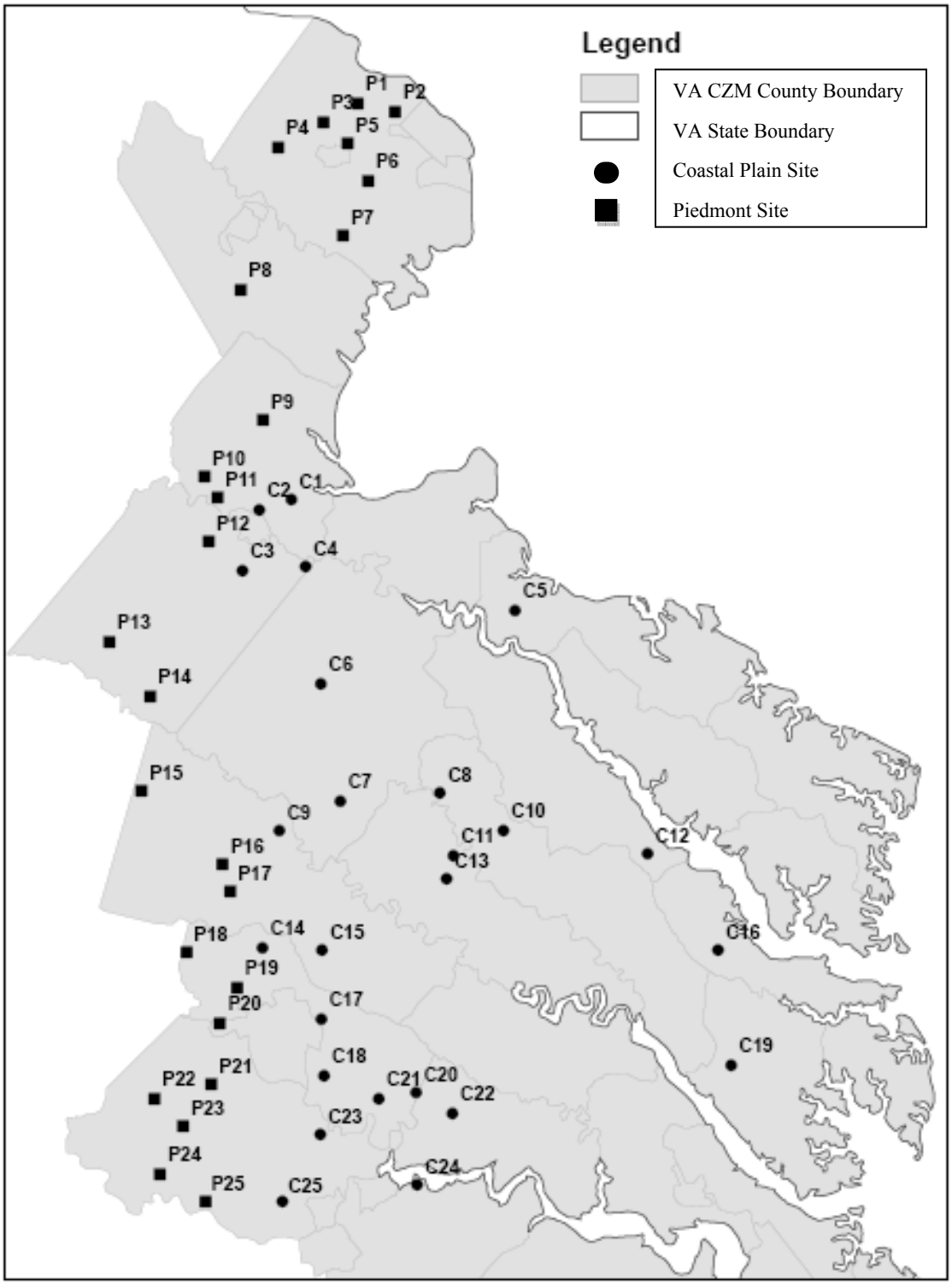

Figure 3.2. Map of the 50 Coastal Plain and Piedmont study sites within the Coastal Zone Management Area of Virginia

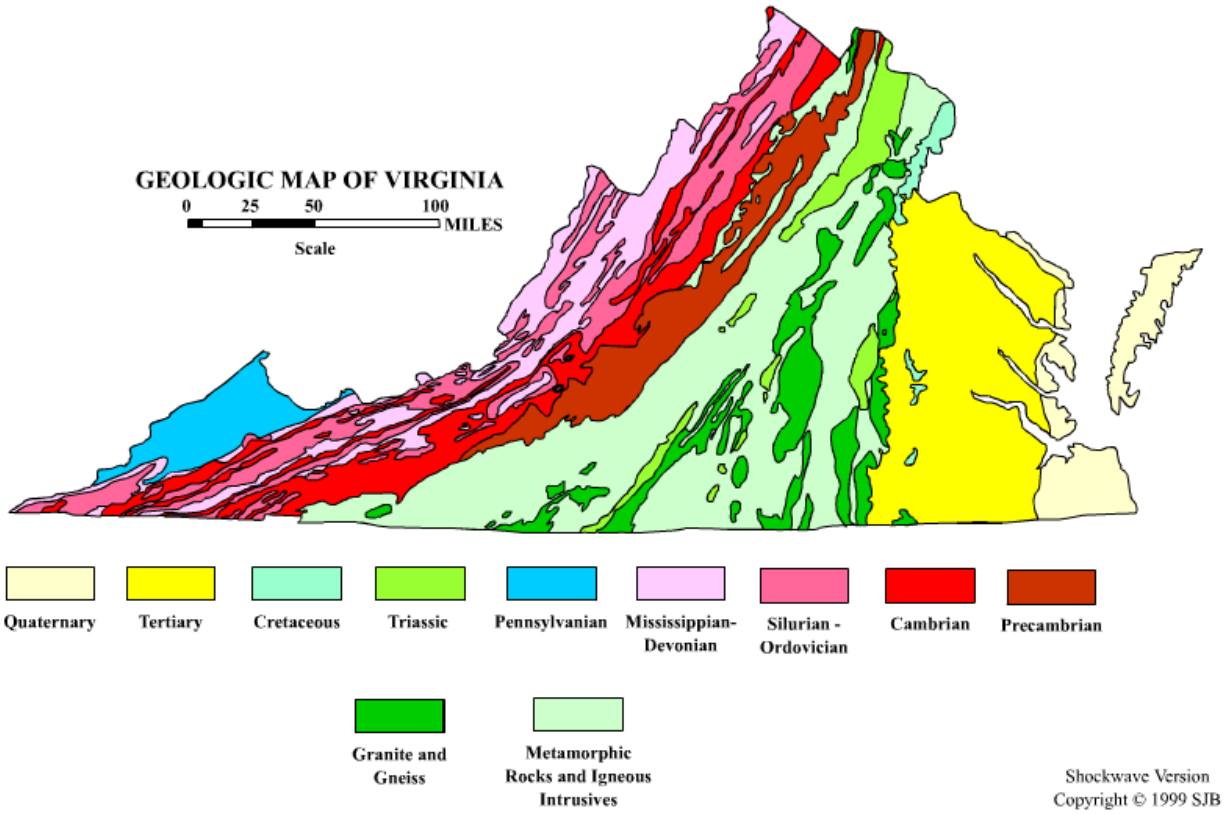

Figure 3.3. Geologic map of Virginia representing divisions of the rock record based on age (Fitchter and Baedke 2000)

Table 3.1. USM riparian buffer categories (USACE and VADEQ 2007)

Category	Description
Optimal	Tree stratum (dbh > 3 inches) present, with > 60% tree canopy cover. Wetlands located within the riparian areas are scored as optimal, where dbh = the diameter at breast height.
Suboptimal	*High Suboptimal*: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and containing both herbaceous and shrub layers or a non-maintained understory. *Low Suboptimal*: Riparian areas with tree stratum (dbh > 3 inches) present, with 30% to 60% tree canopy cover and a maintained understory. Recent cutover (dense vegetation).
Marginal	*High Marginal*: Non-maintained, dense herbaceous vegetation with either a shrub layer or a tree layer (dbh > 3 inches) present, with <30% tree canopy cover. *Low Marginal*: Non-maintained, dense herbaceous vegetation, riparian areas lacking shrub and tree stratum, areas of hay production, and ponds or open water areas. If trees are present, tree stratum (dbh >3 inches) present, with <30% tree canopy cover with maintained understory.
Poor	*High Poor*: Lawns, mowed, and maintained areas, nurseries; no-till cropland; actively grazed pasture, sparsely vegetated non-maintained area, recently seeded and stabilized, or other comparable condition. *Low Poor*: Impervious surfaces, mine spoil lands, denuded surfaces, row crops, active feed lots, trails, or other comparable conditions.

Table 3.2. Summary of data layers collected for spatial analysis in GIS

Data Description	Data Development Source	Resolution	Download Source
Virginia county boundary	National Atlas of the United States	30 m	USGS National Map Seamless Server (USGS 2007)
Virginia state boundary	National Atlas of the United States	30 m	USGS National Map Seamless Server (USGS 2007)
Virginia roads	Bureau of Transportation Statistics	30 m	USGS National Map Seamless Server (USGS 2007)
Virginia 1993 geologic map	Virginia Department of Mines, Minerals, and Energy (1993)	30 m	USGS National Map Seamless Server (USGS 2007)
Percent impervious cover for 1990	Ikonos satellite imagery and Landsat Thematic Mapper database	30 m	Woods Hole Research Center (Woods Hole 2007)
Percent impervious cover for 2000	Ikonos satellite imagery and Landsat Thematic Mapper satellite database	30 m	Woods Hole Research Center (Woods Hole 2007)
Change in percent impervious from 1990 to 2000	Ikonos satellite imagery and Landsat Thematic Mapper database	30 m	Woods Hole Research Center (Woods Hole 2007)

Table 3.3. Summary of dependent and independent variables used for statistical analysis

Dependent variable	Description	Independent variable	Description
W_{BF}	Bankfull cross-sectional width	A_{WS}	Watershed Area
D_{BF}	Bankfull cross-sectional mean depth	PIC_{2000}	Percent impervious cover for 2000
A_{BF}	Bankfull cross-sectional area	$PIC_{1990\text{-}2000}$	Change in percent impervious cover from 1990 to 2000
P_{BF}	Bankfull cross-sectional wetted perimeter	PIC_R	Percent Impervious Cover Ratio
R_{BF}	Bankfull cross-sectional hydraulic radius	*Roads*	Total roads in watershed
WD_R	Bankfull cross-sectional width to depth ratio		
W_{FP}	Flood-prone width		
ER_A	Enlargement ratio for cross-sectional area		
ER_W	Enlargement ratio for cross-sectional width		
ER_D	Enlargement ratio for cross-sectional depth		
E_R	Entrenchment ratio		
S_B	Channel bed slope		
S_{WS}	Water surface slope		
D_{PR}	Maximum residual pool depth		

Table 3.4. Summary of non-correlated independent variables used for multiple linear regression within each site group

Site Group	Independent Variables					
	Model No.	A_{WS}	PIC_{2000}	$PIC_{1990\text{-}2000}$	PIC_R	*Roads*
All Sites	*A1*	X	X			
	A2	X		X	X	
Coastal Plain Sites	*C1*	X	X		X	
	C2	X			X	X
	C3			X	X	
Piedmont Sites	*P1*	X	X			
	P2	X			X	X
	P3	X		X	X	

3.5. References

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Chapter 4: Field-Based Results and Discussion

4.1. Report on Channel Enlargement and Sediment Loads from Existing and Historic Channel Cross-sections (Product #4)

This report will document the methods used for Tier 1, the data collected (geomorphic and watershed), and present our findings regarding the relationship between watershed characteristics and channel enlargement. In addition, we will provide an estimate of annual sediment load due to channel enlargement in relation to multivariate analyses of stream, watershed, and physiographic characteristics.

In an effort to locate historic stream cross-sections for the Tier 2 sites, we contacted members of the advisory committee and various county and state agencies including, but not limited to, Hanover County, Fairfax County, and VDOT. However, we were unable to locate any documents referencing historic cross-sections for our sites. We searched for other resources at the Virgina Tech library (the government document repository), but were unable to locate any information. In addition, we searched the FEMA archives for Flood Insurance Studies (FIS). Of the 12 sites, we were able to locate studies at or near two study sites. While the documents referenced historic cross-sections, but actual surveyed cross-section data was not included in the FIS. An effort was made to contact the FEMA Flood Mitigation Division, however, we were unable to locate the surveyed historic cross-section data for inclusion in this report.

4.2. Rapid Geomorphic Survey and Watershed Condition (Tier 1) Data Analysis Report (Product #5)

This report will document the methods used for Tier 1, the data collected (geomorphic and watershed), and present our findings regarding the relationship between watershed characteristics and channel enlargement. In addition, we will provide an estimate of annual sediment load due to channel enlargement in relation to multivariate analyses of stream, watershed, and physiographic characteristics.

The goal of this section of our project was to assess and quantify sediment contributions due to channel enlargement (erosion) of first- through third-order urban streams in the Coastal Zone Management (CZM) Area of Virginia. We attempted to achieve this goal by developing relationships between channel enlargement and upstream watershed condition. The main objectives are to:

1. Measure morphological features of streams in watersheds with varying levels and ages of urbanization in two physiographic regions, the Coastal Plan and Piedmont, of Virginia, USA;
2. Develop relationships between watershed urbanization characteristics (TIA and age) and channel enlargement; and
3. Estimate sediment loading due to channel enlargement for use in statewide Nonpoint Source Pollution (NPS) assessment and management.

To test these research objectives, the following hypotheses were developed:

Hypothesis 1: There is a significant difference in the morphological features of streams between physiographic regions.

Hypothesis 2: There is a relationship between watershed urbanization characteristics (TIA and age) and morphological features of streams.

Hypothesis 3: There is a relationship between watershed urbanization characteristics (TIA and age) and channel enlargement.

4.2.1. Hypothesis 1: Differences between Coastal Zone and Piedmont channel morphology

We first compared the existing regional curve data sets to test whether or not non-urban streams in the Coastal Plain (Krstolic and Chaplin 2007) were different from those in the Piedmont (Cinotto 2003) physiographic region. When the regional curve data for the Coastal Plain and Piedmont regions were tested, the WBF, DBF, and WDR means were significantly different ($p < 0.05$); however, ABF and SB were not significantly different ($p > 0.05$; Table 4.4; Figs. 4.1-4.3). In general, the Piedmont streams are larger than Coastal Plain streams for a given watershed area. Inspection of Figures 4.1-4.3 indicates that this is mostly due to Piedmont channels being wider than their Coastal Plain counterparts.

In Figures 4.4 through 4.12 we present our measured stream characteristics with the regional curves for WA versus ABF, DBF, and WBF. In general, our streams followed the trends of the regional curves, although our Coastal Plain streams tended to be smaller in size than the regional curves (see Figs. 4.4-4.6). This difference could be due to differences in identifying bankfull in the field for the various projects. Inspection of Figure 4.7 highlights several important points concerning our Piedmont study sites: 1) there are two major outliers (see two sites with WA between 20-30 km2), which are much smaller than expected; and 2) in general, our study streams have smaller watershed areas than most of the lower extent of the regional curves. The two outliers in Figure 4.7 were hereafter eliminated from our analysis (study sites P03 and P15), while we determine the reasons for their extremely small sizes given the watershed areas determined through GIS analysis (and many visual checks). It is possible that natural watershed boundary has been modified through stormwater drainage

infrastructure (especially for P03, which is fairly urbanized), or we measured a smaller stream that was very close to the larger stream we intended to sample.

The bankfull cross-sectional area for all of the study sites ranged from 0.2 to 9.2 m2. Piedmont sites had larger average bankfull cross-sectional areas than the Coastal Plain sites (1.6 m2 and 1.3 m2, respectively). The average bankfull width for Piedmont sites was 5.1 m, while the average width for the Coastal Plain sites was 3.6 m. The mean bankfull depths for both regions were similar (Coastal Plain, 0.30 m; Piedmont, 0.34 m). In the Coastal Plain, the sites had larger average width to depth ratios than in the Piedmont (13.2 and 17.9, respectively).

The mean values for hydraulic radius, flood-prone width, and residual pool depths for each region were similar. All measured dependent variables are presented by site name in Tables 4.1 through 4.3.

Next we conducted statistical analyses to determine whether or not the Piedmont and Coastal Zone streams in our study were morphologically different. The Wilcoxon Rank Sum Test on all normalized dependent variables resulted in only WBF and PBF being found statistically different between the Coastal Plain and Piedmont ($p < 0.05$; Table 4.4). Therefore, as with the regional curves, our Piedmont study sites tended to be wider than their Coastal Plain counterparts. For all other measured, dependent variables (ABF, DBF, WDR, RBF, ER, WFP, DPR, SB, and SWS) the normalized means for the Coastal Plain and Piedmont sites were not significantly different ($p > 0.05$; Table 4.4).

4.2.2. Hypothesis 2: Relationships between watershed urbanization and channel morphology

The watershed sizes for our study sites ranged from 0.3 to 43.5 km2. The median watershed size for Coastal Plain sites was 3.4 km2, while the watersheds for the Piedmont sites were larger with a median size of 5.7 km2. Plots of watershed area (km2) versus ABF, DBF, and WBF are presented for both physiographic regions in Figures 4.13 through 4.15. As found in the regional curves, our Piedmont streams were larger than the Coastal Plain streams for a given watershed size, particularly with respect to bankfull channel width.

We present plots of enlargement ratios (ERA, ERD, and ERW) versus watershed area in Figures 4.16 through 4.18. Here we see that there is no particular pattern of enlargement ratio across a watershed area gradient. In fact, the level of variability in channel enlargement is not surprising (Cianfrani et al. 2006) given the uncertainty inherent in these computations. The computation of enlargement is based on comparisons between our measured bankfull parameters and the regional curves. The regional curves, in turn, were developed by selecting stable stream sections near long-term flow monitoring stations. At each site used for the regional curves, the field team had to estimate bankfull elevation, and extremely subjective parameter even with existing gage data. In short, bankfull elevation selection in the field is subjective, and our study sites were NOT located on stable streams.

In Figures 4.19 through 4.21 we present comparisons of percent impervious cover (PIC2000) versus ERA, ERD, and ERW. The percent impervious cover (PIC2000) for watersheds ranged from 0.01 to 54.5. The Piedmont sites had higher percent impervious cover with a mean value of 9.7%, while the Coastal Plain sites had a mean

value of 3.4%. The range in watershed-level percent impervious cover for sites in the Coastal Plain (0.01 to 18.8%) was smaller than the Piedmont sites (0.04 to 54.5%). There is no clear pattern of enlargement of streams along an urban gradient (Figures 4.19-4.21). In addition to uncertainties induced by bankfull estimates and the fact that our streams were not stable, local disturbances, age of urbanization and upstream management practices can have an immense impact on the impact of urbanization on stream morphology. Below, we provide a paired comparison of a subset of our study sites with similar watershed sizes to further explore the variability experienced in enlargement ratios.

All independent watershed variables for our study sites are presented in Table 4.5. Sites located in the Piedmont had a mean number of road crossings over streams (Roads) of 4.5, while the Coastal Plain sites had a mean of 3.2. When assessing recent watershed urbanization, from 1990 to 2000 the project watershed's experienced increases in percent impervious cover ranging from 0.0 to 10.8%. Piedmont sites generally experienced more urbanization within this 10-year period than the Coastal Plain sites.

The results of the stepwise multiple linear regressions yielded the highest number of significant models for site group, Coastal Plain, with 15 significant models. The significant models included dependent variables ABF, WBF, DBF, PBF, WDR, RBF, ERD, and ERA, with p-values for the models ranging from < 0.0001 to 0.039 (Table 4.6). Site groups, All Sites and Piedmont yielded fewer significant models, with 12 and 3 significant models, respectively (Tables 4.7 and 7.8). The p-values for site group, All Sites ranged from 0.0003 to 0.038, and p-values for site group Piedmont ranged from

0.001 to 0.032. When comparing all site groups, the Coastal Plain models resulted in the largest adjusted R2 values, with a maximum R2 of 0.60 (Table 4.6). In contrast, site groups All Sites and Piedmont resulted in maximum adjusted R2 values of 0.26 and 0.37 respectively (Tables 4.7 and 4.8).

4.2.3. Hypothesis 3: Watershed urbanization, channel enlargement, and sediment loads

The stepwise multiple linear regressions yielded few significant models between enlargement ratios (ERA, ERD, and ERW) and independent watershed variables. For site group, All Sites the most significant model shows an inverse relationship between ERW and WA (p-value = 0.002, adjusted R2 = 0.17; Table 4.7). For site group, Coastal Plain the most significant model shows relationship between ERD, WA, and Roads (p-value = 0.002, adjusted R2 = 0.38; Table 4.6). For site group, Piedmont the most significant models show inverse relationships between ERW and WA and ERA and WA (Table 4.8).

Within each site group, individual sites show both positive (channel enlargement) and negative sediment yields relative to regional curve values. The sediment yield for the Coastal Plain sites ranged from -4.8 to 4.8 m3 per 1 m length of stream, and the Piedmont sites showed -7.0 to 2.2 m3 per 1 m length of stream (Table 4.3).

4.2.4. Paired Watershed Comparisons

Since there was so much variability and uncertainty in the computation of enlargement ratios (ERA, ERD, and ERW), we selected a subset of paired sites with

similar watershed areas and different levels of imperviousness (PIC2000). We selected a total of 9 pairs, 4 in the Coastal Plain and 5 in the Piedmont (Table 4.9). The fact that enlargement ratios depends on consistency in defining bankfull and that regional curves are developed at stable stream reaches, makes conclusions on the impacts of urbanization on channel morphology difficult. By evaluating paired stream reaches with similar watershed sizes, but different levels of urbanization can be very informative (Pizzuto et al. 2003). Cross-sectional profiles are provided in Figures 4.20 through 4.28 for all the paired sites, where the rural site is on the top and the more urban site is on the bottom.

Inspection of Figures 4.20 through 4.28 reveals several interesting patterns. The bankfull elevation is identified in each cross-sectional plot with a short horizontal line. We can see from these plots, that if the bankfull elevation were determined to be at another elevation, the results could be very different (both in the comparison of the pairs, as well as our computation of enlargement ratios).

We can also see from the paired sites, that there is still much variability even when not depending on bankfull as a channel measure. In Figures 4.20, 4.21, 4.22, and 4.25, the overall channels are wider and deeper for the urban sites (bottom) than their rural pair, which is what much of the literature suggests (Pizzuto et al. 2000; Hession et al. 2003). However, for all additional pairs (Figures 4.23, 4.24, 4.26, 4.27, and 4.28) the rural sites (top) have larger channels than their urban counterparts. An important point here is that variability in enlargement ratios can not be blames solely on the elusiveness of bankfull elevation. Rather, the variability from site to site must be due to unaccounted for watershed characteristics or localized impacts.

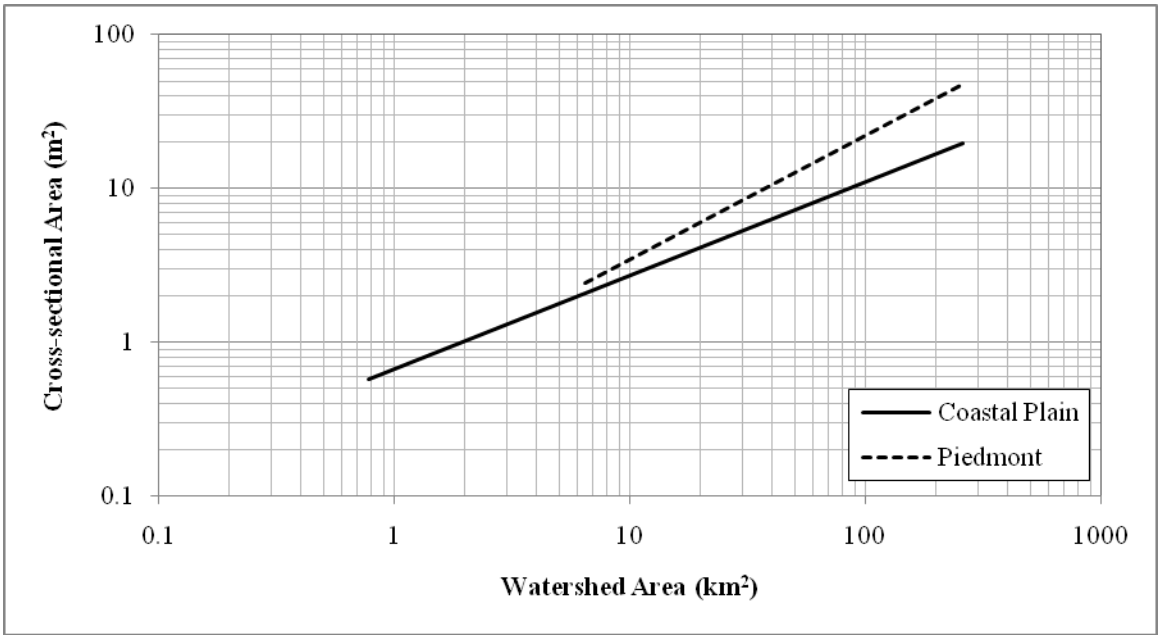

Figure 4.1. Regional curves relating bankfull area and watershed area (km^2) for streams in the non-urban, Coastal Plain Physiographic Province of Virginia (Krstolic and Chaplin 2007) and the Piedmont Physiographic Province of Pennsylvania and Maryland (Cinotto 2003)

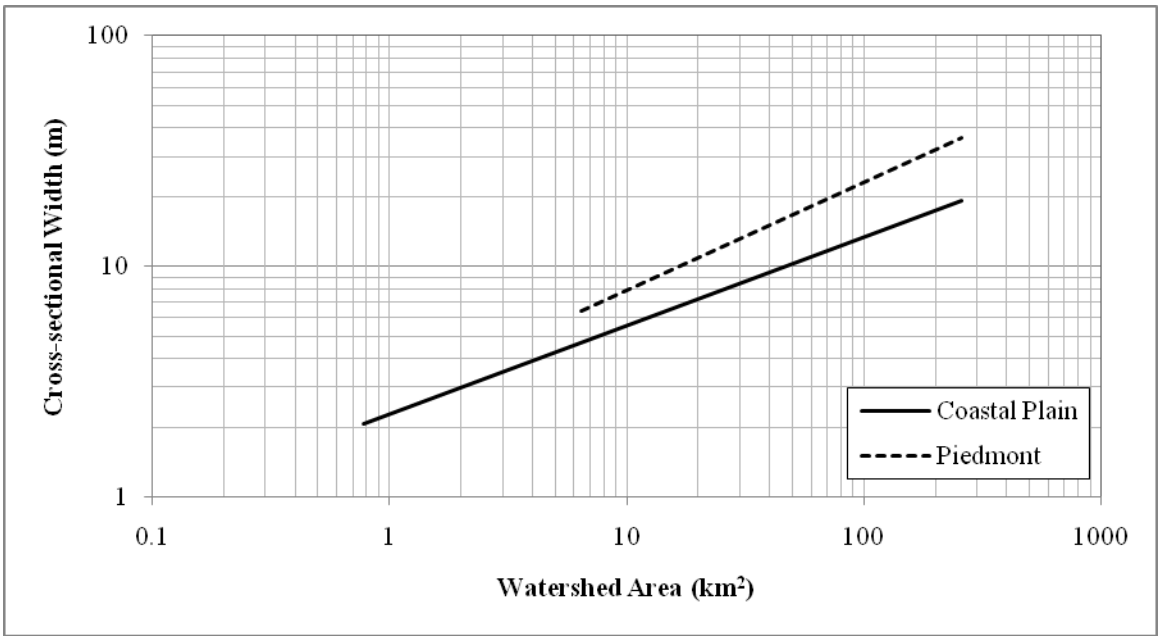

Figure 4.2*. **Regional curves relating bankfull width and watershed area (km^2) for streams in the non-urban, Coastal Plain Physiographic Province of Virginia (Krstolic and Chaplin 2007) and the Piedmont Physiographic Province of Pennsylvania and Maryland (Cinotto 2003)***

