A Sediment Budget for the Pipers Creek Watershed: Applications for Urban Stream Restoration

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A thesis submitted in partial fulfillment of the
Requirements for the degree of

Master of Science in Engineering

University of Washington

2002

Program Authorized to Offer Degree: Civil and Environmental Engineering

University of Washington
Graduate School

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Abstract

A Sediment Budget for the Pipers Creek Watershed: Applications for Urban Stream Restoration

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Changes in land use and hydrology resulting from urbanization alter the processes of sediment production, delivery, and fluvial transport within a watershed. In this study, a sediment budget was constructed for the Pipers Creek watershed to describe how the magnitude and character of sediment production has changed as a result of basin urbanization and subsequent engineering efforts to control channel enlargement and erosion. In addition, the condition of instream sediment was evaluated to determine if the physical characteristics of the substrate currently constrains the quality of salmonid habitat.

The current sediment-production rate in the Pipers Creek watershed is estimated at 120 ± 20 tonnes km^{-2} $year^{-1}$. Whereas this rate is half of the estimated maximum sediment-production rate following the onset of urbanization but prior to efforts to control erosion, it remains six times greater than the estimated production rate before development. Currently, the primary sources of sediment in the basin are channel enlargement (40%), landslides (30%), and sediment produced from urban land uses (28%).

In the mainstem of Pipers Creek, the grain-size distribution of coarse substrate particles (>8 mm), and estimates of the average particle transport rate for bedload sediment (190 m yr^{-1}) indicate the quantity of coarse sediment being delivered to the channel is not a concern for resource managers; however, fine

sediment being delivered by hillslope processes and urban runoff may impair quality salmonid habitat. The percentages of fine sediment (< 8 mm) found in the bedload sediment here are correlated in other studies with reduced rates of salmonid reproductive success.

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ACKNOWLEDGEMENTS

I would like to thank my advisor, Derek Booth, for his insight and perspective throughout this project as well as for his suggestions during the review process. I would also like to thank my other committee members, Catherine Petroff and Susan Bolton, for their advice and thoughtful comments. In addition, I am very grateful to Seattle Public Utilities, and Darla Inglis in particular, for the initial motivation for this project as well as for financial assistance. Finally, I am forever grateful to Meredith Lohr, who has provided constant encouragement and immeasurable support in so many ways.

INTRODUCTION

The quantity and quality of sediment supplied to a channel are governing influences on the dynamic and complex processes that determine the channel's geomorphologic and ecologic character. Variations in sediment supply, as well as in transport capacity (flow regime) and riparian vegetation, may result in a physical response expressed by changes in channel form (Montgomery and Buffington, 1997). As various biota use fluvial sediment in different capacities, changes to the character of that sediment may also result in habitat degradation, specifically to the channel substrate utilized by salmonids for spawning (Chapman, 1988; Quinn and Peterson, 1992). The changes that occur to a watershed as it becomes urbanized can significantly alter the sources and rates of sediment delivery to a channel network (Wolman, 1967; Nelson and Booth, 2002). These changes, in combination with alterations to the hydrologic regime and the character of riparian vegetation, can result in notable changes to a stream's geometry, hydraulic characteristics, and water quality (Wolman, 1967; Hammer, 1972; Booth, 1990; Pizzuto et al., 2000). These types of physical changes to urban channels present challenges to land managers required to protect infrastructure and restore quality habitat (May et al., 1997). Characterizing the regime of sediment supply and instream distribution can assist successful mitigation of the negative effects of watershed urbanization on stream channels.

Whereas erosion is a ubiquitous component of natural landscape-forming processes, changes produced by urbanization can increase or decrease the amount of sediment that is delivered to a channel system as well as alter the fate of sediment once it enters the channel (Pizzuto et al. 2000). A change in the magnitude and character of supplied sediment will result in a change in the character of sediment within the stream (Montgomery and Buffington, 1997). During a basin's urbanization, construction causes significant disturbance of the landscape and in doing so may generate significant sediment available for transport to receiving streams during storm events (Wolman and Schick 1967). Increases in fine sediment supplied to a stream network can affect water quality, as nutrients and metals from the urban landscape are bound with clay particles (Novotny and Olem, 1994). This can result in eutrophication of receiving waters, an increase the toxicity of deposited fine sediments, and an increase in turbidity. Additionally, deposition of fine sediment may fill pore spaces between coarse particles in gravel-bedded streams. This can reduce intragravel flow and subsequently the transmission of dissolved oxygen, which can have a significant impact on incubating salmonid embryos (Chapman 1988). Increases in coarse sediment supply typically results in aggradation of the bed surface. This can reduce flow capacity within the channel and increase the risk of flooding.

Alternatively, a mature urban basin may experience significant decreases in sediment production (Trimble, 1995). As channel banks are armored, hillslopes are stabilized, and surfaces are paved, the sources of sediment in an urban basin become limited. If the sediment input is less than the capacity of the stream to transport sediment, erosion within the channel will likely occur. This can coarsen the instream sediment and lead to armoring of the stream bed (Montgomery and Buffington, 1997).

The physical changes made to a basin during urbanization can significantly alter its hydrologic regime, compounding the potential for instream erosion (Booth, 1991). During development, soil compaction and the removal of organic debris and vegetation result in a decrease of the hydrologic storage capacity of near-surface soils, while the construction of roads and structures increases the amount of impervious surfaces. This results in a decrease of storage and infiltration of precipitation during storm events and leads to a rapid response in stream discharge following precipitation events (Booth, 1990; Konrad and Booth, 2002). The hydrologic regime following basin urbanization thus is typically characterized by higher peak discharges occurring with increased frequency (Wolman, 1967; Hollis, 1975). This altered flow regime tends to have greater capacity to transport sediment and greater erosive power due to increased shear stresses in the channel.

The combination of altered hydrologic and sediment supply regimes can result in a wide variety of channel responses. Quasi-equilibrium responses may be subtle and go unnoticed over long periods of time, whereas in other cases changes in channel form are dramatic. In early stages of basin urbanization, increased sediment supply and the characteristic 'flashy' urban hydrologic regime impart opposing effects on channel morphology. Whereas these changes can sometimes lead to aggradation and decreases in channel volume, more dramatic is the increase in channel cross-sectional area, predictable evolutionary sequence of channel incision, and degradation that can occur following urbanization (Hammer 1972, Booth 1991, Simon 1995). Where channel gradient is moderate to high and local geologic material is susceptible to erosion, channel enlargement can be rapid to catastrophic (Booth 1990, Booth and Henshaw 2001). Such changes in channel dimension can result in the process of channel erosion becoming a major source of sediment in an urbanizing watershed (Trimble 1997, Nelson and Booth 2002).

Such changes in the physical character of urban streams have been recognized for decades within the developing basins of the Puget Sound region, and there are increasing efforts to mitigate the physical and biologic degradation that has resulted. In the Pipers Creek watershed in Seattle, Washington, the altered hydrologic regime associated with near-complete basin urbanization has caused dramatic channel erosion and enlargement. The changes in land-use that are associated with basin urbanization, along with changes in sediment production that accompanied increased channel erosion, have altered both the sources and rates of sediment production in the basin. The purpose of this thesis is to quantify the processes of sediment production and storage within stream channels of the Pipers Creek watershed in order to guide future enhancement efforts. The following questions guide the investigation:

- How have the physical processes associated with basin urbanization altered sediment delivery to the stream network?
- What is the character of instream sediment that has resulted from the current processes of sediment production and transport?

These questions were addressed by constructing a sediment budget for the Pipers Creek watershed that details the sources and rates of sediment production in the basin, as well as the quantity, quality, and distribution of instream sediment that has resulted.

CHAPTER 1- BACKGROUND

Basin Description

The Pipers Creek watershed is located in northwest Seattle, Washington (Figure 1.1). It is approximately 7.4 km^2 in area and ranges in elevation from sea level where it enters Puget Sound to 150 m at the northeast corner of the watershed. The watershed is composed of two distinct topographic regions. A relatively flat plateau forms the upper portion of the watershed; steep hillsides and ravines characterize the lower watershed. Pipers Creek and its tributaries are located almost entirely within the ravines of the lower watershed. The slope of the basin, as measured by the difference in height between the points of highest and lowest elevation divided by the distance between these locations, is 0.06 (6%). As the basin is extensively developed, its boundaries no longer follow natural topography but instead are defined by roadways and their drainage systems. The Pipers Creek watershed is bounded on the north by NW 145th Street, on the south by NW 80th Street, and Fremont Avenue N on the east. The western boundary of the watershed traverses hillslopes irregularly down to Puget Sound at the Pipers Creek outflow in Carkeek Park.

Land Use

The Pipers Creek watershed is heavily urbanized, with almost 90% of the basin's area developed. Initial development began in the watershed in the 1920s; however, the most significant building phase occurred in the early 1950s and new developments continued through the 1970s. Development within the basin is located almost exclusively on the upper plateau portion of the watershed. According to data from the City of Seattle, approximately 75% of the basin is medium-density single family housing, 7% is high-density multi family housing, and 7% is commercial or industrial (Washington State Geospatial Data Archive, 2001). Parks occupy the remaining 11% of the basin. Carkeek Park is approximately 0.8 km^2 and occupies the majority of the lower watershed and almost 98% of park space in the basin.

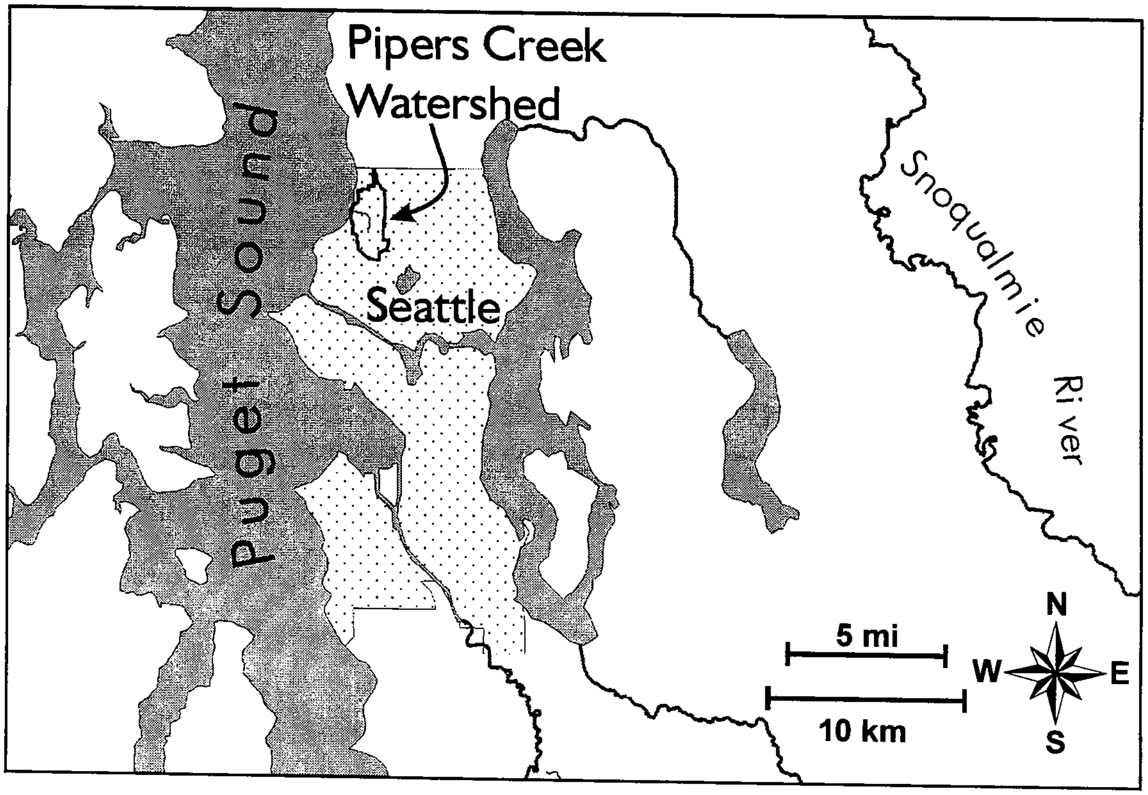

Figure 1.1. Vicinity of the Pipers Creek watershed.

Stream Network

Pipers Creek is a third-order stream network flowing west into Puget Sound. The stream order is based on field surveys of perennial channels and is according to the Horton-Strahler approach (Strahler, 1952). The drainage density of the Pipers Creek watershed is approximately 0.8 km of stream for every square kilometer of watershed (Horton, 1945). The stream length used to determine drainage density is also based on field surveys of existing perennial channels. Due to the extensive urban character of the basin, the majority of surface water is collected and transported by either subsurface storm drains or surficial drainage ditches. As a result there are few remnants of 'natural' stream channels in the upper portion of the watershed and open channels exist almost exclusively within Carkeek Park and the ravines and open spaces of the lower watershed. As such, the drainage density within the lower watershed, approximately 7.3 km of stream per square kilometer, is much higher than that of the surrounding developed areas or the watershed as a whole. Base flow in Pipers Creek is supplied by groundwater delivered by both numerous steep seep-fed tributaries and storm drains. During precipitation events these storm drains discharge surface water gathered from the upper basin directly to Pipers Creek and its tributaries.

The three main alluvial stems within the Pipers Creek stream network are Pipers Creek, Venema Creek, and Molendorph Creek (Figure 1.2). Venema Creek joins Pipers Creek 600 m from its discharge location into Puget Sound. Molendorph Creek joins Venema Creek approximately 235 m upstream of its confluence with Pipers Creek. According to the channel classification system of Montgomery and Buffington (1997), these are predominantly plane-bed channels. There are some morphological exceptions where constructed channel modifications force short cascades or step-pool sections.

Pipers Creek and its tributaries have long been subjected to channel modifications. The main stem of Pipers Creek was straightened in a Civilian Conservation Corps (CCC) project in 1933 and further channel construction occurred in 1948. A sewage treatment plant was constructed upstream of the Pipers-Venema confluence in 1953. A trunk sewer main for the facility that runs adjacent to Pipers Creek for much of its length was constructed at the same time. The sewage treatment facility was converted to a pumping station in 1993 and is currently operated by King County (City of Seattle Municipal Records).

Channel enlargement within Pipers Creek has been recognized and addressed in Carkeek Park for over 30 years. In 1973, a series of 14 boulder weirs were constructed on the main stem of Pipers Creek upstream of the

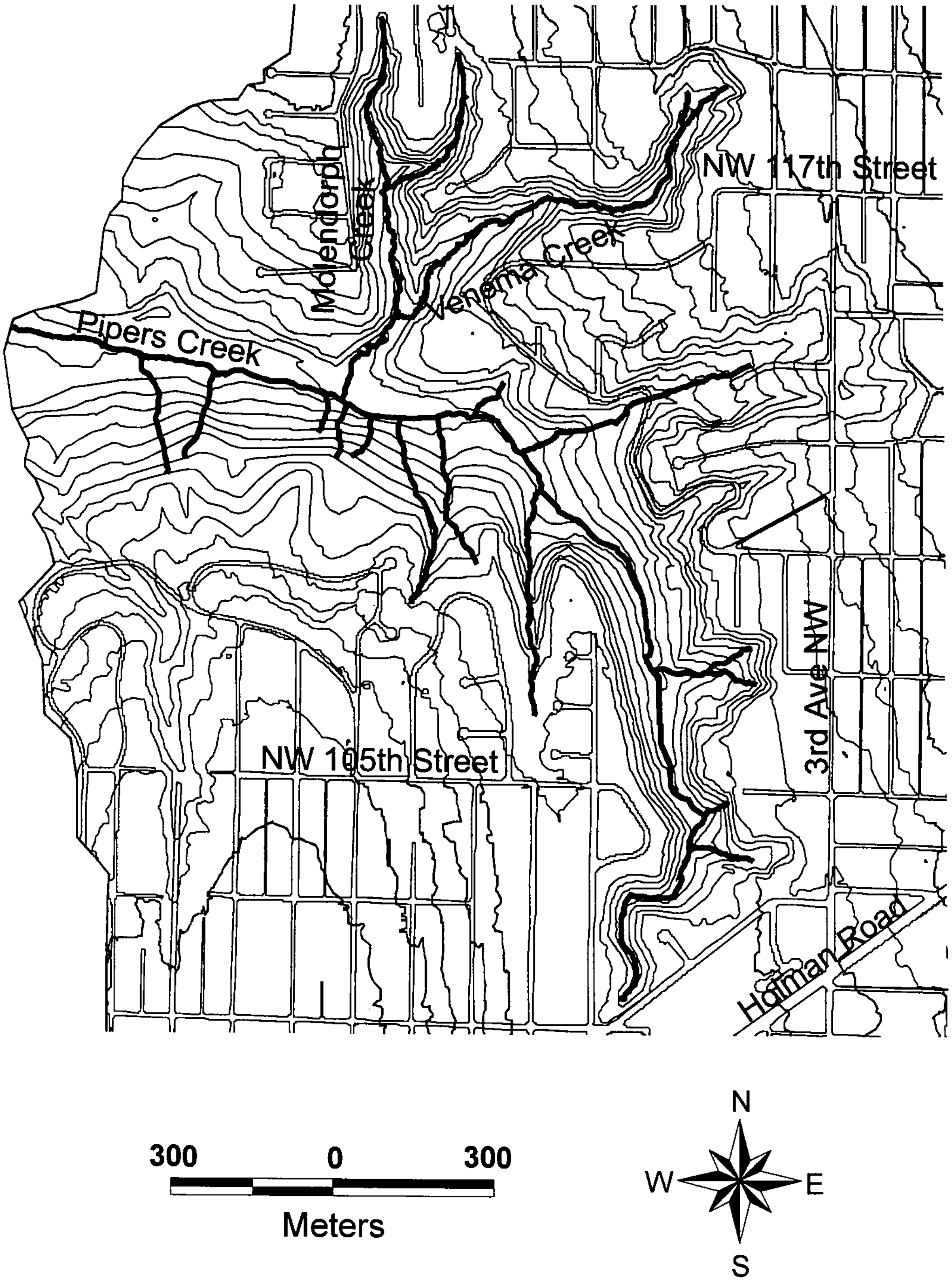

Figure 1.2. Channel network of the Pipers Creek watershed.

treatment facility; prior to this, eroding banks had been protected by rip-rap. In 1979 the EPA declared the park a pilot restoration project. At this time a series of log weirs were constructed in a steep unnamed tributary that flows into Pipers Creek opposite the upstream end of the treatment facility (Pipers Creek Watershed Action Plan: The Review and Course Corrections 2000). A report by Gaia Northwest, Inc. (1997; later amended by Herrera Environmental Consultants, 1998) addressed the state of erosion in Carkeek Park at that time and prioritized remediation strategies. Erosion and sedimentation control projects based on these investigations were initiated in 1998 and 1999 by Seattle Public Utilities. The instream projects were focused on Pipers Creek downstream of the King County facility, the first 300 meters of Venema Creek, and the main stem of Molendorph Creek. Grade control structures including log and boulder weirs were installed in both Pipers Creek and Venema Creek, and bank protection was added on all three main stems. Additional erosion-control efforts included the construction of stormwater bypass lines to capture stormwater runoff from roads neighboring the park and transmit the water down the steep hillslopes into the creek system. Prior to these bypass lines, stormwater flows eroded gullies in the hillsides downslope of their discharge into the park.

Like many local stream networks, Pipers Creek once supported strong returns of anadramous fish and early records show that fish traps were maintained at the creek's outflow (City of Seattle Municipal Records). Fish passage was blocked with the construction of the railroad line in the late 1920's. After an absence of more than half a century, salmon runs were reintroduced in 1987. A variety of salmonids now return to Pipers Creek, including introduced Coho (*Oncorhynchus kisutch*) and native Chum (*Oncorhynchus keta*), Steelhead (*Oncorhynchus mykiss*), and Cutthroat (*Oncorhynchus clarkii*). In the fall of 2001 and winter of 2002, 250 Chum and 155 Coho returned to spawn in Pipers

Creek, though there are no data on the success of the progeny of these spawning salmonids (Washington Trout, 2001; Lynch, 2002).

Geology

The surficial geology of the Pipers Creek watershed consists primarily of Quaternary glacial deposits resulting from the Vashon stade of the Fraser glaciation. Deposition of the glacial drift of the Vashon stade occurred between 17,000 and 13,500 years ago (Booth, 1987). The glacial units exposed in the Pipers Creek watershed (from youngest to oldest) include till (Vashon Till), advance outwash (Esperance Sand), and glaciolacustrine deposits (Lawton Clay). These units are overconsolidated as a result of being overridden by up to 1000 meters of glacial ice (Thorson, 1989). Thin, recent deposits of alluvium and colluvium are also present locally throughout the basin.

The character of each unit is unique and significant to the processes of erosion that are occurring in the Pipers Creek watershed. Vashon Till is a poorly sorted mixture of sand, silt, gravel, and clay, with occasional cobbles and boulders. It is very dense and relatively impermeable. Esperance Sand is highly permeable fine to medium sand. Locally the Esperance Sand contains beds of silt and gravel; the gravel content typically increases in abundance and size towards the top of the unit (Crandell et al., 1965). Lawton Clay results from sedimentation occurring in a proglacial lake that formed in front of the advancing lobe of Vashon-age ice. The unit locally consists of laminated to massive light-gray silt. The upper contact with the Esperance Sand can be gradational with transitional interbeds of silt and sand. The Lawton Clay is relatively impermeable and acts as an aquatard to downward migrating ground water in the Esperance Sand. As a result, this contact is commonly marked by the occurrence of springs and slope instability. Local grain-size distributions of the units in the basin are presented in Chapter 4.

CHAPTER 2 - LITERATURE REVIEW

Literature relevant to the construction of sediment budgets, sediment production in urban landscapes, channel enlargement resulting from urbanization, and the effect of variations in substrate character on salmonid habitat was reviewed for this study.

Sediment Budgets

Sediment production and distribution within a basin are complex processes that are difficult to quantify precisely. Erosion and deposition are dynamic and variable in both time and space, and therefore any rate attributed to these processes is only an estimate. However, a sediment budget can provide an excellent framework with which to evaluate sediment production, storage and transport in a basin. In its most complete form, a sediment budget details the rates and processes of erosion and transport on hillslopes and in channels, as well as temporary storage elements and the rate of weathering and breakdown of particles while in transport or storage (Dietrich et al., 1982).