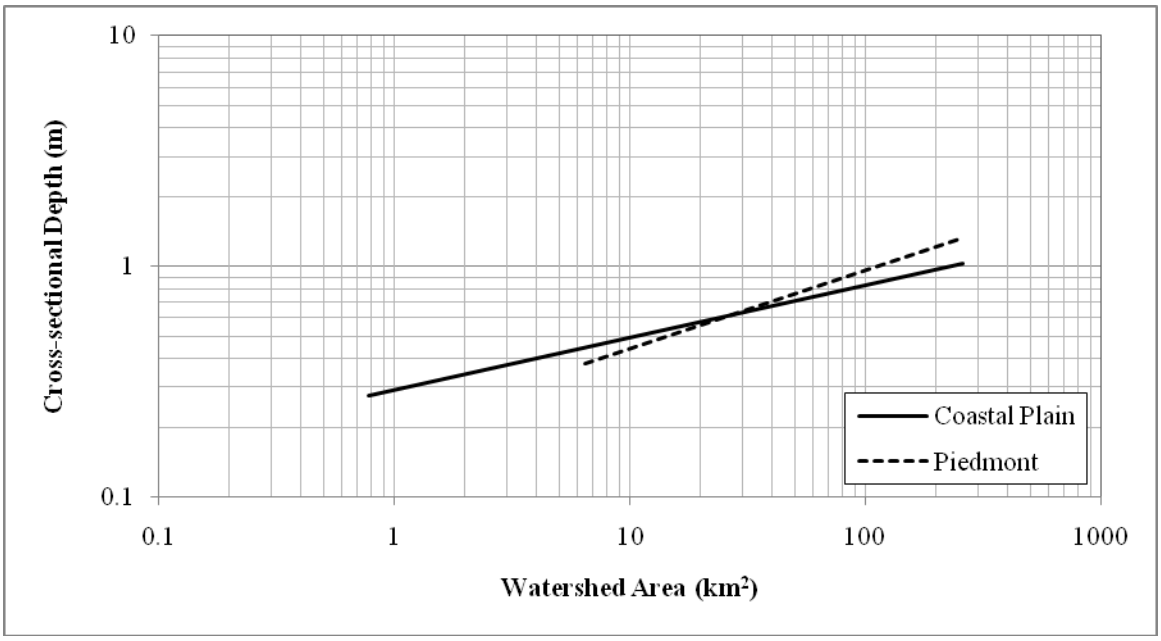

Figure 4.3. ***Regional curves relating bankfull depth (m) and watershed area (km^2) for streams in the non-urban, Coastal Plain Physiographic Province of Virginia (Krstolic and Chaplin 2007) and the Piedmont Physiographic Province of Pennsylvania and Maryland (Cinotto 2003)***

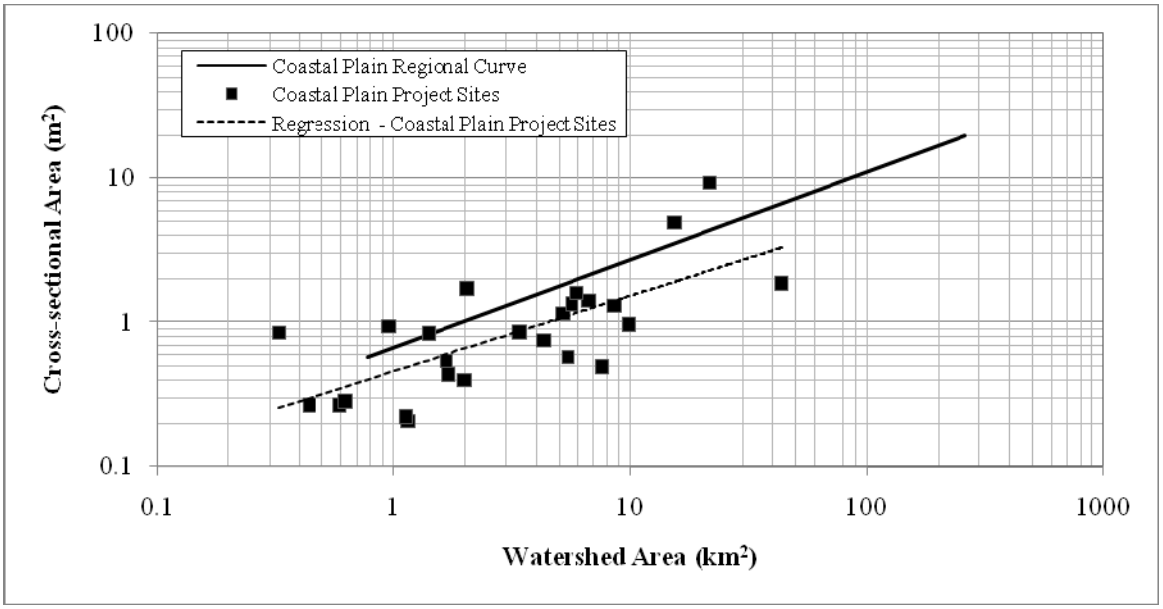

Figure 4.4. ***Coastal Plain regional curve (Krstolic and Chaplin 2007) and measured project data relating bankfull area (m^2) and watershed area (km^2)***

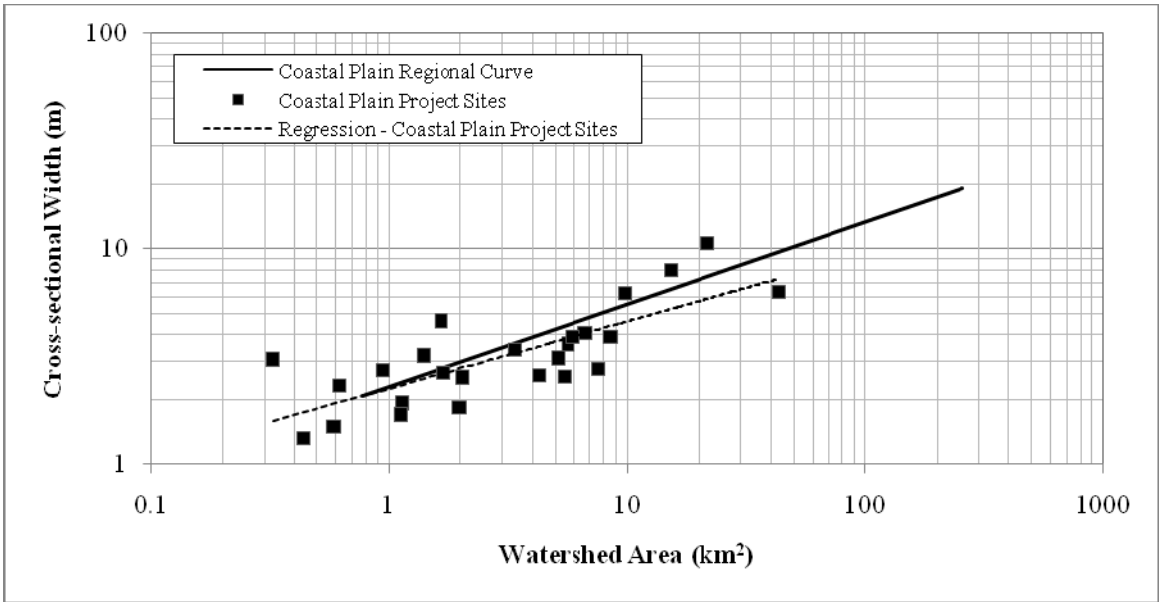

Figure 4.5. ***Coastal Plain regional curve (Krstolic and Chaplin 2007) and measured project data relating bankfull width (m) and watershed area (km^2)***

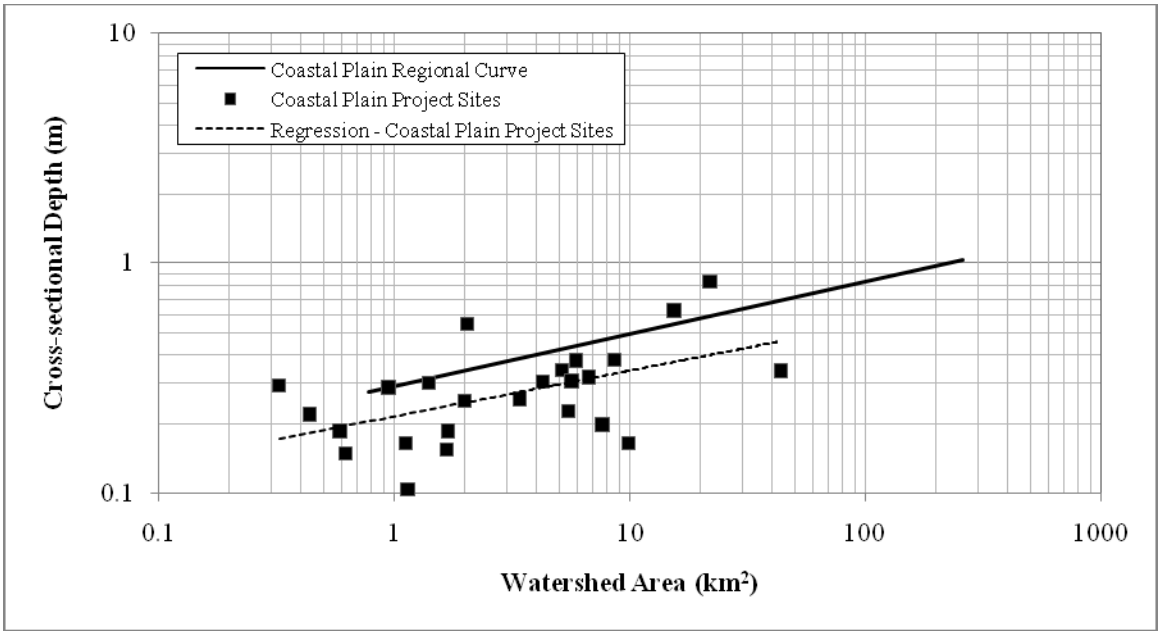

Figure 4.6. ***Coastal Plain regional curve (Krstolic and Chaplin 2007) and measured project data relating bankfull depth (m) and watershed area (km^2)***

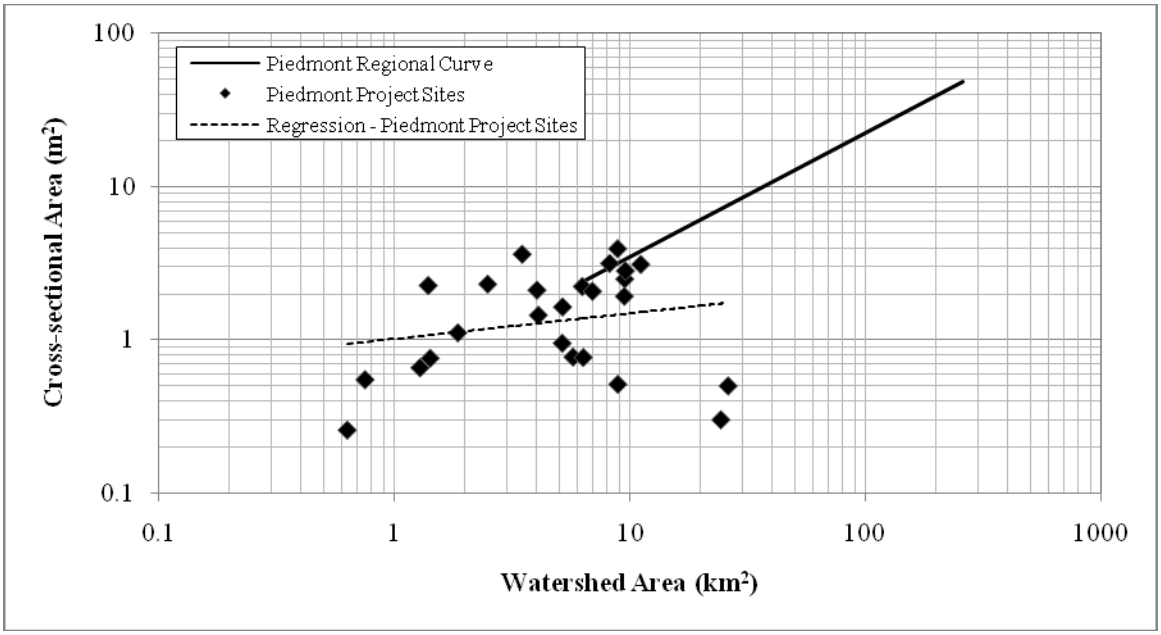

Figure 4.7. ***Piedmont regional curve (Cinotto 2003) and measured project data relating bankfull area (m^2) and watershed area (km^2) (with outliers)***

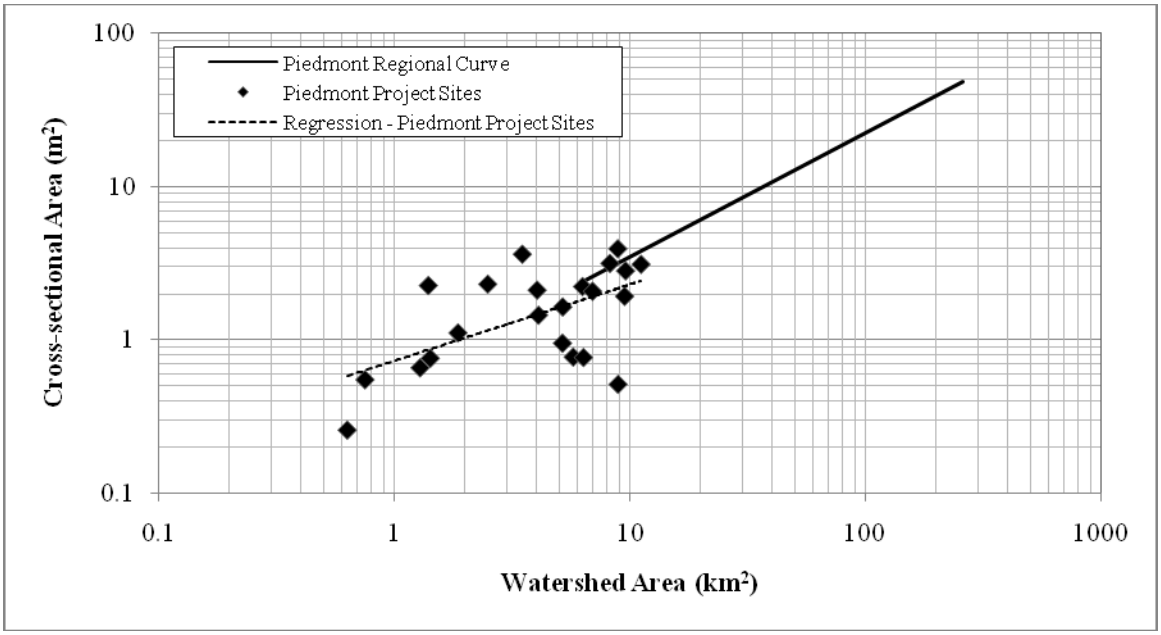

Figure 4.8. ***Piedmont regional curve (Cinotto 2003) and measured project data relating bankfull area (m^2) and watershed area (km^2) (without outliers)***

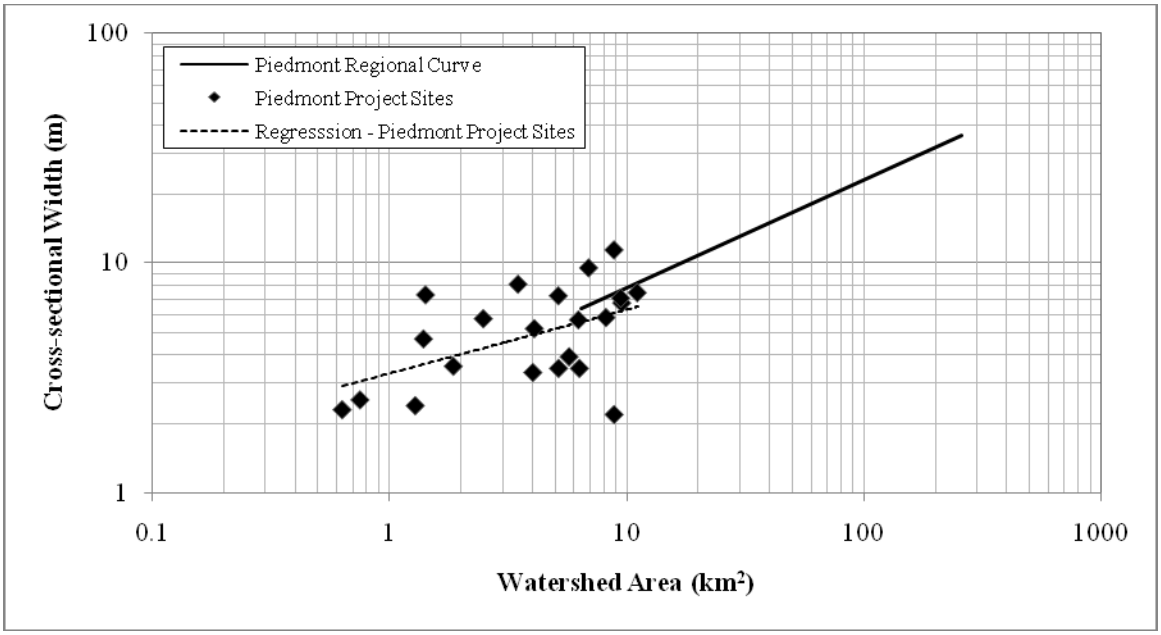

Figure 4.9. ***Piedmont regional curve (Cinotto 2003) and measured project data relating bankfull width (m) and watershed area (km^2) (without outliers)***

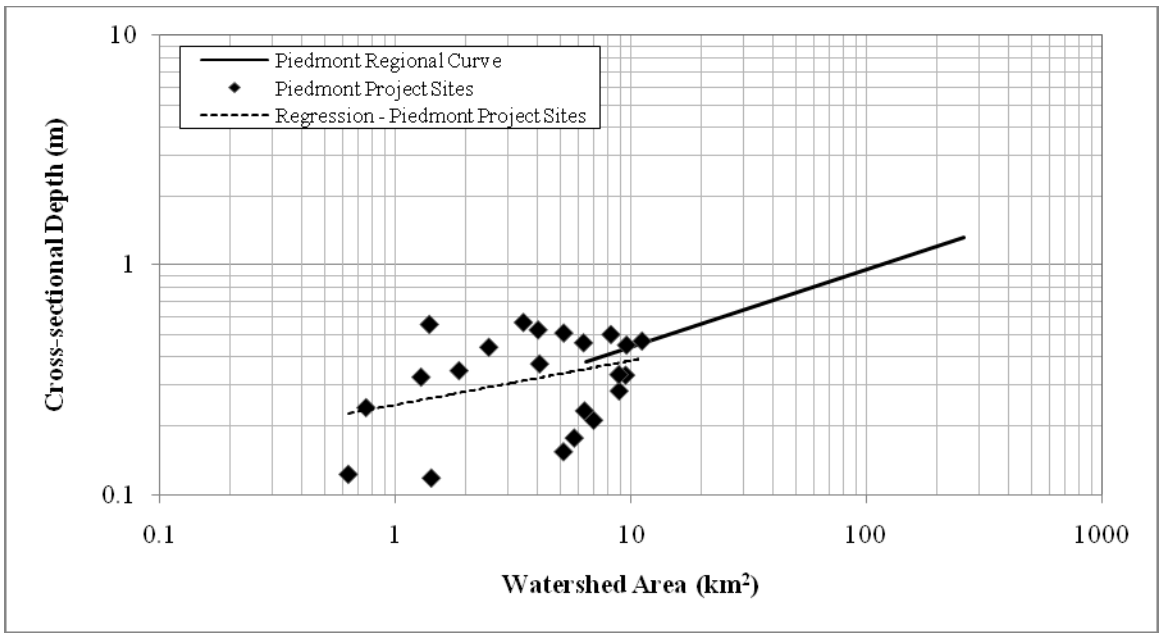

Figure 4.10. ***Piedmont regional curve (Cinotto 2003) and measured project data relating bankfull average depth (m) and watershed area (km^2) (without outliers)***

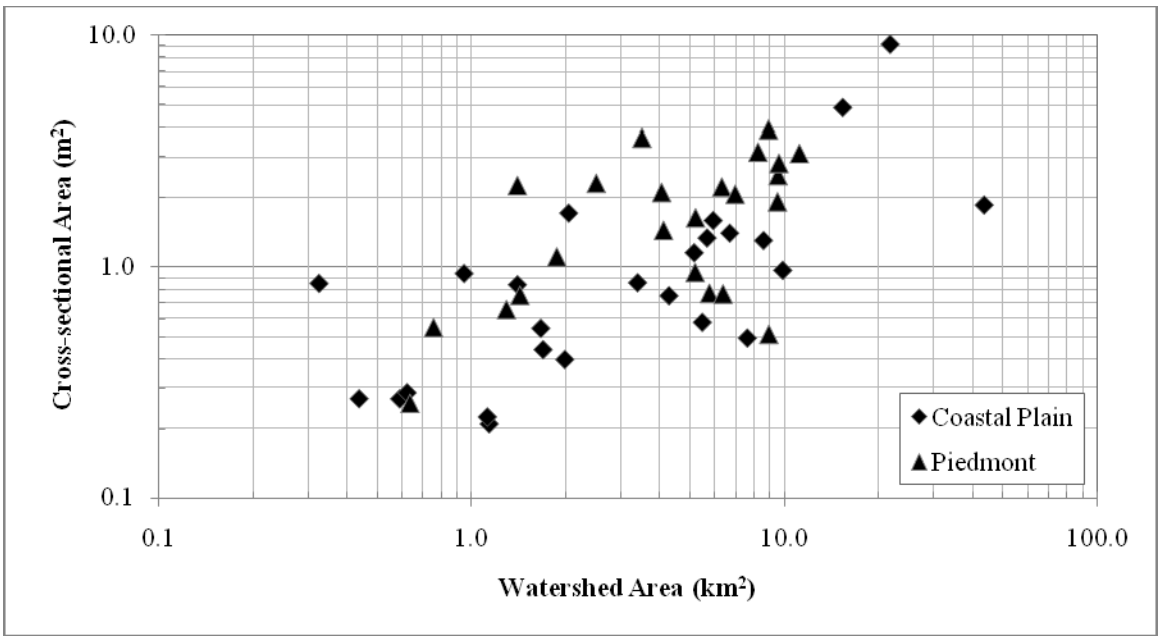

Figure 4.11. ***Measured project data relating bankfull cross-sectional area (m^2) and watershed area (km^2) categorized by region (without outliers)***

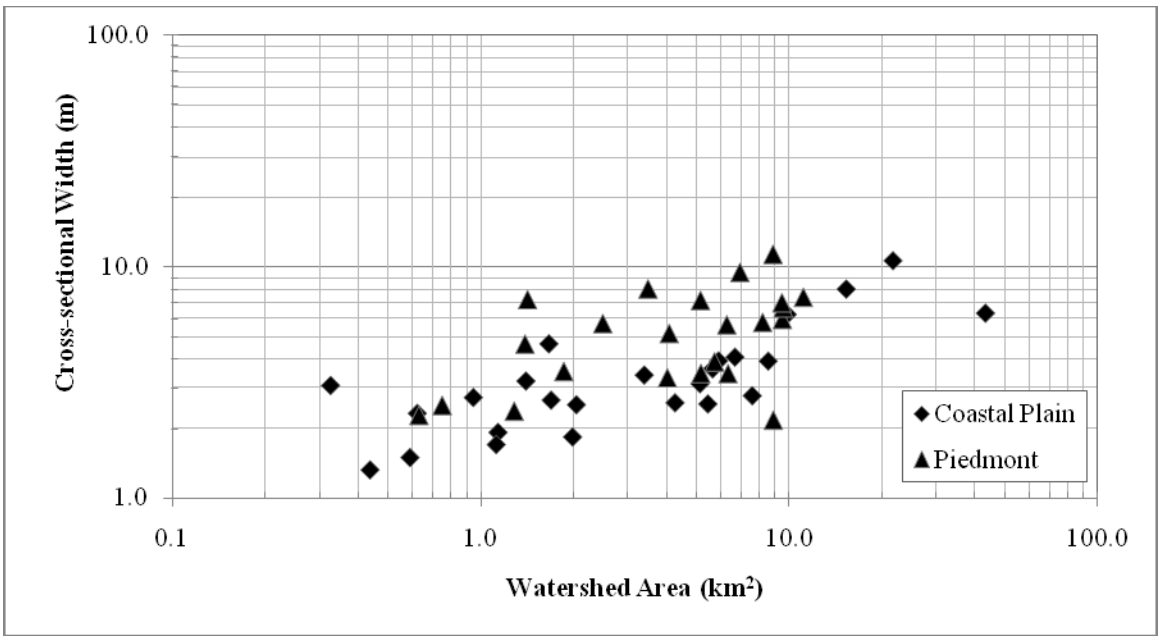

Figure 4.12. ***Measured project data relating bankfull width (m) and watershed area (km^2) categorized by region (without outliers)***

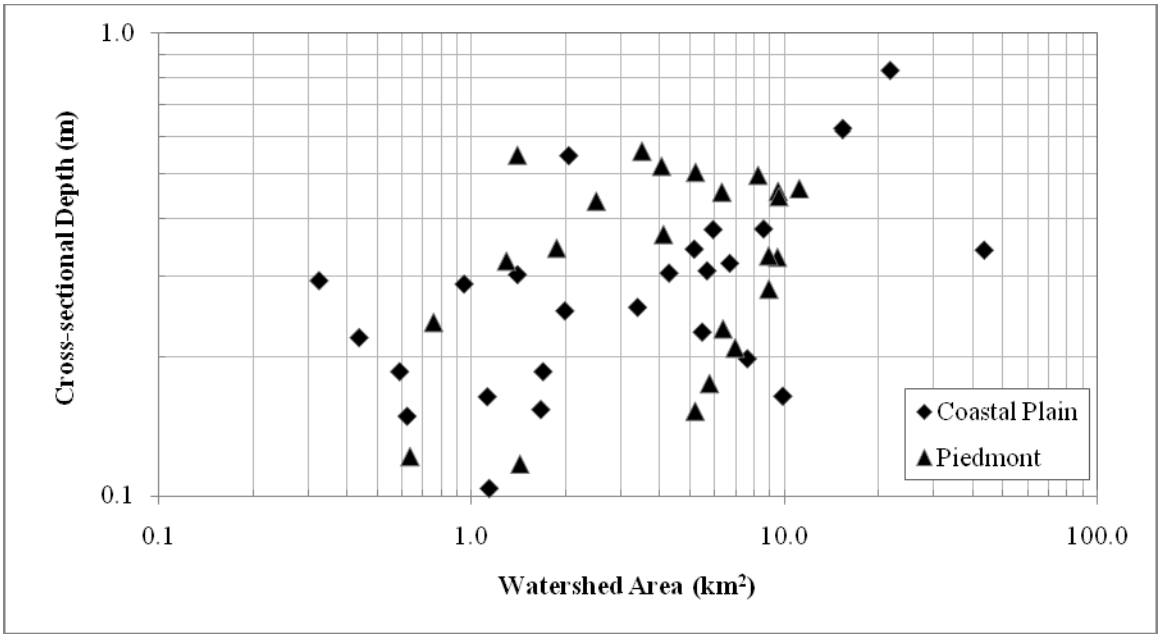

Figure 4.13. ***Measured project data relating bankfull depth (m) and watershed area (km^2) categorized by region (without outliers)***

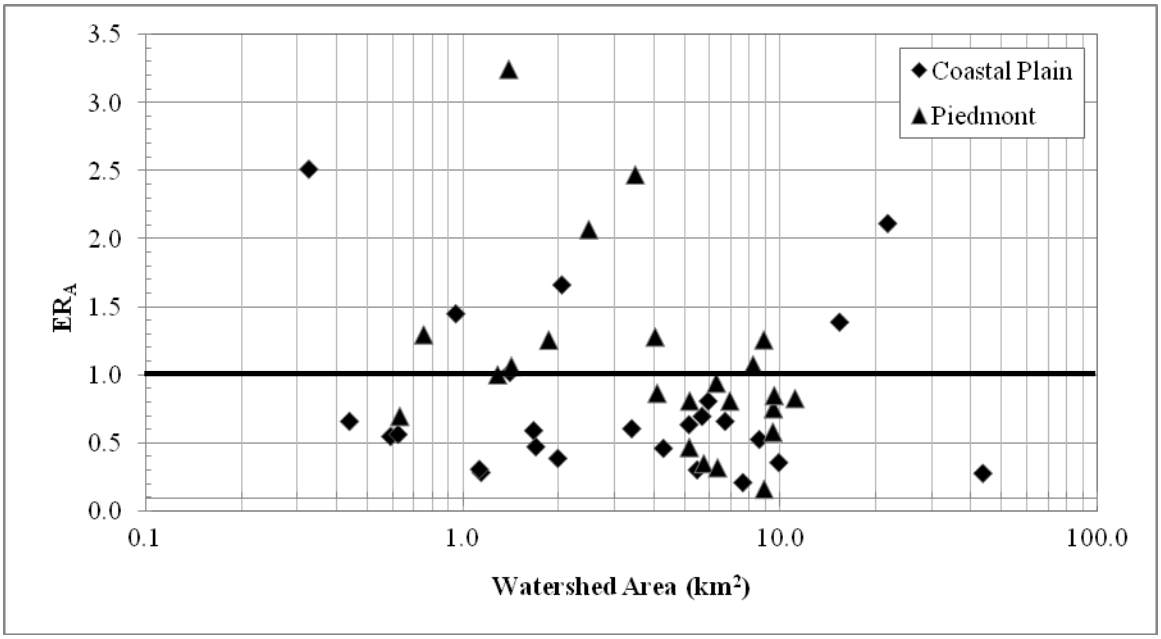

Figure 4.14. ***Measured project data relating enlargement ratio for bankfull cross-sectional area (ER$_A$; m^2) and watershed area (km^2) categorized by region (without outliers)***

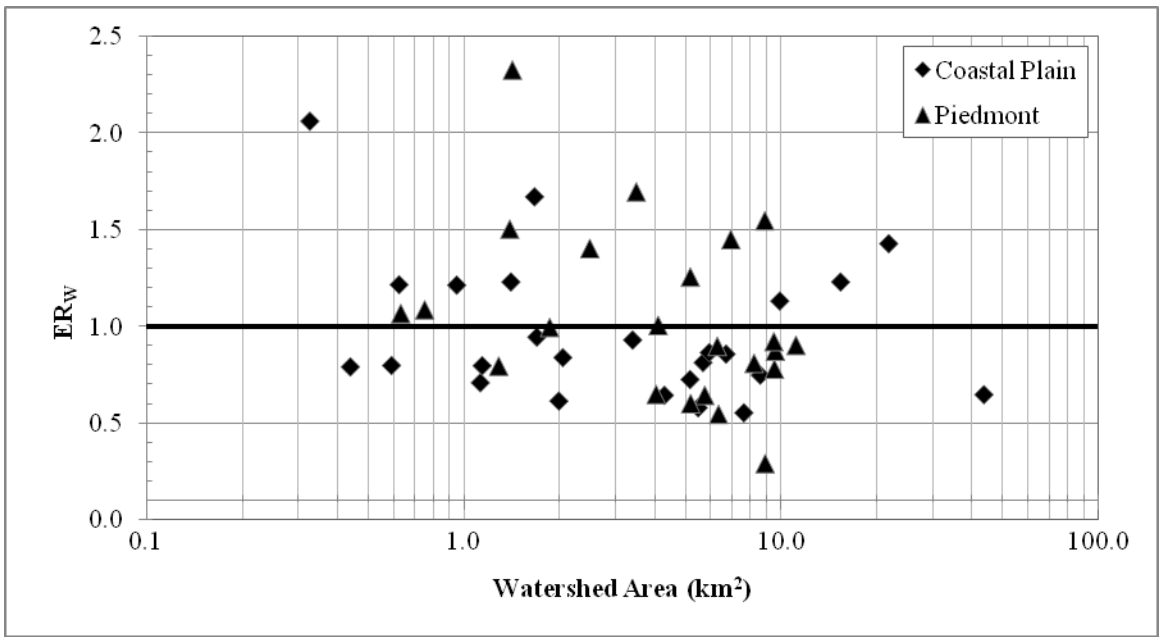

Figure 4.15. ***Measured project data relating enlargement ratio for cross-sectional width (ER$_w$; m) and watershed area (km^2) categorized by region (without outliers)***

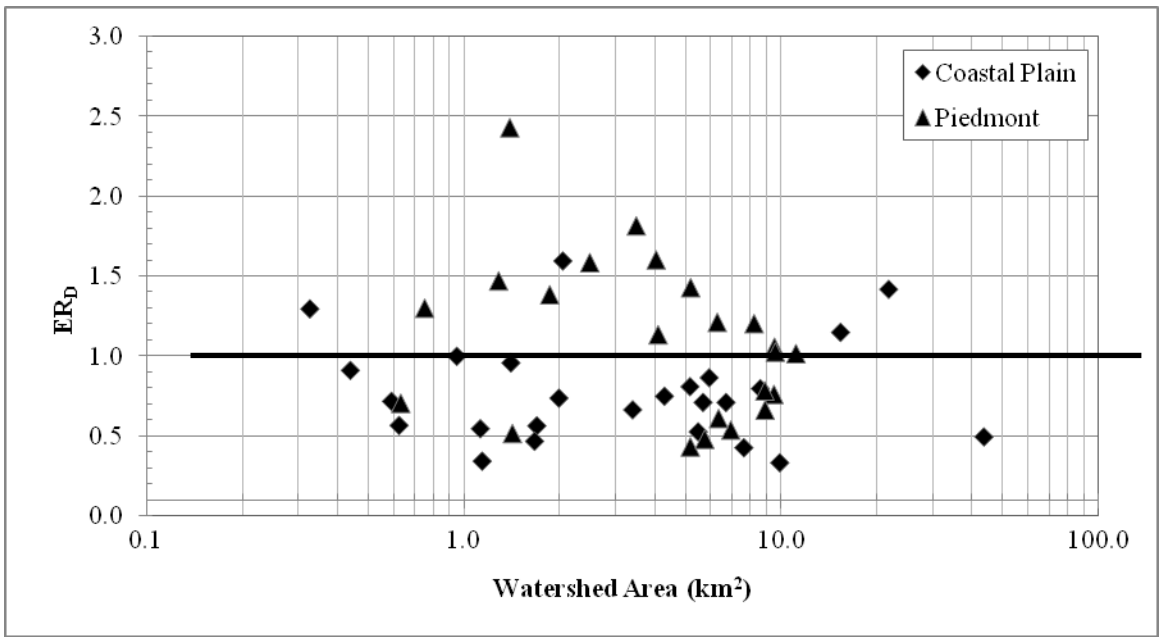

Figure 4.16. ***Measured project data relating enlargement ratio for cross-sectional depth (ER$_D$; m) and watershed area (km^2) categorized by region (without outliers)***

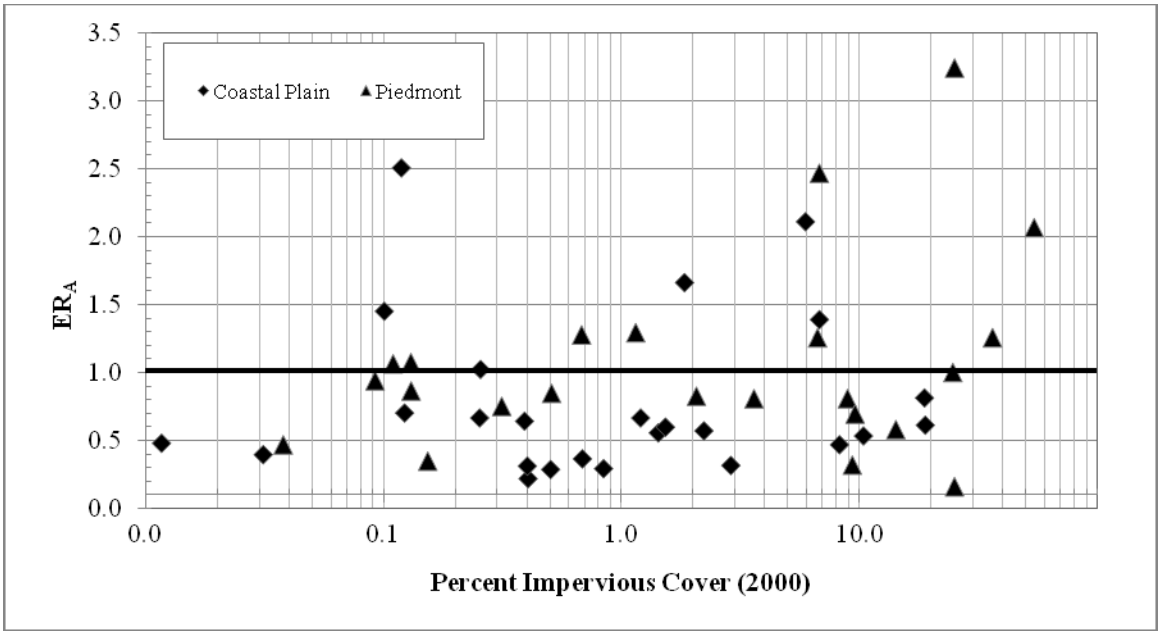

Figure 4.17. ***Measured project data relating enlargement ratio for bankfull cross-sectional area (ER$_A$; m^2) and percent impervious cover (2000) categorized by region (without outliers)***

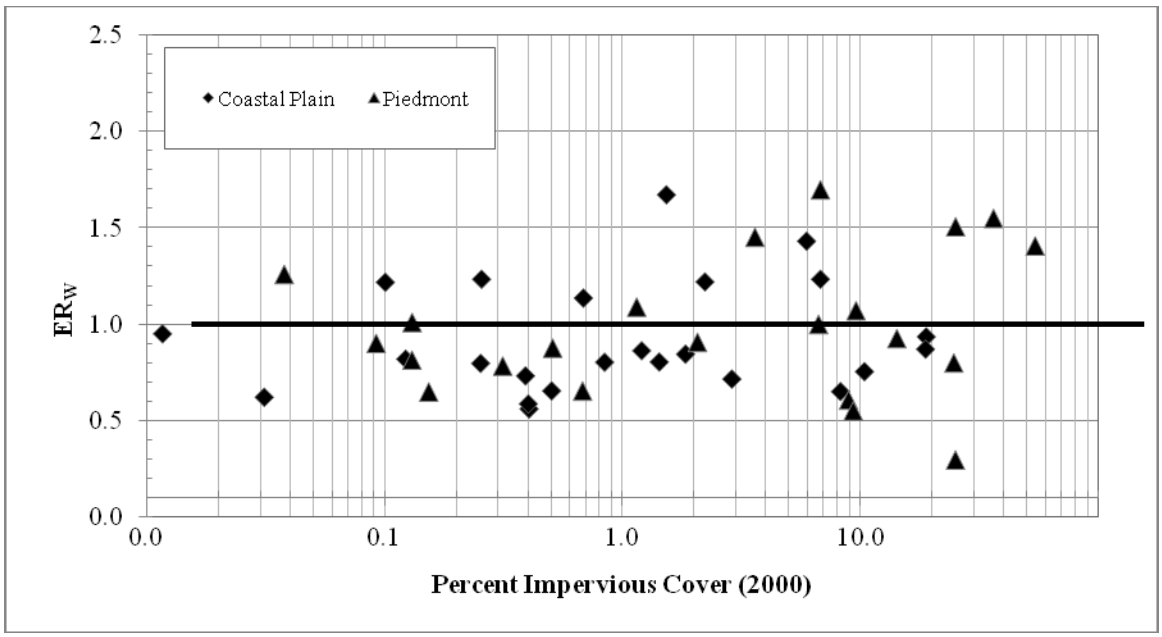

Figure 4.18. ***Measured project data relating enlargement ratio for cross-sectional width (ER$_W$; m) and percent impervious cover (2000) categorized by region (without outliers)***

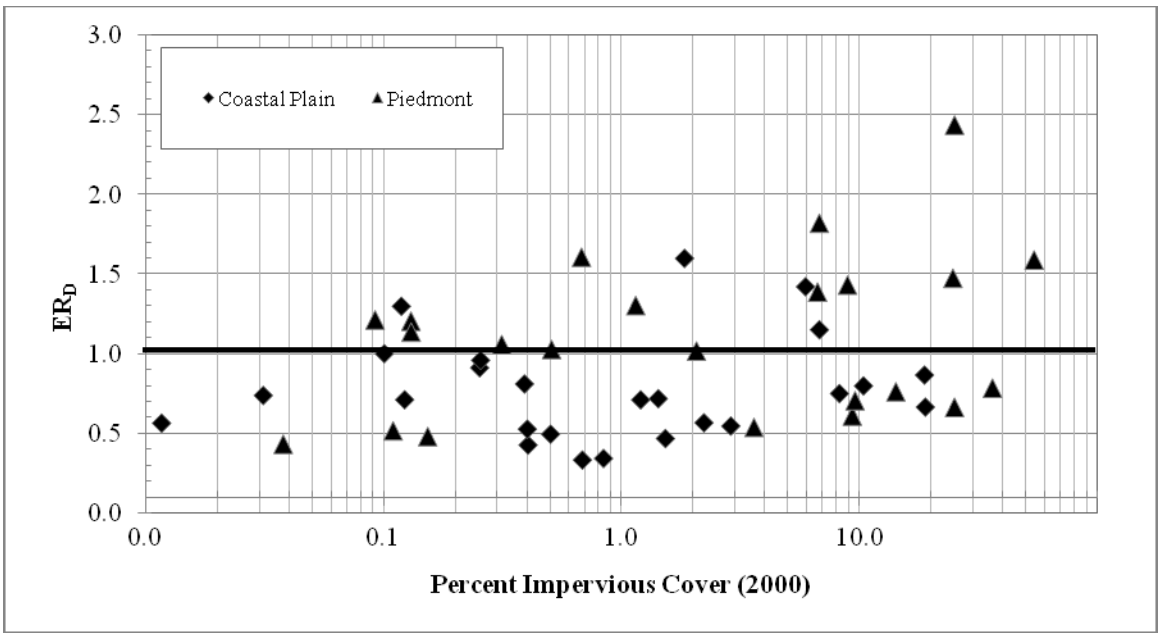

Figure 4.19. ***Measured project data relating enlargement ratio for cross-sectional depth (ER$_D$; m) and percent impervious cover (2000) categorized by region (without outliers)***

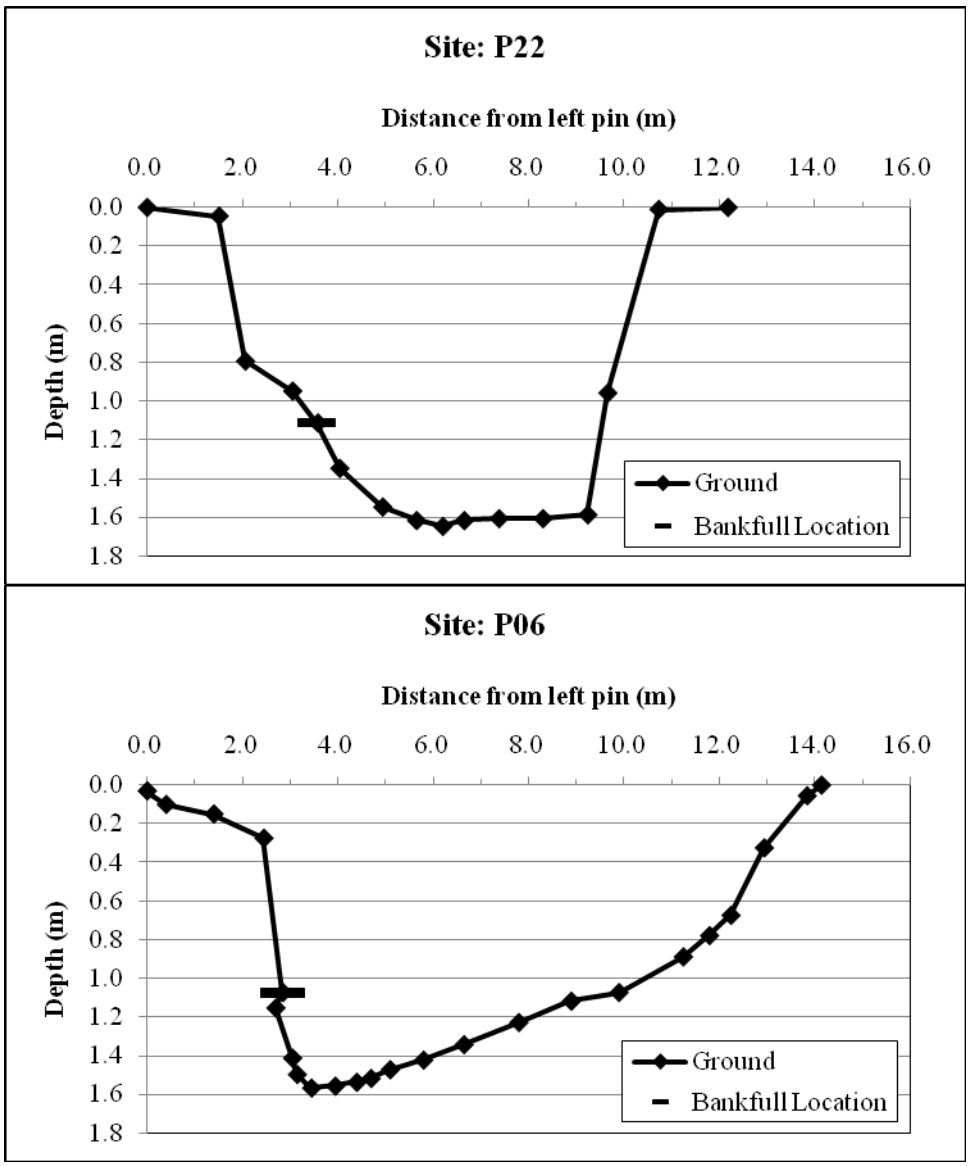

Figure 4.20. ***Plots of bankfull area (m^2) for paired sites, P22 (rural) and P06 (urban)***

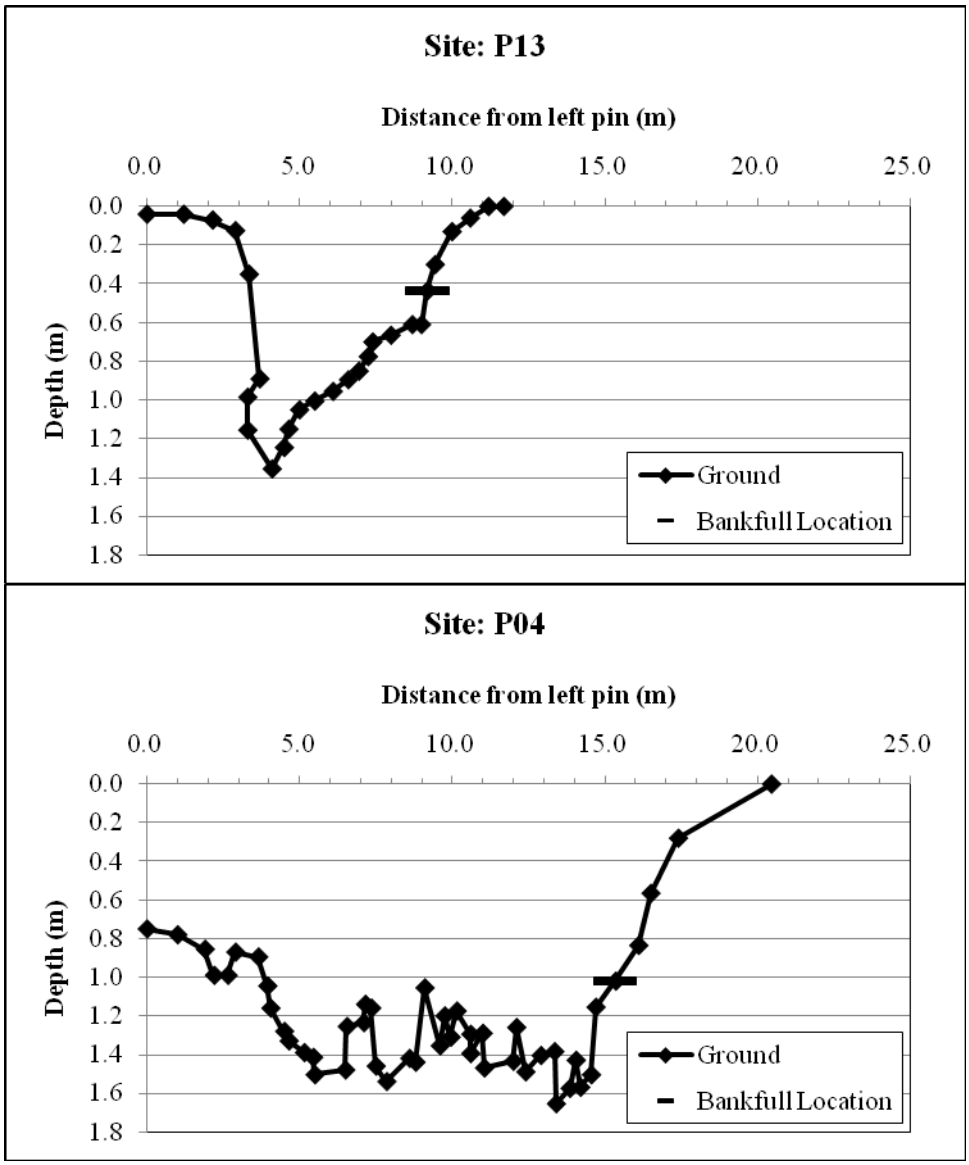

Figure 4.21. ***Plots of bankfull area (m^2) for paired sites, P13 (rural) and P04 (urban)***

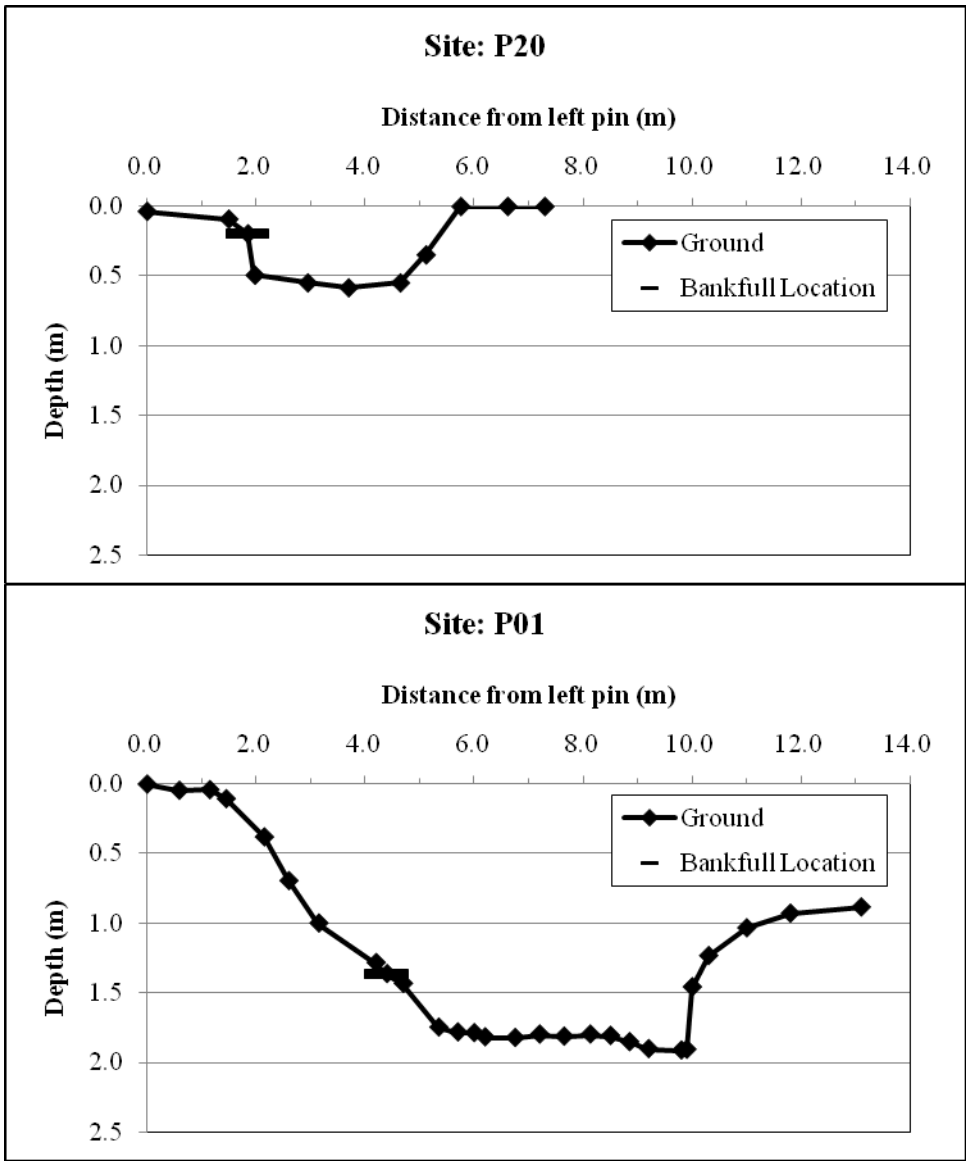

Figure 4.22. ***Plots of bankfull area (m^2) for paired sites, P20 (rural) and P01 (urban)***