The general equation that describes a sediment budget investigation is:

$$I + \Delta S = O,$$

where I is the mass or volume of sediment input to the channel network over a specific period of interest (production), O is the mass or volume of sediment output from the channel network over the same period (yield), and ΔS is the change in mass or volume of sediment stored in the channel network. For most investigations undertaken with the goal of guiding resource management decisions, determining the sources, rates, and grain-size distributions of sediment entering a channel network typically suffices (Reid and Dunne, 1996). In order to determine the rate of sediment exported from a basin, or its yield, both changes in sediment storage within the channel network and sediment transport must also be analyzed. Measurement of all three components of the equation is necessary to avoid errors inherent in determining one term by subtraction, but is often difficult to accomplish in practice (Kondolf and Matthews, 1991).

The majority of sediment budgets that have been completed are for basins that are primarily forested in order to assess the effects of changes in land use. A number of studies have been completed both in the western United States (Dietrich and Dunne, 1978; Lehre 1982; Roberts and Church, 1986; Slaymaker, 1993) and in western Washington (Reid, 1981; Madej, 1982; King County, 1995; Paulson, 1997; Nelson and Booth, 2002). In mountainous regions, hillslope mass wasting, including landslides and debris flows, has commonly been determined to be the dominant sediment-producing process (Dietrich and Dunne, 1978; Lehre, 1982; Slaymaker, 1993, Paulson, 1997). In the Clearwater Basin in Oregon's Coast Range, Dietrich and Dunne (1978) determined that debris flows initiating from bedrock hollows were the most significant mechanism delivering hillslope sediment to fluvial channels. Lehre (1982) found similar results looking at the Lone Tree Creek basin in the California Coast range north of San Francisco. There, sediment generated from debris slides and flows represented over half the yearly production. Looking at the effect of geology and land-use on sediment production, Paulson (1997) completed partial sediment budgets for 10 sub-basins of the Skagit River, finding landslides to be the greatest sediment source. Nelson and Booth (2002) also found this to be true in the Issaquah Creek basin, even though portions of the watershed are urbanizing rapidly.

Other studies have found sources separate from hillslope mass wasting processes to be significant contributors to overall sediment production. Roberts and Church (1986) found that stream bank erosion in disturbed watersheds within the Queen Charlotte Ranges of British Columbia contributed sediment at rates comparable to landslides and debris flows. In the logged Clearwater Basin, Reid (1981) found that road construction and road surface erosion were significant contributors of sediment even though landslides were the primary sediment source. Madej (1982) determined that road surface erosion was, in fact, the dominant sediment producer in the Big Beef Creek basin. There, due to changes in land use, sediment production associated with roads including sheetwash on road surfaces, disturbance-related landslides, and erosion of roadside ditches contributed seven times the amount contributed by naturally occurring mass wasting processes, and almost 90% of the basin total. A similar response to changes in land use was seen by Trimble (1997) in one of the few investigations of sediment production in an urbanizing watershed. Trimble (1997) determined that approximately two-thirds of the sediment produced in the San Diego Creek basin between 1983 and 1993 resulted from channel enlargement.

Sediment Production in Urban Systems

Only a limited number of studies have examined sediment sources within urban landscapes, and there are few comprehensive analyses of urban sediment production. The majority of the investigations looking at urban sediment sources have addressed sediment produced during construction and from channel enlargement (Wolman and Schick, 1967; Wolman, 1967; Hammer, 1972; Booth and Henshaw, 2001). Other studies have addressed the sediment yield from different urban land use categories (Marselek, 1978; Bannerman et al.,1984; City of Bellevue, 1995; Horner, 1992; Reinelt, 1996). Each of these sources can be a significant supplier of sediment, but few efforts have been made to synthesize such endeavors into sediment budgets within urban watersheds.

As land is converted from its natural state during basin urbanization, there is a change in the delivery of both sediment and water to the channel network. During the process of construction and development, the removal of vegetation, and the exposure and displacement of soils may increase sediment yield by a factor of two to over 100 (Wolman 1967, Wolman and Schick 1967). A reduction of vegetation and organic-rich soils, coupled with a loss of hydrologic storage capacity due to the compaction of earth surfaces during construction and increased impervious surfaces results in accelerated runoff rates that increase the magnitude, duration, and frequency of peak discharges (Hollis, 1975; Booth, 1991).

Table 2.1. Sediment production results from previous investigations.

Source (year)	Location	Basin Size (km^2)	Primary Land Use	Sediment Production (tonnes km^{-2} $year^{-1}$)
Reid (1981)	Clearwater River, Washington	370	Forest/ logging	269-387
Madej (1982)	Big Beef Creek, Washington	38	Forest/ logging/ urban	185
Lehre (1982)	Lone Tree Creek, California	1.74	Grassland/ forest	902
Slaymaker (1993)	Lilooet River, B.C.	3150	Forest	200
King County (1995)	Tibbetts Creek, Washington	14.7	Forest/quarry/urban	77
Trimble (1997)	San Diego Creek, California	288	Urban/ agriculture	520
Nelson and Booth (2002)	Issaquah Creek, Washington	142	Forest/ urban	55

Initially, increases in both sediment supply and stormwater runoff may result in increased sediment transport and channel aggradation and widening; however, as construction rates wane, so does upland sediment delivery, and widening continues as channels incise (Wolman 1967, Hammer 1972). Rates of channel enlargement are strongly affected by channel slope and the underlying geology, and change can occur gradually or catastrophically (Booth 1990). While changes in stream form can be dramatic, restabilization has been documented when basin conditions are relatively unchanged for a period of decades (Henshaw and Booth 2000). This process of degradation and subsequent restabilization is well illustrated in the field based conceptual model of channel evolution proposed by Simon (1995).

Sediment production from areas of urban land use have largely been evaluated using measurements of TSS at a downstream discharge location. The Nationwide Urban Runoff Program (NURP) was conducted in order to evaluate the pollutant loading from stormwater discharges in urban settings (US EPA, 1983). The City of Bellevue, Washington, located east of Seattle across Lake Washington, was included in this study. This investigation was continued in the Bellevue Urban Runoff Program (BURP) study which was completed in the early 1990s (City of Bellevue, 1995). Both studies included determination of pollutant yield coefficients including total suspended solids (TSS). Sites representing various land-uses and degrees of urbanization were monitored to evaluate patterns in stormwater discharge characteristics. As the monitored basins represent multiple land-uses, classifications, and degrees of urbanization, the pollutant yield coefficients generated in these studies are not easily applied to other basins. The TSS yield coefficient from the BURP study, however, can be used for comparison with other land use specific yield coefficients.

Other local studies have been conducted that address TSS yield coefficients for specific land-use classes. Horner (1992) compiled TSS pollutant yield coefficients for various land-use classes nationwide from previously published studies as part of a Master Drainage Plan for a King County development. King County also produced a study of the Laughing Jacobs Creek subcatchment evaluating TSS yield coefficients for urban land-use classes and construction sites (Reinelt, 1996). TSS yield coefficients from these two King County investigations are utilized in this study (Reinelt, 1996; Horner, 1992).

Streambed Sediment as Salmonid Habitat

The character of streambed sediment is one of a limited number of parameters that may influence the quality of salmonid habitat. Water quality, temperature, rearing habitat, and the hydrologic discharge regime all may be limiting factors at certain salmonid life stages. It is commonly asserted that excessive fine-grained sediment is detrimental to the success of salmonid spawning (May et al., 1997); however, the field studies that support this claim are limited. A large portion of the body of literature on the negative affects of fine sediment on salmonid reproduction and emergence results from laboratory investigations (Everest et al., 1987; Chapman, 1988).

Though limited in number, field studies do support results from laboratory investigations that indicate excessive fine sediment in streambed substrate limits the success of salmonid survival to emergence. Koski (1966) found that when 30% of streambed sediment was finer than 3.3 mm, and 21% was finer than 0.85 mm, fry emergence in coho salmon redds in Oregon were negatively affected. Koski (1975) also found a negative correlation to the survival from egg deposition to emergence for chum salmon when greater than 27% of total sediment was finer than 3.3 mm. In the first year of a study investigating coho salmon in the Clearwater River in Washington, Tagart (1976) found that when more than 20% of substrate sediment was finer than 0.85 mm survival to emergence was reduced by 50%. The same relationship, however, was not demonstrated in the second year of the study. In the same study, results also showed the concentration of dissolved oxygen (DO) is related inversely to sediment finer than 0.85 mm, indicating sediment of this size may have prevented the intragravel flow of DO. A threshold of approximately 20% sediment finer than 0.85 mm to produce this effect was seen in that study. Cederholm et al. (1981) also found an inverse relationship between survival of coho salmon and sediment finer than 0.85 mm. A 50% reduction in the survival to emergence of coho in natural redds occurred when the fraction of fine sediment (<0.85 mm) reached about 25%. These findings are consistent with those of McHenry et al. (1994) who found that, in a study of spawning gravel quality in five watersheds in the Olympic Peninsula of Washington, the survival of coho from egg to alevin declined rapidly above a threshold level of 13% of substrate sediment finer than 0.85 mm. Together, these studies indicate that substrate composed of excessive fine sediment, from 13% to 25% of substrate sediment finer than 0.85 mm, and about 30% finer than 3.3 mm, may limit the survival to emergence of salmonids.

CHAPTER 3 - METHODS

Characterization of Channel Morphology

For evaluation of channel morphology, as well as for sediment production and storage, the stream network was separated into reach segments (Figure 3.1). The morphological evaluation of reaches was based on their channel form, bank stability, confinement, and entrenchment (Montgomery and Buffington, 1997; Henshaw and Booth, 2000). Channel form was described using the reach classification procedure of Montgomery and Buffington (1997). This process-based classification system provides a context for assessing influences on channel form.

The particular diagnostic features used to assess channel form are listed in Table 3.1. Channel confinement can strongly influence the reach response to changes in sediment supply and discharge, and so it is a significant parameter in an evaluation of sediment production and storage (Montgomery and Buffington, 1997). A channel is considered *confined* if the width of the valley floor is less than twice the width of the active channel. Channel entrenchment can occur following changes in sediment supply and discharge when naturally unconfined channels incise and become isolated from their flood plains. The extent of entrenchment in the study reaches is therefore a good indication of channel degradation. To assess the condition of bank erosion, reaches were classified using qualitative criteria for bank stability (Henshaw and Booth, 1999) based on indicators of bank erosion and the condition of riparian vegetation (Table 3.2). Patterns in bank stability help determine the extent and severity of streambank erosion within the channel network. Widespread signs of unstable banks within a reach are indicators of continued channel enlargement.

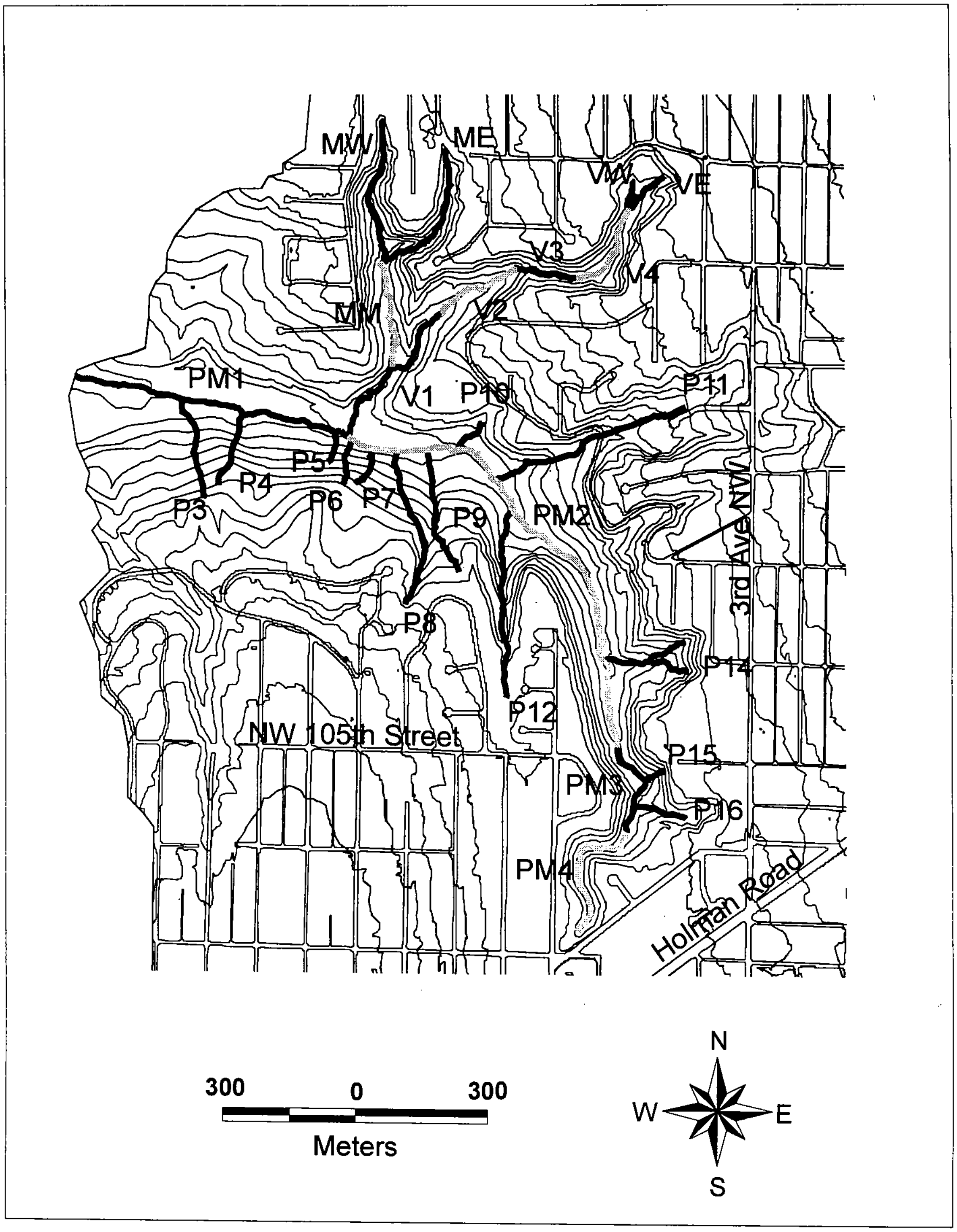

Figure 3.1. Delineation of study reaches used for this investigation. Breaks between reaches of mainstem channels are indicated by changes in the reach tone.

Table 3.1. Diagnostic features for evaluating channel type (from Montgomery and Buffington, 1997)

	Dune ripple	**Pool riffle**	**Plane bed**	**Step pool**	**Cascade**	**Bedrock**	**Colluvial**
Typical bed material	Sand	Gravel	Gravel-Cobble	Cobble-boulder	Boulder	Rock	Variable
Dominant roughness elements	Sinuosity	Bedforms	Grains, banks	Bedforms	Grains, banks	Boundaries	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Fluvial, hillslope, debris flow	Hillslope, debris flow
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined

Table 3.2. Bank stability classification criteria (from Henshaw and Booth, 2000)

Classification category	Description
Stable	Perennial vegetation to waterline
	No raw or undercut banks (except for some erosion on outside of meander bends)
	No recently exposed roots
	No recent tree falls
Slightly unstable	Perennial vegetation to waterline in most places
	Some scalloping of banks
	Minor erosion and/or bank cutting
	Recently exposed tree roots rare but present
Moderately unstable	Perennial vegetation to waterline sparse (mainly scoured or stripped by lateral erosion)
	Bank held by hard points (trees, boulders) and eroded back elsewhere
	Extensive erosion and bank undercutting
	Recently exposed tree roots and fine root hairs common
Unstable	No perennial vegetation at waterline
	Banks held only by hard points
	Severe erosion of both banks
	Recently exposed tree roots common
	Tree falls and/or severely undercut trees common

Sediment Production

Sediment production in the Pipers Creek watershed has occurred over four distinct periods: before basin development, following the onset of basin development but prior to significant changes in sediment production, during basin urbanization subsequent to increases in sediment production but prior to channel-stabilization measures, and under the current conditions following channel stabilization and bank armoring throughout much of the channel network. This investigation characterizes sediment production in the earliest and two most recent production periods; prior to basin development, following the onset of increased sediment production resulting from basin urbanization but prior to channel-stabilization measures, and under current conditions. The pre-development period ended near the turn of the century as the first settlers to the region began to develop roads and alter the landscape. The largest period of growth in the basin began around 1945 and growth continued through the 1970s (City of Seattle Municipal Records). This growth is also visible in aerial photographs from this period. The first records of channel degradation are from 1948, and this time serves as the beginning for the period following the onset of basin urbanization but prior to erosion control measures (City of Seattle Municipal Records). The end of this period is less well defined as major channel stabilization projects were initiated in 1973 and grade control, bank protection, and erosion mitigation projects have been completed as recently as 1999 (Review and Course Corrections, 2000). Calculated sediment production for this period represents the estimated maximum production rate that likely occurred in the early 1970s, when basin development was nearing completion but significant attempts to limit channel enlargement were not yet established. The current period of sediment production represents the basin conditions that have resulted following the completion of these most recent projects.

As the magnitude of sediment production and the sources of erosion vary between the periods, there are differences in the methodologies utilized to determine the sediment production rates during each. The different methodologies required for each period are described within each source subsection below.

Particle-Size Distribution of Produced Sediment

The particle-size distribution of each sediment source was estimated to evaluate the overall character of sediment production in the basin, specific sources of fine and coarse sediment, and the change in the character of sediment production through time. The geologic units encountered in the Pipers Creek watershed were introduced in Chapter 2. The proportion of sediment contributed from each of these units was recorded during evaluation of sediment production for each source. Bulk sieve analyses of the Vashon Till, Esperance Sand, and alluvial bank deposits complement published reports on grain size information of the Lawton Clay as well as sediment that is produced from urban land uses. The grain-size distribution of colluvial deposits was estimated based on the upslope geologic units contributing sediment. Bulk samples were mechanically sieved using a series of meshes with 90, 63, 45, 31.5, 16, 11.2, 8, 4.75, 4, 2.0, 0.425, and 0.075 mm^2 openings. These sieve openings, except for 4.75 mm^2, represent half-phi bins from the Wentworth scale. This exception is included as it is a lower bound for describing gravel particles in different engineering classification schemes.

Methods for describing the boundary between fine and coarse sediment and sand- and gravel-sized particles have been established by various researchers and organizations over a wide range of values. According to several engineering classification schemes, "coarse-grained material" consists of sand and gravel as well as larger cobble and boulder particles (Holtz and Kovacs, 1981). The boundaries used to define the size limits of sand, gravel and other soil particles, however, varies between such schemes. A particle diameter of 0.075 mm is the lower limit for sand particles according to the American Society for Testing and Materials (ASTM), the American Association for State Highway and Transportation Officials (AASHTO), and the United Soil Classification System (USCS), whereas a value of 0.06 mm is used by the Massachusetts Institute of Technology (M.I.T.) to define this limit. The boundary between sand and gravel is 4.75 mm within the ASTM and USCS classification systems but 2.0 mm according to AASHTO and M.I.T.

Further variances in the description of grain sizes is found within investigations of sediment production and fluvial sediment transport. Perkins (1989) defined sediment greater than 2 mm as gravel, whereas Nelson and Booth (2002) used this same particle-size to indicate the boundary between "fine" and "coarse" sediment. In these and similar studies, particle-class boundaries are based on the character of sediment that is transported in suspension or as bedload, but such definitions are dependent on the physical characteristics of the fluvial system under investigation. Additional complications are introduced by trying to incorporate the character of salmonid spawning substrate. For example, the term 'spawning gravel' is used to indicate the substrate sediment used for redd construction, regardless of the distribution of grain sizes present (Everest et al., 1987; Kondolf and Wolman, 1993). In reference to spawning gravel, "fine sediment" is usually mentioned in terms of its real or perceived negative impacts on substrate quality and the defining limit generally ranges from 6.35 mm to 0.83 mm (Koski, 1966; Tappel and Bjorn, 1983; Chapman, 1988), spanning the range used to divide gravel from sand.

In this investigation, the boundary between "fine" and "coarse" sediment is defined as a particle diameter of 8 mm. The primary reason for this definition is that the pebble count method used to characterize surface sediments stored in the channel network (further described later in this chapter) does not discern between particles smaller than 8 mm. This particle size, therefore, is the smallest that can be accurately used to describe the grain-size distribution of stored sediment. Other studies have also suggested that material finer than 8 mm should be treated as a separate population based on sampling logistics and the size of particles that form the gravel framework of stream beds (Wilcock et al., 1996; Devries, 2000).

Urban Land Use

Sediment-producing sources from the developed portion of the basin that were considered in this study include residential and commercial areas, and construction activity. The contribution of sediment from urban land uses are calculated in the same way for both periods of sediment production since the onset of basin urbanization. Sediment washed from the urban landscape is assumed to be "fine grained" (< 8 mm) as defined earlier in this chapter.

Residential and Commercial Areas

Urban areas produce sediment through road surface erosion, atmospheric deposition, and landslides. Urban sediment production was not measured during this study. Instead, sediment yield coefficients calculated by other researchers have been evaluated and those most suitable for the Pipers Creek basin were employed (Table 3.3). Three land-use classes were utilized in this study: single-family residential (medium density), multi-family residential (high density), and commercial. The surface area of each land-use class was calculated using data from King County (Washington State Geospatial Data Archive, 2001).

The median TSS yield coefficients from the range reported by Horner (1992) have been used for the different land-use classes here. Horner reviewed published TSS yield coefficients for different land uses for the Covington Master Drainage Plan (Horner 1992). Covington is located in King County, Washington, approximately 40 km (25 miles) southeast of the Pipers Creek watershed. Median values from the range reported by Horner (1992) were also applied in a sediment budget of the Issaquah Creek basin, located approximately 20 km (12 miles) east of Seattle (Nelson and Booth, 2002).

Table 3.3. Published yield coefficients for land-use classifications in the Pipers Creek basin (Adapted from Nelson, 1999).