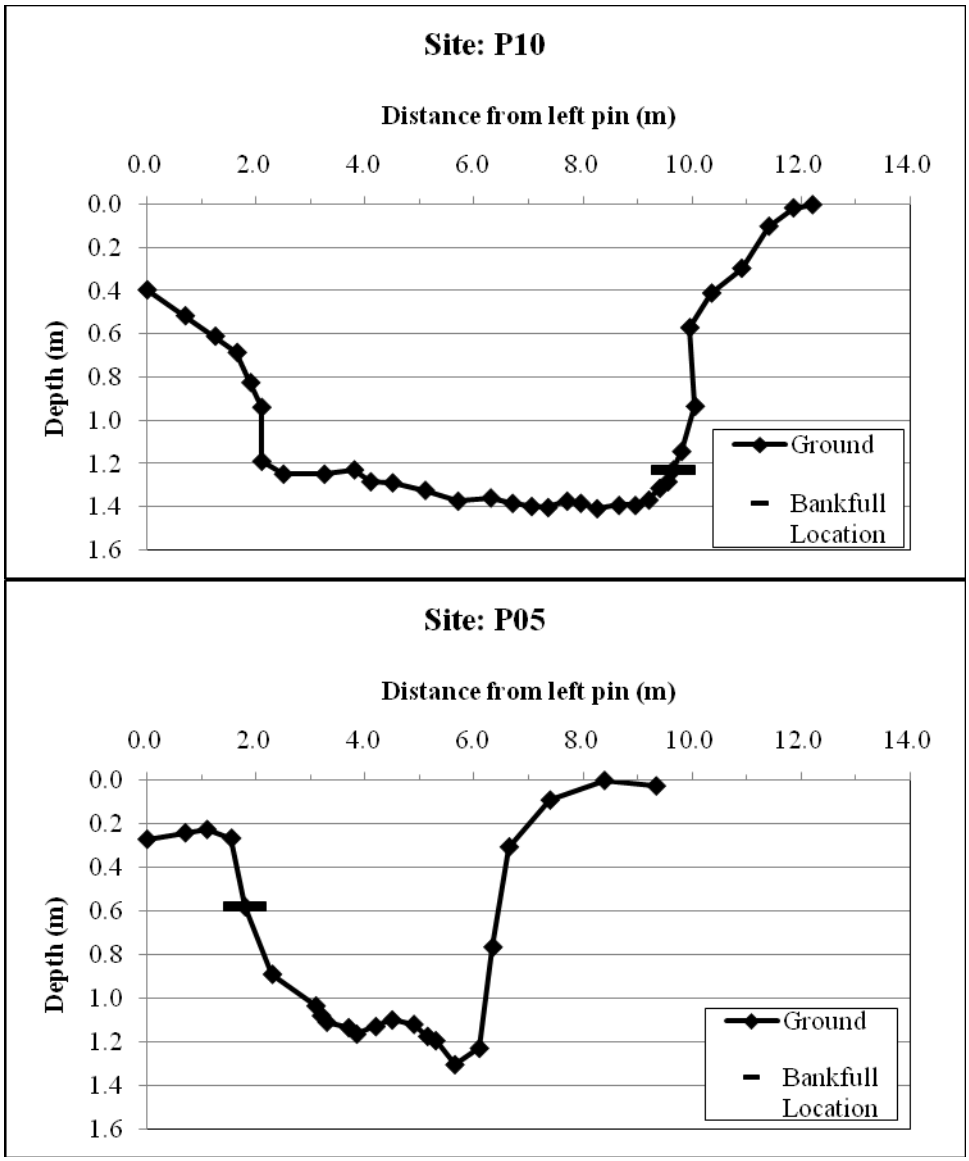

Figure 4.23. ***Plots of bankfull area (m^2) for paired sites, P10 (rural) and P05 (urban)***

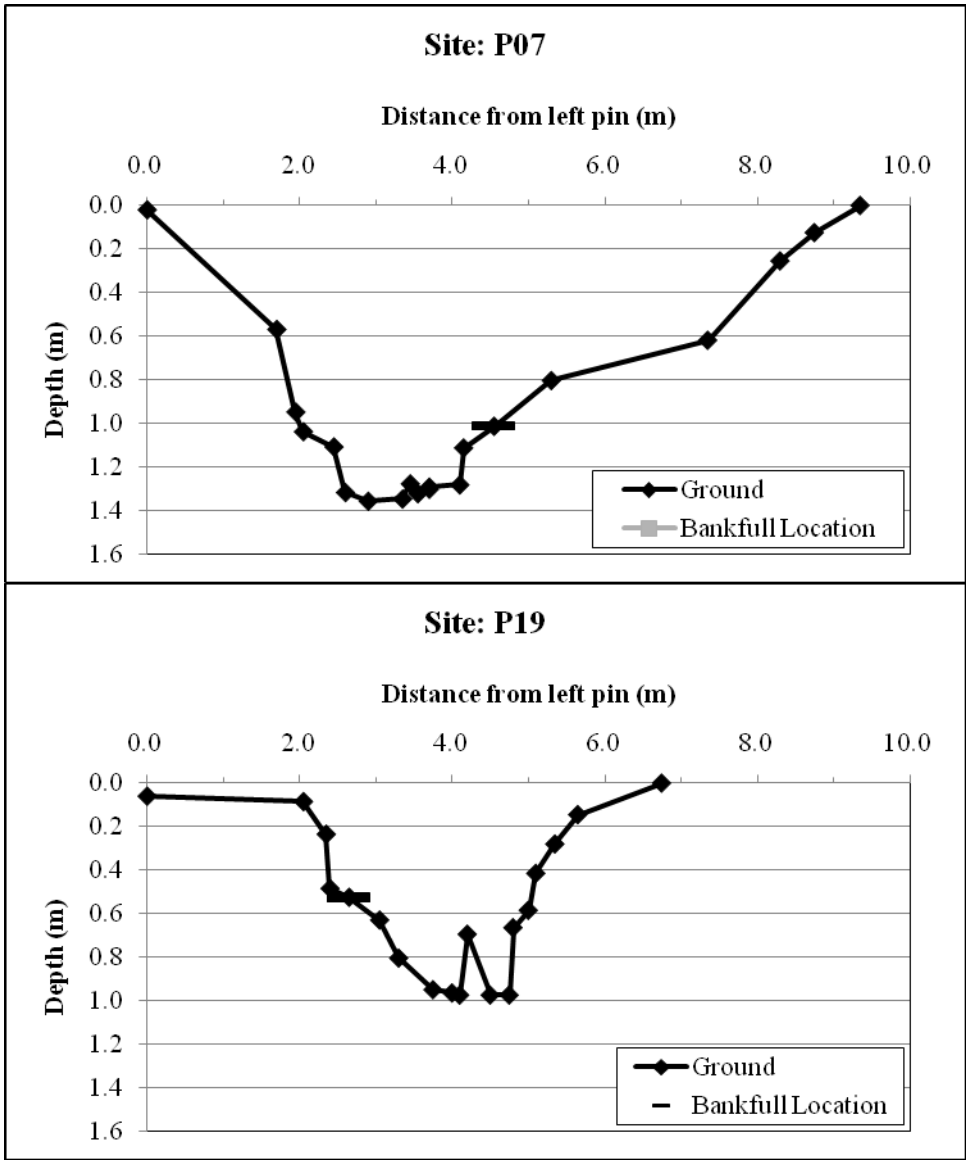

Figure 4.24. ***Plots of bankfull area (m^2) for paired sites, P07 (rural) and P19 (urban)***

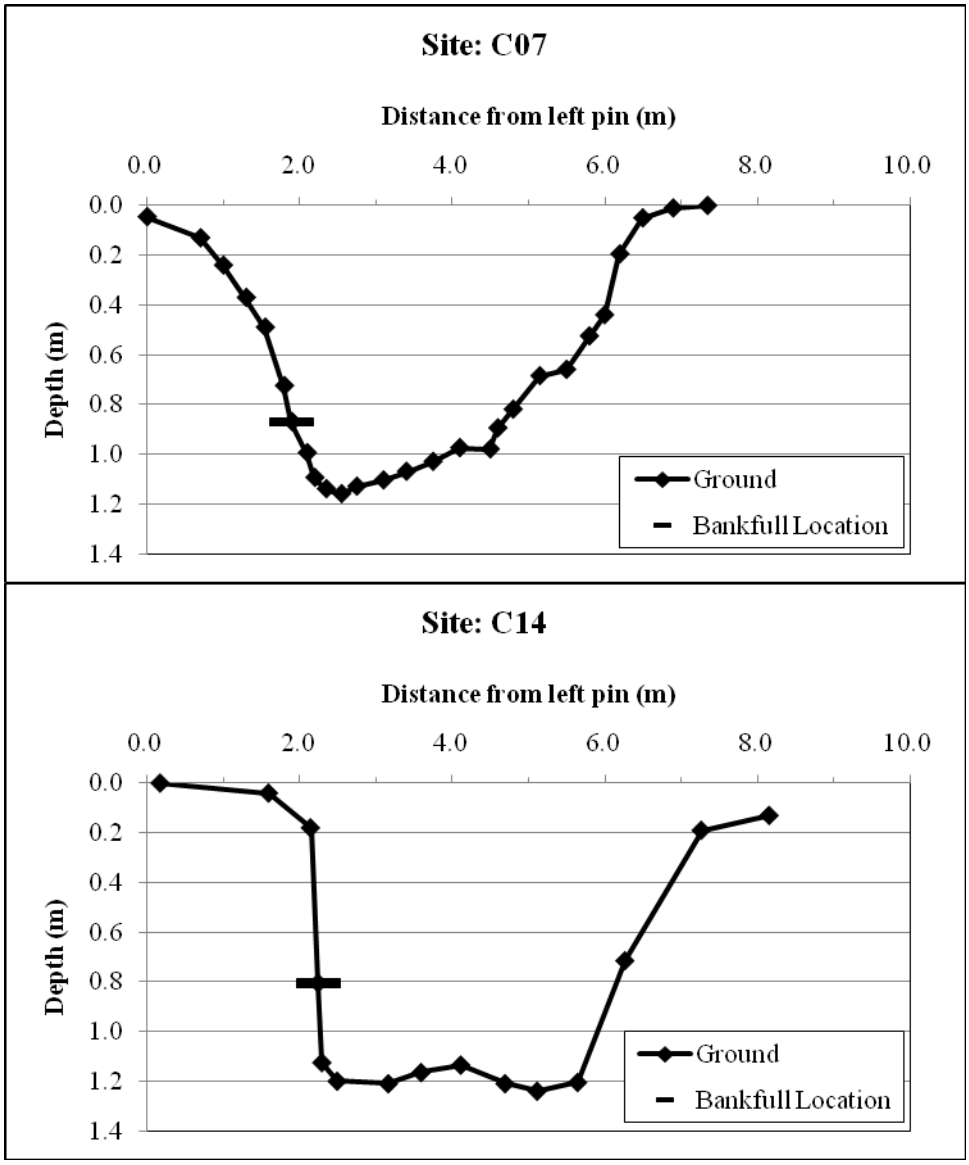

Figure 4.25. ***Plots of bankfull area (m^2) for paired sites, C07 (rural) and C14 (urban)***

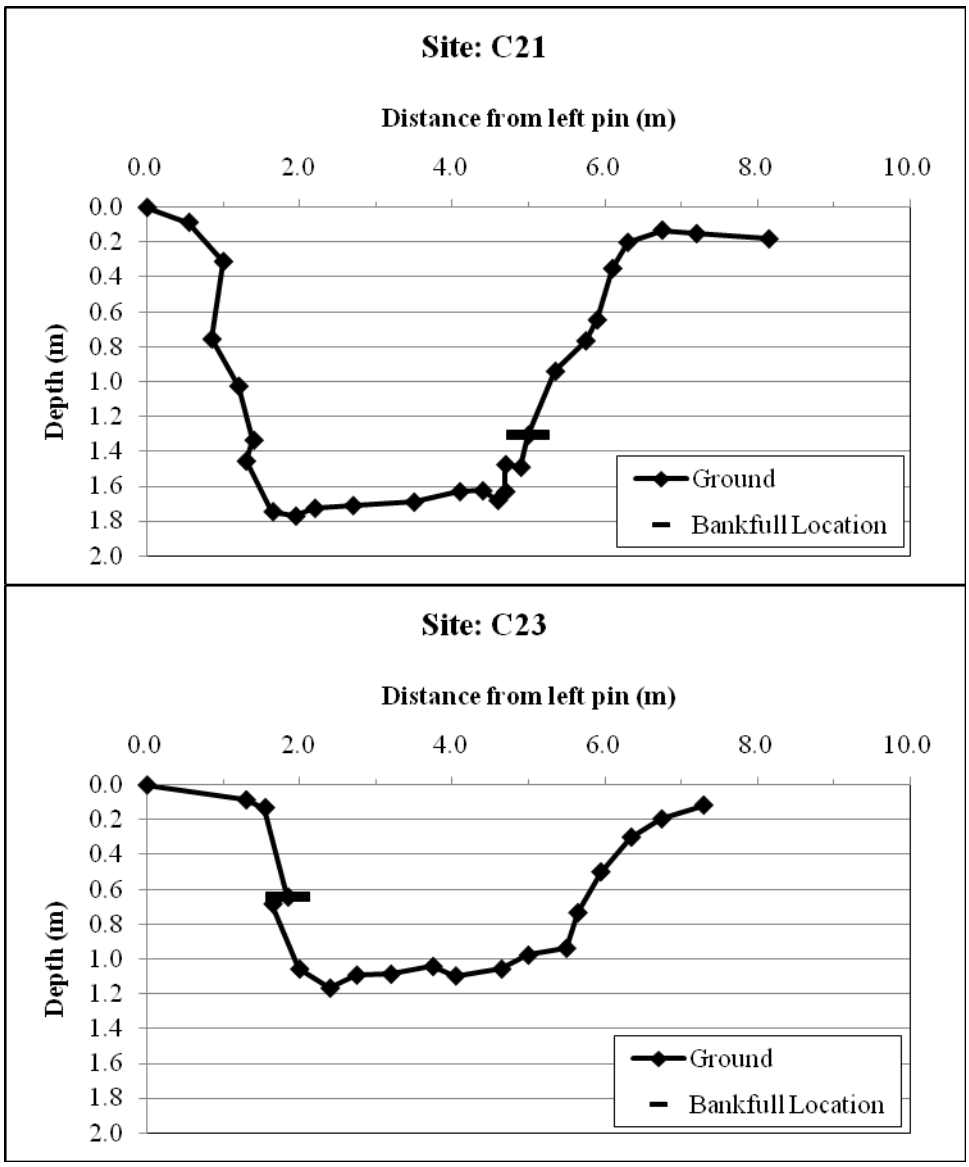

Figure 4.26. ***Plots of bankfull area (m^2) for paired sites, C21 (rural) and C23 (urban)***

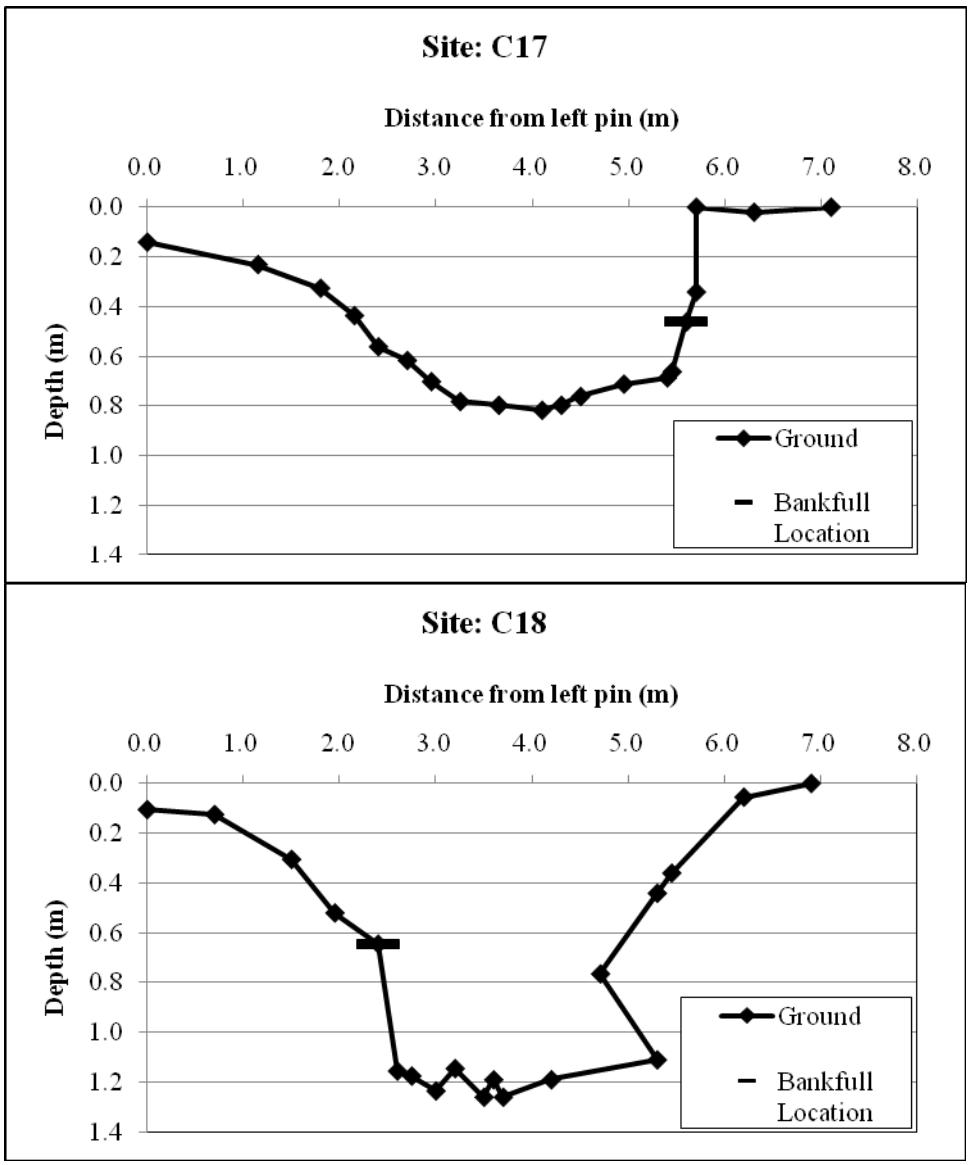

Figure 4.27. Plots of bankfull area (m2) for paired sites, C18 (rural) and C17 (urban)

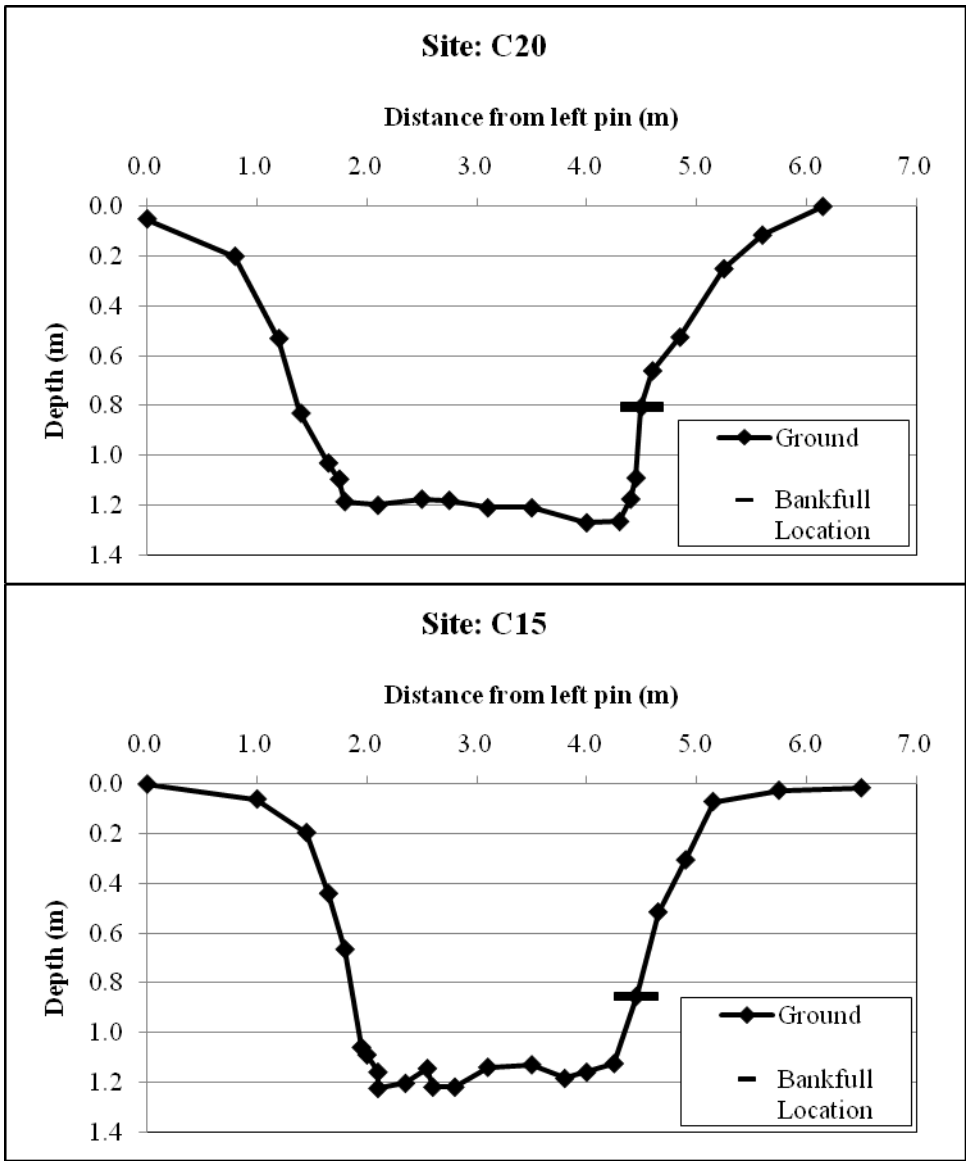

Figure 4.28. ***Plots of bankfull area (m^2) for paired sites, C20 (rural) and C15 (urban)***

Table 4.1. Measured dependent cross-section variables by site name

Site Name	A_{BF} (m^2)	W_{BF} (m)	D_{BF} (m)	P_{BF} (m)	WD_R	R_{BF} (m)	E_R	W_{FP} (m)
C01*	0.27	1.49	0.19	1.78	8.05	0.15	1.04	1.55
C02	4.88	8.01	0.62	9.19	12.88	0.53	1.39	11.10
C03	9.18	10.63	0.83	11.61	12.79	0.79	1.54	16.35
C04	0.44	2.65	0.19	2.70	14.26	0.16	1.17	3.10
C05	0.21	1.92	0.10	2.08	18.53	0.10	1.72	3.30
C06*	0.22	1.70	0.16	1.76	10.38	0.13	10.18	17.30
C07	0.49	2.77	0.20	2.90	13.97	0.17	1.37	3.80
C08*	0.94	2.72	0.29	3.95	9.46	0.24	1.36	3.70
C09	0.29	2.32	0.15	2.54	15.62	0.11	1.85	4.30
C10	0.58	2.55	0.23	2.70	11.27	0.21	2.75	7.00
C11	0.97	6.23	0.16	6.60	37.91	0.15	1.15	7.15
C12	0.27	1.32	0.22	1.53	6.00	0.18	2.12	2.80
C13	0.54	4.64	0.15	4.28	30.22	0.13	1.16	5.40
C14*	1.31	3.91	0.38	4.34	10.32	0.30	1.23	4.80
C15*	0.75	2.58	0.30	3.00	8.48	0.25	1.18	3.05
C16	0.85	3.06	0.29	3.54	10.48	0.24	1.08	3.30
C17	0.86	3.40	0.26	3.40	13.29	0.25	1.72	5.85
C18	1.72	2.53	0.55	4.28	4.63	0.40	6.45	16.30
C19	1.41	4.07	0.32	4.76	12.74	0.30	24.60	>100
C20	1.16	3.12	0.34	3.90	9.10	0.30	1.25	3.90
C21	1.34	3.62	0.31	4.59	11.78	0.29	1.20	4.35
C22	0.40	1.83	0.25	2.04	7.29	0.19	65.09	119.35
C23*	1.60	3.91	0.38	4.66	10.37	0.34	1.47	5.75
C24	0.84	3.20	0.30	3.41	10.63	0.25	1.66	5.32
C25	1.86	6.30	0.34	6.43	18.50	0.29	1.33	8.40
P01*	2.31	5.73	0.44	6.21	13.13	0.37	1.60	9.15
P02	0.51	2.18	0.28	2.61	7.75	0.20	1.63	3.55
P03	0.50	1.80	0.33	2.15	5.43	0.23	1.79	3.22
P04*	3.93	11.45	0.33	13.70	34.51	0.29	2.04	23.35
P05	2.26	4.67	0.55	5.20	8.52	0.43	2.47	11.55
P06	1.92	7.05	0.33	7.52	21.39	0.26	1.40	9.85
P07	0.55	2.53	0.24	2.90	10.61	0.19	1.86	4.70
P08	0.95	7.22	0.15	7.41	47.18	0.13	1.26	9.10
P09	0.26	2.29	0.12	2.37	18.77	0.11	1.11	2.55
P10	0.76	7.28	0.12	7.46	61.99	0.10	1.06	7.75
P11*	3.11	7.44	0.46	7.91	16.03	0.39	1.59	11.85
P12	0.77	3.47	0.23	3.66	15.06	0.21	1.43	4.95
P13	3.16	5.79	0.50	6.77	11.68	0.47	17.26	>100
P14	1.45	5.18	0.37	5.84	14.04	0.25	2.17	11.25
P15	0.30	1.58	0.23	1.75	6.96	0.17	0.88	1.40
P16*	2.82	6.71	0.45	7.06	15.05	0.40	1.52	10.18
P17	2.11	3.33	0.52	4.58	6.42	0.46	0.63	2.10
P18	3.62	8.10	0.56	8.32	14.48	0.44	1.43	11.60
P19*	0.66	2.39	0.32	3.10	7.38	0.21	1.59	3.80
P20*	1.11	3.55	0.35	3.82	10.28	0.29	21.42	76.00
P21	1.64	3.47	0.50	3.95	6.90	0.41	8.06	28.00
P22	2.49	5.98	0.46	6.31	13.05	0.39	1.51	9.00
P23	2.07	9.56	0.21	10.74	45.58	0.19	0.94	9.00
P24	0.77	3.90	0.18	4.03	22.23	0.19	1.14	4.45
P25	2.23	5.66	0.46	6.30	12.41	0.35	1.96	11.10

***Tier 2 site**

Table 4.2. Measured dependent longitudinal profile variables by site name

Site Name	$D_{PW-Upstream\ Pool}$ (m)	$D_{PR-Upstream\ Pool}$ (m)	$D_{PW-Downstream\ Pool}$ (m)	$D_{PR-Downstream\ Pool}$ (m)	S_{WS}	S_B
C01*	0.13	0.12	0.15	0.06	0.005	0.006
C02	0.36	0.24	0.25	0.21	0.004	0.002
C03	0.45	-0.04	0.37	0.16	0.003	0.005
C04	0.22	0.23	0.10	0.25	0.012	0.012
C05	0.10	0.02	0.12	0.06	0.001	0.001
C06*	0.09	0.03	0.09	0.04	0.008	0.005
C07	0.09	0.03	0.09	0.04	0.008	0.005
C08*	0.17	0.15	0.15	0.15	0.009	0.009
C09	0.32	0.37	0.13	0.14	0.009	0.009
C10	0.25	0.16	0.50	0.35	0.002	0.000
C11	0.43	0.37	0.10	0.03	0.003	0.003
C12	0.34	0.33	0.00	0.14	-0.001	-0.001
C13	0.36	0.31	0.10	0.10	0.003	0.000
C14*	0.25	0.22	0.06	0.04	0.003	0.003
C15*	0.15	0.12	0.31	0.21	0.011	0.017
C16	0.03	0.01	0.10	0.06	0.009	0.009
C17	0.44	0.32	0.40	0.37	0.005	0.003
C18	0.24	0.11	0.69	1.32	0.010	0.010
C19	N/A	N/A	0.65	0.35	-0.001	0.001
C20	0.18	0.13	0.11	0.03	0.012	0.012
C21	0.09	0.06	0.08	0.02	0.004	0.004
C22	0.65	0.59	0.45	0.38	0.002	0.003
C23*	0.34	0.29	0.19	0.09	0.016	0.018
C24	0.05	0.04	0.09	0.02	0.005	0.007
C25	0.40	1.12	0.80	0.83	0.001	0.001
P01*	0.58	0.47	0.52	0.45	0.004	0.003
P02	0.15	0.13	0.14	0.13	0.018	0.018
P03	0.09	0.03	0.09	0.04	0.008	0.005
P04*	0.31	0.19	0.33	0.23	0.012	0.015
P05	0.40	0.38	0.29	0.24	0.009	0.010
P06	0.29	0.23	0.68	0.68	0.008	0.007
P07	0.03	0.06	0.10	0.04	0.041	0.041
P08	0.48	0.48	0.15	0.15	0.005	0.005
P09	0.15	0.15	0.23	0.19	-0.008	0.004
P10	0.26	0.21	0.08	0.05	0.006	0.007
P11*	0.26	0.19	0.25	-0.81	0.005	0.004
P12	0.25	0.28	0.10	0.09	-0.001	-0.001
P13	0.47	0.48	0.25	0.24	0.004	0.004
P14	0.23	0.17	0.25	0.26	0.018	0.018
P15	0.05	0.04	0.07	0.03	0.007	0.008
P16*	0.28	0.25	0.88	0.38	0.003	0.004
P17	0.00	0.38	0.00	0.12	0.010	0.010
P18	0.09	0.03	0.31	0.19	0.003	0.005
P19*	0.06	0.04	0.14	-0.04	0.012	0.013
P20*	0.33	0.28	0.45	0.37	0.004	0.004
P21	0.33	0.28	0.14	0.09	0.008	0.007
P22	0.19	0.11	0.13	0.14	0.002	0.001
P23	0.26	0.25	0.24	0.22	0.016	0.013
P24	0.04	0.02	0.20	0.13	0.003	0.004
P25	0.31	0.27	0.37	0.31	0.004	0.004

Tier 2 site

Table 4.3. Enlargement ratios and sediment yield by site name

Site Name	ER_W	ER_D	ER_A	Sediment Yield (m^3)
C01*	0.80	0.72	0.55	-0.22
C02	1.23	1.15	1.39	1.37
C03	1.43	1.42	2.11	4.83
C04	0.95	0.57	0.48	-0.48
C05	0.80	0.35	0.29	-0.52
C06*	0.71	0.55	0.31	-0.49
C07	0.56	0.43	0.21	-1.80
C08*	1.22	1.00	1.45	0.29
C09	1.22	0.57	0.57	-0.22
C10	0.58	0.53	0.31	-1.30
C11	1.13	0.34	0.36	-1.72
C12	0.79	0.91	0.66	-0.14
C13	1.67	0.47	0.59	-0.37
C14*	0.75	0.80	0.53	-1.16
C15*	0.65	0.75	0.46	-0.87
C16	2.06	1.30	2.51	0.51
C17	0.93	0.67	0.61	-0.55
C18	0.84	1.60	1.66	0.68
C19	0.86	0.71	0.66	-0.72
C20	0.73	0.81	0.64	-0.65
C21	0.82	0.71	0.70	-0.58
C22	0.62	0.74	0.39	-0.62
C23*	0.87	0.87	0.81	-0.37
C24	1.23	0.96	1.02	0.02
C25	0.65	0.50	0.28	-4.75
P01*	1.41	1.59	2.07	1.19
P02	0.29	0.67	0.16	-2.62
P03	0.15	0.54	0.07	-7.00
P04*	1.55	0.79	1.26	0.81
P05	1.51	2.43	3.24	1.56
P06	0.93	0.76	0.58	-1.37
P07	1.09	1.30	1.30	0.13
P08	1.26	0.44	0.47	-1.07
P09	1.07	0.71	0.70	-0.11
P10	2.33	0.52	1.07	0.05
P11*	0.91	1.02	0.83	-0.64
P12	0.55	0.61	0.32	-1.61
P13	0.81	1.21	1.08	0.22
P14	1.01	1.14	0.87	-0.22
P15	0.13	0.38	0.04	-6.78
P16*	0.88	1.03	0.85	-0.50
P17	0.65	1.61	1.28	0.46
P18	1.70	1.82	2.47	2.16
P19*	0.80	1.47	1.00	0.00
P20*	1.00	1.39	1.26	0.23
P21	0.61	1.43	0.81	-0.38
P22	0.78	1.06	0.75	-0.81
P23	1.45	0.54	0.81	-0.49
P24	0.65	0.48	0.35	-1.42
P25	0.90	1.21	0.94	-0.13

***Tier 2 site**

Table 4.4. Results of the Wilcoxon Rank Sum Test on Coastal Plain and Piedmont sites for the regional curve data (n=20; Krstolic and Chaplin 2007; Cinotto 2003) and measured project data (n=50)

Regional Curve Parameters		Measured Project Variables	
Variable	*p-value*	Variable	*p-value*
A_{BF}^{+}	0.98	A_{BF}^{+}	0.39
W_{BF}^{++}	0.00*	W_{BF}^{++}	0.04*
D_{BF}^{++}	0.00*	D_{BF}^{++}	0.81
WD_R	0.00*	P_{BF}^{++}	0.03*
S_B	0.77	WD_R	0.31
		R_{BF}^{++}	0.64
		E_R	0.83
		W_{FP}^{++}	0.42
		$D_{PR\text{ - Upstream pool}}^{++}$	0.77
		$D_{PR\text{ - Downstream pool}}^{++}$	0.77
		S_B	0.31
		S_{WS}	0.45

$^{+}$ Normalized by dividing by *WA*
$^{++}$ Normalized by dividing by square root of *WA*
* Significant model, $p < 0.05$

Table 4.5. Independent watershed variables by site name

Site Name	*WA* (km^2)	Roads	Geologic Rock Division$^+$	PIC_{1990} (%)	PIC_{2000} (%)	$PIC_{1990\text{-}2000}$ (%)	PIC_R
C01*	0.6	2	TE	0.65	1.42	0.45	0.32
C02	15.4	7	TE	3.69	6.76	2.75	0.41
C03	21.8	15	TE	3.87	5.91	1.77	0.30
C04	1.7	0	TE	0.00	0.01	0.00	0.00
C05	1.1	0	TE	0.37	0.84	0.45	0.54
C06*	1.1	0	TE	2.57	2.87	0.19	0.06
C07	7.6	0	TE	0.10	0.40	0.29	0.72
C08*	0.9	2	TE	0.01	0.10	0.05	0.53
C09	0.6	3	TE	1.63	2.22	0.39	0.18
C10	5.5	0	TE	0.05	0.40	0.29	0.73
C11	9.9	0	TE	0.08	0.68	0.45	0.66
C12	0.4	1	TE	0.02	0.25	0.20	0.78
C13	1.7	0	TE	0.30	1.53	0.86	0.57
C14*	8.6	14	TE	4.17	10.36	5.23	0.51
C15*	4.3	5	TE	3.66	8.21	3.79	0.46
C16	0.3	1	TE	0.03	0.12	0.06	0.49
C17	3.4	1	TE	11.51	18.83	6.61	0.35
C18	2.0	3	TE	0.26	1.84	1.36	0.74
C19	6.7	1	TE	0.52	1.20	0.62	0.52
C20	5.1	2	TE	0.01	0.39	0.35	0.89
C21	5.7	2	TE	0.00	0.12	0.08	0.64
C22	2.0	0	TE	0.01	0.03	0.01	0.48
C23*	5.9	6	TE	9.13	18.68	8.96	0.48
C24	1.4	2	TE	0.02	0.26	0.16	0.63
C25	43.5	14	TE	0.05	0.50	0.37	0.74
P01*	2.5	3	MI	52.71	54.49	1.65	0.03
P02	8.9	11	MI	22.11	25.18	2.75	0.11
P03	26.2	27	MI	9.49	13.16	3.22	0.24
P04*	8.9	10	MI	25.27	36.41	10.81	0.30
P05	1.4	8	MI	21.89	25.22	2.99	0.12
P06	9.5	9	MI	12.59	14.28	1.43	0.10
P07	0.8	0	MI	0.36	1.15	1.00	0.87
P08	5.2	0	MI	0.02	0.04	0.01	0.24
P09	0.6	2	MI	4.24	9.62	4.56	0.47
P10	1.4	0	MI	0.01	0.11	0.08	0.69
P11*	11.1	5	MI	0.83	2.07	1.16	0.56
P12	6.3	5	GG	2.85	9.36	5.52	0.59
P13	8.2	3	GG	0.01	0.13	0.08	0.63
P14	4.1	0	MI	0.02	0.13	0.07	0.51
P15	24.4	4	MI	0.02	0.22	0.16	0.73
P16*	9.6	2	GG	0.09	0.51	0.35	0.68
P17	4.0	1	GG	0.13	0.68	0.51	0.76
P18	3.5	4	GG	1.66	6.80	4.94	0.73
P19*	1.3	3	GG	18.11	24.81	5.56	0.22
P20*	1.9	6	GG	3.36	6.68	2.30	0.34
P21	5.2	3	GG	2.33	8.94	5.84	0.65
P22	9.5	0	TR	0.02	0.31	0.26	0.82
P23	6.9	5	GG	0.36	3.61	2.73	0.76
P24	5.7	1	GG	0.00	0.15	0.12	0.77
P25	6.3	0	GG	0.03	0.09	0.06	0.67

*Tier 2 site

$^+$GG = Granite and Gneiss, MI = Metamorphic Rocks and Igneous Intrusives, TE = Tertiary, TR = Triassic

Table 4.6. Significant stepwise multiple linear regression models (α = 0.25) for site group, Coastal Plain (Correlation models: C1, C2, C3)

Parameters+			Results*									
y (log)	x (log)		SSE	MSE	R^2	R^2 Adj	Cp	*p* (Model)	*p* (Variables)	Standardized Beta	PRESS	PRESS ≈ SSE ?
A_{BF}	*WA*		0.60	0.03	0.45	0.43	1.36	0.002	*WA*: 0.000	*WA*: 0.674	0.77	YES
	WA	*Roads*	0.40	0.02	0.64	0.60	2.28	<0.0001	*WA*: 0.007, *Roads*: 0.003	*WA*: 0.440, *Roads*: 0.488	0.60	YES
W_{BF}	*WA*		0.29	0.01	0.59	0.57	0.71	0.000	*WA*: <0.000	*WA*: 0.768	0.36	YES
	WA	*Roads*	0.27	0.01	0.62	0.59	2.53	<0.0001	*WA*: 0.000; *Roads*: 0.189	*WA*: 0.671, *Roads*: 0.203	0.37	YES
D_{BF}	*WA*	PIC_{2000}	0.04	0.00	0.33	0.27	2.12	0.012	*WA*: 0.023, PIC_{2000}: 0.197	*WA*: 0.450, PIC_{2000}: 0.244	0.05	YES
	WA	*Roads*	0.03	0.01	0.58	0.54	2.00	0.000	*WA*: 0.195, *Roads*: 0.001	*WA*: 0.226, *Roads*: 0.626	0.04	YES
	$PIC_{1990\text{-}2000}$		0.05	0.00	0.17	0.14	1.43	0.039	$PIC_{1990\text{-}2000}$: 0.039	$PIC_{1990\text{-}2000}$: 0.416	0.06	YES
P_{BF}	*WA*		0.31	0.01	0.55	0.54	0.24	<0.0001	*WA*: <0.000	*WA*: 0.745	0.39	YES
	WA	*Roads*	0.27	0.01	0.63	0.59	2.01	<0.0001	*WA*: 0.001, *Roads*: 0.055	*WA*: 0.600, *Roads*: 0.302	0.37	YES
WD_R	*WA*	*Roads*	0.57	0.03	0.27	0.20	3.00	0.032	*WA*: 0.017, *Roads*: 0.034	*WA*: 0.539, *Roads*: -0.471	0.75	YES
R_{BF}	*WA*	PIC_{2000}	0.03	0.00	0.39	0.33	2.03	0.005	*WA*: 0.009, PIC_{2000}: 0.185	*WA*: 0.503, PIC_{2000}: 0.241	0.04	YES
	WA	*Roads*	0.02	0.00	0.58	0.54	2.03	<0.0001	*WA*: 0.063, *Roads*: 0.002	*WA*: 0.309, *Roads*: 0.561	0.03	YES
	$PIC_{1990\text{-}2000}$		0.04	0.00	0.18	0.14	1.35	0.036	$PIC_{1990\text{-}2000}$: 0.036	$PIC_{1990\text{-}2000}$: 0.420	0.05	YES
ER_D	*WA*	*Roads*	0.42	0.02	0.43	0.38	2.43	0.002	*WA*: 0.023, *Roads*: 0.001	*WA*: -0.447, *Roads*: 0.744	0.59	YES
ER_A	*WA*	*Roads*	1.25	0.06	0.35	0.29	2.13	0.009	*WA*: 0.025, *Roads*: 0.004	*WA*: -0.473, *Roads*: 0.643	1.79	YES

+ Log-transformed x and y variables in regression models

*SSE=Error sum of squares; MSE=Mean squared error; R^2=Coefficient of determination; R^2 Adj=Adjusted coefficient of determination; p=measure of probability; Standardized Beta=Estimate of analysis performed on standardized variables; PRESS=Predicted residual sums of squares

Table 4.7. Significant stepwise multiple linear regression models (α = 0.25) for site group, All Sites (Correlation models: A1, A2)

Parameters+			Results*									
y (log)	x (log)		SSE	MSE	R^2	R^2 Adj	Cp	*p* (Model)	*p* (Variables)	Standardized Beta	PRESS	PRESS ≈ SSE ?
A_{BF}	*WA*	PIC_{2000}	1.41	0.03	0.29	0.26	3.00	0.000	*WA* : 0.000, PIC_{2000}: 0.169	*WA* : 0.496, PIC_{2000}: 0.172	1.63	YES
	WA	$PIC_{1990\text{-}2000}$	1.41	0.03	0.29	0.26	2.06	0.000	*WA* : 0.000, $PIC_{1990\text{-}2000}$: 0.171	*WA* : 0.487, $PIC_{1990\text{-}2000}$: 0.173	1.62	YES
W_{BF}	*WA*		1.33	0.03	0.24	0.22	0.55	0.000	*WA* : 0.000	*WA* : 0.485	1.46	YES
D_{BF}	*WA*	PIC_{2000}	0.09	0.00	0.21	0.18	3.00	0.004	*WA* : 0.006, PIC_{2000}: 0.094	*WA* : 0.379, PIC_{2000}: 0.222	0.10	YES
	WA	$PIC_{1990\text{-}2000}$	0.09	0.00	0.20	0.17	2.05	0.005	*WA* : 0.007, $PIC_{1990\text{-}2000}$: 0.128	*WA* : 0.371, $PIC_{1990\text{-}2000}$: 0.204	0.10	YES
P_{BF}	*WA*		1.31	0.03	0.23	0.21	0.86	0.000	*WA* : 0.000	*WA* : 0.480	1.44	YES
R_{BF}	*WA*	PIC_{2000}	0.07	0.00	0.22	0.19	3.00	0.003	*WA* : 0.417, PIC_{2000}: 0.180	*WA* : 0.002, PIC_{2000}: 0.171	0.08	YES
	WA	$PIC_{1990\text{-}2000}$	0.07	0.00	0.22	0.19	2.20	0.003	*WA* : 0.003, $PIC_{1990\text{-}2000}$: 0.185	*WA* : 0.408, $PIC_{1990\text{-}2000}$: 0.175	0.08	YES
ER_W	*WA*		2.13	0.04	0.19	0.17	1.10	0.002	*WA* : 0.002	*WA* : -0.437	2.39	YES
ER_D	*WA*	PIC_{2000}	1.77	0.04	0.13	0.09	3.00	0.036	*WA* : 0.125, PIC_{2000}: 0.025	*WA* : -0.213, PIC_{2000}: 0.317	1.98	YES
ER_A	*WA*	PIC_{2000}	5.37	0.11	0.17	0.14	3.00	0.012	*WA* : 0.005, PIC_{2000}: 0.169	*WA* : -0.391, PIC_{2000}: 0.187	6.26	YES
	WA	$PIC_{1990\text{-}2000}$	5.31	0.11	0.18	0.15	2.57	0.009	*WA* : 0.004, $PIC_{1990\text{-}2000}$: 0.125	*WA* : -0.405, $PIC_{1990\text{-}2000}$: 0.209	6.13	YES

+ Log-transformed x and y variables in regression models
*SSE=Error sum of squares; MSE=Mean squared error; R^2=Coefficient of determination; R^2 Adj=Adjusted coefficient of determination; p=measure of probability; Standardized Beta=Estimate of analysis performed on standardized variables; PRESS=Predicted residual sums of squares

Table 4.8. Significant stepwise multiple linear regression models (α = 0.25) for site group Piedmont (Correlation models: P1, P2, P3)

Parameters+		Results*									
y (log)	x (log)	SSE	MSE	R^2	R^2 Adj	Cp	*p* (Model)	*p* (Variables)	Standardized Beta	PRESS	PRESS ≈ SSE ?
ER_W	*WA*	1.32	0.06	0.37	0.34	1.22	0.001	*WA*: 0.001	*WA*: -0.607	1.68	YES
ER_D	*WA*	0.92	0.04	0.19	0.15	2.09	0.032	*WA*: .032	*WA*: -0.431	1.12	YES
ER_A	*WA*	2.75	0.12	0.39	0.37	1.03	0.001	*WA*: .001	*WA*: -0.628	3.55	YES

+ Log-transformed x and y variables in regression models

*SSE=Error sum of squares; MSE=Mean squared error; R^2=Coefficient of determination; R^2 Adj=Adjusted coefficient of determination; p=measure of probability; Standardized Beta=Estimate of analysis performed on standardized variables; PRESS=Predicted residual sums of squares

Table 4.9. Independent and dependent characteristics of paired study sites

Site Name	*WA* (km^2)	PIC_{2000} (%)	A_{BF} (m^2)	W_{BF} (m)	D_{BF} (m)
C07	7.6	0.40	0.49	2.77	0.20
C14*	8.6	10.36	1.31	3.91	0.38
C15*	4.3	8.21	0.75	2.58	0.30
C20	5.1	0.39	1.16	3.12	0.34
C17	3.4	18.83	0.86	3.40	0.26
C18	2.0	1.84	1.72	2.53	0.55
C21	5.7	0.12	1.34	3.62	0.31
C23*	5.9	18.68	1.60	3.91	0.38
P01*	2.5	54.49	2.31	5.73	0.44
P20*	1.9	6.68	1.11	3.55	0.35
P05	1.4	25.22	2.26	4.67	0.55
P10	1.4	0.11	0.76	7.28	0.12
P06	9.5	14.28	1.92	7.05	0.33
P22	9.5	0.31	2.49	5.98	0.46
P04*	8.9	36.41	3.93	11.45	0.33
P13	8.2	0.13	3.16	5.79	0.50
P07	0.8	1.15	0.55	2.53	0.24
P19*	1.3	24.81	0.66	2.39	0.32

Tier 2 site

4.3. Detailed Geomorphic Surveys and Watershed Condition (Tier 2) Data Analysis Report (Product #6)

This report will document the methods used, the data collected (geomorphic and watershed), and a comparison between field-based channel erosion monitoring over a six-month period versus physiographic region/land use for each of the Tier 2 sites. We will provide an estimate of annual sediment load due to channel enlargement in relation to multivariate analyses of stream, watershed (e.g. land use), and physiographic characteristics.

From the original set of 50 Tier 1 sites, we selected a subset of 12 (6 Coastal Plain, 6 Piedmont) sites to monitoring for channel change over time. The 12 Tier 2 sites were selected based on the following factors: 1) we needed 6 sites within each physiographic region; 2) we wanted the sites within each region to represent a gradient of watershed-level urbanization (from rural to urban); and 3) we solicited feedback from our Advisory Committee on appropriate sites, as well as information regarding where we would expect older versus newer development. It is important to note that we did NOT select these Tier 2 sites prior to collecting Tier 1 data. Therefore, we did not place permanent rebar in the Tier 2 sites until our second visit during the Fall 2007.

During the study period, one riffle cross-section for each of the 12 Tier 2 sites was surveyed three times (Summer 2007, Fall 2007, and Spring 2008) to assess channel change over-time. Since the first surveyed cross sections (Summer 2007) were conducted prior to installing permanent rebar, the Summer 2007 plots (Figures 4.29-4.40) had to be aligned with the second two surveys visually, using obvious breaks in

slope, etc. Therefore, some of the differences seen between Summer 2007 cross-sectional plots and later plots might be due to error in alignment. However, since the permanent rebars were in place for the Fall 2007 and Spring 2008 surveys, their cross-sectional plots are aligned correctly, and more can be made of changes between these two time periods.

Plots for the repeated surveys of each site are presented on Figures 4.29 through 4.40. Few changes in cross-sectional shape and size are observed in sites C14 and P01; however, most other sites experienced some cross-sectional change (Figures 4.32 and 4.35). At sites C08, P16, and P20, there is evidence to suggest possible aggradation during the study period (Figures 4.31, 4.38, and 4.40). Figure 4.33 suggests possible widening of site C15. Changes in streambank shape are observed at sites C01, C23, P11, and P19 (Figures 4.29, 4.34, 4.37, and 4.39), and bed down-cutting is observed at site C06 (Figure 4.30).

In summary, not much change has happened in these streams during the 8-month study period. This is not surprising, especially since we have been in the midst of a major drought throughout this period. The value here is that we now have 12 monumented (with rebar) cross sections that can be monitored for change over a longer time period.