Land Use Classification	TSS Yield Coefficient (kg ha^{-1} year^{-1})	Location	Reference
Single-family residential (medium density, 4-12 units per acre)	97 - 547 (median = 322^{1})	Various	Horner (1992)
	360	Great Lakes	Marselk (1978) in Novotny and Olem (1994)
	216	Wisconsin	Bannerman (1984) in Notney and Olem (1994)
Multi-family residential (high density, > 12 units per acre)	133 - 755 (median = 444^{1})	Various	Horner (1992)
	350	Washington	Reinelt (1996)
	487	Wisconsin	Bannerman (1984) in Notney and Olem (1994)
Commercial/ Industrial	242 - 1,369 (median = 805^{1})	Various	Horner (1992)
	672	Great Lakes	Marselk (1978) in Novotny and Olem (1994)
	957	Wisconsin	Bannerman (1984) in Notney and Olem (1994)

[1] value used to determine sediment production in this study

In a study of the Laughing Jacobs basin, located within the Issaquah Creek basin, Reinelt (1996) determined TSS yield coefficients for both low- and high-density residential areas. The TSS yield coefficient for high-density residential areas (there are no low-density residential areas in the Pipers Creek basin) determined by Reinelt (1996) was not utilized here as the stormwater in the Laughing Jacobs basin passes through stormwater detention facilities where fine sediment can settle out of suspension. As these facilities can remove sediment in stormwater, values generated from a basin using such technology could underestimate the TSS yield in the Pipers Creek basin, where similar stormwater treatment facilities are absent (Comings, 1998). The TSS yield coefficients values from single- and multi-family residential areas in the Laughing Jacobs Creek subcatchment, 50 and 350 kg ha^{-1} year^{-1} respectively, are in fact lower than the values determined by Horner (1992).

Construction

Although the Pipers Creek watershed is heavily developed, construction continues to occur when properties are remodeled or new structures replace older ones. In order to determine the annual sediment production from construction the rate of construction activity is first needed. Data from the City of Seattle Growth Report (2000) indicates growth of approximately 1.4 housing units annually in the Pipers Creek watershed. Of these, 0.3 units are single family (i.e. about one lot every three years) and 1.1 units are multi-family. Single-family residential development in the basin has four to twelve housing units per acre. For the purposes of estimating the area disturbed by construction of single family residences, a mean value of 8 units per acre was utilized. The density of multi-family residential development in the basin is greater, however, and twelve units per acre bound the lower end of the range, and serves to estimate the unit density for calculations of construction-related sediment.

In the study of Laughing Jacobs basin, Reinelt (1996) evaluated the rate of sediment yield from construction sites where Best Management Practices (BMPs) were utilized. The BMPs employed at the study site include detention ponds, water quality swales, nets and blankets, plastic covering, permanent seeding, and sediment ponds. A sediment yield coefficient of 970 kg ha^{-1} yr^{-1} was determined for these sites and was used in this study. Pollutant yield coefficients for stormwater from construction sites in other studies from other parts of the country was also evaluated. These values range from 3750 to 500,000 kg ha^{-1} yr^{-1} (Wolman and Schick, 1967; Novotny and Chesters, 1981). The studies from which these values were taken, however, were conducted prior to the common application of erosion control BMPs, and the value reported by Reinelt (1996) likely reflects the yield from current construction practices.

Forested Land Use

Sediment-production processes from the forested park areas of the basin evaluated in this study include channel enlargement, gully erosion, landslides, and soil creep. These are similar to sediment-producing processes found in other forested lands in the Pacific Northwest; however, the magnitude and extent of sediment production here has been affected by basin urbanization and subsequent efforts to reduce erosion. Rates of sediment production (and storage) were calculated in cubic meters and are converted to metric tonnes. This enables comparison with other studies that have previously reported results using metric tonnes. The conversion was calculated assuming that the dry density of sediment in the basin can be approximated at 1.7 metric tonnes/m^3, based on a particle dry density of 2.65 g/cm^3 and an average porosity of 35%. These values are typical for the characteristics of the soil types encountered in the Pipers Creek watershed, and they also correspond to the range of published values for the Vashon glacial units (Holtz and Kovacs, 1981; Galster and Laprade, 1991). In the Big Beef Creek basin, where the same geologic units are present, Madej (1982) used the same conversion rate. In the Issaquah Creek basin, Nelson (1999) assumed a value of 1.6 metric tonnes/m^3.

Channel Enlargement

As discussed in Chapter 2, basin urbanization and the resulting changes to the hydrologic regime have been shown to impact channel networks, ranging from minor alterations in channel geometry to pervasive incision (Booth 1990). Channel enlargement is widespread within the stream network of the Pipers Creek watershed and has resulted in both mainstem reaches and steeper tributaries where stormwater discharges have degraded and widened the channel from its pre-development condition.

Channel enlargement was evaluated using two methods. In each, sediment production is approximated using the differences between the current and estimated historic channel geometries. The difference between the two methods is the technique that is used to estimate the geometry of historic channels. The historic geometries of steep-tributary channels that have enlarged due to stormwater discharges (P8, P9, P11, P12, and P14) were estimated from the current geometries of steep-tributary channels that have not received stormwater discharges (P3, P4, P5, P6, P7, P16). There are no mainstem alluvial channels in the basin that have not been subjected to stormwater discharges, however, and so the historic channel geometries of Pipers, Venema, and Molendorph creeks were estimated from a regression equation developed in Puget Lowland streams between contributing basin area and bankfull channel cross-sectional area (Booth and Jackson, 1997). The relationship was constructed from data for rural streams in King County with low levels of basin urbanization (Figure 3.2). Contributing basin areas for each reach were determined using a GIS digital elevation model (DEM).

For both methods, current channel geometries were estimated from measurements made during field surveys. Morphologic evidence was used to determine what measurements were taken. In steep-tributary or entrenched-mainstem channels, measurements reflect the channel area that shows significant evidence of erosion. In unentrenched mainstem alluvial channels, measurements reflect the current bankfull geometries, which were assessed by noting the lower edge of perennial riparian vegetation and transitions in bank slopes.

Alternatively, where channels have not been subjected to significant channel enlargement or where engineered-grade control and bank stabilization have halted that process, the extent of current bank erosion was estimated during channel surveys through volume measurements of recent bank slumps. This method is similar to the one used to assess the contribution of sediment from landslides which is described in detail later in this chapter. As such, a total of three methods were used to estimate sediment production from channel enlargement and erosion in current period and the period of sediment production prior to channel stabilization.

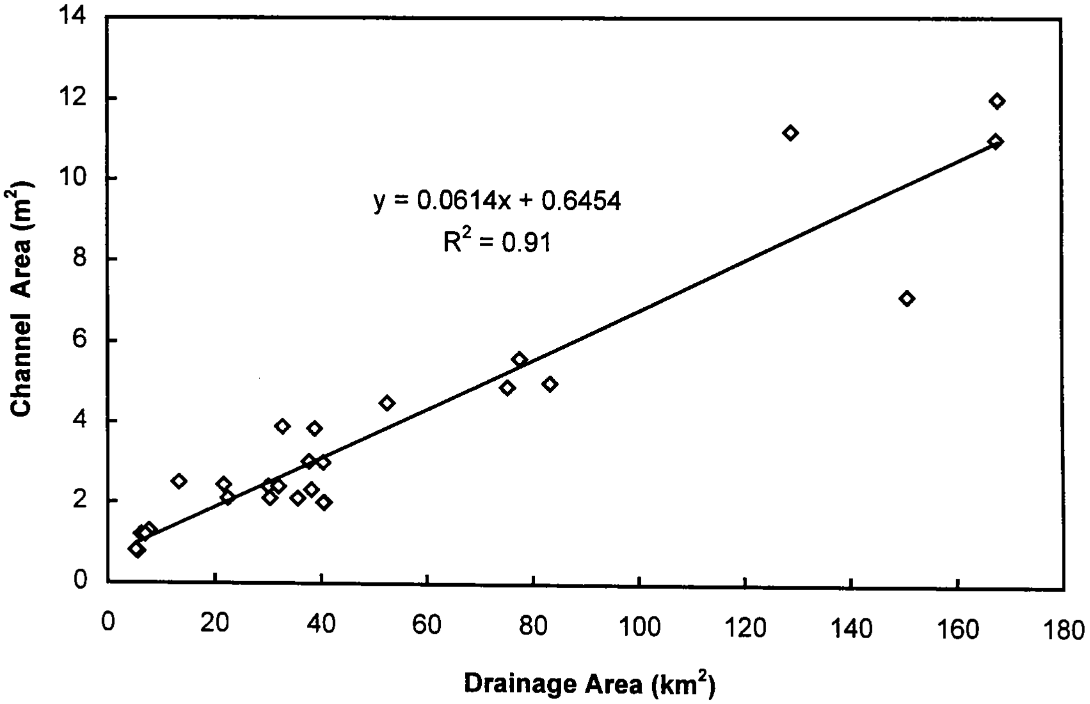

Figure 3.2. Channel area as a function of contributing drainage area for King County rural streams (Adapted from Booth and Jackson, 1997).

The character of sediment produced by channel enlargement was estimated through observations and measurements of exposed geologic units along each study reach during field surveys. The relative proportions of the total volumes contributed from each geologic unit were estimated from current exposures and extrapolations of pre-enlargement channel geometry. These volumes were then combined with the results of the sediment characterizations for each geologic unit to estimate the particle-size distribution of sediment produced from this source.

Gully erosion

Gully erosion in the Pipers Creek watershed occurred where stormwater discharged onto steep erosion-susceptible hillslopes where no significant channels were likely during historic conditions. Gully erosion has been largely eliminated following recent stormwater control projects that have diverted discharges past erodible hillslopes; as such, gully erosion is included only in the post-development period prior to erosion control. The physical extent of stormwater-induced gully erosion was estimated from GIS DEMs and field measurements of gully geometry. Gully erosion was estimated to have occurred over a 50-year period ending in 1999. The character of sediment produced as a result of gully erosion was estimated in the same manner as from channel enlargement.

Landslides

The contribution of sediment from landslides was assessed through field measurements and observations conducted during channel surveys. Landslide volumes were estimated from width, length, and depth measurements of landslide scars adjacent to the channel network. Maximum ages were estimated from observations of vegetation on the landslide scars. The slides were classified into three categories (adapted from Nelson and Booth 2002):

- <5 years— fresh scars with little to no vegetation.
- 5 to 10 years— sparse vegetation consisting primarily of young salmonberries, bracken ferns, and light ground cover.
- 10 to 20 years—moderately dense vegetation of small alders, mature salmonberries, and dense ground cover.

These age classes were calibrated using landslides with known ages identified using data from the City of Seattle's landslide inventory. Though extensive evidence of mass wasting occurs within the active channel areas, these processes are accounted for in the estimates for channel enlargement and erosion. Therefore, only landslides that originated out of active channel areas, primarily on valley walls, were considered in this portion of the sediment budget. Due to the steep nature of the hillslopes and confined character of the channels, the delivery ratio of landslides was nearly 100% for the vast majority of slide scars observed and sediment production rates assume complete delivery.

Due to the observed condition of hillslope instability associated with the widespread degradation of channels in the Pipers Creek watershed, current rates of landslide production are not appropriate for estimating the contribution of landslide-derived sediment in the basin prior to the onset of urbanization. Instead, historic rates for landslide production were estimated by analogy from rates predicted for a comparable basin in an undeveloped state. The Big Beef Creek basin, also located in the Puget Lowland of western Washington, has many similarities to Pipers Creek. Whereas the climate is slightly wetter, the geology and resultant basin topography bear striking resemblance. The dominant geology in both the Big Beef Creek and Pipers Creek basins is that which is typical from the Vashon glaciation, and the gradient of hillslopes adjacent to the channel networks generally exceed 15% (Madej, 1982). A rate of 15 tonnes km^{-2} $year^{-1}$ developed in Big Beef Creek basin for undisturbed forest (Madej 1982) is used to guide historic estimates of landslide sediment production in the Pipers Creek watershed.

The temporal resolution of the landslide methodology permits estimates of landslide production over approximately the last twenty years. Where grade control and bank stabilization were applied to study reaches prior to this time, historic rates are used for estimates of landslide contribution for the period prior to stabilization efforts. Historic rates are also used for the current period where no evidence of slope failure in the last twenty years was evident.

The grain-size distribution of sediment produced from landsliding was determined using a similar methodology to that applied to assess the character of sediment generated from channel enlargement and gully erosion. The relative proportion of material contributed from each geologic unit was estimated from observations of the extent and orientation of geologic exposures in the landslide scarp for each landslide observed. The volume estimates for the units were combined with the grain-size distribution for each to calculate an estimate of the character of sediment produced from each mass wasting locale.

Soil Creep

Soil creep is the down-slope movement of soil particles as a result of gravity. Soil creep results from frost heave, thermal expansion and contraction, and wetting and drying of the soil. Soil creep occurs on all slopes; however, soil creep only contributes sediment directly to stream channels where there is a continuous pathway between slope and channel. In this study, soil creep was not considered to contribute sediment in the current period of sediment production to streambanks that are armored or bordered by a flood plain or broad terrace. Estimates of soil creep prior to erosion control and during the historic period include all reach lengths that are now armored. Soil creep was also evaluated for the steep hillslope adjacent to Carkeek Park Road from NE 110th Street to the park entrance. Drainage ditches below this slope connect directly to tributaries P10 and P11 at road crossings; I observed sediment within these ditches transported to the channel network during storms.

Soil creep rates published in studies conducted in different geographical and geologic provinces show considerable variability. Saunders and Young (1983) published rates of soil creep from conditions representing a variety of hillslope gradients, lithologies, and climate conditions. In this study, the conditions detailed for rates determined by Anderson (1977) most closely resemble conditions in the Pipers Creek watershed. Within a temperate maritime climate, Anderson (1977) reported surface movements of 0.4 to 2.2 mm year $^{-1}$ over a depth of 0.25 m of colluvium. The 11% slope gradient investigated in that study, however, is typically less than those found adjacent to channels in the Pipers Creek watershed. In a different study, a sediment budget constructed in southwest British Columbia, Slaymaker (1993) reports slightly higher rates of 2 to 5 mm year $^{-1}$,over a depth of 0.5 to 1 m of colluvium.

Madej (1982) utilized a rate of 2.5 mm year^{-1} in a sediment budget of the Big Beef Creek basin after reviewing rates of slope creep proposed by Everett (1963), Young (1960), and Kirkby (1967), and including the contribution from tree throw (Dietrich et al., 1982). The geology, climate, and basin relief of the Big Beef Creek basin are similar to those within the Pipers Creek watershed and so a rate of 2.5 mm year $^{-1}$ was chosen for this investigation. Colluvial depths vary within with the steam network of the Pipers Creek watershed. During field surveys, actively eroding banks and fresh landslide scarps provided clear observations of colluvial depths. Measurements at these locations suggest a representative depth of 0.3 m for a basin-wide assessment of sediment production from slope creep. The character of colluvial sediment produced from soil creep was estimated as a composite of upslope contributing geologic units that were observed during field surveys.

Sediment Storage and Transport

Sediment Storage

Sediment storage in the active channel was estimated by evaluating three different types of storage locations: bar storage, channel storage, and storage behind channel structures and weirs. Bar storage, channel storage, and storage behind naturally occurring channel structures such as large woody debris (LWD) and boulder steps are considered short-term storage elements; sediment within bars and the active channel are mobile on nearly a yearly basis, and sediment behind LWD becomes mobile when natural structures break apart or readjust.

Sediment stored behind engineered weirs is considered sediment in long-term storage. Within the Pipers Creek watershed, terraces are present upstream of constructed weirs. The vegetated character of these terraces indicates that the stored sediment is no longer in active transport through the system. The sediment in the active channel of weir terraces is, however, considered in the evaluation of channel storage. The conversion of 1.7 metric tonnes/m^3 is applied here to convert between volume and mass of stored sediment.

Particle-Size Distribution of Stored Sediment

The particle-size distribution of sediment in bar and channel storage is estimated through pebble counts and sieve analyses (Wolman, 1954). Each pebble count included approximately 100 particles chosen randomly across the upstream end of a channel-spanning riffle. I measured and recorded the intermediate axis of each selected particle into half-phi bins for phi values down to -3Φ. The relationship between phi class and diameter in millimeters is:

$$\text{phi} = -\log_2 (\text{diameter in mm}),$$

and so the half-phi size classes (in mm) increase by powers of $2^{0.5}$.

Different minimum particle diameters have been suggested that can effectively be sampled without bias by the human finger (Kondolf, 1997). For this study, 8 mm was found to be the lowest discernable bound for pebble count analysis; particles of lesser diameter counts were recorded as < 8 mm.

Sieve analyses of bed substrate sediment were conducted in the same manner as were contributing geologic units described previously. Samples of bar deposits composed of sand were sieved using a series of meshes with 2.0, 1.0, 0.85, 0.425, 0.15 and 0.075 mm^2 openings.

Channel Deposits

Sieve analyses, pebble counts, and field measurements were used to describe the volume and character of sediment stored in the stream bed. The volume of sediment in channel storage was estimated for each alluvial reach as the product of the active bedload depth, the average wetted channel width at baseflow, and the channel length. The depth of active bedload was estimated using a value of twice the D_{90} of representative surface sediments for the reach (Wilcock et al. 1996). Sediment of the bed surface was characterized by pebble counts and the average channel width and length were determined during field surveys. Pebble counts were completed in the upstream portion of channel-spanning riffles.

The character of channel sediment was estimated in two parts (Figure 3.3). Mean values determined from pebble counts taken throughout the channel network characterize the surface D_{90} layer of bed sediment. The subsurface D_{90} layer was estimated using the grain-size distribution of two bulk samples of subsurface material in combination with the pebble count mean values. The bulk samples were also taken from the upstream portion of channel spanning riffles to be comparable with basin-wide pebble counts. I gathered bulk samples of the subsurface layer after the coarser surface layer was removed by hand. Conversion values relating the D_{10}, D_{16}, D_{50}, D_{84}, and D_{90} of bulk samples and pebble counts from those locations were calculated. By dividing the mean values representing basin-wide bed-surface sediment character by the conversion values relating surface to subsurface sediment character, an estimate for subsurface character throughout the channel network was calculated.

Bar Deposits

The volume and character of sediment in bar deposits was measured during field surveys completed during baseflow conditions. Flow level was checked for baseflow conditions prior to channel-sediment field surveys, which generally return by the second day without precipitation following a storm event. The volume of a bar was calculated from two measurements in the horizontal plane and one measurement in the vertical plane in conjunction with a geometric description of the bar shape. The vertical measurement reflected the height of the bar top above the channel thalweg (Figure 3.4).

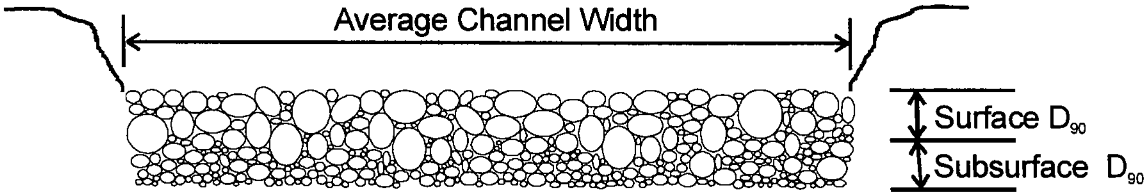

Figure 3.3. Schematic channel cross-section showing channel width measurement and surface and subsurface D90 layers used to evaluate channel bed sediment.

The particle-size distributions of bar deposits were estimated in two ways. Bar deposits containing significant gravel were characterized using average values from six pebble counts; bar deposits composed of sand were characterized using the average values from two bulk sieve samples. Similar to channel sediment, gravel bars were analyzed as a D_{90} surface layer, underlain by finer sediment. The composition of the surface layer was approximated from the gravel-bar pebble count results, and the finer subsurface sediment was characterized using the conversion values established between surface and subsurface sediment for channel-bed sediment.

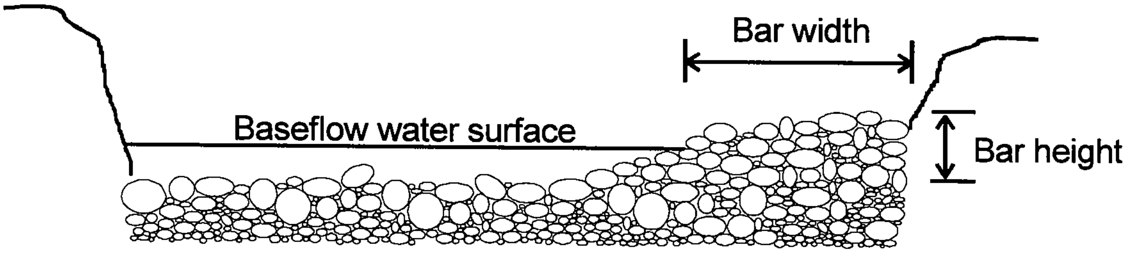

Figure 3.4. Schematic channel cross-section showing bar width measurement at baseflow areal extent and bar height measurement from bed surface to top of bar.

Storage Behind Weirs and LWD

Storage behind weirs and other instream structural elements was evaluated to determine the volume of sediment in long-term storage in terrace formations behind engineered structures as well as in short-term storage behind natural elements of channel complexity. Storage volumes were approximated as wedges using the elevation of the structure above the downstream bed surface, the channel width, and projections of the channel slope. The grain-size distribution of sediment in weir and LWD storages was estimated using estimates of subsurface channel-bed sediment character

Sediment Transport

Bedload Transport

Sediment transport calculations were made using the Bagnold sediment transport equation in reach PM1 to evaluate the character of bedload transport. Lacking a historic record of discharge at any location in the Pipers Creek watershed, a stream gauge was installed at the outset of this study. An Isco 6700 Portable Sampler was used to record flow depths at 15 minute intervals. The flow depth data was transformed using a rating curve equation to determine the discharge record. The rating curve was created by regression of the discharge at five different flow levels (Appendix A). The record of hydrologic discharge for water year (WY) 2002 was used in this analysis of sediment transport.

The Bagnold (1980) sediment transport equation, selected for this study, uses inputs of discharge duration, channel width, depth, slope, and the D_{50} particle size to calculate bedload transport. The discharge data was analyzed to determine the duration of discharges between flows of 0.06, 0.14, 0.28, 0.71, 1.4, 2.8, 5.6 cubic meters per second (cms). These flows are equivalent to 2, 5, 10, 25, 50, 100, and 200 cubic feet per second (cfs). The sediment transport calculations were completed at the mean flow between the group boundaries.

For example, sediment transport for the duration of flows between 1.4 and 2.8 cms was calculated using a discharge of 2.1 cms. The rating curve equation was used to determine flow depth for sediment transport calculations. Flow width was estimated through a regression of width and discharge measured during the construction of the rating curve. A slope of 1.5%, measured in the field from indicators of bankfull flow, such as perennial vegetation and breaks in streambank slope, was used to calculate sediment transport. This slope also approximates the average reach gradient. The D_{50} particle size was determined from pebble counts performed during the characterization of streambed sediment. The D_{50} value used was the average of five pebble counts sampled within 40 meters up and downstream of the gauging location. Sediment transport calculations, along with the rating curve and width to discharge regression are presented in Appendix A.

The Bagnold sediment transport equation is an empirical expression based on the relationship between the unit stream power available at a given discharge and the threshold unit stream power necessary to initiate bedload transport. In an assessment of bed load sediment transport formulae, Gomez and Church (1989) found the Bagnold equation to be the most reliable means for estimating the magnitude of sediment transport in channels of this general size with limited hydraulic information. Even so, the precision of this equation is limited with anticipated uncertainty of ± 2-fold.

The precipitation during WY 2002 was approximately 120% of the 30-year normal (National Weather Service, 2002). Depending on the pattern and intensity of precipitation, sediment transport rates calculated using the discharge history from this single year is likely to be higher than the long-term average. To explore the potential range of errors introduced by relying on this single year, sediment transport was also calculated for potential discharge regimes representing 100% and 80% of normal precipitation, by dividing the transport discharge durations from WY 2002 by 1.2 and 1.5 respectively.

Particle Transport Rate

Calculations of the reach-averaged annual bedload travel distance (L_B), or particle transport rate, can assist in evaluating the response time of a channel to changes in sediment supply and the sensitivity of different reaches to increased bed load. The annual bedload travel distance can be calculated, on a strictly mass-balance basis, by dividing the channel length (L_C) of the reach of interest by an estimate of particle residence time (R). Particle residence time is equivalent to the quotient of the short-term storage volume (S_S) and the bedload transport rate (T_B), or:

$$L_B = \frac{L_C}{R}, \text{ where}$$

$$R = \frac{S_S}{T_B}$$

CHAPTER 4 – RESULTS

Reach Characterization

Channel form in the Pipers Creek watershed is dominated by entrenched plane-bed channels (Table 4.1). Within the channel network, approximately 50% of the total stream length has received some form of grade control measures, and approximately 15% has received some form of bank protection.

Sediment Production

Particle-Size Distribution of Produced Sediment

Sediment produced in the Pipers Creek watershed is derived from both the urban landscape and the forested slopes adjacent to the channel network. The fraction of sediment produced from urban land uses was not measured directly during this investigation, however, visual observations of deposited sediment within drainage ditches in the commercial and residential neighborhoods in the basin support the assumption that sediment produced from this source is fine grained (< 8 mm) as defined by this analysis. Sieve analysis of bulk samples of Vashon Till, Esperance Sand, and Venema Creek alluvium are shown in Figure 4.1. The proportions of coarse and fine sediment from all contributing geologic units are presented in Table 4.2; the greatest difference is between the alluvium and the relatively gravel-poor glacial deposits. The data from the grain size analysis is contained in Appendix B.

Table 4.1. Summary of the physical assessment of channel conditions.

Reach	Channel Type[1]	Reach gradient (%)	Bank stability[2]	Confinement	Entrenchment	Grade Control and Bank Protection
PM1	plane bed, forced pool-riffle, forced step-pool	1.4	armored to slightly unstable	unconfined	entrenched	Log and boulder weirs, ~50% of reach is armored
PM2	plane bed, cascade	2.7	slightly unstable	unconfined	unentrenched to entrenched	Boulder weirs, ~30% of reach is armored
PM3	plane bed	3.5	stable to moderately unstable	unconfined	unentrenched to entrenched	~20% of reach is armored
PM4	plane bed	4.2	stable to slightly unstable	unconfined	unentrenched	None
V1	plane bed, forced step-pool	3.8	armored to moderately unstable	unconfined to moderately confined	entrenched	Log and boulder weirs, ~40% of reach is armored
V2	plane bed, cascade	8.5	slightly to moderately unstable	unconfined	unentrenched	None
V3	plane bed, step pool, cascade	8.5	moderately to completely unstable	confined	entrenched	Minor coir log bank protection

[1] Based on Montgomery and Buffington (1997).

[2] Based on Henshaw and Booth (2002).

Table 4.1 cont. Summary of the physical assessment of channel conditions.

Reach	Channel Type[1]	Reach gradient (%)	Bank stability[2]	Confinement	Entrenchment	Grade Control and Bank Protection
V4	plane bed	8.2	slightly to moderately unstable	moderately confined	entrenched	None
VW	plane bed	6.1	slightly to moderately unstable	unconfined	moderately entrenched	None
VE	plane bed	6.9	slightly to moderately unstable	unconfined	entrenched	None
MM	plane bed	5.2	slightly to moderately unstable	moderately confined to confined	moderately entrenched	Minor coir log bank protection
ME	plane bed, step pool	11.5	slightly to moderately unstable	confined	entrenched	None
MW	plane bed, step pool	10.7	slightly to completely unstable	unconfined to confined	unentrenched to entrenched	None
P3	colluvial	17.3	slightly to moderately unstable	confined	moderately entrenched to entrenched	None

[1] Based on Montgomery and Buffington (1997).

[2] Based on Henshaw and Booth (2002).

Table 4.1 cont. Summary of the physical assessment of channel conditions.

Reach	Channel Type[1]	Reach gradient (%)	Bank stability[2]	Confinement	Entrenchment	Grade Control and Bank Protection
P4	colluvial	20.5	slightly to moderately unstable	confined	moderately entrenched to entrenched	None
P5	colluvial	14.1	stable to moderately unstable	confined	moderately entrenched	None
P6	colluvial	19.9	stable to moderately unstable	confined	moderately entrenched	None
P7	colluvial	16.4	moderately to completely unstable	confined	moderately entrenched to entrenched	None
P8	plane bed, step-pool, cascade	21.7	slightly to completely unstable	confined	entrenched	Log weirs
P9	plane bed, step-pool, cascade	18	stable to completely unstable	confined	entrenched	Fabric wrapped coir-log weirs
P10	plane bed	11.2	moderately unstable	unconfined	unentrenched to entrenched	None

[1] Based on Montgomery and Buffington (1997).

[2] Based on Henshaw and Booth (2002).

Table 4.1 cont. Summary of the physical assessment of channel conditions.

Reach	Channel Type[1]	Reach gradient (%)	Bank stability[2]	Confinement	Entrenchment	Grade Control and Bank Protection
P11	plane bed	8.1	slightly to completely unstable	confined	entrenched	None
P12	plane bed, step pool	15.9	moderately to completely unstable	confined	entrenched	None
P14	plane bed, step pool	17.2	moderately to completely unstable	confined	entrenched	None
P15	plane bed, cascade	36.5	slightly to moderately unstable	confined	entrenched	None
P16	plane bed, step pool	14.1	stable to moderately unstable	moderately confined to confined	moderately entrenched	None

[1] Based on Montgomery and Buffington (1997).

[2] Based on Henshaw and Booth (2002).

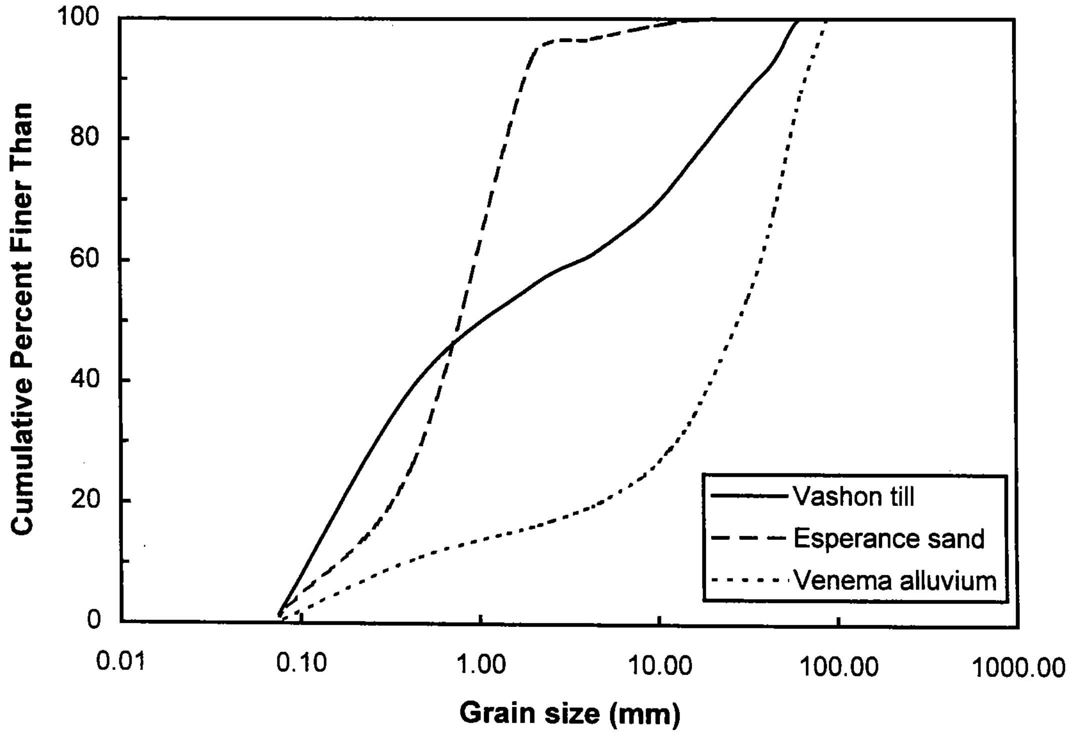

Figure 4.1. Grain-size distribution curves for geologic units contributing coarse-grained sediment.

Urban Land Use

Residential and Commercial Areas

Within the Pipers Creek watershed, areas of residential and commercial land uses together are estimated to contribute 250 tonnes of sediment annually. Single-family residential development makes up 78% of the total basin and produces 190 tonnes year^{-1} (Table 4.3). Multi-family residential and commercial areas each compose about 7% of the basin and contribute, on average, 24 and 40 tonnes of sediment per annum respectively.

Construction

Development of the Pipers Creek watershed is effectively complete, and rates of construction within the basin are low. Construction rates for the Pipers

Creek watershed estimated using the City of Seattle Growth Report 2000 indicate that residential construction occurs very infrequently, with most years not having even one newly developed parcel. The resulting average rate of sediment production is approximately 0.5 tonnes year^{-1} (Table 4.4); less than 1% of all sediment generated from the urban landscape.

Table 4.2. Summary of the particle-size distribution of sediment sources in the forested areas of the Pipers Creek watershed.

Source Unit	Percent Fine-Grained (< 8 mm)	Percent Coarse-Grained (> 8 mm)
Vashon Till	67.0	33.0
Esperance Sand	98.4	1.6
Lawton Clay	100.0	0.0
Colluvium 1 - till and sand	82.7	17.3
Colluvium 2 - sand and clay	99.2	0.8
Venema Alluvium	24.3	75.7

Forested Land Use

Sediment production resulting from channel enlargement, landslides, soil creep, and gully erosion was evaluated within the forested areas that encompass the lower watershed and border the stream network of Pipers Creek. Contribution of these sources was evaluated for each reach, though reaches do not necessarily receive sediment from every source. Sediment production by reach for each period and source is presented in Appendix C.

Table 4.3. Sediment production from residential and commercial land uses.

Land Use Class	TSS Yield Coefficient (kg ha^{-1} year^{-1})	Area of Land Use (km^2)	Sediment Production (tonnes year^{-1})
Single-Family Residential (medium density, 4-12 units per acre)	322[1]	5.85	190
Multi-Family Residential (high density, >12 units per acre)	444[1]	0.53	24
Commercial / Industrial	805[1]	0.50	40
Total		**6.88**	**250**

[1] Median value of those reported by Horner (1992).

Table 4.4. Sediment production from construction activities.

Land Use Class	Construction rate (units year^{-1})	Avg. unit size (ha)	Construction area (ha year^{-1})	TSS Yield Coefficient (kg/ha^{-1} year^{-1})	Sediment produced (tonnes year^{-1})
Single-Family Residential	0.30	0.50	0.15	970[1]	0.15
Multi-Family Residential	1.1	0.34	0.37	970[1]	0.36
Total					**0.51**

[1] From Reinhalt (1996).

Channel Enlargement

Table 4.5 shows the rate of sediment production and the proportions of fine and coarse sediment for each reach over the two most recent periods. Channel enlargement was the largest source of sediment in the period following basin urbanization. Although the magnitude of sediment production has been greatly reduced, it remains the primary sediment source in the current period.

The average annual sediment production of 350 tonnes year^{-1} from channel enlargement and erosion accounts for 40% of the basin total. This rate is less than half of the 730 tonnes year^{-1} that was produced prior to the grade-control and bank stabilization projects constructed over the last thirty years. Of the sediment produced by channel enlargement, approximately 90% is fine-grained and 10% is coarse-grained. Channel enlargement and erosion is the largest contributor of both fine and coarse sediment, producing 38% and 65% of the totals respectively.

Landslides

The primary driving mechanisms behind landsliding in the Pipers Creek watershed are groundwater emergence and channel erosion that undermine the toes of steep slopes. Whereas these mechanisms have likely generated the majority of landslide sediment since the recession of the last glacial period, channel incision and widening that occurred following urbanization appear to have oversteepened hillslopes and increased the rate of landslide-derived sediment. Since the onset of urbanization, the projects aimed at controlling channel enlargement have also resulted in slight decreases in the rate of landslide sediment production (Table 4.6). This reduction in landslide sediment production likely follows a reduction in undercutting of slope toes as the channels have restabilized.

Soil Creep

Sediment production resulting from soil creep has not been significantly altered by urbanization, although some changes have occurred. Channel modifications, where banks have been physically stabilized to block the path of hillslope sediment entering the channel, and locations where channels have been eliminated altogether, result in changes to the delivery of soil creep sediment. The introduction of roads through forested residential areas with drainage swales

Table 4.5. Summary of channel enlargement production rates and sediment character.

Reach	Before Stabilization Efforts			Current		
	Total (tonnes year^{-1})	Fine sediment, (tonnes year^{-1})	Coarse sediment, (tonnes year^{-1})	Total (tonnes year^{-1})	Fine sediment, (tonnes year^{-1})	Coarse sediment, (tonnes year^{-1})
PM1†	85.6	55.4	30.2	0.0	0.0	0.0
PM2†	191.0	152.4	38.6	0.6	0.6	0.0
PM3†	10.3	8.2	2.1	0.0	0.0	0.0
PM4	0.0	0.0	0.0	0.0	0.0	0.0
V1†	3.6	3.4	0.2	1.0	0.8	0.3
V2	50.5	40.6	10.0	50.5	40.6	10.0
V3†	43.7	42.7	1.0	43.7	42.7	1.0
V4	98.3	94.9	3.4	98.3	94.9	3.4
VW	0.6	0.5	0.1	0.6	0.5	0.1
VE	12.5	10.3	2.2	12.5	10.3	2.2
MM†	25.4	19.7	5.7	5.3	4.1	1.2
ME	10.9	8.4	2.4	10.9	8.4	2.4
MW	15.2	11.1	4.1	15.2	11.1	4.1
P3	5.7	5.2	0.5	5.7	5.2	0.5
P4	0.4	0.3	0.0	0.4	0.3	0.0
P5	0.1	0.1	0.0	0.1	0.1	0.0
P6	0.0	0.0	0.0	0.0	0.0	0.0
P7	0.0	0.0	0.0	0.0	0.0	0.0
P8	22.5	21.9	0.6	22.5	21.9	0.6
P9	71.7	69.7	1.9	5.0	4.8	0.2
P10	0.6	0.6	0.0	0.6	0.6	0.0
P11	6.8	5.9	0.9	6.8	5.9	0.9
P12	55.8	49.2	6.6	55.8	49.2	6.6
P14	15.1	13.9	2.0	15.1	13.9	2.0
P15†	0.0‡	0.0‡	0.0‡	0.0	0.0	0.0
P16	0.0	0.0	0.0	0.0	0.0	0.0
Total	**730**	**618**	**112**	**354**	**319**	**35**

† Bank-stabilization or erosion-control projects have been completed in these reaches

‡ P15 channel-enlargement before channel stabilization is accommodated by gully erosion.

Table 4.6. Landslide production rates by reach including current rates of fine and coarse sediment.

Reach	Historic	Before Stabilization Efforts	Current		
	Total (tonnes year^{-1})	Total (tonnes year^{-1})	Total (tonnes year^{-1})	Fine sediment (tonnes year^{-1})	Coarse sediment (tonnes year^{-1})
PM1	11.3	11.3†	0.0	0.0	0.0
PM2	18.8	18.8†	16.1	15.1	1.0
PM3	4.2	4.2†	0.6	0.5	0.1
PM4	4.7	4.7†	4.7	4.3	0.4
V1	5.6	5.6†	0.0	0.0	0.0
V2	3.4	0.0	0.0	0.0	0.0
V3	2.7	11.7	11.7	10.7	1.0
V4	4.5	37.4	37.4	34.8	2.7
VW	2.4	2.4‡	2.4‡	1.9	0.4
VE	3.3	3.3‡	3.3‡	2.7	0.6
MM	4.4	1.1	1.1	0.7	0.3
ME	5.5	14.4	14.4	11.0	3.4
MW	5.3	12.4	12.4	10.6	1.7
P3	4.0	0.0	0.0	0.0	0.0
P4	2.8	0.2	0.2	0.2	0.0
P5	2.4	2.4‡	2.4‡	2.3	0.0
P6	2.4	2.4‡	2.4‡	2.4	0.0
P7	1.9	1.9‡	1.9‡	1.9	0.0
P8	4.5	48.9	48.9	48.5	0.5
P9	4.5	35.0	1.8	1.7	0.1
P10	1.5	0.0	0.0	0.0	0.0
P11	1.4	0.0	0.0	0.0	0.0
P12	5.5	61.6	61.6	58.9	2.7
P14	3.8	45.3	45.3	43.2	2.1
P15	0.5	0.5‡	0.5‡	0.4	0.0
P16	0.9	0.9‡	0.9‡	0.9	0.0
Total	**112**	**326**	**270**	**253**	**17**

†Historic rate used as grade control and bank stabilization were applied to study reaches prior to the temporal resolution of the landslide methodology.

‡Historic rate used due to lack of recent landslide evidence.

that connect to tributaries in the stream network have provided new pathways for creep-produced sediment. These landscape alterations explain the changes in soil creep production over time (Table 4.7). Details of soil creep by reach are included in Appendix C.

Gully Erosion

Prior to recent erosion-control projects implemented by Seattle Public Utilities, stormwater flowed uncontrolled onto steep hillslopes above the Pipers Creek stream network in various locations surrounding Carkeek Park. Tight-lining stormwater down steep slopes, has, generally mitigated these discrete sources of sediment. The outfall locations are now typically constructed with gabion baskets to dissipate erosional forces of the stormwater. These erosional gullies no longer produce sediment, but prior to mitigation they were major sediment sources, producing 530 tonnes year^{-1}, including 470 tonnes year^{-1} of fine sediment and 60 tonnes year^{-1} of coarse sediment.

Synthesis of Sediment Production

Basin urbanization and subsequent efforts to stabilize channels and reduce erosion rates have resulted in fluctuating rates of sediment production over the last half-century. Current levels of sediment production are half of the maximum estimated rate, yet they remain almost six times greater than predicted historic rates (Table 4.8). Figure 4.2 illustrates the change in sediment production between the periods.

Table 4.7. Soil creep sediment production over the different sediment production periods.

Production Period	Total (tonnes year^{-1})	Fine sediment (tonnes year^{-1})	Coarse sediment (tonnes year^{-1})
Historic	15	13	2
Before Stabilization Efforts	16	14	2
Current	12	10	2

Table 4.8. Comparison of sediment production rates over the three production periods analyzed.

Production Period	Total sediment production (tonnes year^{-1})	Fine sediment production (tonnes year^{-1})	Coarse sediment production (tonnes year^{-1})	Sediment production (tonnes km^{-2} year^{-1})
Historic	134	116	18	18
Before Erosion Control	1854	1657	197	247
Current	888	834	54	118

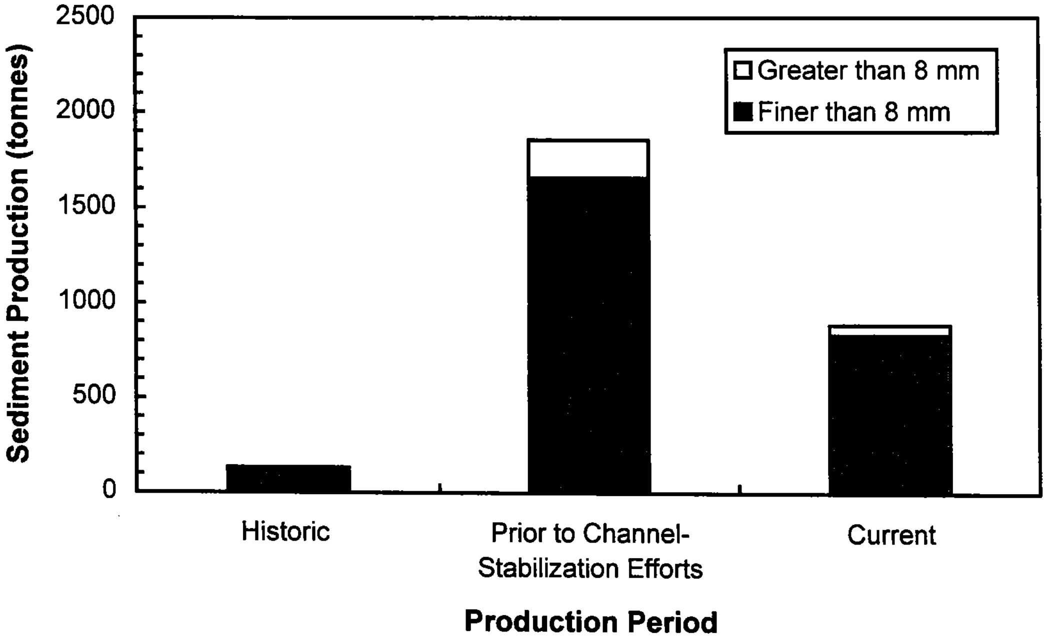

Figure 4.2. Comparison of the magnitude of sediment production over the three analyzed production periods.