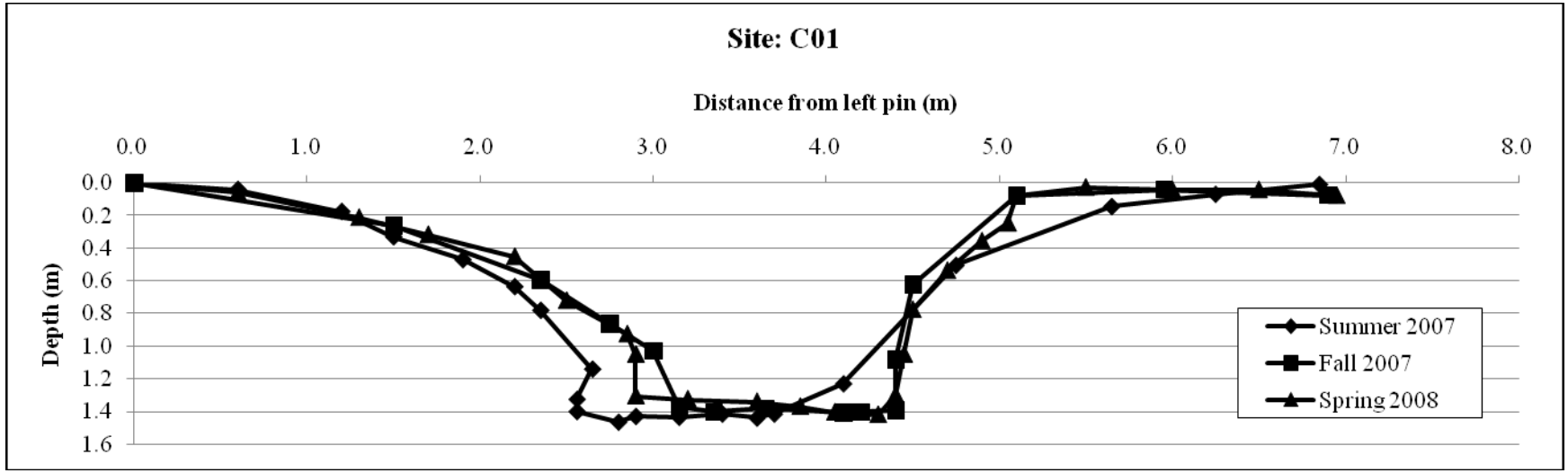

Figure 4.29. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C01

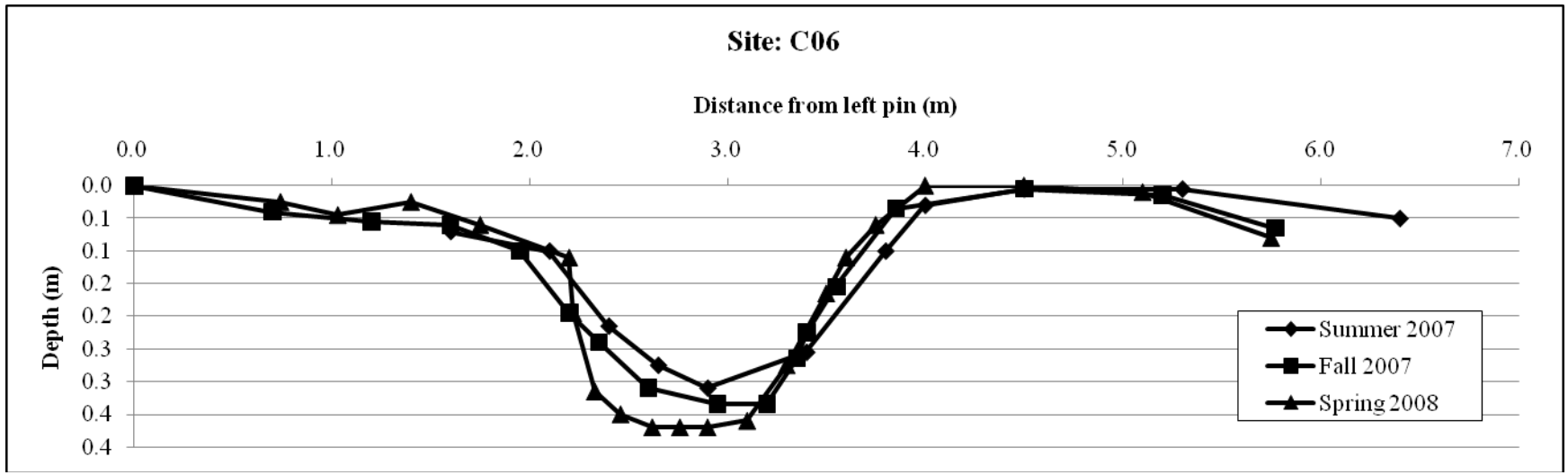

Figure 4.30. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C06

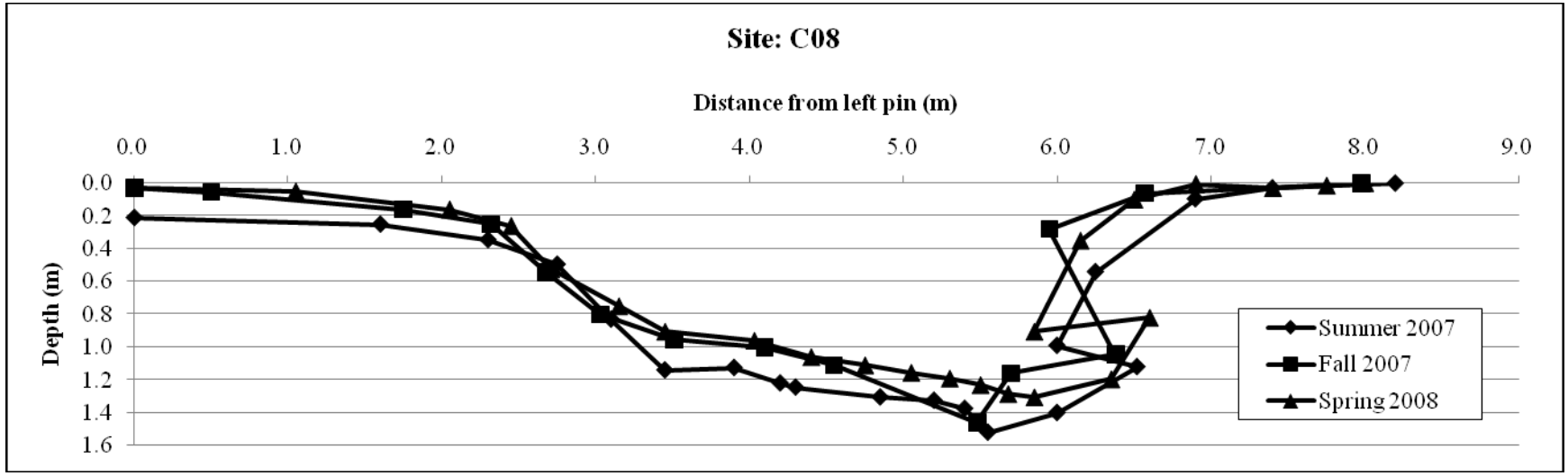

Figure 4.31. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C08

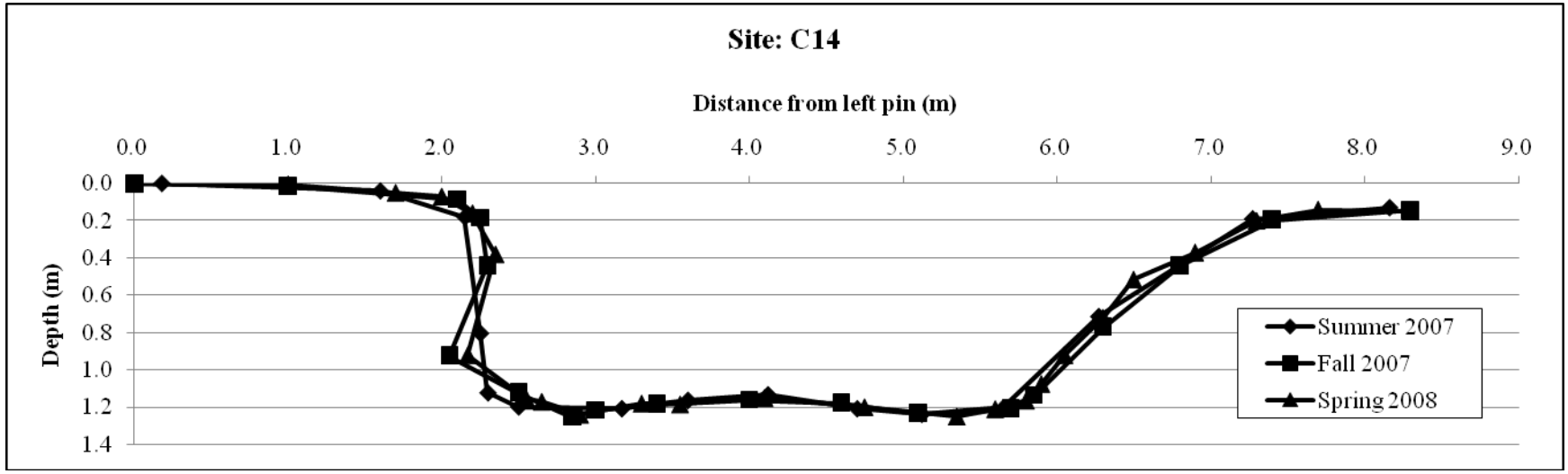

Figure 4.32. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C14

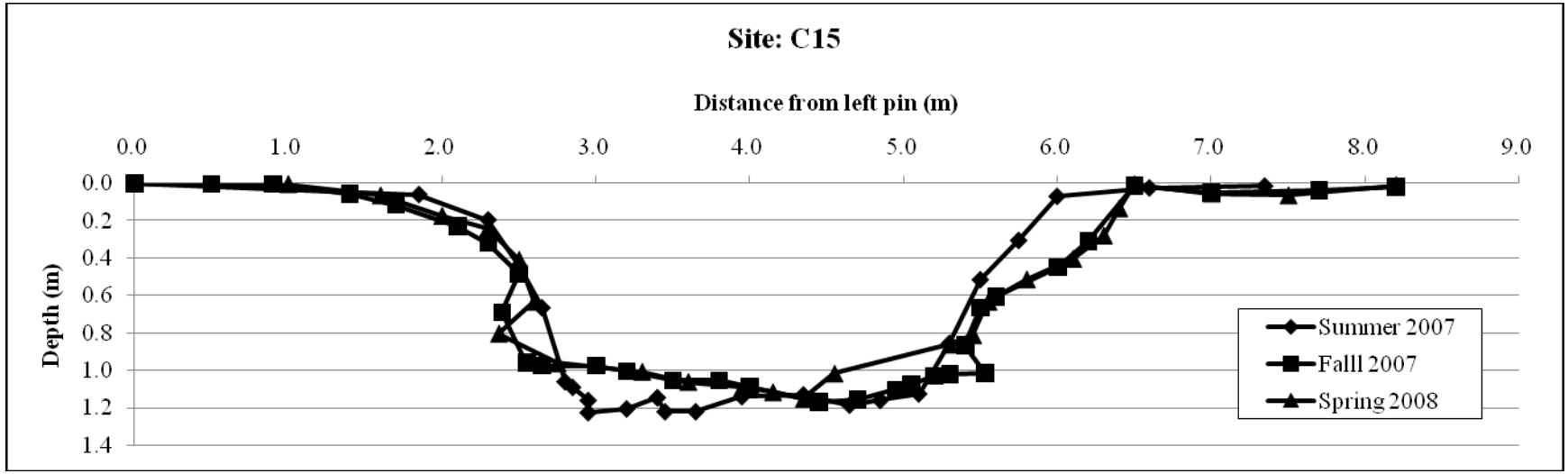

Figure 4.33. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C15

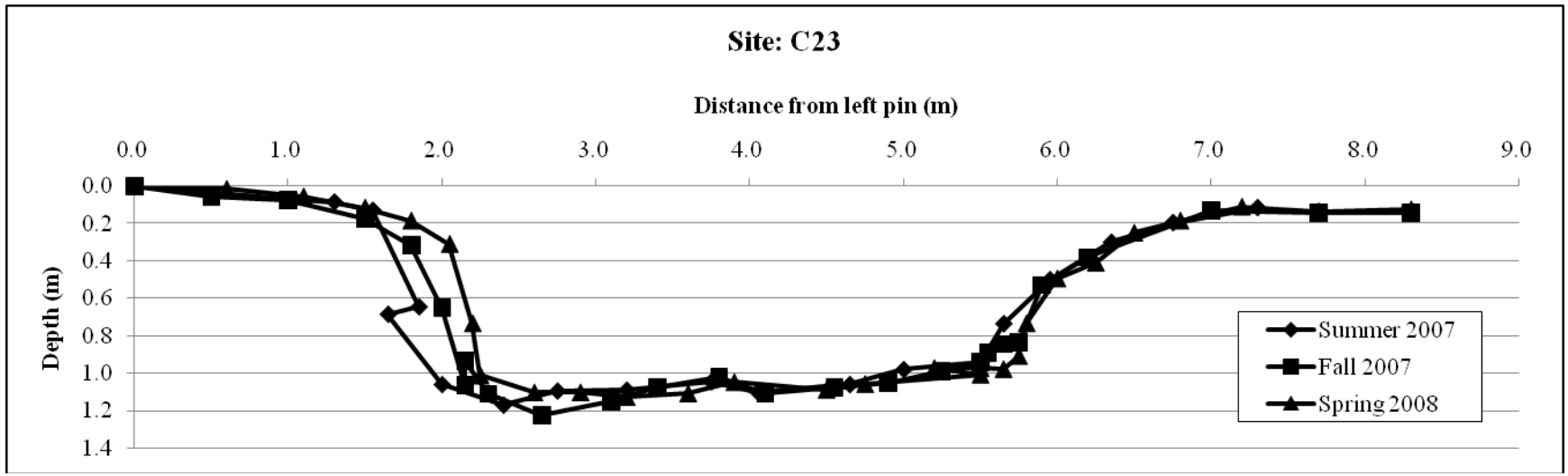

Figure 4.34. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for coastal plain site, C23

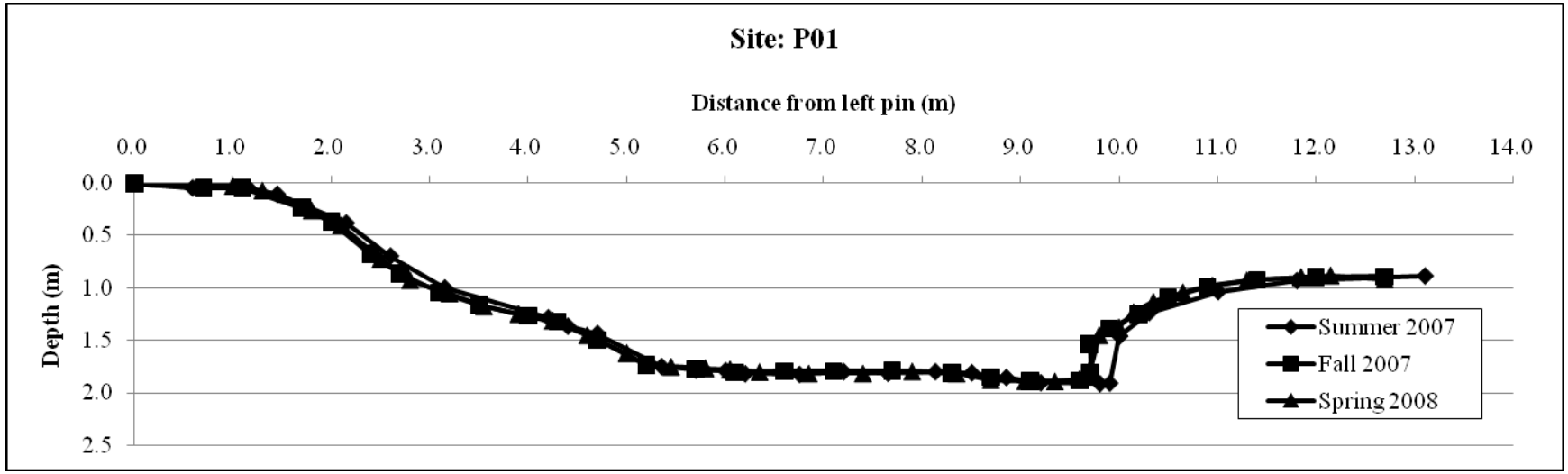

Figure 4.35. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P01

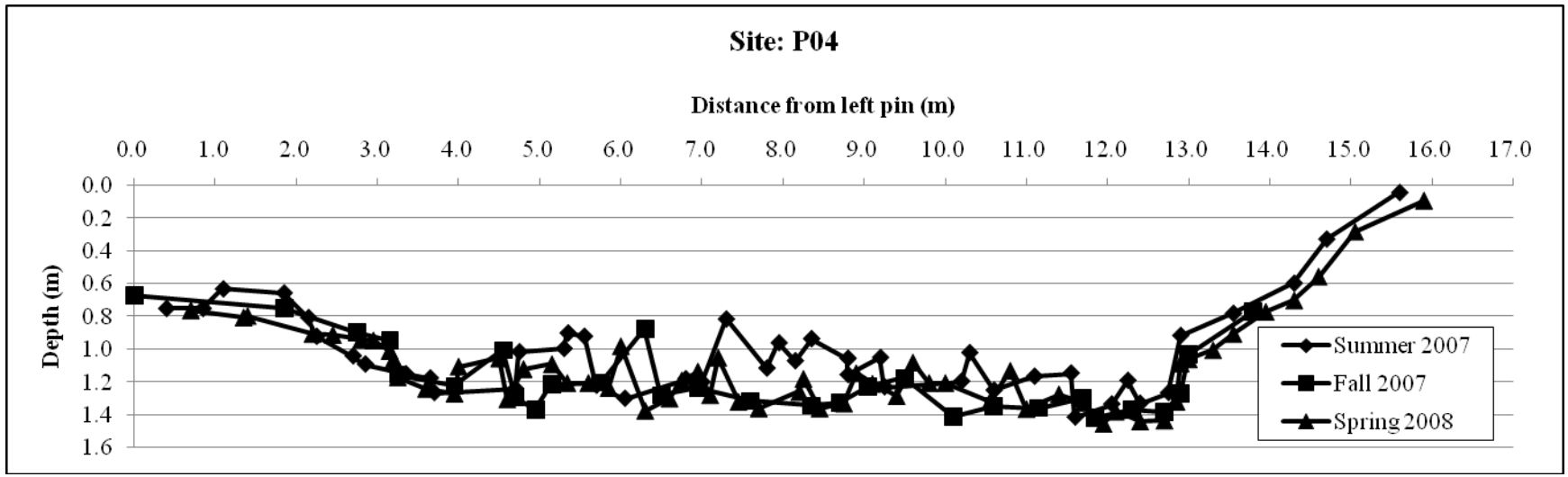

Figure 4.36. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P04

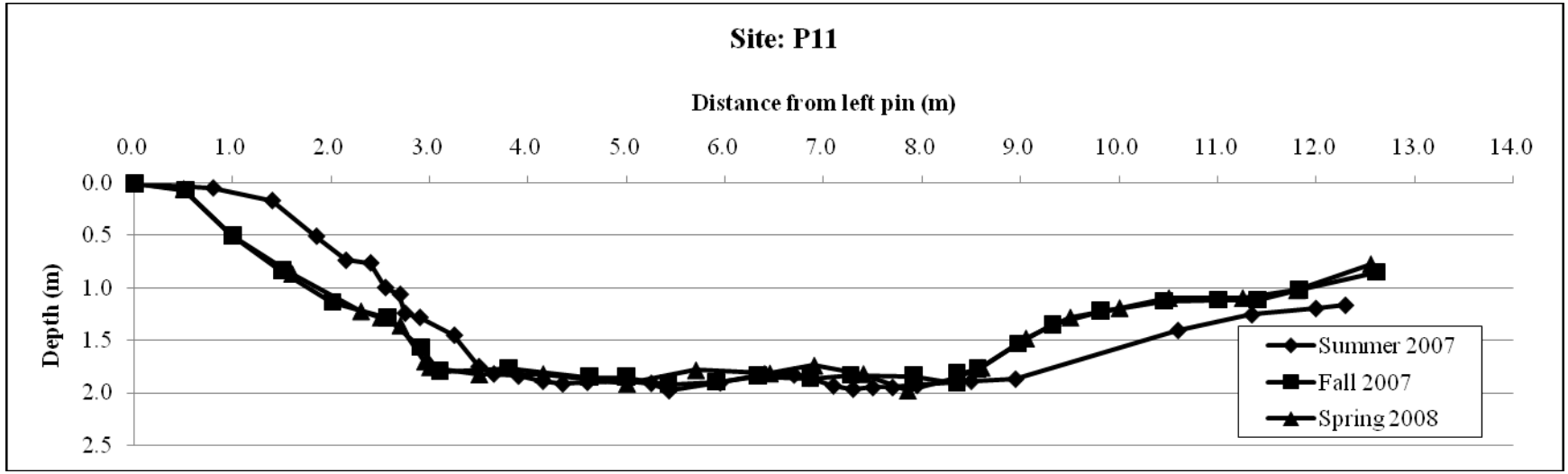

Figure 4.37. Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P11

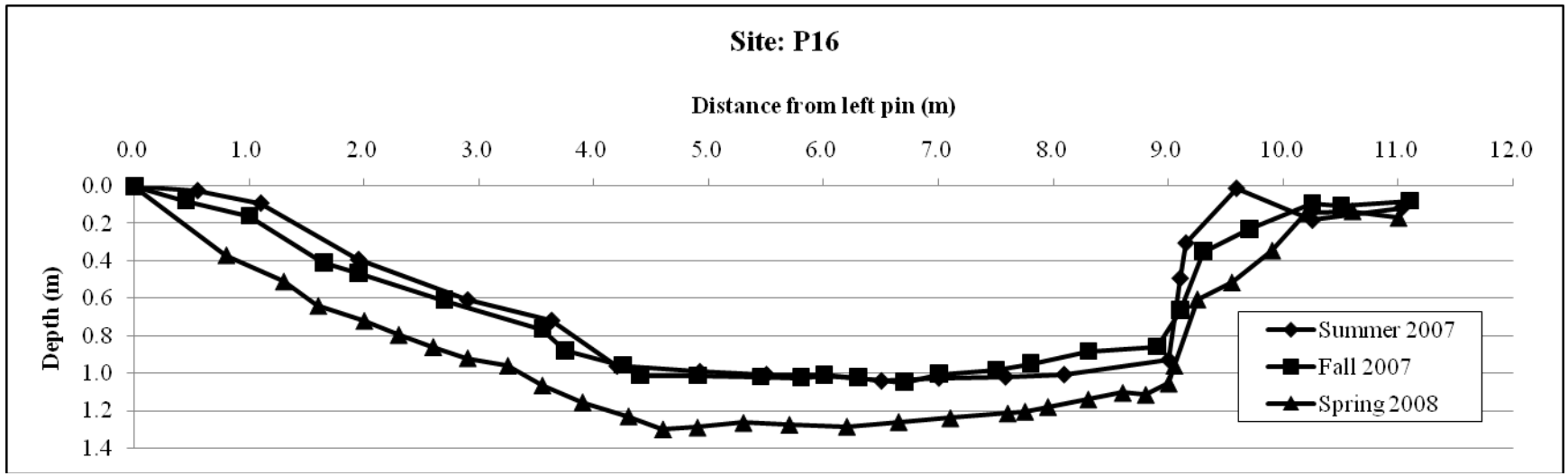

Figure 4.38. ***Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P16***

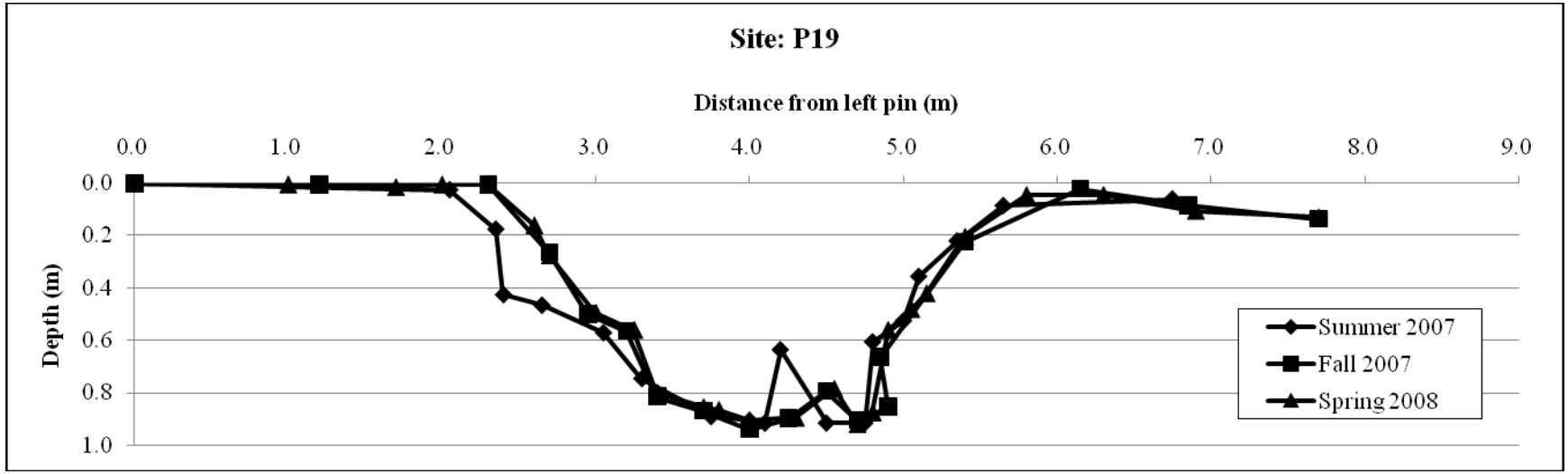

Figure 4.39. ***Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P19***

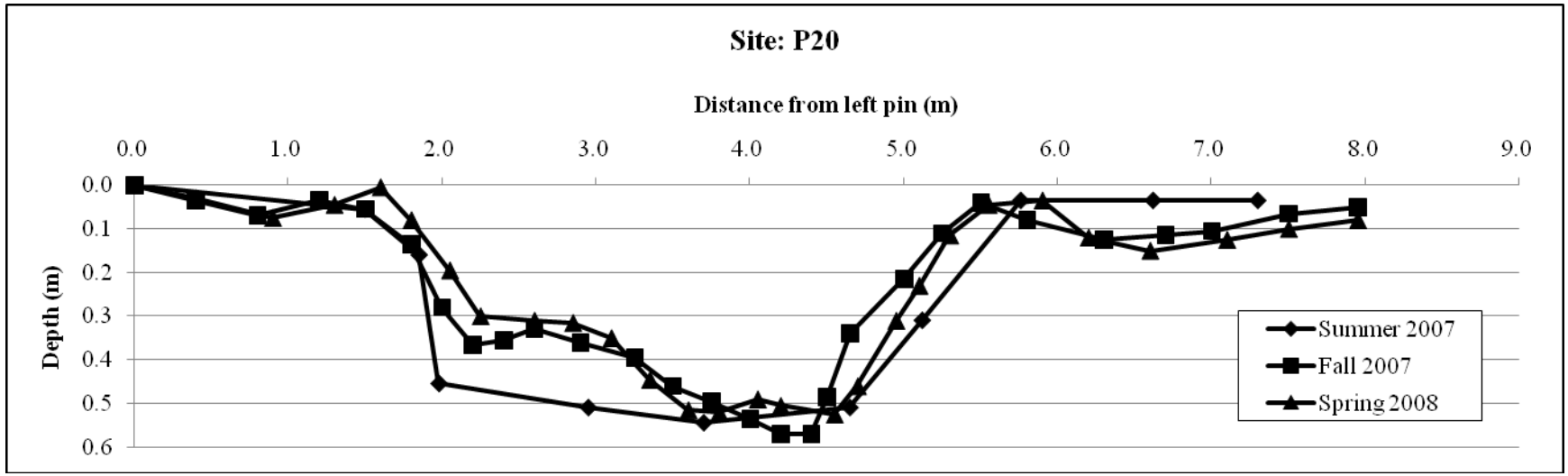

Figure 4.40. ***Riffle cross-sectional surveys performed in Summer 2007, Fall 2007, and Spring 2008 for piedmont site, P20***

Chapter 5: Modeling Results and Discussion

5.1. Comparison of Select Channel Erosion Models Characteristics, Abilities, and Requirements (Product #2)

5.1.1. Overview of Model Selection for Review

A starting point in the process of identifying appropriate models for review was the study performed by Staley et al. (2006), which identified the majority of these models without going into the details provided by this project. A web search was also conducted, with specific querying of primary modeling-support agencies, to identify other models that might be available and/or appropriate. The following models in were reviewed with respect to their channel erosion capabilities. Websites for each model are listed at the end of this chapter along with a list of references used for each of the models reviewed, listed alphabetically by model.

As is shown in Table 5.1, there are essentially two types of models encompassed in this review – watershed-scale models and reach-scale models. Watershed models typically simulate surface runoff and erosion and may either include a channel component, or include the capability of linking with a reach-scale model for the instream routing of the upland erosion delivered to the stream. The reach-scale models, on the other hand, typically rely on boundary conditions to provide the inputs from the watershed area – either output from a watershed-scale model or a time series of flow and sediment –and focus mainly on instream processes.

Three other models were reviewed, but were determined not to have any applicability to the model application needs of the Virginia Coastal Zone Management

Program addressed by this project. Those models were the Channel-Hillslope Integrated Landscape Development (CHILD) model (Tucker et al., 1999), the Watershed Characterization System (WCS; EPA, 2003), and the Watershed Erosion Prediction Project watershed model (WEPPwatershed; Ascough et al., 1995). The CHILD model is a triangulated integrated network (TIN)-based landscape evolution model that presents long-term visualization of channel formation, and is more a research conceptualization tool rather than a numerical model. While the CHILD model does produce long-term sediment loads, they are not partitioned between upland and channel sources, the loads are not verifiable, and the model, still undergoing development, has not been distributed by the current developers. The WCS model was deemed inappropriate because its sediment budget routine did not explicitly include channel erosion considerations, and the supporting databases currently have only been developed for states in EPA Region 4 (Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina and Tennessee). While the WEPPwatershed model has a channel element for representing channel erosion, it was intended for small watersheds without perennial streams, and was not considered appropriate for describing large stream channel erosion. Additional references and websites of these models are listed at the end of this chapter.

Table 5.1. Listing of Models Reviewed for Channel Erosion Capabilities

Model	Name	Model Version	Model Type	Developer
AGNPS 2001	AGricultural Non-Point Source Pollution Model	4.0	watershed	Theurer and Bingner, USDA-ARS
ANSWERS-2000	Areal Non-point Source Watershed Environment Simulation Model		watershed	Beasley and Huggins, Purdue University; Dillaha et al. Virginia Tech
CCHE1D	Center for Computational and Hydroscience Engineering 1-Dimensional Model	3.0	reach	NCCHE, University of Mississippi (USDA-ARS)
CONCEPTS	CONservational Channel Evolution and Pollutant Transport System Model	2.0	reach	Langendoen, USDA-ARS
GWLF	Generalized Watershed Loading Functions Model	2006	watershed	Haith et al., Cornell University; Evans et al., Pennsyvania State; Yagow, Virginia Tech
HEC-6	Hydrologic Engineering Center	6.0	reach	USACE
HSPF	Hydological Simulation Program - FORTRAN	12.0	watershed	Bicknell et al., Aqua Terra (USEPA)
SAM	SAM Hydraulic Design for Channels Model		reach	USACE
SPARROW	SPAtially Referenced Regressions On Watershed Attributes Model	2.0	watershed	USGS
SRH-1D (GSTAR)	Sedimentation and River Hydraulics 1-Dimensional Model	2.0	reach	USBR
SWAT	Soil and Water Assessment Tool	2005	watershed	Arnold et al., USDA-ARS
WARMF	Watershed Analysis Risk Management Framework Model	6.0	watershed	Herr et al., EPRI

5.1.2. Model Descriptions

The following model descriptions were obtained from various user guides and model documentation, published reports, other reviews, and personal experience with the models.