The relative contribution from different sediment sources has changed along with the total magnitude and character of sediment. In the current regime of sediment production, channel enlargement accounts for approximately 40% of all sediment produced, sediment from urban land uses and landslides each provide about 30%, and soil creep contributes the remaining fraction (Table 4.9). During the period of greater sediment production prior to channel-stabilization efforts, the relative contribution from channel enlargement was much the same, however, gully erosion was also occurring and contributed approximately one-quarter of the total. Sediment from urban land-uses, landslides, and soil creep made up the remainder (Table 4.10). Summaries of fine and coarse sediment production for each of the sources in the two periods following urbanization are shown in Table 4.9 and Table 4.10.

Table 4.9. Summary of sediment production by source for the current production period.

Source	Total Sediment Production (tonnes year^{-1})	Fine Sediment Production (tonnes year^{-1})	% of Total Fine Sediment Produced by Source	Coarse Sediment Production (tonnes year^{-1})	% of Total Coarse Sediment Produced by Source
Channel Enlargement	354	319	38	35	65
Urban Sediment	252	252	30	0	0
Landslides	270	253	30	17	31
Soil Creep	12	10	1	2	4
Total	**888**	**834**	**99**[1]	**54**	**100**

[1] The sum of the percentages is less than 100 due to rounding.

Table 4.10. Summary of sediment production by source for the period following urbanization and prior to erosion-control efforts.

Source	Total Sediment Production (tonnes year^{-1})	Fine Sediment Production (tonnes year^{-1})	% of Total Fine Sediment Produced by Source	Coarse Sediment Production (tonnes year^{-1})	% of Total Coarse Sediment Produced by Source
Channel Enlargement	730	620	37	110	56
Gully Erosion	530	465	28	65	33
Urban Sediment	252	252	15	0	0
Landslides	326	306	18	20	10
Soil Creep	16	14	1	2	1
Total	**1850**	**1660**	**99**[1]	**197**	**100**

[1] The sum of the percentages is less than 100 due to rounding.

Uncertainty Analysis

Each sediment source included in the construction of the sediment budget has uncertainty associated with it. The values used for sediment production from urban areas, construction, and soil creep were selected from a broad range of published values. For some of these sources the median value was used to calculate sediment production, while for others, basin-specific conditions guided the selection of a particular rate. For channel enlargement, landslide sediment production, and gully erosion during the period prior to channel stabilization and erosion control, the production rates are dependant upon the age over which production is estimated to have occurred. The results of an uncertainty analysis designed to illustrate the effects of the variables used in this investigation are presented in Figure 4.11.

A few guiding principles and equations directed the uncertainty analysis. The range of values from which a variables were chosen were assumed to be uniformly distributed and that the median value would approximate the mean. Although it is unlikely that the range of values for each variable display this distribution, there are insufficient published data values to determine the actual distribution. This is a conservative approach, as it generates the largest range of possible error. For each range of possible values assumed to have a uniform distribution, the mean and standard deviation were calculated as:

$$\text{Variable Mean, } (\mu_x) = (x_{max} + x_{min})/2$$

$$\text{Variable Standard Deviation, } (\sigma_x) = (x_{max} - x_{min})/\sqrt{12}$$

The mean sediment production for each source is calculated in the general form:

$$\text{Mean Source Production, } (\mu_y) = f(\mu_x)$$

Table 4.11. Results of uncertainty analysis for the current period of sediment production.

Sediment Source	Variables for which mean was calculated	Range of Values	Mean Value[1]	Mean Sediment Production (tonnes/year)	Standard Deviation (tonnes/year)	Value Used	Calculated Sediment Production[2] (tonnes/year)
Med-density residential[3]	Yield coefficient	97 - 547 kg $ha^{-2}yr^{-1}$	322	188	22	322	188
High-density residential[3]	Yield coefficient	133 - 755 kg $ha^{-2}yr^{-1}$	444	24	10	444	24
Commercial/ Industrial[3]	Yield coefficient	242 - 1,369 kg $ha^{-2}yr^{-1}$	806	40	16	806	40
Construction	Yield coefficient	970 – 3,750 kg $ha^{-2}yr^{-1}$	2,360	1.24	0.42	970	0.51
Channel Enlargement	Duration of Enlargement	50 - 80 years	65	272	38	50	354
Landslides	Age	5 - 20 years	12.5	340	120	Various	290
Soil Creep	Creep Rate	0.4 - 5.0 mm/yr	2.7	13	6.2	2.5	12

Notes:

[1] Mean was calculated assuming a uniform distribution of the range of values.

[2] Refers to the estimates for the current production period as calculated according to the methods described in Chapter 3.

[3] Sediment production was calculated using mean yield coefficients.

The standard deviation of the mean sediment production for each source (σ_y) is calculated as:

$$(\sigma_y)^2 = \left[\left(\frac{\partial y}{\partial x}\right) \times \sigma_x\right]^2,$$

which is evaluated at the variable mean, μ_x (NIST/SEMATECH, 2002).

The range of error for the calculated sediment production was estimated as the square root of the sum of squared standard deviations for each of the sediment sources. For the current average yearly sediment production of approximately 900 tonnes year^{-1} the range of error is ± 130 tonnes year^{-1}, and for the sediment production rate normalized by basin area (120 tonnes km^{-2} year^{-1}) the range of error is approximately ± 20 tonnes km^{-2} year^{-1}.

Sediment Storage and Transport

Sediment Storage

Particle-Size Analysis of Stored Sediment

The particle-size distributions of streambed sediment and bar deposits were estimated in order to characterize sediment stored in the active channel. Pebble count results from riffles throughout the stream network show the coarse-grained nature of the streambed sediment (Figure 4.3). The results show a wider variance in the coarse fraction than in the fine fraction and also that fine sediment makes up about 10% of the surface D_{90} layer in the channel bed. The study reach where each pebble count was performed and the numerical values for D_{10}, D_{16}, D_{50}, D_{84}, and D_{90} for each count are presented in Appendix D. Figure 4.4 shows the grain-size distribution for two bulk sieves analyses of subsurface bed sediment and two pebble counts performed at corresponding locations. The relationship between the surface and subsurface particle-size distributions of

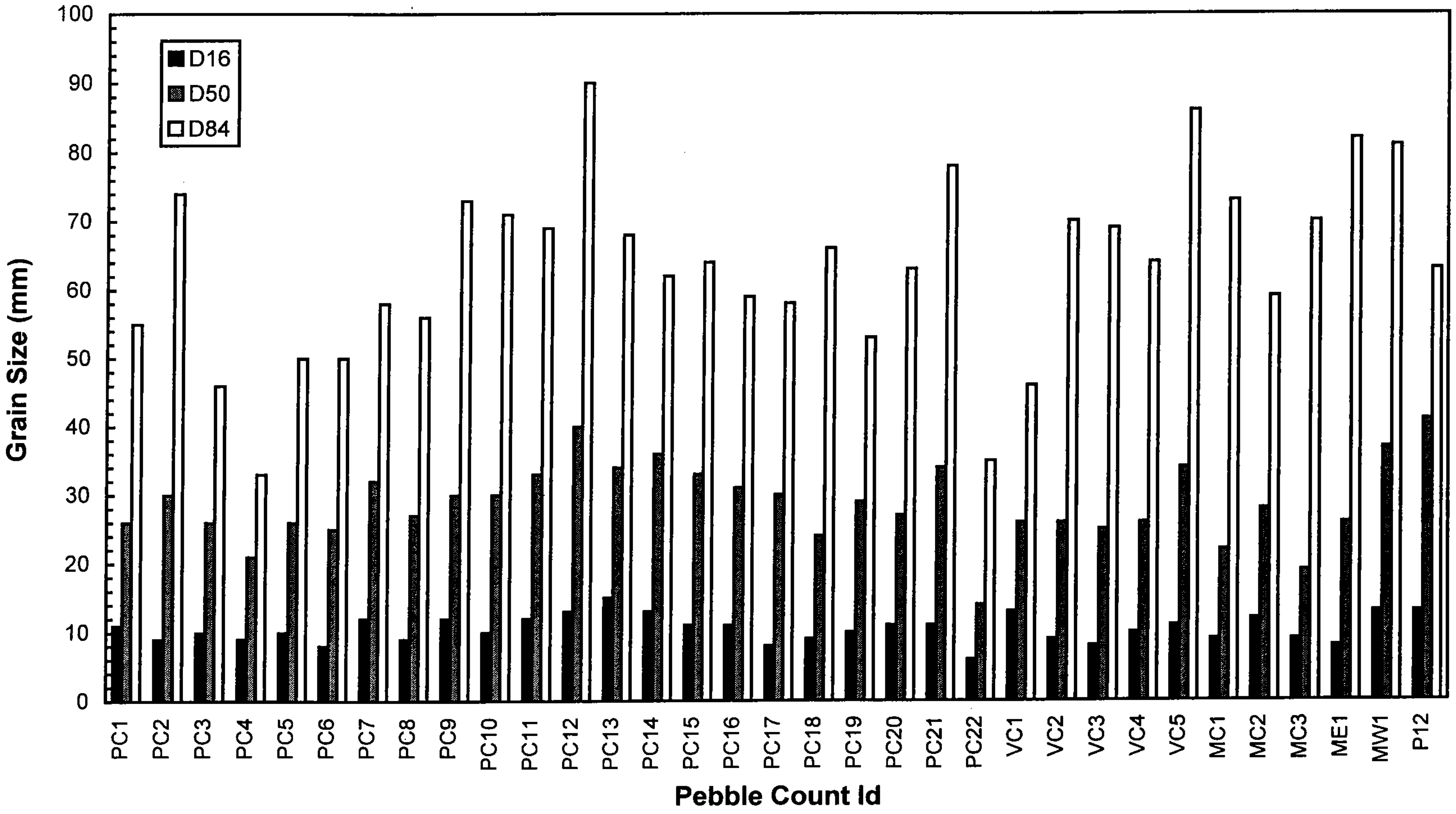

Figure 4.3. Grain-size distribution for pebble counts from throughout the channel-network.

these samples was used to estimate the character of subsurface sediment in the channel basin-wide. Most non-vegetated bar deposits in the active channel are predominantly gravel whereas others are composed almost exclusively of sand. The particle-size distributions of bar deposit sediment (both sieve and pebble count results) are presented in Figure 4.5.

Volume of Stored Sediment

The active channel, bar deposits, and wedges behind natural structures account for approximate 2200 m^3 of stored sediment (Table 4.12). Sediment in the channel bed, in bar deposits, and behind natural structures account for 80%, 12%, and 8% of the total short-term storage, respectively. A nearly equivalent volume is stored more permanently behind engineered structures. Calculations for sediment storage are presented in Appendix D.

Composition of Stored Sediment

The composition of short-term storage elements is presented in Table 4.13. Coarse-grained sediment (greater than 8 mm in diameter) composes almost three-quarters of the stored total. Fine-grained sediment (< 8 mm) makes up the remainder.

Sediment transport

Bedload Transport

Table 4.14 show the results of the sediment transport calculations made in reach PM1 for the discharge history measured during WY 2002, as well as for the estimated discharge durations for years receiving 100% and 80% of normal precipitation. The calculated rates for bedload transport vary from 180 to 260 tonnes $year^{-1}$. Measured sediment transport rates tend to range from half to twice that of calculated rates (Basil and Gomez, 1989). The probable bedload

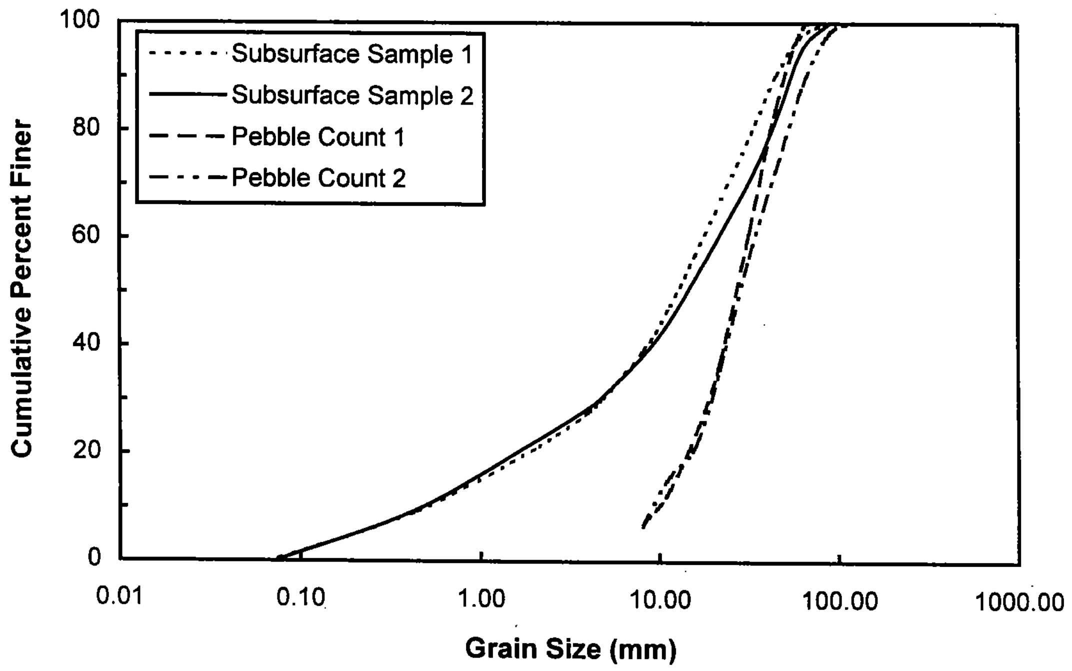

Figure 4.4. Grain-size distribution curves for bulk sieve analyses and pebble counts corresponding locations.

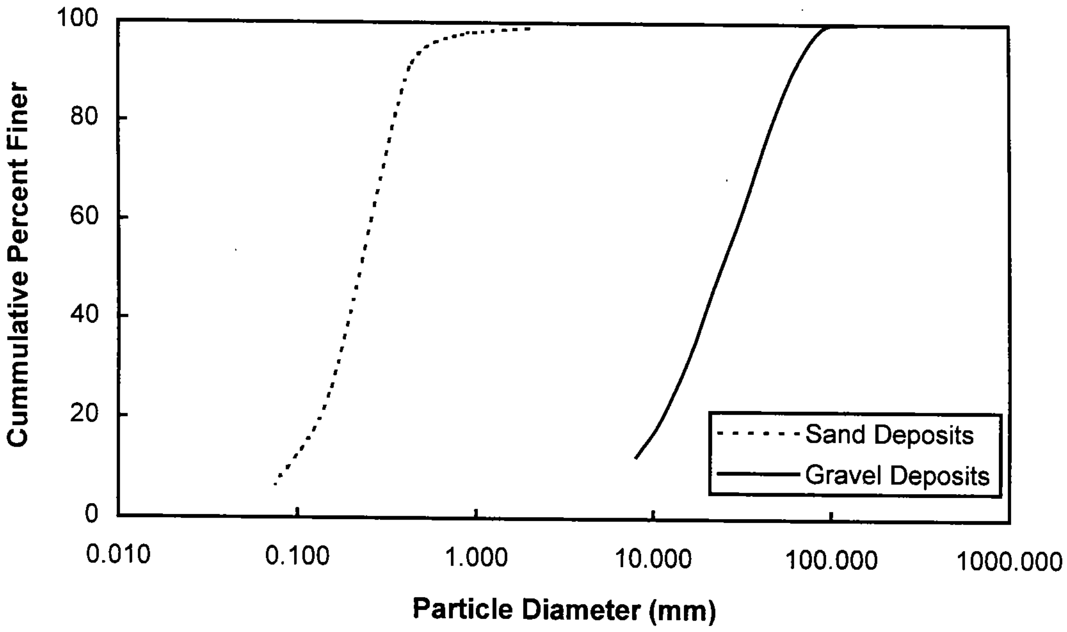

Figure 4.5. Grain-size distribution curves for sand and gravel bar deposits.

Table 4.12. Summary of storage within the channel network.

Reach	Short-Term Storage Elements			Long-term Storage Behind Engineered Structures (m^3)	Total Sediment in Short-Term Storage (m^3)	Total Sediment in Short-Term Storage (tonnes)	Unit Short-term Storage (m^3/m)
	Channel Deposits (m^3)	Bar Deposits (m^3)	Storage Behind Natural Structures (m^3)				
PM1	384.4	32.6	0.0	260.0	417.0	708.9	0.70
PM2	306.4	65.6	0.0	1625.0	372.0	632.3	0.38
PM3	37.2	17.3	0.0	0.0	54.4	92.5	0.24
PM4	12.8	0.0	0.0	0.0	12.8	21.8	0.05
V1	80.5	11.8	0.0	116.0	92.4	157.0	0.30
V2	110.8	13.1	0.0	0.0	124.0	210.7	0.69
V3	79.6	1.3	9.3	0.0	90.2	137.5	0.56
V4	83.7	59.5	46.5	0.0	189.7	243.4	0.59
VW	18.5	0.0	0.0	0.0	18.5	31.5	0.15
VE	51.9	0.0	0.0	0.0	51.9	88.2	0.30
MM	77.0	22.1	21.8	0.0	120.9	168.5	0.42
ME	92.2	12.6	38.1	0.0	142.9	178.2	0.37
MW	105.0	13.1	47.5	0.0	165.6	200.8	0.41
P8	22.7	3.2	0.0	21.9	25.9	44.0	0.11
P9	26.3	0.4	0.0	86.9	26.7	45.5	0.11
P10	3.0	0.0	0.0	0.0	3.0	5.1	0.04
P11	13.7	0.0	0.0	0.0	13.7	23.3	0.18
P12	179.0	1.3	0.0	0.0	180.3	306.5	0.62
P14	48.1	1.9	0.0	0.0	50.0	84.9	0.24
P16	12.8	0.3	0.0	0.0	13.1	22.3	0.17
TOTALS	**1750**	**256**	**163**	**2110**	**2170**	**3400**	

Table 4.13. Grain-size composition of sediment in short-term storage.

			Coarse-grained			Fine Grained		
	Total (m^3)	**Total (tonnes)**	**% > 8 mm**	**Total > 8 mm (m^3)**	**Total > 8 mm (tonnes)**	**% < 8 mm**	**Total < 8 mm (m^3)**	**Total < 8 mm (tonnes)**
Channel Deposits	1750	2970	77	1350	2290	23	400	675
Bar Deposits	256	435	63	161	274	37	95	161
Behind Natural Structures	163	277	62	101	172	38	62	105
Total	**2170**	**3680**	**74**	**1610**	**2740**	**26**	**560**	**940**

transport ranges presented in Table 4.14 address this variability between the calculated and observed values. Long-term average bedload transport likely falls between 90 and 520 tonnes year^{-1}, the high and low end members for these ranges. Bedload transport calculations are presented in Appendix A.

Particle Transport Rate

Calculations of particle transport rate, or the annual travel distance of bed sediment, is presented in Table 4.15. The calculations, made for reach PM1, are based on bedload transport rates (as well as reach length and short-term storage volume, see Chapter 3). As such, the results are presented in the same format to reflect both a range of discharge regimes as well as variability between calculated and observed bedload transport rates.

Table 4.14. Results of Bedload Transport Calculations.

Character of Yearly Precipitation on which Discharge Regime is based	Calculated Bedload Transport Rate (tonnes year^{-1})	Probable Range of Bedload Transport Rates (tonnes year^{-1})
120% of Normal[1]	260	130-520
100% of Normal[2]	220	110-430
80% of Normal[2]	180	90-360

[1] Measured in reach PM1 during WY 2002.

[2] Calculated based on WY 2002 discharge history.

Table 4.15. Results of Particle Transport Calculations.

Character of Yearly Precipitation on which Discharge Regime is based	Calculated Particle Transport Rate (m year^{-1})	Probable Range of Particle Transport Rates (m year^{-1})
120% of Normal[1]	220	110-450
100% of Normal[2]	190	95-370
80% of Normal[2]	150	80-310

[1] Measured in reach PM1 during WY 2002.

[2] Calculated based on WY 2002 discharge history.

CHAPTER 5 – DISCUSSION

Sources of Error and Uncertainty

The processes of sediment production and transport are spatially and temporally variable by nature. These natural variations, together with the use of data from other studies and assumptions, have introduced both error and uncertainty into the results of this investigation.

The results of the analysis of sediment production are most sensitive to errors and assumptions made regarding the sources that produce the most sediment. Since the onset of urbanization, channel enlargement has been the greatest source of sediment in the basin. To determine the change in channel dimensions since the onset of urbanization, errors have potentially been introduced in two ways. First, as historic channel geometries were not available to this study they needed to be estimated. Changes in channel dimension to steep-tributary channels were estimated from other undisturbed tributaries in the basin. Errors from this source should be minimal because the cross-sectional areas of undisturbed channels in the basin are relatively uniform (0.60 m^2 ± 0.16 m^2), and because the cross-sectional areas of these undisturbed steep tributaries are an order of magnitude smaller than those of the enlarged steep tributaries (Appendix C).

Changes in channel dimension to the alluvial reaches in the basin, however, must be deduced more indirectly, relying on a regional regression with contributing basin area to estimate pre-development channel geometry. Although the relationship between channel cross-sectional area and contributing basin area shows only modest scatter (± 35%) it is not precise, and some error is inherent in the application of such a regression. In addition, the exact determination of predevelopment sub-basin areas for each reach of Pipers Creek is no longer possible. During urbanization of the basin, grading, the construction of roads and drainage swales, and other topographic alterations associated with development have obscured the historic boundaries between sub-basins. Any miscalculation in estimating sub-basin size, however, is minimized by the slope of the regression equation (Figure 3.2); an error of 10% in basin size yields a difference of only 2% in predicted channel cross-sectional area.