AGNPS 2001

This USDA-ARS system of models has evolved from the original grid-based AGricultural NonPoint Source Pollution Model (AGNPS) that modeled individual storm events to the hydrologic response unit-based AnnAGNPS annualized version of model (Young et al., 1989; Cronshey and Theurer, 1998). The latest version of AGNPS now has an interface that optionally links with either the CONCEPTS or the CCHE1D reach model for enhanced channel erosion modeling and the REMM model for riparian buffer assessment. AGNPS is essentially an upland erosion watershed-scale model that simulates runoff based on curve numbers and hillslope soil loss based on the Revised Universal Soil Loss Equation (RUSLE). The interface contains a number of internal

reference databases to assist in parameter evaluation of watershed and land use characteristics for upland erosion simulation. The model includes first order power relationships for classic and ephemeral gullying, impoundment volume-discharge relationships, and provisions for accounting for landslides in upstream areas. All of the upland processes include calibration and rely on a form of simplified delivery ratio for estimating sediment delivered to the watershed outlet. This system has variously been called AnnAGNPS, AGNPS98, and AGNPS 2001, and in this review essentially refers to the capabilities of the AnnAGNPS component.

The AnnAGNPS model, a revision of the original AGNPS model, expanded from a single event based model to a continuous simulation model using a daily time step. AnnAGNPS also includes new components designed to account for sources of concentrated sediments, such as gullies, and non-precipitation water additions, such as irrigation practices. Instream sediment transport capacity is determined using algorithms for shear velocity, effective transport factor, and bed shear stress, as applied to the erodible fraction of the bed. The sediment deposition algorithm is a function of a unitless deposition number, the unit-width sediment transport capacity, and both the upstream and downstream unit-width sediment discharges. Sediment routing is based upon sediment transport and capacity relationships using the Bagnold stream power equation.

ANSWERS

ANSWERS-2000, a continuous simulation, distributed parameter nonpoint source model for simulating runoff, sediment, and nutrients from disturbed watersheds was updated by Byne (2000) to include a critical-shear rill detachment subroutine, an improved interrill detachment subroutine, and a channel scour subroutine (Byne, 2000;

Zeckoski, 2002). The previous version of ANSWERS-2000 did not simulate channel scour. The new detachment equations are based on process-oriented equations developed for the WEPP model and can be applied to ungaged watersheds with a wide variety of soils and land use conditions.

The ANSWERS-2000 model calculates flow in a cell based upon a stage-discharge relationship utilizing Manning's equation. The simulated flow rate in the channel is assumed equal to the cumulative flow from upslope contributing channels and the overland flow rate of the cell containing the channel. A channel cell is assumed rectangular and the channel bottom is considered erodible to the depth of a user-specified nonerodible fraction. The detachment capacity in a channel cell is calculated in the same manner as for upland erosion and then applied to the erodible fraction. Bottom scour is calculated from the adjusted channel erodibility, the excess shear stress, the erodible fraction, and the soil bulk density. Eroded depth is calculated by multiplying the bottom erosion rate by a time increment. If transport capacity is insufficient to transport all eroded material, then deposition occurs and the eroded depth is adjusted for deposited material. If the channel bottom has a nonerodible layer, bottom erosion ceases at this depth and scour switches to the streambanks. Channel widening is calculated by assuming that the shear stress is uniform along the streambanks and that the streambank erosion rate is the same as the bottom erosion rate. If channel widening occurs, then the conveyance in the channel cell is adjusted according to the new channel width.

The ANSWERS-2000 watershed model was further modified by Zeckoski (2002) by adding components to simulate atmospheric deposition and urban management

practices, including wet ponds, dry ponds, and infiltration trenches. Another BMP simulated in ANSWERS that might be appropriate for urban applications is grassed waterways (Beasley and Huggins, 1981).

CCHE1D

This one-dimensional channel network model was developed by the Center for Computational and Hydroscience Engineering at the University of Mississippi in cooperation with USDA-ARS (Wu and Vieira, 2000). This is a Windows-based finite difference application that runs as an ArcView extension. The model handles instream processes only, and depends on linkage with a surface runoff watershed model, such as AnnAGNPS or SWAT, for time-series inputs of flow and sediment. The model includes four options for calculating sediment transport and procedures for estimating many channel parameters. The model is currently limited to subcritical flows, although local supercritical conditions are allowed. The model outputs changes in channel morphology and a time-series of unsteady flow and sediment on an event-basis at small time intervals (seconds to hours). While much flexibility is available for model configuration, considerable technical expertise is required to appropriately apply the model within a specific watershed.

The CCHE1D flow model simulates unsteady flow in channel networks using either the diffusive wave model or the dynamic wave model, taking into account the difference between the flows in the main channel and the floodplains of a compound channel, as well as the influence of hydraulic structures, such as culverts, flumes, bridge crossings and drop structures. The CCHE1D sediment transport model calculates non-uniform sediment transport in rivers and streams using a non-equilibrium

transport model. Four methods are available for calculating sediment transport capacity. The model simulates bank erosion, bed material sorting, and channel widening processes, along with mass bank failure using stability analysis algorithms. Existing formulas are provided to calculate parameters such as bed-material porosity, non-equilibrium adaptation strength, wash-load size range and mixing layer thickness.

CONCEPTS

The Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) model is a process-based, dynamic computer model that simulates open-channel hydraulics, sediment transport, and channel morphology (Langendoen, 2000). CONCEPTS simulates one-dimensional flow, graded-sediment transport, and bank-erosion processes in open channels along the centerline of stream corridors. The stream corridor is conceptualized as a series of reaches connecting cross sections. The model ignores cross-stream variations induced by riffles and point bars, constrictions and obstructions such as woody debris or rocks. The model uses a distributed flow routing method to model the effects of instream hydraulic structures on stream corridor rehabilitation designs. The CONCEPTS model is based on channel width adjustment and streambank mechanics research conducted at the National Sedimentation Laboratory. Sediment transport rates are a function of flow hydraulics, bed composition, and upstream sediment supply. The composition of the channel bed may change as particles are eroded from or deposited on the bed, thereby changing flow hydraulics and fractional transport rates. The model computes channel evolution by tracking bed changes and channel widening. The bank erosion module accounts for basal scour and mass wasting of unstable cohesive banks. CONCEPTS can simulate transport of both

cohesive and non-cohesive sediments, both in suspension and on the bed, and selectively by size classes. Channel boundary roughness can vary across a channel and floodplain cross section.

GWLF

The Generalized Watershed Loading Function (GWLF) model is a continuous simulation loading function model used to evaluate long-term loads from agricultural and mixed land use watersheds (Haith et al., 1992). GWLF simulates runoff and sediment delivery using the curve number (CN) method, the Universal Soil Loss Equation (USLE) modified for daily rainfall, and a sediment delivery ratio. A daily water balance is performed by the model, although output is generated on a monthly basis. Dai et al. (2000) have developed a windows-based version called BasinSim, and Evans et al. (2002) have translated the GWLF code into Visual Basic, developed an interface to the model based on the commonly used GIS software package ArcView, and named it AVGWLF.

The original GWLF model does not contain a channel or streambank erosion component. In 2003, Evans et al. developed a technique for estimating streambank erosion based on statistical relationships between lateral erosion rates and watershed characteristics. This algorithm was then incorporated into AVGWLF, as well as into a modified version being used in Virginia (Yagow, 2004). Lateral erosion rate is calculated as a product of an empirical coefficient based on watershed characteristics and a power function of the monthly flow. Monthly channel sediment load is calculated as the lateral erosion rate times the mean channel depth, bulk density and channel length. Additionally, an instream routing and sediment transport component has reportedly

been added and linked with the BasinSim version (Shoemaker et al., 2005). The BasinSim component uses a generic ArcView interface to prepare input files and stream networks that link multiple watersheds in a study area. The model uses the Muskingum-Cunge method for flow routing and simulates sediment transport in three particle size classes (Shoemaker et al., 2005). This component appears to be proprietary and was not available for review.

HEC-6

This reach-scale numerical model was developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC, 1997). HEC-6 is a one-dimensional, movable boundary, open channel flow model. HEC-6 is designed to simulate long-term trends of scour and/or deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and/or stage, or from modifying the channel geometry (e.g., encroaching on the floodplains). HEC-6 can be used to evaluate deposition in reservoirs (both the volume and location of deposits), design channel contractions required to maintain navigation depths or decrease the volume of maintenance dredging, predict the influence that dredging has on the rate of deposition, estimate possible maximum scour during large flood events, and evaluate sedimentation in fixed channels. Based upon a continuous flow record, a series of water surface profiles are calculated that provide corresponding energy slope, velocity, and depth at each cross section. These predictions are used to estimate potential sediment transport rates at each section. These estimates are then considered with flow volume and sediment yield from upstream sources to determine sediment scour and deposition. A mass balance approach is used to calculate the amount of scour or deposition in each

section, and the cross section is then adjusted accordingly. The sediment calculations are performed by particle size fraction to simulate hydraulic sorting and armoring.

HSPF

Hydrologic Simulation Package – Fortran (HSPF) is a comprehensive package for continuous simulation of watershed hydrology and water quality for a wide range of conventional and non-conventional pollutants (Bicknell et al., 2001). HSPF was designed for application to most watersheds using existing meteorologic and hydrologic data, although the input data requirements are extensive. HSPF consists of a set of modules arranged in a hierarchical structure which uses a time-series data management system for input and output. In HSPF, a subwatershed is conceptualized as a group of various pervious and impervious land uses that drain to a representative stream reach. Several small subwatersheds and stream reaches may be networked to represent larger drainage areas. Land processes for pervious and impervious areas are simulated through runoff generation, sediment generation and transport, and generation and transport of multiple water quality constituents. The hydrology module includes provision for several types of soil storages, interception, infiltration, evapotranspiration, interflow, groundwater loss and overland flow. Overland sediment fate and transport is simulated for three particle size fractions. Urban aspects include the ability to represent lined channels, commercial withdrawals and discharges, and buildup/washoff on impervious land segments.

HSPF assumes that scour or deposition of inorganic sediment does not affect the hydraulic properties of the channel. Sand, silt, and clay are simulated as being deposited in different areas of the bed, so that the deposition or scour of each material

is not linked to the other fractions. Neither armouring nor longitudinal movement of bed sediments is modeled.

SAM

The Sediment Assessment Model (SAM) is a point model that simulates steady-state uniform flow and considers erosion, entrainment, transport, deposition and compaction within a single stream cross-sectional area (Thomas et al., 2002). The SAM model evolved as a result of research conducted in the Flood Control Channels Research Program in the US Army Corps of Engineers' Coastal and Hydraulics Laboratory (CHL) in the 1980's and early 1990's. In 2001, CHL contracted with Owen Ayres & Associates, Inc., to put the DOS-based SAM into a more user-friendly interface. Owen Ayres & Associates, Inc. developed a Windows interface (SAMwin; http://www.ayresassociates.com/Web_SAMwin/overview.htm) which uses the same executable programs. Owen Ayres & Associates, Inc. has exclusive rights to sell and support the SAM package to the private sector and to all government agencies except the Corps of Engineers.

The SAM model was designed for use as an aid in the design of stable channels, considering all of the five fundamental sedimentation processes – erosion, entrainment, transportation, deposition, and compaction. SAM provides the computational capability to include all these processes except the compaction of the deposited bed sediments. It does not allow for variation of particle size distribution over time. While SAM only considers a single cross section, and not a stream reach, the cross section can be described in several ways, including simple or compound trapezoidal channels or irregular channels. There are four modules in the SAM modeling package. The

hydraulics module, SAM.hyd, calculates the width, depth, slope and n-values for stable channel cross-sections with variable roughness in alluvial material. SAM.sed calculates sediment transport capacity according to a wide range of sediment transport functions, while SED.yld calculates the sediment yield, and SAM.aid evaluates channel stability in terms of the cost of maintaining the constructed channel.

SPARROW

The SPAtially Referenced Regressions On Watershed attributes (SPARROW) is a watershed modeling technique for relating water-quality measurements of a specific pollutant made at a network of monitoring stations to attributes of the watersheds containing the stations (Schwarz et al., 2006). SPARROW uses statistical nonlinear regression methods to create a simple, structural model of riverine water quality that is calibrated using a mass balance approach to account for changes in contaminant flux. Regression equations relate measured transport rates in streams to spatially referenced descriptors of pollution source, land surface, and stream channel characteristics. The model empirically estimates the origin and fate of contaminants throughout the stream network. The statistical parameters estimation in SPARROW also provides a means for calculating uncertainty in model coefficients and water-quality predictions.

The user chooses and defines which characteristics to include in the regression analyses around which the model is built. The basis of the model structure in SPARROW is provided by a detailed stream reach network with digital elevation model (DEM)-delineated watersheds to which all monitoring stations and GIS data on watershed properties are spatially referenced. This spatially distributed model structure allows separate statistical estimation of land and water parameters that quantify the

rates of pollutant delivery from sources to streams and the transport of pollutants to downstream locations within the stream network (Smith et al., 1997).

The intent of SPARROW models is to describe the long-term, steady state water quality and flow conditions in streams. Contaminant source inputs are assumed to be in balance with the estimated sinks and measured riverine output such that there is a conservation of mass among the model components that describe the source inputs, sinks, and the instream flux of contaminants (Schwarz et al., 2006).

SRH-1D

Sedimentation and River Hydraulics, One Dimensional – (SRH-1D, previously known as GSTAR) is a one-dimensional general numerical model developed to simulate and predict sediment transport and related river morphological changes due to natural or human influences (Huang and Greimann, 2007). The model includes both hydraulic and sediment transport components and is intended for use in natural rivers and manmade canals. It is a mobile boundary model with the ability to simulate steady or unsteady flows, internal boundary conditions, looped river networks, cohesive and non-cohesive sediment transport, and lateral inflows. EPA and the U.S. Bureau of Reclamation (USBR) were funding partners in model development. The model simulates fractional sediment transport, bed sorting, bed armoring, point and nonpoint sources of flow and sediment, and internal boundary conditions such as time-stage tables, rating curves, weirs, bridges, and gates. The model is for use in either simple or complex alluvial rivers where the one-dimensional assumption is appropriate.

SWAT

The Soil and Water Assessment Tool (SWAT) is a watershed-scale model developed for the USDA Agricultural Research Service (ARS; Neitsch et al., 2002; Neitsch et al., 2005). SWAT is a continuous simulation model that was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is physically-based and uses specific information about weather, soils, topography, vegetation, and land management practices occurring in the watershed to simulate water flow, sediment transport, crop growth, and nutrient cycling. SWAT conceptualizes a watershed as a network of subwatersheds connected by stream reaches, with each subwatershed composed of a number of unique combinations of soil and vegetation types, referred to as hydrologic response units (HRUs). Water, nutrients, sediment, and other pollutants from each HRU are simulated and aggregated in each subwatershed and then routed through the stream network to the watershed outlet. For urban areas, SWAT employs buildup and washoff routines similar to those in the Storm Water Management Model (SWMM). The model was originally developed for use in ungaged watersheds, but as more components have been added, calibration is necessary. SWAT generally uses readily available inputs and allows assessment of many types of land management strategies. SWAT is currently under active development and the SWAT website (http://www.brc.tamus.edu/swat/soft_model.html) should be visited for updates on recent modifications.

SWAT calculates channel flow routing based on one of two optional modifications of the kinematic wave method – the variable storage routing method based on the

continuity equation and the Muskingum wedge and prism storage method. Channel sediment routing occurs through simulation of both degradation and deposition of channel sediments. Channel bed and bank erosion are simulated as a function of channel erodibility and channel cover factors, using a simplified version of the Bagnold stream power relationship. Deposition occurs at flow rates less than the peak channel velocity.

WARMF

The Watershed Analysis Risk Management Framework (WARMF) is a continuous watershed model included as part of a decision support system developed by the Electric Power Research Institute (EPRI) that can guide stakeholders to a consensus watershed management plan (Herr et al., 2000; Chen et al., 2001). WARMF uses data commonly available from National Climatic Data Center, EPA, USGS, and the Natural Resources Conservation Services, together with all necessary databases, simulation models, and graphical software, integrated into a Windows™ graphical user interface. WARMF is now compatible with the data extraction and watershed delineation tools of EPA BASINS.

WARMF represents a river basin by a network of connected river segments and lakes, with each segment receiving drainage from a defined land catchment. Meteorological data are input to simulate runoff, nonpoint source pollution load, river hydrology, and river water quality. The computing engine in WARMF was taken from the Integrated Lake-Watershed Acidification Study (ILWAS) model. The hydrologic module simulates canopy interception, snow pack accumulation and snow melt, infiltration through soil layers, evapotranspiration, ex-filtration of groundwater to stream segments,

kinematic wave routing of stream flows, and flow routing within the terminal reservoir. WARMF can also simulate stratified lakes or reservoirs with either a one-dimensional option (vertically stratified, horizontally mixed) or a two-dimensional option (CE-QUAL-W2). WARMF models each stream segment as a continuously stirred tank reactor (CSTR). A mass balance is performed during each time step in each river segment, based on the mixing of water and pollutants entering from the upstream segment with the water and pollutants in a given river segment from the previous time step. These loads are then adjusted based on the applicable sinks and sources for specific constituent.

Algorithms for sediment erosion and pollutant transport from upland areas were adapted from ANSWERS and the Universal Soil Loss Equation (USLE; Shoemaker et al., 2005). Upland detached clay and silt are assumed to remain in suspension during overland flow, while detached sand may be re-deposited, if the bedload transport capacity is exceeded. The bedload transport capacity of sand is a function of the shear velocity, shear stress, Reynolds Number, and critical shear stress. The suspended clay, silt, and sand derived from upland soil erosion are then routed to the river segment. The suspended sediment may be decreased by deposition on the river bed or be increased by bed and bank erosion. Scouring and bank erosion are assumed to occur when the flow velocity exceeds a critical value. The particle size distribution for the river bed is assumed the same as for the river banks. For the sand fraction, the model calculates critical shear stress and the bedload carrying capacity using the same equations used for overland flow. The sand fraction that exceeds the bedload carrying capacity is deposited immediately. Clay and silt are deposited to the bed according to their settling

velocities and the remaining suspended sediment is transported to the downstream segment (Chen et al., 2001). For urban applications, the pollutant buildup and washoff routines from impervious areas were adapted from SWMM. One BMP with potential application to Virginia CZM areas is the buffer strip. Buffer strips can be simulated in WARMF as an idealized rectangle catchment, with its length perpendicular to the direction of flow.

5.1.3. Comparison of Model Characteristics

This section consists of a series of tables that compare, to the extent possible, the model characteristics, identified through a review of technical and user documentation and related literature, and not through actual hands-on model set-up and execution. These tables include identifiable channel erosion modeling components, broad types of model inputs related to channel degradation, the ability to represent channel stabilization BMPs, and available user support. Table 5.2 summarizes those components of bed and bank erosion, bank mass wasting, and instream transport that characterize the capability of each model to simulate channel degradation processes. The list of channel degradation components was developed in an iterative fashion as the reviews were underway, because they were described in different ways by different authors, and many models conceptualized channel degradation in different ways. The components are not necessarily exclusive, as there is some overlap between “deposition” and “transport capacity”, and “general degradation” represents some combination of detachment and transport or a combination of both bank and bed

erosion and bank slope failure. “Stream widening” is included as well as “stream bank erosion,” as some models calculate streambank retreat without changing the channel dimensions, although the use of the term for GWLF was an empirical calculation without update of the channel dimensions.

Table 5.2. Channel Erosion Model Component Summary

Channel Erosion Components	AGNPS 2001	ANSWERS-2000	CCHE1D	CONCEPTS	GWLF	HEC-6	HSPF	SAM	SPARROW	SRH-1D (GSTAR)	SWAT	WARMF
stream bank erosion - detachment	N	N	Y	Y	N	Y	Y	N	N	Y	Y	Y
streambank erosion - mass bank failure	N	N	Y	Y	N	N	N	N	N	Y	N	N
bed erosion - detachment	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
bed erosion - deposition	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
bed erosion - armoring	N	Y	Y	N	N	Y	N	N	N	Y	N	N
channel erosion - transport capacity	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y
channel erosion - graded sediment transport	Y	Y	Y	Y	N	Y	Y	Y	N	Y	N	Y
channel erosion - general degradation	N	N	N	N	Y	N	N	Y	Y	N	N	N
distinguishes non-cohesive vs cohesive particles	Y	Y	Y	Y	N	Y	Y	N	N	Y	N	N
stream widening (lateral erosion)	N	Y	Y	Y	Y	Y	N	N	N	Y	Y	N
overbank sedimentation	N	N	Y	Y	N	Y	N	N	N	Y	Y	N

Degradation within a channel segment requires information about upstream inputs of flow and sediment loads, as well as parameters that describe the susceptibility of channel beds to scour and the streambanks to erosion and mass wasting. Upland flow and sediment loads can either be simulated, or entered as boundary conditions. Where boundary conditions are required, they are often required as an input hydrograph, a time-series of flow and concentrations, or a time-series of flow and a sediment rating curve. One of the primary influences on channel erosion and its control is upstream hydrology. While there are many procedures that can be used to simulate changes in upland hydrology, these fall more in the realm of watershed modeling and are not explicitly detailed in this review. Except for discharge controls on reservoirs and riparian

buffers, the list of instream best management practices (BMPs) in Table 5.4 represent model capabilities that represent instream practices for control of channel erosion.

Table 5.3 describes how the upstream conditions are defined in each model, and some of the broad input parameters required for evaluation of channel degradation.

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Table 5.3. Channel Erosion Model Inputs

Channel Erosion Model Input Data	AGNPS 2001	ANSWERS-2000	CCHE1D	CONCEPTS	GWLF	HEC-6	HSPF	SAM	SPARROW	SRH-1D (GSTAR)	SWAT	WARMF
Upstream Flow												
boundary condition	N	N	Y	Y	N	Y	N	Y	N	Y	N	N
simulated	Y	Y	N	N	Y	N	Y	N	Y	N	Y	Y
Upland Erosion												
boundary condition	N	N	Y	Y	N	Y	N	Y	N	Y	N	N
simulated	Y	Y	N	N	Y	N	Y	N	Y	N	Y	Y
Stream Bank Erosion												
particle size distribution	Y	N	N	Y	N	N	N	N	N	Y	N	N
shear stress	N	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y
vegetation	Y	N	N	Y	N	N	N	N	N	Y	N	N
Channel Bed Erosion												
particle size distribution	Y	Y	Y	Y	N	Y	Y	Y	N	Y	N	Y
depth to bedrock	Y	N	N	Y	N	Y	Y	N	N	Y	N	N
shear stress	N	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y
roughness	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
slope	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	Y
porosity, hydraulic conductivity	N	N	Y	Y	N	Y	Y	N	N	N	N	N
channel cross-section profiles	Y	N	Y	Y	N	Y	Y	Y	N	Y	N	Y
Watershed Attributes					Y				Y			
Observed Data for Calibration	N	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y

Table 5.4. Model Representation of Channel Degradation Best Management Practices

Ability to Represent Channel Degradation BMPs	AGNPS 2001	ANSWERS-2000	CCHE1D	CONCEPTS	GWLF	HEC-6	HSPF	SAM	SPARROW	SRH-1D (GSTAR)	SWAT	WARMF
reservoir release rates	Y	N	Y	N	N	Y	Y	N	N	Y	Y	Y
stream bank stabilization	Y	Y	Y	Y	N	N	N	Y	N	Y	N	N
channel restoration (cross-section and slope modifications)	Y	N	Y	Y	N	Y	Y	Y	N	Y	Y	Y
in-stream hydraulic structures	N	Y	Y	Y	N	Y	N	N	N	Y	N	N
riparian buffers	Y	Y	N	Y	N	N	Y	N	N	N	N	Y

Models must not only have the capabilities for modeling desired processes, but information must also be available to assist users in understanding how the model works, in evaluating parameters, and in understanding model limitations. Table 5.5 summarizes the user support available for each model.

Table 5.5. Available User Support

User Support	AGNPS 2001	ANSWERS-2000	CCHE1D	CONCEPTS	GWLF	HEC-6	HSPF	SAM	SPARROW	SRH-1D (GSTAR)	SWAT	WARMF
User Interface	Y	N	Y	N	D	D	Y	Y	Y	D	Y	Y
User documentation	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Technical documentation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Developer support	Y	N	Y	Y	N	F	Y	F	N	N	Y	Y
Proprietary?	N	N	N	N	N	N	N	Y	N	N	N	N

D = DOS-based interface
F = fee-based support.

5.1.4. Data Needs and Availability

Common data needs for both reach-scale and watershed-scale models include inputs related to hydrology and elevation. Data for many of the hydrologic parameters

are available in digital form through the USGS National Hydrography Datasets (NHD) which includes both waterbodies and stream reach attributes, such as reach lengths. Model inputs related to elevation, such as land slope, are readily derived from Digital Elevation Model (DEM) data, though the resolution of these grid cells is generally not sufficient for defining channel slopes. Also, GIS routines are available for using DEMs to define drainage networks, which are needed for surface and instream routing and for defining reach connectedness.

Watershed models have greater data needs than reach models simply because they are simulating the entire area draining into the stream network, but reach-scale models require more site-specific information. Additional data needs of watershed models include climate, land use, and soils data. Typical climate data required by models include precipitation and temperature, at a minimum; some models, such as HSPF, require a large array of additional climatic data. Temperature and precipitation records are readily available from the National Oceanic and Atmospheric Administration (NOAA), though the period of record at most stations requires correction for accumulated and missing data. The US EPA has also assembled a nationwide database of the additional climatic inputs required by HSPF that can serve as a source for other models as well. Land uses are generally used by models to represent nonpoint sources of surface runoff and sediment in a watershed. Land use data have become more widely available, both through the National Land Classification Datasets in 1992 and 2001. In Virginia, high resolution aerial imagery in the Virginia Base Mapping Program is also available for interpreting land use, although boundaries would still need to be digitized for analysis within a GIS.

Soils data are also required for definition of particle size distribution and many related soil characteristics. Fortunately, all areas within the coastal zone management area in Virginia have county-level soil surveys in digital form available on the web. Nevertheless, some of the soil characteristics required by the various channel erosion models are very site specific, cannot be estimated from soil survey data, and must be obtained by field measurements (e.g. critical shear stress).

In addition to these general data requirements, many of the models have additional specific parameters needed for simulating channel degradation. Virtually all of the reach-scale models require channel cross-section profile measurements. The following list may not be comprehensive because of the multitude of parameters required by, and options available in, some models, but it gives an idea of some of the parameters that may require site-specific measurements or calibration.