Another potential source of error in channel-enlargement production rates lies in specifying a date at which urbanization initiated channel enlargement. Channel changes have been assumed to occur since 1950, as the largest phase in urban development within the basin began around that time. Development has occurred in the basin since the early 1920s, however, and if channel change began at that time then the rates of sediment production relating to channel enlargement would be up to 35% lower than calculated. The onset of significant channel instability has been associated with a contributing effective impervious area (EIA) in a basin of about 10 percent (Booth and Jackson, 1997). This level would have been crossed as the Pipers Creek watershed developed from medium-density residential (1 unit per acre) to "suburban" density (4 units per acre) around mid-century (Dinicola, 1989). This transition between medium and suburban density is evident from aerial photos taken in 1944 and 1961.

Sediment production rates for urban land-uses within the Pipers Creek watershed were not evaluated during this study. Instead, regional rates determined to be most applicable to the Puget Lowland have been applied. A range of sediment yield coefficients have been published; application of different values within that range would clearly result in changes to sediment production rates. For residential and commercial urban land uses, the yield coefficients applied here represent means over a range of values reported and so the scale of probable error is minimized. As the rate of construction in the basin is minimal, any error associated with the assumption of the yield coefficient would be negligible with respect to the total amount of sediment produced. Potential errors also exist through assumptions made in determining the sediment production from urban land areas in the period prior to erosion control. Through some of that earlier period, construction rates were likely higher than they are at present; however, current rates of construction in the basin have been applied to both periods of increased sediment production analyzed here.

Any error associated with the process of slope creep is nearly insignificant. The creep rate used in this study in near the mean of potential rates that could be applied. Even a doubling of the rate used here would increase the overall contribution of slope creep to the net total by less than 2%.

Predicted fractions of coarse and fine sediment depend not only on estimated production rates but also on geologic units that clearly vary in character from one location to another. An effort was made to gather samples from locations that typified the units as observed in outcrops in the basin; however, natural variability of these geologic units guarantees some imprecision in calculations made from the results. Potential errors are most likely from the Vashon Till as the other units (Esperance Sand and Lawton Clay) are almost exclusively fine-grained, and local alluvium deposits are almost entirely coarse grained. Within samples of Vashon Till from various locations in the Puget Sound basin, the amount of material finer than 8 mm in diameter ranges between about 55% and 95% (Olmsted, 1969). Approximately 66% of the Vashon Till sample analyzed in this study is finer than 8 mm, which is towards the coarser end of local grain-size distributions. If the average amount of material finer than 8 mm contributed from the Vashon Till were closer to the regional average of 75%, the estimate for the current rate of coarse-sediment production would be reduced by less than 10%.

The variable character of climate and precipitation also plays a large role in the variability of sediment production. The rates of sediment production for many of the sources evaluated in this investigation are sensitive to both yearly precipitation variability and climatic conditions over a longer period, as well as such factors as landslide episodicity and the erosion rates of particular geologic units. The calculated rates for sediment production are therefore average long-term rates, because they have been derived from data that integrates long-term averages, and not those expected yearly.

Due to limited hydrologic data for the basin, only one year of record was available for calculations of sediment transport. As climatic conditions and precipitation are extremely variable from year to year, use of such a limited data set can clearly provide only an order of magnitude estimate rather than a long-term averaged rate. The cumulative precipitation for the water year utilized for sediment transport calculations was approximately 120% of normal. Efforts were made to compensate for the brief discharge record through analysis of other estimated discharge regimes. Therefore, where the results of the sediment transport calculations hopefully provide a probable range of sediment transport conditions that can aid management decisions, the estimates are based on insufficient data for robust results.

The uncertainty analysis for sediment production in the current period shows that the range of uncertainty is ±20 tonnes km^{-2} $year^{-1}$, or approximately 17%, of the estimated rate of 120 tonnes km^{-2} $year^{-1}$. This value represents the potential variance in sediment production due to the unpredictable nature of the processes that produce sediment, the use of data from other studies, and assumptions made during production calculations. It does not take into consideration uncertainty associated with sediment production processes that are outside the scope of this investigation, such as sediment delivered from landslides with recurrence intervals of greater than 20 years. Any increase in the range of uncertainty or changes in the estimated production rates from such components would not alter the observed relationships between sediment production, transport, and storage, and therefore would not compromise the management implications of this study.

Sediment Production

General Patterns of Sediment Production

Current patterns of sediment production within the Pipers Creek watershed results from nearly complete upland-basin urbanization and the effects of the runoff generated from these urban areas on steep, erosion-susceptible channels downstream from development. Results of investigations of sediment production in other basins provide an opportunity to evaluate the accuracy of the sediment production rates estimated here (Figure 5.1). Differences in topography, climate, methodologies, and basin land use make any such comparisons challenging, but the analysis can provide an adequate order-of-magnitude assessment.

Although few sediment budgets have been completed for basins where the primary land uses are urban, Madej's (1982) study of the Big Beef Creek basin provides an interesting comparison to the Pipers Creek basin because of geologic similarities between the two. Sediment production rates are similar (185 vs. 120 tonnes km^{-2} $year^{-1}$), but the principle sediment sources to Big Beef Creek were surface erosion of unpaved roads and disturbance-related landslides. Sediment budgets completed by Trimble (1997) and Nelson and Booth (2002) are two of the very few sediment budgets with a significant urban land-use component. Owing to differences in these watersheds, however, their production rates differ by an order of magnitude and bracket that calculated for Pipers Creek.

The grain-size distribution of sediment currently delivered to the Pipers Creek channel network is finer than that which was delivered prior to the onset of basin urbanization. While the texture of local geologic units is overwhelmingly fine grained, urbanization of 90% of the basin area has further increased the overall proportion of fine sediment delivered. Assuming that the relative proportions of fine and coarse sediment produced by the naturally occurring mass-wasting processes of channel erosion, landsliding, and soil creep have remained steady through time, the sediment-delivery processes of channel enlargement and erosion from residential and commercial areas due to urbanization have increased the fraction, and more significantly, the overall magnitude of fine sediment production (Figure 4.2).

Table 5.1. Comparison of sediment production results for sediment budgets evaluating basin with urban land-uses.

Source (year)	Location	Basin Size (km^2)	Primary Land Use	Sediment Production (tonnes km^{-2} year^{-1})
Nelson and Booth (2002)	Issaquah Creek, Washington	142	Forest/ urban	55
Madej (1982)	Big Beef Creek, Washington	38	Forest/ logging/ urban	185
Trimble (1997)	San Diego Creek, California	288	Urban/ agriculture	520
This Study	Pipers Creek, Washington	7.5	Urban/ forest	120

Channel Enlargement and Gully Erosion

Channel enlargement and gully erosion are common expressions of the increased stormwater discharges that follow basin urbanization. The severity and extent of channel erosion are influenced by a channel's gradient, natural or artificial grade controls, geologic substrate, and transition to stormwater inputs from a point discharge (Booth and Henshaw, 2001). In the Pipers Creek watershed, channel enlargement has occurred on a large scale and continues to occur where steep channels with little grade control flow over erosion-susceptible substrate and receive concentrated stormwater discharges. In contrast, gully erosion, once a large source of sediment in the basin, has largely been eliminated.

Sediment production that results directly from the erosive capacity of stormwater discharges (channel enlargement and gully erosion) has been significantly reduced in the Pipers Creek watershed; however, it continues to rank as the largest source. The total sediment production due to channel erosion and gully incision has been reduced by 70% over the last thirty years and has decreased the total sediment production rate by over half from its estimated post-development maximum. This reduction has resulted from channel-stabilization efforts specifically targeting these sources. Erosion-control projects in alluvial channels have largely consisted of grade controlling structures, deflector logs, and bank armoring. Gully erosion has been effectively decreased by rerouting stormwater that previously discharged directly onto steep hillslopes. However, current sediment production remains many times higher than projected historic rates, and 40% of the watershed's estimated current sediment production is still generated by channel enlargement. Where erosion-control methods have not been applied, significant channel degradation continues in response to the altered hydrologic regime that followed basin-wide changes in land use. Furthermore, landsliding will almost certainly occur in response to current channel enlargement and this process has the potential to encroach on public and private land uses adjacent to the channel network. These adjustments will continue until a new equilibrium is established, channel banks and hillslopes are further stabilized, or the increased discharges that drive erosion are reduced.

The results for erosion due to stormwater discharges estimated here are similar to those from other investigations of sediment production in urbanizing basins where channel enlargement has been evaluated. In the San Diego Creek basin in southern California, Trimble (1997) determined that channel erosion provided approximately two-thirds of the total sediment yield between 1983 and 1993. During Trimble's study the San Diego Creek basin was developing rapidly and was approximately 50% urbanized. In the Pipers Creek watershed, during a similar period of basin development and prior to the implementation of channel-stabilization measures, channel and gully erosion together accounted for almost 90% of sediment production. Within the much more lightly urbanized Issaquah Creek basin, Nelson and Booth (2002) also determined channel enlargement to be a noteworthy source of sediment production. There, channel enlargement was found to contribute 20% of the total sediment production at a time when the basin was 19% urbanized and channels were largely unarmored.

Urban Land Uses

Surface runoff from the urban landscape transports sediment from developed areas and also gives rise to the increased discharges that cause channel erosion and enlargement. The total sediment production from residential and commercial areas has increased following urbanization, and more significantly, the composition of the sediment delivered from these areas is overwhelmingly fine grained and this has resulted in a fining of the sediment supplied to channels.

Instream Sediment Character and Transport

The details of sediment storage in the channel network of Pipers Creek demonstrate a current imbalance between the delivery and transport of fine and coarse sediment.

Within the Pipers Creek watershed, annual fine-sediment production (850 tonnes year $^{-1}$) is approximately equivalent to the amount of fine sediment measured in short-term storage in the active channels (940 tonnes). In contrast, the short-term storage of coarse sediment (2740 tonnes) is equivalent to many years of coarse-sediment production at the current rate (54 tonnes year^{-1}). The differences illustrate a great disparity between the residence times of fine- and coarse-grained particles within the channel system. Fine sediment is generally transported through the stream network during storm events, but the patterns of coarse sediment transport are not as clear. In the lower mainstem of Pipers Creek (PM1), bedload transport is calculated at 220 tonnes year^{-1}. This is four times greater than the current rate of coarse sediment production (54 tonnes year^{-1}) but only slightly greater than the estimated rate of coarse sediment production prior to channel-stabilization and erosion-control efforts (200 tonnes year^{-1}). It would seem then that the current regime of sediment transport is effectively "mining" the sediment previously delivered to the channel during the basin's earlier and most prolific production period.

With the current rates of coarse-sediment production and transport, a decrease in storage volume and increase in substrate diameter can be expected over the next two decades. Adjustment of the sediment transport calculations indicates, however, that a balance between bedload transport and the current rate of coarse-sediment production would be accomplished by an insignificant increase in the D_{50} particle diameter (from 35 mm to 51 mm). As a reduction in short-term storage should compensate jointly with substrate coarsening for the recent decrease in sediment supply, the magnitude of each response is not likely to significantly alter the physical character of sediment in the channel network.

Calculations of the reach-averaged annual bed load travel distance (L_B) assist in evaluating the response time of a channel to changes in sediment supply and the sensitivity of different reaches to increases or decreases in bed load. In reach PM1, the mean bedload transport is estimated at 220 tonnes year^{-1} and the short-term storage in the reach is approximately 700 tonnes. An estimate for particle residence time is approximately 3.2 years. As the reach length is 600m, L_B is estimated at 190 m year^{-1}.

This rate of annual bed load travel distance of 190 m year^{-1} is comparable to estimates of bedload sediment velocity in other investigations. Beechie (2001) completed an empirical analysis of selected reach characteristics and annual bedload travel distance in forested rivers and streams of the Pacific Northwest (not including Pipers Creek). The results indicate a strong correlation between annual bedload travel distance and bankfull channel width (w_{bf}), where $L_B \approx 20w_{bf}$. In Pipers Creek, the ratio between bankfull channel width and the annual bedload travel distance is closer to 40:1, twice the predicted value. An annual bedload travel distance higher than that predicted by the regression could be explained by the relatively simplistic channel form of the reach and flashier, more transport-effective discharges of urban streams (Konrad et al., 2002). Though modifications to control the streambed grade and provide bank protection have also created some local structural complexity that encourages bar formation, the prevailing plane-bed morphology and channel entrenchment does not promote instream sediment storage. As travel distance is limited only by trapping in bars, these channel conditions should result in accelerated sediment velocities (Beechie 2001). Comparison of measured and inferred particle transport rates in other gravel-bedded streams of similar bankfull widths and gradients in western Washington indicate that the rate determined here is within a commonly reported range (Table 5.2).

The range of annual bedload transport rates have current and future resource management implications. These rates indicates that coarse substrate is neither flushing excessively rapidly through the channel network nor is it immobile, two conditions that would indicate a severe deterioration of the natural equilibrium found between sediment supply and transport, and no management action is currently necessary to maintain an adequate supply of coarse sediment to the main alluvial channels in the stream network, particularly those utilized by salmonids for spawning. Further decreases in the rates of sediment delivery, or an increase in the channel complexity would both tend to move Pipers Creek towards reported values of bed load travel distance in less-disturbed Pacific Northwest streams.

Although the channel morphology and hydrologic regime in the Pipers Creek watershed promote efficient sediment transport, the overall percentage of

Table 5.2. Particle transport rates for gravel bedded streams in Washington with similar basin size, gradient, and bankfull width.

Source	Location	Basin Size (km^2)	Gradient (%)	w_{bf} (m)	L_B (m $year^{-1}$)
This Study	Pipers Creek, Washington	7.4	1.5	5	190[1]
Perkins (1989)	Salmon Creek, Washington	9.1	2	9	190
Madej (1982)	Big Beek Creek, Washington	38	1	20.5	206
WDNR (1994)	Hansen Creek, Washington	8	2.2	11	104

[1] This value is based on the calculated sediment transport rate for discharge during 100% normal precipitation year

fine sediment in the stream substrate may be high enough to limit the success of spawning salmonids. Spawning is limited almost exclusively to reaches PM1 and V1, which are 600m and 300m in length respectively. Pebble count results indicate that the amount of substrate less than 8 mm does not vary significantly throughout each reach (Figure 4.3 and Appendix D). Within reach PM1, the particle-size distributions of the two subsurface-sediment samples indicate levels of fine sediment that have been associated in other studies (based on field data) with reductions in the survival to emergence of coho and chum salmon. Within these studies assessing the effect of fine sediment on salmonid spawning success, different percentages of different size fractions of spawning substrates have been investigated and show strong correlation (see Chapter 2). As such, no specific parameter of local substrate character has been isolated or identified as “most degrading.” The grain-size distributions of the local subsurface samples, however, are similar to values that have been correlated with degraded spawning conditions (Figure 5.1). The physical character of substrate material in the spawning reaches of the Pipers Creek stream network thus may limit successful coho and chum reproduction.

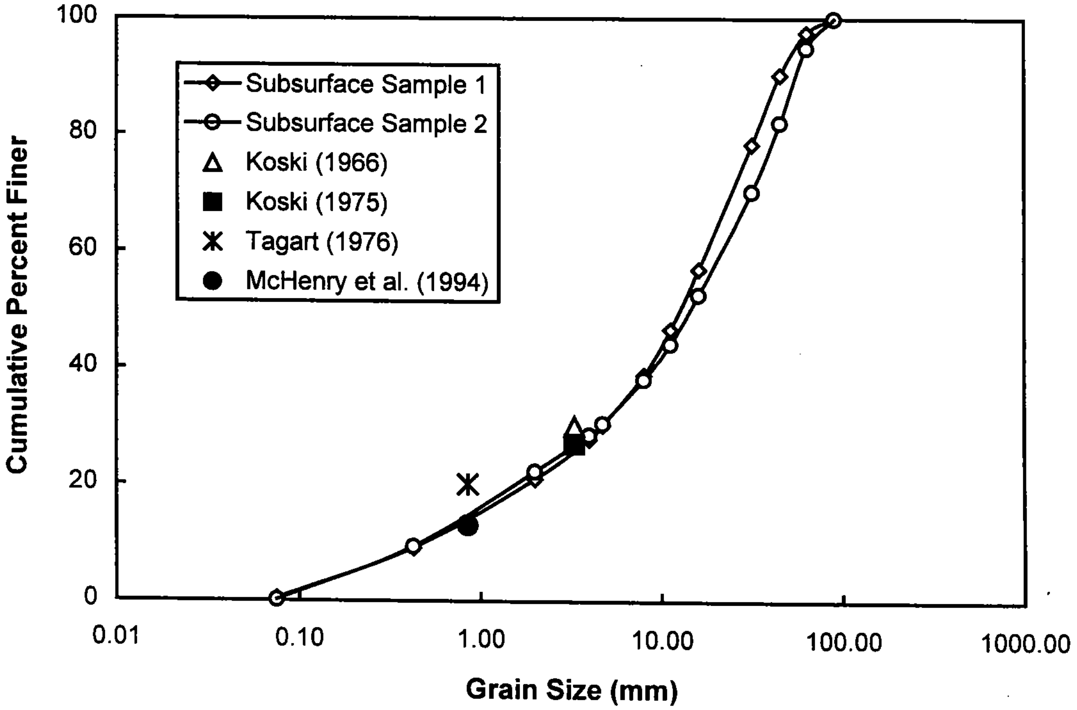

Figure 5.1: **Grain-size distribution curves for subsurface samples from reach PM1. Also shown are substrate qualities that have been correlated in prior field studies with decreased survival to emergence of salmonids.**

CHAPTER 6 - CONCLUSION AND RECOMMENDATIONS

Sediment production in the Pipers Creek watershed has been reduced over the last 30 years through efforts at streambed grade control, bank protection, and stormwater diversions, yet current sediment production remains six times greater than the estimated historic rate. Stormwater discharges continue to enlarge channels that have not been stabilized or armored and also transport more coarse sediment than is currently delivered to the channel network annually. Also, the magnitude of fine sediment production is seven times the historic rate and may result in degraded spawning conditions. Continued channel enlargement, the future of coarse sediment in the channel network, and the potential consequences of the overall magnitude of fine-sediment production are the most important management issues addressed in this investigation.

Channel erosion and enlargement is presently the largest overall and coarse-sediment source in the basin; this will continue until further channel-stabilization is completed or a new equilibrium is established between transport capacity, sediment supply, and channel form, probably still many years in the future. Further stabilization of 15% of the total channel network (V3, V4, P12, P14) could reduce the overall sediment production by about one-quarter of the current rate. Perhaps more significantly, further channel stabilization may be warranted in certain reaches (V3, V4, and P12) in order to prevent hillslope adjustments (landslides) that could threaten properties adjacent to the Pipers Creek channel network. Potential error associated with the calculation of sediment produced through channel enlargement would only reduce the overall production rate (by approximately one-third) and would neither reduce the significance of channel enlargement as a sediment source nor affect the potential consequences of unmitigated channel enlargement.

Current reductions in the delivery of sediment to the channel network have altered the balance between coarse sediment production and transport. The entire range of probable bedload transport rates exceeds the current estimate of coarse sediment production. The response to this reduction in coarse-sediment supply will be a decrease in short-term sediment storage and coarsening of the substrate. These adjustments will occur over the next one to two decades, yet the magnitude of either response is not likely to degrade general fluvial processes or habitat quality and no management action is currently necessary to maintain the condition of coarse sediment in Pipers Creek. Continued evaluation of substrate character and channel cross-sections are recommended, however, to monitor the long-term effects of the recent decreases in sediment supply.

Prior to basin urbanization, sediment production processes generated fine and coarse sediments simultaneously and primarily during large storm events. Now, even small storms wash fine sediment from urban areas and deliver them to the channel network. That sediment increases turbidity and may be deposited in the active channel during relatively low flows to infill gravel pore spaces and potentially reduce the flow of water and delivery of dissolved oxygen to salmonid redds. The fine-sediment content of the substrate in the spawning reaches (PM1 and V1) has been associated with degraded habitat in other studies, and may limit the reproductive success of salmonids. Analysis of the rates of survival to emergence of salmonids in Pipers Creek is warranted. If fine sediment, currently delivered at seven times its estimated historic rate, is found to degrade spawning conditions than a reduction in fine sediment production could be accomplished through further channel stabilization or efforts to reduce the contribution of fine sediment from the urban portion of the basin. Reduction of fine sediment delivered from urban areas would improve water quality, which would also lead to enhanced habitat conditions.

The urbanization of the Pipers Creek watershed has had profound effects on the regime of sediment production and delivery to Pipers Creek and its tributaries. Engineering efforts to mitigate the significant physical degradation to the channel network that has resulted from increased stormwater discharges associated with urbanization have reduced the accelerated rates of sediment production from their maximum. Yet by stabilizing the streambed and armoring banks in response to the altered hydrologic regime, the natural interaction between channels and the adjacent hillslopes that is part of a dynamic and complex ecosystem is diminished. The success of salmonid reproduction within the engineered channel network and under the current conditions of sediment production is not yet known, but such research could determine existing constraints to reproductive success and guide further habitat-enhancement efforts.

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Appendix A – Rating Curve and Sediment Transport Calculations

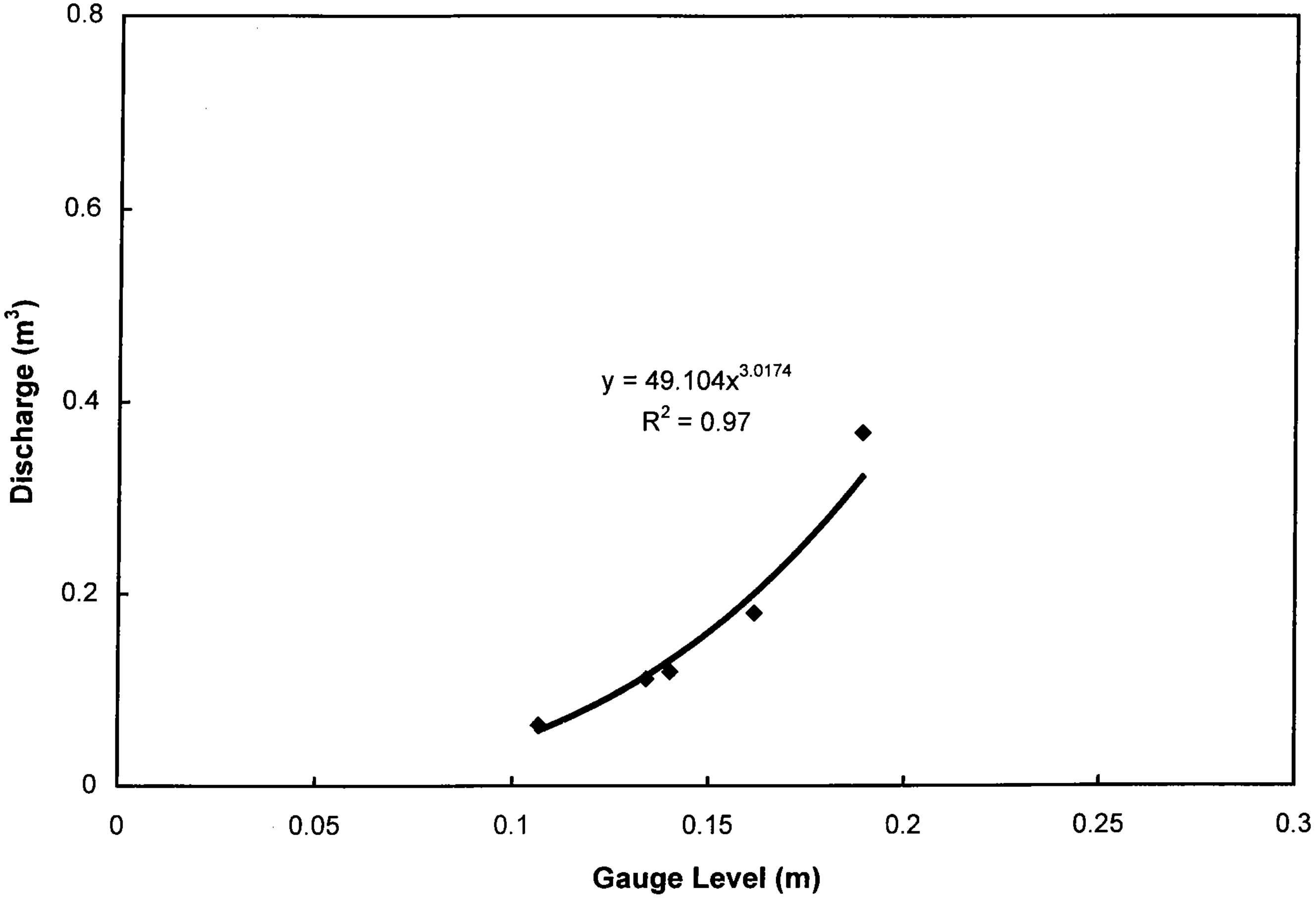

Figure A-1. Rating curve for gauge on Pipers Creek mainstem in reach PM1.

Sediment Transport Calculations

Bedload transport in reach PM1 was calculated using the Bagnold sediment transport equation (Bagnold, 1980). The Bagnold equation follows:

$$i_b = i_{br}\left[\frac{\omega - \omega_o}{0.5}\right]^{3/2}\left(Y/Y_r\right)^{-2/3}\left(D_{50}/D_r\right)^{-1/2}$$

and

$$\omega = \tau\bar{u}$$

and

$$\omega_o = 290 \times (D_{50})^{3/2} \times \log\left(12Y/D_{50}\right)$$

and

$$\tau = \rho g R S$$

Where:

i_b is the submerged sediment transport rate

i_{br} is the reference value of i_b (=0.01)

ω is the specific stream power

ω_o is the critical specific stream power for initiation of sediment motion

Y is the flow depth

Y_r is the reference depth (=0.1)

D_{50} is the mean bed particle size

D_r is the reference bed particle size (=0.0011)

τ is the shear stress

$\bar{u}$ is the mean stream velocity

ρ is the specific gravity of water

g is the acceleration of gravity

R is the hydraulic radius

S is the slope

Table A-1. Sediment transport calculations for WY 2002 (120% of normal).

D_{50} (m)	Depth (m)	Width (m)	Discharge (m)	Slope (m/m)	w_o (kg/m^2)	w (kg/m^2)	i_b (kg/m-sec)	Dry rate (kg/sec)	Current duration (hr)	Total transport rate (kg/yr)
0.0350	0.13	3.22	0.10	0.0150	3.12	0.46	0.00	0.00E+00	7578.25	0
0.0350	0.17	3.41	0.21	0.0150	3.33	0.93	0.00	0.00E+00	642.25	0
0.0350	0.22	3.57	0.50	0.0150	3.56	2.09	0.00	0.00E+00	337.75	0
0.0350	0.28	3.78	1.06	0.0150	3.77	4.22	0.01	4.62E-02	152.75	25405
0.0350	0.35	3.95	2.12	0.0150	3.96	8.06	0.18	1.14E+00	46.25	189718
0.0350	0.44	4.12	4.25	0.0150	4.14	15.47	0.71	4.68E+00	2.25	37916
0.0350	0.49	4.31	4.31	0.0150	4.22	15.00	0.62	4.26E+00	0.5	7664

Total= 260703

Total (tonnes)= 261

Table A-2. Sediment transport calculations for 100% of normal.

D_{50} (m)	Depth (m)	Width (m)	Discharge (m)	Slope (m/m)	w_o (kg/m^2)	w (kg/m^2)	i_b (kg/m-sec)	Dry rate (kg/sec)	Current duration (hr)	Total transport rate (kg/yr)
0.0350	0.13	3.22	0.10	0.0150	3.12	0.46	0.00	0.00E+00	7611.88	0
0.0350	0.17	3.41	0.21	0.0150	3.33	0.93	0.00	0.00E+00	642.25	0
0.0350	0.22	3.57	0.50	0.0150	3.56	2.09	0.00	0.00E+00	337.75	0
0.0350	0.28	3.78	1.06	0.0150	3.77	4.22	0.01	4.62E-02	127.29	21171
0.0350	0.35	3.95	2.12	0.0150	3.96	8.06	0.18	1.14E+00	38.54	158098
0.0350	0.44	4.12	4.25	0.0150	4.14	15.47	0.71	4.68E+00	1.88	31597
0.0350	0.49	4.31	4.31	0.0150	4.22	15.00	0.62	4.26E+00	0.42	6387
									Total=	217252
									Total (tonnes)=	217

Table A-3. Sediment transport calculations for 80% of normal.

D_{50} (m)	Depth (m)	Width (m)	Discharge (m)	Slope (m/m)	w_o (kg/m^2)	w (kg/m^2)	i_b (kg/m-sec)	Dry rate (kg/sec)	Current duration (hr)	Total transport rate (kg/yr)
0.0350	0.13	3.22	0.10	0.0150	3.12	0.46	0.00	0.00E+00	7639.90	0
0.0350	0.17	3.41	0.21	0.0150	3.33	0.93	0.00	0.00E+00	642.25	0
0.0350	0.22	3.57	0.50	0.0150	3.56	2.09	0.00	0.00E+00	337.75	0
0.0350	0.28	3.78	1.06	0.0150	3.77	4.22	0.01	4.62E-02	106.08	17642
0.0350	0.35	3.95	2.12	0.0150	3.96	8.06	0.18	1.14E+00	32.12	131748
0.0350	0.44	4.12	4.25	0.0150	4.14	15.47	0.71	4.68E+00	1.56	26331
0.0350	0.49	4.31	4.31	0.0150	4.22	15.00	0.62	4.26E+00	0.35	5322

Total= 181044
Total (tonnes)= 181

Table A-4. **Sediment transport calculations for 100% of normal with enlarged D_{50}.**

D_{50} (m)	Depth (m)	Width (m)	Discharge (m)	Slope (m/m)	w_o (kg/m^2)	w (kg/m^2)	i_b (kg/m-sec)	Dry rate (kg/sec)	Current duration (hr)	Total transport rate (kg/yr)
0.0510	0.13	3.22	0.10	0.0150	4.94	0.46	0.00	0.00E+00	7578.25	0
0.0510	0.17	3.41	0.21	0.0150	5.31	0.93	0.00	0.00E+00	642.25	0
0.0510	0.22	3.57	0.50	0.0150	5.71	2.09	0.00	0.00E+00	337.75	0
0.0510	0.28	3.78	1.06	0.0150	6.08	4.22	0.00	0.00E+00	127.29	0
0.0510	0.35	3.95	2.12	0.0150	6.41	8.06	0.04	2.40E-01	38.54	33330
0.0510	0.44	4.12	4.25	0.0150	6.74	15.47	0.40	2.62E+00	1.88	17700
0.0510	0.49	4.31	4.31	0.0150	6.88	15.00	0.33	2.31E+00	0.42	3459

Total= 54489

Total (tonnes)= 54

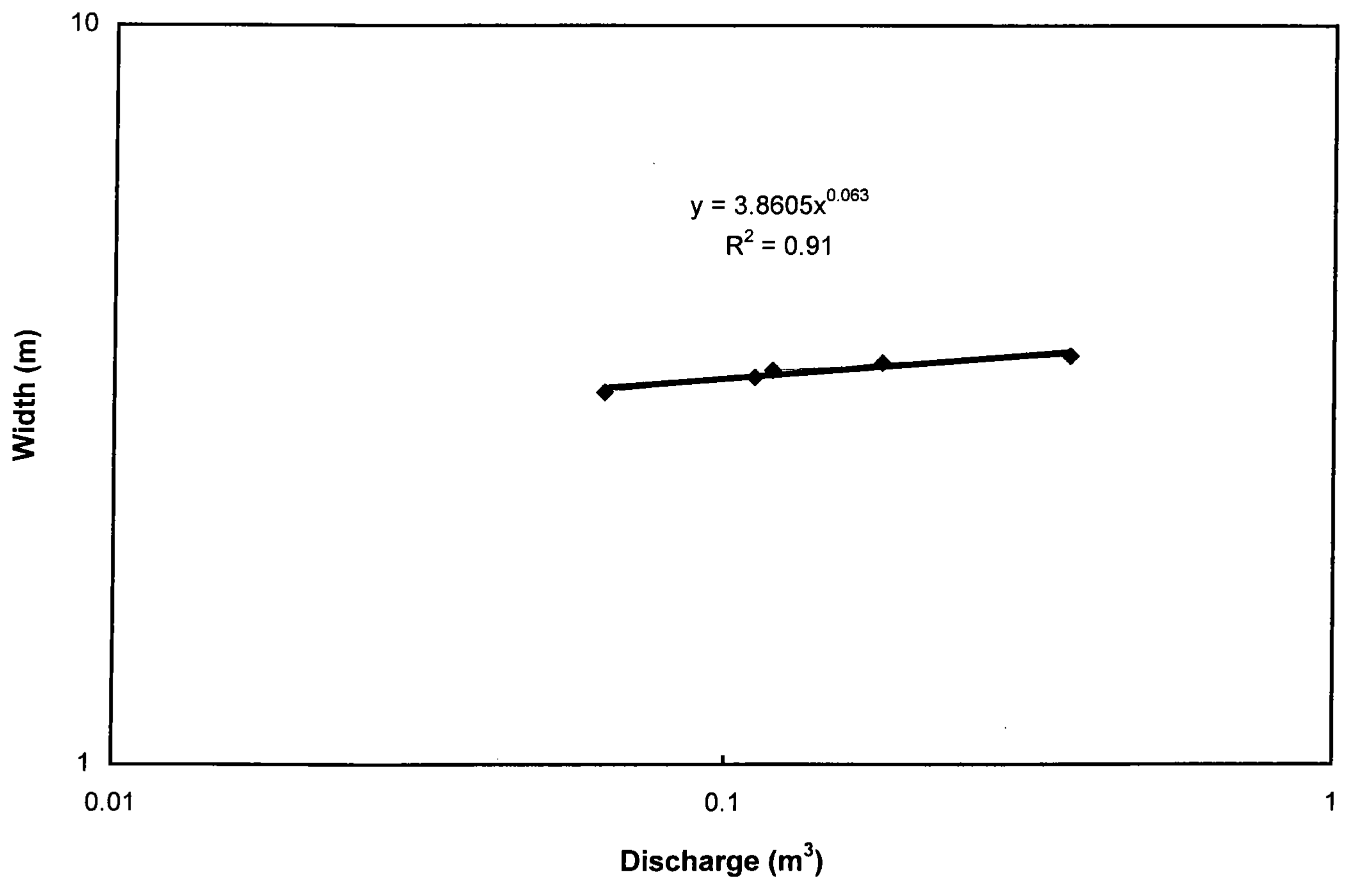

Figure A-2. Width vs. discharge regression from gauge location used for sediment transport calculations.

Appendix B – Bulk Grain-Size Analysis Data for Contributing Geologic Units

Table B-1. Data from production-unit bulk sieve analysis samples.

Sieve Opening (mm)	Vashon till		Esperance sand		Venema Creek Alluvium	
	Cumulative Weight retained (g)	Cumulative % Finer Than	Cumulative Weight retained (g)	Cumulative % Finer Than	Cumulativ Weigh retaine (g	Cumulative % Finer Than
90.00	0	100.0	0	100.0		100.0
63.00	0	100.0	0	100.0	4173.	87.0
45.000	1648.3	92.9	0	100.0	10300.	68.0
31.500	2824.1	87.9	0	100.0	14907.	53.7
16.000	5378	76.9	23.4	99.8	20961.	35.0
11.200	6698.8	71.2	112.8	99.2	23006.	28.6
8.000	7683.5	67.0	225.8	98.4	24386.	24.3
4.750	8841.1	62.0	420.9	97.0	25721.	20.2
4.000	9156.3	60.6	499.5	96.4	26049.	19.2
2.000	10234.7	56.0	912.1	93.5	27036.	16.1
0.425	14138.1	39.2	10297.2	26.5	28792.	10.7
0.075	22909.5	1.5	13854.2	1.1	3214	0.3
pan	26202.4		14000.7		32585.	

Appendix C – Sediment Production Data and Calculations

Table C-1. Channel enlargement calculations for alluvial mainstem reaches.

Reach	Enlarged Reach Length (m)	Avg. Existing Channel Area (m^2)	Estimated Original channel area (m^2)	Net Channel Enlargement (m^3)	Net Channel Enlargement (m^3)/50year	Net Channel Enlargement (tonnes)/50year
PM1	600	5.3	1.11	2519	50	86
PM2	969	6.7	0.95	5619	112	191
PM3	83	4.5	0.82	302	6	10
V1	74	2.2	0.77	106	2	4
V2	180	9.0	0.72	1487	30	51
V3	144	9.6	0.68	1286	26	44
V4	241	12.7	0.66	2892	58	98
VW	100	0.8	0.65	19	0	1
VE	175	2.7	0.65	367	7	12
MM	234	3.9	0.68	746	15	25
MW	55	8.8	0.66	447	9	15
ME	195	2.3	0.66	320	6	11
Total					**322**	**548**

Table C-2. Representative geometries for steep-tributary channels that have not received stormwater discharges.

Reach	depth (m)	width (m)	Cross-sectional area (m^2)
P3	0.46	1.83	0.84
P4	0.61	0.91	0.56
P5	0.61	0.91	0.56
P6	0.61	0.61	0.37
P7	0.76	0.91	0.70
P16	0.61	0.91	0.56

Mean=	0.60
Standard deviation=	0.16

Table C-3. Channel-enlargement calculations for P8.

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
8	1.2	0.9	1.1	26	9
21	1.8	2.4	4.5	43	58
31	1.2	2.6	3.2	33	32
51	3.0	2.1	6.5	66	130
62	0.9	1.8	1.7	36	18
74	1.2	2.1	2.6	39	31
104	1.2	2.1	2.6	98	78
124	0.6	2.4	1.5	66	30
152	1.8	2.4	4.5	92	125
165	2.4	2.0	4.8	43	63
205	2.4	1.5	3.7	131	149
237	1.2	1.8	2.2	105	71

Subtotal=	793
Less estimated original=	132
Total (m^3)=	661
Over 50 years (m^3)=	13.2
Over 50 years (tonnes)=	22.5

Table C-4. Channel-enlargement calculations for P9.

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
14	3.7	0.9	3.3	14	23
28	1.8	2.7	5.0	14	59
36	4.6	2.7	12.5	8	70
45	1.8	4.6	8.4	9	94
51	1.8	4.6	8.4	6	50
55	1.8	4.6	8.4	4	33
61	1.8	4.6	8.4	6	50
73	3.0	4.1	12.5	12	125
77	4.6	6.1	27.9	4	81
80	4.6	6.1	27.9	3	84
100	4.6	6.1	27.9	20	557
120	3.0	6.1	18.6	20	464
127	1.8	4.6	8.4	7	94
137	1.8	4.6	8.4	10	84
147	2.4	5.3	13.0	10	107
167	1.8	3.8	7.0	20	200
182	0.6	0.9	0.6	15	56
190	0.9	2.4	2.2	8	11
200	0.9	2.4	2.2	10	22
212	0.9	1.8	1.7	12	23
220	0.6	1.1	0.7	8	9
228	0.0	0.0	0.0	8	3

Subtotal=	2301
Less estimated original=	169
Total (m^3)=	2108
Over 50 years (m^3)=	42.0
Over 50 years (tonnes)=	71.7

Table C-5. Channel-enlargement calculations for P11.

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
4	0.9	0.6	0.6	4	2
20	4.6	0.3	1.4	16	22
44	1.8	1.5	2.8	24	67
48	1.2	2.7	3.3	4	13
60	2.1	2.4	5.2	12	62
75	2.1	2.4	5.2	15	78

Subtotal=	245
Less estimated original=	45
Total (m^3)=	200
Over 50 years (m^3)=	4
Over 50 years (tonnes)=	6.8

Table C-6. Channel-enlargement calculations for P12.

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
28	3.7	1.2	4.5	28	62
40	3.7	3.0	11.2	12	94
58	4.6	6.1	27.9	18	351
108	3.0	1.4	4.2	50	801
170	3.0	1.4	4.2	62	259
292	0.6	0.6	0.4	122	278

Subtotal=	1845
Less estimated original=	203
Total (m^3)=	1642
Over 50 years (m^3)=	32.8
Over 50 years (tonnes)=	55.8

Table C-7. Channel-enlargement calculations for P14.

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
25	2.1	0.9	2.0	25	36
38	1.8	1.8	3.3	13	34
54	1.8	2.0	3.6	16	56
70	2.4	0.9	2.2	16	47
75	2.4	0.9	2.2	5	11
90	2.4	2.7	6.7	15	67
151	0.0	0.0	0.0	61	204

Subtotal=	455
Less estimated original=	91
Total (m^3)=	364
Over 50 years (m^3)=	7.3
Over 50 years (tonnes)=	12.4

South Branch

Location (m)	Width (m)	Depth (m)	Area (m^2)	Length from previous location (m)	Volume (m^3)
29	1.8	3.2	5.9	29	85
36	0.9	0.6	0.6	7	22
55	0.0	0.0	0.0	19	5

Subtotal=	113
Less estimated original=	33
Total (m^3)=	80
Over 50 years (m^3)=	1.6
Over 50 years (tonnes)=	2.7

Reach P14 Totals	
Total (m^3)=	443
Over 50 years (m^3)=	8.9
Over 50 years (tonnes)=	15.1

Table C-8. Percent contribution from each geologic unit to channel enlargement sediment production.

Reach	Venema Till (VT)	Esperance Sand (ES)	Lawton Clay (LC)	Colluvium 1	Colluvium 2	Venema Alluvium (AL)
PM1				25	25	50
PM2		25	25	25		25
PM3		25	25	25		25
V1				25	75	
V2		50		25		25
V3			75	12.5	12.5	
V4		75		12.5	12.5	
VW				100		
VE				100		
MM		20	20	35		25
MW	40		30	15		15
ME	40		40	10		10
P8		60	30	10		
P9		60	30	10		
P11			50	40		10
P12			70	15		15
P14		20	60	10		10

Table C-9. Current soil creep calculations.

Reach	Length (m)	Length considered (m)	Col depth (m)	Rate (m/yr)	Creep volume (m^3/yr)	Creep volume (tonnes/yr)
PM1	600	240	0.30	0.0025	0.2	0.3
PM2	969	581	0.30	0.0025	0.4	0.7
PM3	225	180	0.30	0.0025	0.1	0.2
PM4	250	125	0.30	0.0025	0.1	0.2
V1	308	154	0.30	0.0025	0.1	0.2
V2	180	360	0.30	0.0025	0.3	0.5
V3	144	288	0.30	0.0025	0.2	0.4
V4	241	482	0.30	0.0025	0.4	0.6
VW	125	250	0.30	0.0025	0.2	0.3
VE	175	350	0.30	0.0025	0.3	0.4
MM	234	468	0.30	0.0025	0.4	0.6
MW	290	580	0.30	0.0025	0.4	0.7
ME	280	560	0.30	0.0025	0.4	0.7
P3	211	422	0.30	0.0025	0.3	0.5
P4	150	300	0.30	0.0025	0.2	0.4
P5	125	250	0.30	0.0025	0.2	0.3
P6	130	260	0.30	0.0025	0.2	0.3
P7	100	200	0.30	0.0025	0.2	0.3
P8	240	480	0.30	0.0025	0.4	0.6
P9	240	480	0.30	0.0025	0.4	0.6
P10	82	164	0.30	0.0025	0.1	0.2
P11	75	150	0.30	0.0025	0.1	0.2
P12	292	584	0.30	0.0025	0.4	0.7
P14	200	400	0.30	0.0025	0.3	0.5
P15	75	150	0.30	0.0025	0.1	0.2
P16	50	100	0.30	0.0025	0.1	0.1
Carkeek Pk. Rd.	763	763	0.30	0.0025	0.6	1.0
TOTALS	5991	9321			7	12

Table C-10. Soil creep calculations prior to channel stabilization and bank armoring.