AGNPS:

- Empirical gully and landslide power curve coefficients and exponents
- *Critical shear stress* is the shear stress at which gully erosion occurs.
- *Impoundment seepage* is a constant value seepage rate through the embankment.
- *Valley and reach scour codes* by particle type are codes indicating whether different sized particles are allowed to scour reach valleys and channels, respectively.

ANSWERS:

- Empirical power function coefficients and exponents related to bed detachment, scour, and sand load
- Bed *critical* bed *shear stress* for deposition and scour by particle size
- *Mass of buried residue in root zone* is calculated within the top 0.15 m of the soil.
- *Nonerodible fraction of channel bottom* is the portion of the channel bottom considered armoured.

CCHE1D:

- *Thalweg elevation* is the elevation of the lowest point in the channel, typically considered to be the center of the channel.
- *Sediment grain shape factor* is a parameter related to the shape of particles – the Corey shape factor value of 0.7 is the default value in CCHE1D.
- *Bed porosity* can either be measured or calculated with one of the two empirical formulas included in CCHE1D.
- *Bank cohesion* and *friction angle* are required for analysis of bank mass failure.
- *Critical shear stress* is the shear stress at which soil particles are detached from the bank or bed.
- Hydraulic structure definitions.

CONCEPTS:

- *Critical shear stress*
- *Bank composition* is the particle size distribution for streambanks.
- Hydraulic structure definitions
- *Bed porosity*
- *Hiding factor*
- Cohesive bank parameters include the *hydraulic gradient* and the *angle of seepage*
- Bank cohesion and friction angle are required for analysis of bank mass failure.
- Roughness variability (Manning's *n*) across the channel and corresponding flood plain

GWLF:

- The *seepage coefficient* represents the amount of flow lost as seepage to deep storage.
- The *recession coefficient* is a measure of the rate at which streamflow recedes following the cessation of a storm.
- *Livestock density* (with stream access or in loafing lots) is the number of animal units per acre – a parameter in the calculation of the regression coefficient for the lateral erosion rate.

HEC-6:

- *Movable bed portions and limits* are channel extents that will be moved vertically due to scour and deposition; overbank areas beyond the left and right boundaries of the movable portion are treated as fixed bed areas.
- *Conveyance limits* are bounds of the lateral extent of a cross section that active flow does not occupy.
- *Contraction and expansion coefficients* are design elements to allow for channel transitions where a sudden change in area is accompanied by sharp corners.

HSPF:

- Empirical power function coefficients and exponents related to bed detachment, scour, and sandload
- *Critical bed shear stress* for deposition and scour by particle size
- *Erodibility coefficient*

SAM:

- *Bed material geometric gradation coefficient*
- Meander shape and scale parameters
- *Channel-forming discharg*e
- *Critical shear stress*
- The *Cowan multiplier* provides additional roughness in gravel beds related to surface irregularities, variability in channel shape, obstructions, vegetation and meandering.

SPARROW: Essentially all parameters are user-defined or statistically estimated.

SRH-1D:

- *Ineffective flow* is used to define a portion of a cross section where water is not actively conveyed. In an ineffective flow area, water ponds and the velocity of the water is close to zero.
- *Dry areas* are used to define an area protected by levees.
- *Blocked areas* are used to define a portion of a cross section permanently blocked by a hydraulic structure or other feature.
- The *angle of repose* defines the maximum bank angle within the cross section.
- The *active layer thickness* is the thickness over which mixing of sediment occurs.
- Critical shear stress

- Hiding factors
- Time to reference bulk density
- Hydraulic structure definitions.

SWAT:

- *Effective hydraulic conductivity* in main channel alluvium
- The *channel erodibility factor* is conceptually similar to the soil erodibility factor used in the USLE equation. Channel erodibility is a function of properties of the bed or bank materials. Channel erodibility can be measured with a submerged vertical jet test device or a flume study.
- The *channel cover factor* is defined as the ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover.

WARMF: Bed and bank scouring coefficients and exponents used as calibration parameters.

5.2. Synthesis of Channel Erosion Modeling Procedures for Virginia CZMA (Product #3)

5.2.1. Strengths and Weaknesses of Each Model for Simulating Channel Erosion in Urban Areas of the Non-tidal Coastal Zone

AGNPS

Strengths: The AGNPS system builds on many widely used and accepted models – RUSLE, CREAMS, EPIC, and GLEAMS. The modeling process is also very "customizable," with no limit on the number of study areas, reaches, or simulation duration. The user may specify different outputs for different sub-watersheds within the model area. Additionally, other models within the AGNPS suite can use AnnAGNPS outputs for simulating more specialized aspects of a watershed.

Limitations: The model does not perform as a true continuous simulation model, as there is no carry over of intermediate storage loads from one day to the next, so all runoff and associated sediment loads are "delivered" to the outlet before the next day's simulation begins. The model does not carry over stream sediment deposition or scour. Point-source loading rates included in the model are also limited to constant loading rates throughout the simulation period.

ANSWERS

Strengths: The strengths of the new ANSWERS-2000 erosion submodels are that they are process-based and more closely represent conditions that occur in the field through simulation of erodibility as a function of porosity, soil type, and crop growth-stage and their effect on sediment detachment. The process-based routines also allow BMP evaluation without preliminary performance data for calibration (Byne, 2000). Several BMPs that can be simulated in ANSWERS include field borders and grass waterways. The URBANIZED module can also simulate urban curb and drain placement.

Limitations: The limitations associated with the new submodels are the increased data requirements for the model and the uncertainty associated with estimating some of the required parameters such as rill spacing or critical shear stress. While the theory of critical shear stress is process-oriented, many of the sub-parameters are obtained

through empirical regression. Streambank mass wasting is also not considered in the model.

The new urban model subroutine (URBANIZED) is limited for use on watersheds with impervious cover of 30% or less, due to the simplified representation of hydrology from urbanized watersheds. The pond subroutines are very simplified and limit simulation to ponds with simple geometries. Ponds are represented as a fixed surface area and trapped sediment is not resuspended. It is assumed that the wet pond will remain at the permanent designed pool elevation between storm events. Currently, this subroutine cannot represent extensive stormwater drainage networks, and curbed roads cannot cross stream networks (Zeckoski, 2002). Lastly, ANSWERS-2000 does not have a user-friendly interface that incorporates recent modifications and there currently is no readily available source of user support.

CCHE1D

Strengths: The CCHE1D flow model is currently recommended for simulation of subcritical flow in rivers and streams. It can also handle local supercritical and transcritical flows without hydraulic jumps in isolated cross sections.

Limitations: The CCHE1D model is currently limited to application in dendritic channel networks with a single outlet. CCHE1D does not differentiate between lengths along the main channel and lengths along the flood plain, such as in meandering streams, and is not recommended for estuarine applications. In CCHE1D, bed and suspended loads are combined as bed-material load, so the instream sediment calculation is de-coupled from the solution of flow equations.

CONCEPTS

Strengths: CONCEPTS was designed specifically to model channel degradation and stream restoration. The model tracks sediment flow through instream hydraulic structures and can account for changes in channel morphology through simulation of channel scour, bank erosion/channel widening, and bank failure.

Limitations: The model does not simulate sinuosity or consolidation of deposited, cohesive sediment. Extensive site-specific data are needed.

GWLF

Strengths: The model requires minimal data inputs, but provides a mean of generating seasonally variable loads representative of diverse upland erosion sources.

Limitations: The streambank erosion component is empirical and probably not widely transferable. While the streambank component is useful, in that it represents a previously missing portion of watershed sediment loads, its usefulness is limited to headwater watersheds without the confounding influences of reservoirs or tidal influences, and would not be recommended for use in coastal areas. The BasinSim version of GWLF with the reported Muskingum-Cunge flow routing method has not been available for review.

HEC-6

Strengths: HEC-6 simulates in detail the volume of sediment deposited, scoured, and passing through each stream cross-section. HEC-6 is useful for long-term simulations of changing sediment and hydraulic conditions, channel design, and reservoir dredging. Urban-related features simulated include channel dredging, levees, and encroachment in the riparian corridor.

Limitations: HEC-6 cannot simulate the development of meanders, laterally distribute sediment loads across a cross-section, or route flow around islands; it is limited to one inflow between any two cross-sections. HEC-6 is not designed for single flood events.

HSPF

Strengths: HSPF is a modular, comprehensive watershed model that can be set up in a very simple or very complex manner, depending on user requirements for representing pollutant sources and land management options. HSPF can simulate both upland and receiving water processes simultaneously and can simulate at a variety of time-steps. HSPF is highly flexible and can be configured for non-typical, as well as typical, pollutants with many user-defined options. EPA's BASINS and WinHSPF are useful interfaces in initiating new users and in assisting with model parameter valuation, although it limits the use of some advanced features in HSPF, such as the Special Actions module. Urban simulated features include lined channels, impervious land segments, and water withdrawals and discharges.

Limitations: HSPF relies on many empirical relationships to represent physical processes. It spatially lumps land use representation at the sub-watershed level and requires extensive input data and observed data for calibration. HSPF is limited to one-dimensional flow in well-mixed rivers and reservoirs (Shoemaker et al., 2005).

SAM

Strengths: SAM provides reasonable time-averaged results in cases where the river is neither aggrading nor degrading, but is in general equilibrium. SAM is useful is designing riprap installations.

Limitations: Sediment transport functions in SAM must be used with care. There is no allowance for variability in the size class distribution over time or space. Since in natural rivers the size class distribution of bed material varies with discharge, reach, time of year, and other temporal factors, the use of a fixed, average size class distribution for all calculations presents the possibility that the calculated transport rates will not be representative of the natural river. SAM simulates at a single cross-section and cannot simulate varying discharge nor reach loading, except as broad averages. Since SAM applies the sediment transport functions at a point, it is not appropriate for application to watersheds or regional areas.

SPARROW

Strengths: This model is capable of simulating an individual pollutant at different spatial scales using national level datasets including RF1 (stream reach files), NLCD (USGS land use/land cover), and STATSGO (NRCS soil data). The model is very flexible in user-specified dependent variables and is appropriate for application to large-scale systems where monitored stream network data are available. SPARROW can also account for reservoir storage and sediment trapping.

Limitations: The model is limited to broadly estimating pollutant loads and fate/transport characteristics. The model is not applicable for use on individual watersheds, except as part of a larger modeling effort, since typical models developed to-date have been based on statistical relationships developed using national and regional water quality datasets. Use of state, county, and local level datasets would be needed for better discrimination at the watershed level. The model does not separate upland and channel erosion.

SRH-1D

Strengths: SRH-1D simulates areas undergoing geomorphic adjustment or likely to experience future adjustment, to quantify those adjustment processes for future conditions, and to estimate changes in a river system caused by dam construction, dam removal, or sediment sluicing.

Limitations: SRH-1D is limited to one-dimensional solutions for flow simulation. SRH-1D cannot simulate secondary currents, transverse movement, transverse variation, or lateral diffusion. This, in turn, prevents the model from simulating river meandering, point bar formation, pool-riffle formation, and planform changes. It also may not be able to simulate local deposition and erosion caused by water diversions, bridges and other instream structures. (Greimann, 2007).

SWAT

Strengths: SWAT is a physically-based model that uses many readily available inputs facilitated by a GIS interface. SWAT is well-supported with good documentation, and is suitable for watersheds ranging from small to very large. Urban-related features include runoff from directly-connected and disconnected impervious areas and impervious area sediment loads from USGS regressions or SWMM buildup/washoff routines.

Limitations: SWAT is not suitable for simulating sub-daily events such as a single storm event.

While SWAT has the flexibility to sub-divide watersheds for better spatial discretization, a large watershed can be divided into hundreds of HRUs resulting in many hundreds of input files. SWAT's data management structure does not currently allow for input simplification for identical files used in different sub-watersheds making file management difficult in complex watersheds. The current version also does not have a good model output post-processor.

WARMF

Strengths: WARMF incorporates graphical user interface (GUI) formatting and linkage with Geographic Information System (GIS) mapping to facilitate model use. WARMF is now compatible with the data extraction and watershed delineation tools of EPA BASINS. The GUI is user-friendly and represents results in an understandable format. One of the urban–related features simulated is street sweeping.

Limitations: The TMDL module allocation reductions appear to reduce all upstream sources equally, and can not be applied to individual sources (Shoemaker et al., 2005).

5.2.2. Channel Degradation Model Characteristics Related to the Non-tidal Coastal Zone Management Area

Many characteristics of channel degradation models will be similar between physiographic areas, though their values will vary. Two characteristics that are most prevalent in the coastal zone are that of low gradient and the dominance of non-cohesive soils. Several models have the capability of simulating both cohesive and non-cohesive soils and most models should be able to adequately simulate lower gradients. However, in extremely flat areas, local surveys and higher resolution elevation data (as compared to typical 30-m DEM data) will be needed to adequately delineate drainage areas and calculate slope. The non-tidal coastal area in Virginia also tends to have larger upstream drainage areas, as most streams in the coastal zone have originated in the higher elevation headwaters of the Piedmont and Valley and Ridge areas. Another important characteristic in properly simulating channel degradation in any downstream area is some measurement of the “connectedness” of the channel with the floodplain. Figure 5.1 presents a sediment budget performed by Allmendinger et al. (2007) which illustrates this point: the figure shows that, where the floodplain is well-connected to the stream channel, the net erosion from higher order streams is minimal. If the floodplain in this example were disconnected, it is possible that no deposition would occur on the floodplain, so that not only the upland sediment, but also the sediment detached from instream channel enlargement, would all be delivered downstream, increasing the sediment yield from this watershed by about 50%.

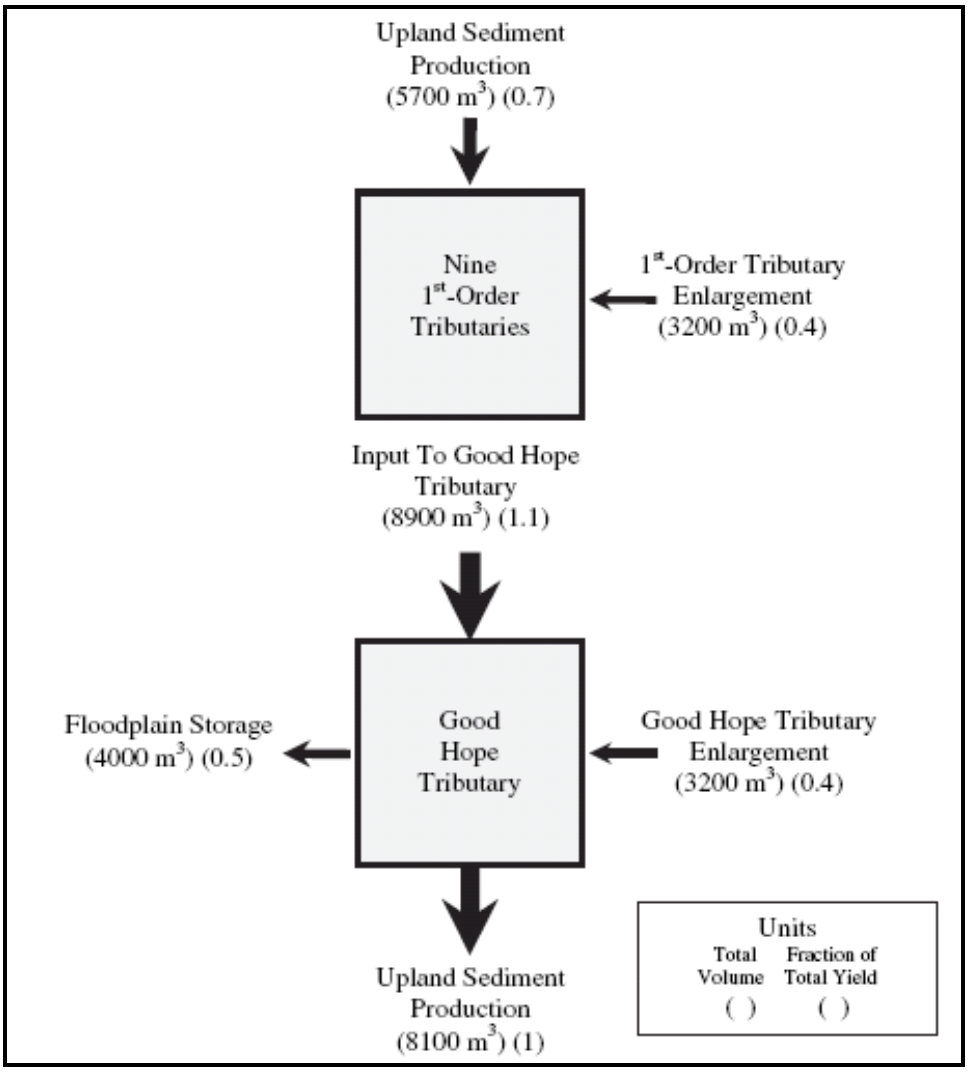

Figure 5.1. Sediment Budget, Good Hope Watershed (Allmendinger et al., 2007)

5.2.3. Channel Degradation Model Characteristics Related to Urban Areas

The impact of urban areas on channel degradation is represented in these models by how they affect the upland hydrology – both the timing and volume of runoff. Therefore, in most of the reach-scale models, upland hydrology is not simulated and urban influences are mainly represented in the inflow hydrograph and as instream hydraulic structures. In the upland watershed areas, the ability to simulate impervious

areas is important, including whether they are directly connected to storm flow drains. Point source flows and sediment loads are characteristic of urban areas, as are instream structures such as road and utility crossings, the percentage of disturbed land, the presence of dams, the degree of channelization, and the amount of human activity in the riparian zone. Since regression models, such as SPARROW, can be configured with any characteristic the model developer feels are significant, all of these characteristics could be considered in such a model.

5.2.4. Recommended Approach to Channel Degradation Modeling for Virginia

Channel degradation simulation is still difficult to quantify because of the huge spatial and temporal variability in factors that affect it. Precise simulation of channel degradation from an individual stream reach is still somewhat limited, although the knowledge base is improving. A realistic goal of watershed-scale channel degradation modeling is to provide a relative scale to this source, within an order of magnitude or two.

The list of desirable characteristics in a channel degradation model for estimation of sediment loading from the stream channel boundary include the capability to consider the influence of instream hydraulic structures, and the ability to represent non-cohesive sediments, connectedness with the floodplain, and channel restoration through changes in channel cross-sections and slopes (Table 5.6). Other significant capabilities include the representation of urban features, such as impervious surfaces, and upstream influences, such as dams and reservoirs. While these other latter considerations can be

represented as boundary conditions, or generated using a watershed model, they are still pertinent to this discussion.

Table 5.6. Comparison of Key Model Characteristics

Key Characteristics	Watershed-Scale Models							Reach-Scale Models				
	AGNPS 2001	ANSWERS-2000	GWLF	HSPF	SWAT	WARMF	SPARROW	CCHE1D	CONCEPTS	HEC-6	SAM	SRH-1D (GSTAR)
represent upland processes	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N
distinguishes cohesive vs. non-cohesive soils	Y	Y	N	Y	N	N	N	Y	Y	Y	N	Y
incorporates urban features	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y
connection with flood plain	N	N	N	N	Y	N	N	Y	Y	Y	N	Y
influence of reservoirs/dams	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y
in-stream hydraulic structures	N	Y	N	Y	N	N	N	Y	Y	Y	N	Y
channel restoration (cross-section and slope)	Y	N	N	Y	Y	Y	N	Y	Y	Y	Y	Y

The channel degradation models reviewed during this study can be classified generally as either watershed-scale models or reach-scale models, although some of the modeling systems blur this delineation by incorporating interfaces that format watershed model output for input to the reach-scale models. Also, channel degradation modeling is not conducted as a stand-alone simulation, but as a desired addition to upland erosion modeling being performed for statewide assessments and for Chesapeake Bay watershed analyses. Therefore, reach-scale models alone are not sufficient for the statewide analyses needed. To address the needs of erosion modeling in Virginia's coastal zone management area, an approach is needed that will provide estimates of both channel and upland sediment sources based on comparable methodologies, so that any differences in magnitudes between the two sources are not the result of the methods used.

The process of comparing channel degradation models was not straight-forward, as the models reviewed were each developed for very different purposes, and in some

cases information from portions of some models was not readily available. However, from the information gathered, there are two approaches that have been identified that may serve the purposes of the state for channel degradation modeling in the urbanized coastal zone of Virginia – a linked watershed-reach modeling approach, and a deductive modeling approach. The linked watershed-reach model approach would use a combination of a watershed model to perform upland modeling with linked output into a reach-scale model for performing instream routing and sedimentation processes. The deductive modeling approach would use a combination of two models – one which simulates combined upland and channel erosion, and one which simulates only upland erosion – with channel erosion quantified through subtraction of simulated outputs.

The linked watershed-reach model possibilities include the following combinations:

- AGNPS with either CONCEPTS or CCHE1D
- GWLF and the Muskingum flow routing routine
- HSPF and either CCHE1D or SRH-1D
- SWAT and CCHE1D

With the linked watershed-reach approach, running the combined models provides an estimate of the combined upland and channel sediment loads at the watershed outlet. Running the watershed models by themselves provides load estimates from the upland sources only. From these suggested combinations, most of the linkages already exist, with the following exceptions. The description of the GWLF linkage has not been thoroughly explored as it was developed by a consultant and is not available for review. While the HSPF linkages do not currently exist, HSPF is very flexible in the output configuration and should be able to be linked without a significant effort. Of the watershed models, GWLF has been used several times for statewide nonpoint

assessment modeling, and the HSPF-based Chesapeake Bay Watershed Model 5.0 is currently being configured for the entire state of Virginia. Although AGNPS and SWAT models of the entire state have not been developed, such large scale models have been developed in other states and could certainly be applied to sub-areas, such as the coastal zone watersheds in Virginia. As can be seen from Table 5.6, no one model or combination is perfect, although several appear to meet the majority of the requirements, especially when used in combination. Of the reach models, input requirements for CONCEPTS, CCHE1D and SRH-1D are all fairly similar.

The deductive modeling combination possibility is SPARROW and AGNPS, GWLF, HSPF, or SWAT. The reasoning for this approach is straight-forward. SPARROW is a regression model between watershed attributes and instream sediment which comes from both upland and instream sources, so its output represents a combination of upland and channel erosion. Therefore, the SPARROW simulated loads minus the upland erosion simulated from a calibrated watershed model should provide reasonable estimates of sediment loading from channel degradation. A SPARROW sediment model is under development for the conterminous U.S., similar to one developed earlier for nutrients (Smith et al., 1997). This model could serve as a starting point for creating a statewide model by incorporating more state-specific data for Virginia and for further modifying the model to include additional explanatory watershed variables as identified in this study.

The strength of the watershed-reach combination modeling approach is that the strengths of the reach models compliment the weaknesses of the corresponding watershed models. In combination, all of the key characteristics identified as desirable

are covered by the identified watershed-reach model combinations. Each of these combinations, however, relies on collection of field measurements of shear stress and other site-specific parameters. While not as physically-based as the watershed-reach combinations, the strength of the deductive modeling combinations is that they may be able to avoid the collection of additional site-specific data, unless dependent variables are specifically identified that cannot be obtained from existing digital sources.

For site-specific estimates of channel degradation on specific channel restoration projects, use of an individual reach-scale model may be appropriate. However, if the purpose is to estimate the overall magnitude of sediment loading from channel degradation from the coastal zone and then to account for improvements from channel restoration projects in various sub-areas, then it makes sense to use the same procedures to keep the relative magnitudes of the larger area and the individual projects on the same basis.

5.2.5. Channel Degradation Model Websites

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ANSWERS: http://dillaha.bse.vt.edu/answers/index.htm
CCHE1D: http://www.ncche.olemiss.edu/index.php?page=freesoftware
CHILD: http://hydrology.mit.edu/index.php/Models/CHILD
CONCEPTS: http://www.ars.usda.gov/Research/docs.htm?docid=5453
GWLF:

- **GWLF 2.0:** Not currently available on the web.
- **AVGWLF:** http://www.avgwlf.psu.edu/
- **BasinSim:** http://www.vims.edu/bio/models/basinsim.html
- **Virginia version:** Available from the author at eyagow@vt.edu

HEC-6: http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm
HSPF: Available through the BASINS download at
http://www.epa.gov/waterscience/basins/b3webdwn.htm
SAM: http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=SOFTWARE;2
SPARROW: http://water.usgs.gov/nawqa/sparrow/sparrow-mod.html
SRH-1D (GSTAR-1D): http://www.usbr.gov/pmts/sediment/model/srh1d/index.html
SWAT: http://www.brc.tamus.edu/swat/soft_model.html
WAMView: http://www.epa.gov/athens/wwqtsc/html/wamview.html
WARMF: http://www.systechengineering.com/warmf.htm
WCS: http://wcs.tetratech-ffx.com/, http://wcs.tetratech-ffx.com/System/System.htm
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Chapter 6: Conclusions

Piedmont streams are larger than Coastal Plain streams for a given watershed area. We found this to be true for the regional curves, as well as for our study sites. This is mostly due to Piedmont channels being wider than their Coastal Plain counterparts. Our streams followed the trends of the regional curves, although our Coastal Plain streams tended to be smaller in size than the regional curves.

We found no particular pattern of enlargement ratio across a watershed area gradient or percent watershed imperviousness. We, therefore, were unable to develop regression equations to allow for the prediction of sediment loads from enlarging channels due to urbanization. In fact, the level of variability in channel enlargement is not surprising given the uncertainty inherent in these computations. Much of our analysis is based on the determination of bankfull stage, in the development of the regional curves and in our site measurements. Bankfull determination is very subjective and extremely difficult to identify in unstable urban or urbanizing streams. Differences in bankfull determination would have an immense impact on channel enlargement estimates, which is how we proposed to estimate sediment load from urban stream channels. However, the variability in enlargement ratios can not be blamed solely on the elusiveness of bankfull elevation since our paired site analysis also resulted in contradictory results.

Our study was designed to eliminate bias in site selection by utilizing Probmon sites. Due to the short study period, historical cross sections were sought for each of the study sites, but historical data could not be found for these sites. Therefore, in the future,

we recommend identifying historical sites and then conducting follow-up field studies, accepting that some bias will occur in site selection. Channel morphology is extremely complex and sensitive to local and historical disturbances. This sensitivity confounds broad-based conclusion and simple estimates of sediment loading from urbanizing stream systems.

Results of this study reinforce the concept that changes in channel morphology are due to a complex interaction between watershed hydrology, watershed geology and soils, previous channel alterations, and instream structures.

From the model reviews, several combinations of watershed-scale, reach-scale, and statistical models have been identified with potential to address characteristics of watersheds in the urbanizing coastal zone management area in Virginia. Important characteristics of the model combinations are that they be able to represent:

- upland urbanizing land use change features,
- differences between cohesive (clay and silt) and non-cohesive (sand and gravel) sediment particles,
- the connectedness between the stream channel and the floodplain,
- in-stream hydraulic structures, including reservoirs and dams, and
- the effects of channel restoration.

In order to identify a specific modeling approach from the potential recommended combinations, a pilot study is recommended that includes a complete setup and parameterization of individual models for one or two typical watersheds in order to refine data needs assessment. Ideally, these watersheds should have discharge and water quality data, as well as historic cross sections to assess model performance. This pilot study would illustrate the effect of model assumptions on study results and quantify the

potential error in the sediment loading estimates. Such a study should be conducted with considerable interaction with state agency personnel to better tailor the modeling approach to state programmatic needs.