Reach	Length (m)	length considered (m)	Col depth (m)	rate (m/yr)	creep volume (m3/yr)	creep volume (tonnes/yr)
PM1	600	1200	0.3	0.0025	0.9	1.5
PM2	969	1938	0.3	0.0025	1.5	2.5
PM3	225	450	0.3	0.0025	0.3	0.6
PM4	250	125	0.3	0.0025	0.1	0.2
V1	308	616	0.3	0.0025	0.5	0.8
V2	180	360	0.3	0.0025	0.3	0.5
V3	144	288	0.3	0.0025	0.2	0.4
V4	241	482	0.3	0.0025	0.4	0.6
VW	125	250	0.3	0.0025	0.2	0.3
VE	175	350	0.3	0.0025	0.3	0.4
MM	234	468	0.3	0.0025	0.4	0.6
MW	290	580	0.3	0.0025	0.4	0.7
ME	280	560	0.3	0.0025	0.4	0.7
P3	211	422	0.3	0.0025	0.3	0.5
P4	150	300	0.3	0.0025	0.2	0.4
P5	125	250	0.3	0.0025	0.2	0.3
P6	130	260	0.3	0.0025	0.2	0.3
P7	100	200	0.3	0.0025	0.2	0.3
P8	240	480	0.3	0.0025	0.4	0.6
P9	240	480	0.3	0.0025	0.4	0.6
P10	82	164	0.3	0.0025	0.1	0.2
P11	75	150	0.3	0.0025	0.1	0.2
P12	292	584	0.3	0.0025	0.4	0.7
P14	200	400	0.3	0.0025	0.3	0.5
P15	75	150	0.3	0.0025	0.1	0.2
P16	50	100	0.3	0.0025	0.1	0.1
Carkeek Pk. Rd.	763	763	0.3	0.0025	0.6	1.0
TOTALS	5991	12370			9	16

Table C-11. Historic soil creep calculations.

Reach	Length (m)	length considered (m)	Col depth (m)	rate (m/yr)	creep volume (m3/yr)	creep volume (tonnes/yr)
PM1	600	1200	0.3	0.0025	0.9	1.5
PM2	969	1938	0.3	0.0025	1.5	2.5
PM3	225	450	0.3	0.0025	0.3	0.6
PM4	250	125	0.3	0.0025	0.1	0.2
V1	308	616	0.3	0.0025	0.5	0.8
V2	180	360	0.3	0.0025	0.3	0.5
V3	144	288	0.3	0.0025	0.2	0.4
V4	241	482	0.3	0.0025	0.4	0.6
VW	125	250	0.3	0.0025	0.2	0.3
VE	175	350	0.3	0.0025	0.3	0.4
MM	234	468	0.3	0.0025	0.4	0.6
MW	290	580	0.3	0.0025	0.4	0.7
ME	280	560	0.3	0.0025	0.4	0.7
P3	211	422	0.3	0.0025	0.3	0.5
P4	150	300	0.3	0.0025	0.2	0.4
P5	125	250	0.3	0.0025	0.2	0.3
P6	130	260	0.3	0.0025	0.2	0.3
P7	100	200	0.3	0.0025	0.2	0.3
P8	240	480	0.3	0.0025	0.4	0.6
P9	240	480	0.3	0.0025	0.4	0.6
P10	82	164	0.3	0.0025	0.1	0.2
P11	300	600	0.3	0.0025	0.5	0.8
P12	292	584	0.3	0.0025	0.4	0.7
P14	200	400	0.3	0.0025	0.3	0.5
P15	25	50	0.3	0.0025	0.0	0.1
P16	50	100	0.3	0.0025	0.1	0.1
TOTALS	6166	11957			9	15

Table C-12. Historic landslide calculations.

Reach	Length (m)	Percent of total length	Total production in basin (m^3/yr)[1]	Total (m^3/yr)
PM1	600	10.1	66	6.6
PM2	1000	16.8	66	11.1
PM3	225	3.8	66	2.5
PM4	250	4.2	66	2.8
V1	300	5.0	66	3.3
V2	180	3.0	66	2.0
V3	144	2.4	66	1.6
V4	241	4.0	66	2.7
VW	125	2.1	66	1.4
VE	175	2.9	66	1.9
MM	234	3.9	66	2.6
MW	290	4.9	66	3.2
ME	280	4.7	66	3.1
P3	211	3.5	66	2.3
P4	150	2.5	66	1.7
P5	125	2.1	66	1.4
P6	130	2.2	66	1.4
P7	100	1.7	66	1.1
P8	240	4.0	66	2.7
P9	240	4.0	66	2.7
P10	82	1.4	66	0.9
P11	75	1.3	66	0.8
P12	292	4.9	66	3.2
P14	200	3.4	66	2.2
P15	25	0.4	66	0.3
P16	50	0.8	66	0.6

[1] Based on rate of 15 tonnes/km^2 from Madej (1982).

Table C-13 . Landslide calculations for reach PM2.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)
507	30	6.1	3.0	1.2	half ellipse	11.9	0.4	5.7	0.2	6.2	0.2
533	30	6.1	9.1	1.5	half ellipse	44.5	1.5	17.0	0.6	27.5	0.9
699	30	6.1	6.1	1.5	half ellipse	29.7	1.0	11.3	0.4	18.3	0.6
824	5	3.0	5.5	1.2	half ellipse	10.7	2.1	5.1	1.0	5.6	1.1
858	20	6.1	15.2	1.8	half ellipse	89.0	4.4	28.3	1.4	60.6	3.0
Totals						185.6	9.4	67.4	3.6	118.2	5.9

Notes: Col is colluvium
LC is Lawton Clay

Table C-14. Landslide calculations for reach PM3.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)
80	20	4.6	3.0	0.9	half ellipse	6.7	0.3	4.2	0.2	2.4	0.1
Totals						6.7	0.3	4.2	0.2	2.4	0.1

Notes: Col is colluvium
LC is Lawton Clay

Table C-15. Landslide calculations for reach V3.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	ES (m^3)	ES/yr (m^3)
39	20	3.0	3.0	0.6	half ellipse	3.0	0.1	2.8	0.1	0.1	0.0
31	20	4.6	3.0	0.9	half ellipse	6.7	0.3	4.2	0.2	2.4	0.1
68	10	2.7	1.8	0.9	half ellipse	2.4	0.2	1.5	0.2	0.9	0.1
93	20	6.1	4.6	0.9	half ellipse	13.3	0.7	8.5	0.4	4.8	0.2
99	10	2.4	3.0	0.9	half ellipse	3.6	0.4	2.3	0.2	1.3	0.1
114	20	6.1	6.1	1.5	half ellipse	29.7	1.5	11.3	0.6	18.3	0.9
128	20	9.1	6.1	1.8	wedge	51.0	2.5	17.0	0.8	34.0	1.7
151	20	6.1	4.6	1.5	half ellipse	22.2	1.1	8.5	0.4	13.7	0.7
Totals						131.8	6.9	56.2	3.0	75.6	3.9

Notes: Col is colluvium
ES is Esperance Sand

Table C-16. Landslide calculations for reach V4.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	ES (m^3)	ES/yr (m^3)
22	20	6.1	9.1	1.8	half ellipse	53.4	2.7	17.0	0.8	36.4	1.8
71	20	12.2	6.1	1.2	half ellipse	47.4	2.4	22.7	1.1	24.8	1.2
106	20	9.1	12.2	1.8	half ellipse	106.8	5.3	34.0	1.7	72.8	3.6
121	20	7.6	9.1	2.4	half ellipse	89.0	4.4	21.2	1.1	67.7	3.4
138	20	7.6	12.2	1.5	half ellipse	74.1	3.7	28.3	1.4	45.8	2.3
143	10	6.1	4.6	0.9	half ellipse	13.3	1.3	8.5	0.8	4.8	0.5
151	20	6.1	1.5	0.9	rect.	8.5	0.4	2.8	0.1	5.7	0.3
154	20	6.1	3.0	1.2	rect.	22.7	1.1	5.7	0.3	17.0	0.8
165	20	12.2	1.2	1.5	half ellipse	11.9	0.6	4.5	0.2	7.3	0.4
Totals						427.0	22.0	144.7	7.7	282.3	14.4

Notes: Col is colluvium
ES is Esperance Sand

Table C-17. Landslide calculations for reach MM.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	AL (m^3)	AL/yr (m^3)	ES (m^3)	ES/yr (m^3)
79	20	6.1	3.0	0.9	half ellipse	8.9	0.4	5.7	0.3	3.2	0.2	0.0	0.0
114	20	3.0	2.4	0.9	half ellipse	3.6	0.2	2.3	0.1	0.0	0.0	1.3	0.1
Totals						12.5	0.6	7.9	0.4	3.2	0.2	1.3	0.1

Notes: Col is colluvium
AL is alluvium
ES is Esperance Sand

Table C-18. Landslide calculations for reach MW.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	ES (m^3)	ES/yr (m^3)	VT (m^3)	VT/yr (m^3)
95	20	5.8	6.1	1.5	half ellipse	28.2	1.4	10.8	0.5	17.4	0.9	0.0	0.0
155	20	7.6	10.7	1.5	half ellipse	64.9	3.2	24.8	1.2	40.1	2.0	0.0	0.0
208	20	7.6	9.1	0.9	half ellipse	33.4	1.7	21.2	1.1	0.0	0.0	12.1	0.6
266	20	4.9	12.2	0.6	half ellipse	19.0	0.9	18.1	0.9	0.0	0.0	0.9	0.0
Totals						145.4	7.3	74.9	3.7	57.5	2.9	13.0	0.6

Notes: Col is colluvium
ES is Esperance Sand
VT is Vashon Till

Table C-19. Landslide calculations for reach ME.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)	VT (m^3)	VT/yr (m^3)
64	20	3.0	6.1	1.2	half ellipse	11.9	0.6	5.7	0.3	6.2	0.3	0.0	0.0
123	20	6.1	9.1	1.5	half ellipse	44.5	2.2	17.0	0.8	0.0	0.0	27.5	1.4
170	20	9.1	12.2	0.9	half ellipse	53.4	2.7	34.0	1.7	0.0	0.0	19.4	1.0
192	20	6.1	12.2	0.6	half ellipse	23.7	1.2	22.7	1.1	0.0	0.0	1.1	0.1
266	20	6.1	6.1	1.8	half ellipse	35.6	1.8	11.3	0.6	0.0	0.0	24.3	1.2
Totals						169.0	8.5	90.6	4.5	6.2	0.3	72.2	3.6

Notes: Col is colluvium
LC is Lawton Clay
VT is Vashon Till

Table C-20. Landslide calculations for reach P8.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)	ES (m^3)	ES/yr (m^3)
23	20	4.6	4.6	1.2	half ellipse	13.3	0.7	6.4	0.3	7.0	0.3	0.0	0.0
29	10	1.8	2.4	0.9	half ellipse	2.1	0.2	1.4	0.1	0.8	0.1	0.0	0.0
42	5	6.1	6.1	1.8	rect.	34.0	6.8	11.3	2.3	22.7	4.5	0.0	0.0
60	10	2.4	2.4	1.8	half ellipse	5.7	0.6	1.8	0.2	3.9	0.4	0.0	0.0
102	20	1.8	2.4	0.9	half ellipse	2.1	0.1	1.4	0.1	0.0	0.0	0.8	0.0
108	20	6.1	6.1	1.8	half ellipse	35.6	1.8	11.3	0.6	0.0	0.0	24.3	1.2
108	20	3.0	3.0	0.9	half ellipse	4.4	0.2	2.8	0.1	0.0	0.0	1.6	0.1
127	20	6.1	4.6	1.2	half ellipse	17.8	0.9	8.5	0.4	0.0	0.0	9.3	0.5
135	20	9.1	6.1	2.4	half ellipse	71.2	3.6	17.0	0.8	0.0	0.0	54.2	2.7
135	10	6.1	6.1	2.4	half ellipse	47.4	4.7	11.3	1.1	0.0	0.0	36.1	3.6
144	20	3.7	3.0	1.5	half ellipse	8.9	0.4	3.4	0.2	0.0	0.0	5.5	0.3
150	20	3.0	3.7	1.2	half ellipse	7.1	0.4	3.4	0.2	0.0	0.0	3.7	0.2
175	20	3.7	3.0	1.2	half ellipse	7.1	0.4	3.4	0.2	0.0	0.0	3.7	0.2
175	10	2.4	1.2	0.6	half ellipse	0.9	0.1	0.9	0.1	0.0	0.0	0.0	0.0
192	20	9.1	9.1	2.7	half ellipse	120.1	6.0	25.5	1.3	0.0	0.0	94.6	4.7
199	20	3.0	3.0	0.9	half ellipse	4.4	0.2	2.8	0.1	0.0	0.0	1.6	0.1
206	20	3.0	6.1	1.2	half ellipse	11.9	0.6	5.7	0.3	0.0	0.0	6.2	0.3
213	20	3.0	3.0	1.5	half ellipse	7.4	0.4	2.8	0.1	0.0	0.0	4.6	0.2
230	20	4.6	3.7	1.8	half ellipse	16.0	0.8	5.1	0.3	0.0	0.0	10.9	0.5
Totals						417.6	28.8	126.2	8.8	34.3	5.3	257.1	14.7

Notes: Col is colluvium
LC is Lawton Clay
ES is Esperance Sand

Table C-21. Landslide calculations for reach P9 before stabilization efforts.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)
77	20	4.6	6.1	1.2	half ellipse	17.8	0.9	8.5	0.4	9.3	0.5
82	20	2.4	6.1	0.5	half ellipse	3.6	0.2	0.0	0.0	3.6	0.2
127	20	12.2	18.3	3.0	half ellipse	355.8	17.8	68.0	3.4	287.9	14.4
138	20	3.0	6.1	1.5	wedge	14.2	0.7	5.7	0.3	8.5	0.4
143	20	3.7	6.1	1.8	wedge	20.4	1.0	6.8	0.3	13.6	0.7
Totals						411.7	20.6	88.9	4.4	322.8	16.1

Notes: Col is colluvium
LC is Lawton Clay

Table C-22. Landslide calculations in reach P9 for the current period.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)
67	5	1.2	1.8	0.6	half ellipse	0.7	0.1	0.0	0.0	0.7	0.1
70	10	2.4	3.7	0.6	rect.	5.4	0.5	0.0	0.0	5.4	0.5
72	5	0.9	0.9	0.9	rect.	0.8	0.2	0.0	0.0	0.8	0.2
125	10	1.8	4.6	0.5	half ellipse	2.0	0.2	0.0	0.0	2.0	0.2
Totals						8.9	1.0	0.0	0.0	8.9	1.0

Notes: Col is colluvium
LC is Lawton Clay

Table C-23. Landslide calculations for reach P12.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)
51	10	7.9	7.6	0.8	half ellipse	24.1	2.4	18.4	1.8	5.7	0.6
54	5	7.6	3.0	1.2	half ellipse	14.8	3.0	7.1	1.4	7.7	1.5
82	20	8.2	6.1	1.1	half ellipse	28.0	1.4	15.3	0.8	12.7	0.6
93	20	9.1	10.1	0.6	half ellipse	29.4	1.5	28.0	1.4	1.3	0.1
105	5	6.1	6.1	1.8	half ellipse	35.6	7.1	11.3	2.3	24.3	4.9
122	20	11.3	7.0	1.8	half ellipse	75.7	3.8	24.1	1.2	51.6	2.6
142	20	7.6	7.6	0.6	half ellipse	18.5	0.9	17.7	0.9	0.8	0.0
154	10	6.1	4.0	0.6	half ellipse	7.7	0.8	7.4	0.7	0.3	0.0
154	20	9.1	15.2	0.5	half ellipse	33.4	1.7	33.4	1.7	0.0	0.0
205	20	18.3	9.1	1.2	half ellipse	106.8	5.3	51.0	2.5	55.8	2.8
214	10	6.7	9.1	1.2	half ellipse	39.1	3.9	18.7	1.9	20.5	2.0
228	20	9.1	6.1	3.0	half ellipse	89.0	4.4	17.0	0.8	72.0	3.6
Totals						502.0	36.2	249.3	17.4	252.7	18.8

Notes: Col is colluvium
LC is Lawton Clay

Table C-24. Landslide calculations for reach P14.

Location (m)	Age	Width (m)	Length (m)	Depth (m)	Shape	Total (m^3)	Total (m^3)/yr	Col (m^3)	Col/yr (m^3)	LC (m^3)	LC/yr (m^3)	ES (m^3)	ES/yr (m^3)
105	5	7.6	7.6	2.4	half ellipse	74.1	14.8	17.7	3.5	56.4	11.3	0.0	0.0
115	5	4.6	4.6	2.1	rect.	22.3	4.5	6.4	1.3	8.0	1.6	8.0	1.6
118	5	4.6	6.1	2.4	rect.	34.0	6.8	8.5	1.7	12.7	2.5	12.7	2.5
187	20	6.1	3.0	1.2	half ellipse	11.9	0.6	5.7	0.3	0.0	0.0	6.2	0.3
Totals						142.3	26.7	38.2	6.8	77.1	15.4	26.9	4.5

Notes: Col is colluvium
LC is Lawton Clay
ES is Esperance Sand

Appendix D – Sediment Storage Data and Calculations

Table D-1. Data from bulk substrate samples in reach PM1.

Sieve Opening (mm)	Bulk sample 1		Bulk sample 2	
	Cumulative Weight retained (g)	Cumulative % Finer Than	Cumulative Weight retained (g)	Cumulative % Finer Than
63.00	1028.1	97.6	1975.4	94.9
45.000	4159.8	90.2	7024	82.0
31.500	9240.3	78.2	11601	70.2
16.000	18260	57.0	18432	52.7
11.200	22651.4	46.6	21737.3	44.2
8.000	25957.6	38.9	24110	38.1
4.750	29657.8	30.1	27065.8	30.5
4.000	30681.7	27.7	27829.4	28.5
2.000	33554.4	21.0	30265.2	22.3
0.425	38598.2	9.1	35292.2	9.4
0.075	42265.2	0.4	38877	0.2
pan	42394.3		39006.8	

Table D-2. Conversion factors relating surface and subsurface particle-size descriptors

	Bulk Sample 1			Bulk Sample 2			Summary of Factors	
	Pebble Count (mm)	Bulk Sieve Analysis (mm)	Factor	Pebble Count (mm)	Bulk Sieve Analysis (mm)	Factor	mean	std dev
D10	9.7	0.5	17.6	9.2	0.5	18.3	18.0	0.5
D16	12.6	1.3	9.4	11.7	1.2	9.5	9.4	0.1
D50	27.4	12.8	2.1	28.8	14.5	2.0	2.1	0.1
D84	45.0	38.0	1.2	58.5	47.8	1.2	1.2	0.0
D90	52.5	44.8	1.2	67.6	56.2	1.2	1.2	0.0

Table D-3. Pebble count details.

Sample ID	Reach	D10	D16	D50	D84	D90
PC1	PM1	8	11	26	55	63
PC2	PM1	6	9	30	74	83
PC3	PM1	6	10	26	46	54
PC4	PM1	6	9	21	33	39
PC5	PM1	8	10	26	50	57
PC6	PM1	5	8	25	50	59
PC7	PM1	9	12	32	58	67
PC8	PM1	6	9	27	56	65
PC9	PM1	9	12	30	73	85
PC10	PM1	7	10	30	71	85
PC11	PM1	9	12	33	69	86
PC12	PM1	8	13	40	90	109
PC13	PM1	11	15	34	68	80
PC14	PM1	9	13	36	62	73
PC15	PM1	8	11	33	64	75
PC16	PM1	7	11	31	59	69
PC17	PM2	5	8	30	58	64
PC18	PM2	7	9	24	66	84
PC19	PM2	8	10	29	53	67
PC20	PM2	8	11	27	63	89
PC21	PM3	8	11	34	78	104
PC22	PM4	3	6	14	35	41
VC1	V1	10	13	26	46	55
VC2	V1	5	9	26	70	85
VC3	V2	6	8	25	69	82
VC4	V2	9	10	26	64	79
VC5	V4	9	11	34	86	103
MC1	MM	6	9	22	73	93
MC2	MM	9	12	28	59	72
MC3	MM	6	9	19	70	83
ME1	ME	5	8	26	82	108
MW1	MW	10	13	37	81	99
P12	P12	9	13	41	63	100
mean		7.4	10	29	63	77
std dev		2	2	6	13	18

Table D-4. Channel storage calculations.

Reach	Reach Length (m)	Channel Width (m)	D90(mm)	D90(m)	Reach Storage (m^3)
P1a	50	3.96	63	0.063	25.0
P1b	50	4.57	83	0.083	38.0
P1c	40	3.96	54	0.054	17.1
P1d	72	4.57	58	0.058	38.2
P1e	94	4.57	67	0.067	57.6
P1f	285	4.57	80	0.08	208.5
P2a	205	3.66	65	0.065	97.5
P2b	670	3.05	75	0.075	306.4
P3	224	2.44	34	0.034	37.2
P4	250	1.83	14	0.014	12.8
V1a	35	2.13	55	0.055	8.2
V1b	235	1.52	85	0.085	60.9
V1c	38	1.83	81	0.081	11.3
V2a	67	6.10	81	0.081	66.2
V2b	113	2.44	81	0.081	44.6
V3a	92	1.83	81	0.081	27.3
V3b	52	0.91	81	0.081	7.7
V3c	88	1.83	81	0.081	26.1
V4	153	1.83	103	0.103	57.7
VW	125	0.91	81	0.081	18.5
VE	175	1.83	81	0.081	51.9
MM	234	1.98	83	0.083	77.0
ME	280	1.52	108	0.108	92.2
MW	290	1.83	99	0.099	105.0
P8	207	0.91	60	0.060	22.7
P9	240	0.91	60	0.060	26.3
P10	82	0.61	30	0.030	3.0
P11	75	1.22	75	0.075	13.7
P12a	200	3.66	70	0.100	146.3
P12b	90	1.83	70	0.100	32.9
P14a	151	1.83	70	0.070	38.7
P14b	55	1.22	70	0.070	9.4
P16	100	0.91	70	0.07	12.8
Total					**1750**

Table D-5. Calculations for surface and subsurface channel deposit particle-size distribution.

Particle-size distribution descriptor	Mean pebble count values (mm)	Conversion factor	Character of subsurface sediment
D10	7.4	18.0	0.4
D16	10	9.4	1
D50	29	2.1	14
D84	63	1.2	53
D90	77	1.2	65

	Greater than 8 mm (%)	Less than 8 mm (%)
Surface D_{90}	89	11
Subsurface D_{90}	66	34

Table D-6. Bar-storage summary details.

Reach	Total volume of bar deposits (m^3)	Volume of sand-bar deposits (m^3)	Volume of gravel-bar deposits (m^3)	Volume greater than 8mm (m^3)	Volume less than 8mm (m^3)
PM1	33	8	25	17	15
PM2	66	7	58	39	27
PM3	17	8	10	6	11
PM4	0	0	0	0	0
V1	12	1	11	8	4
V2	13	0	13	9	4
V3	1	0	1	1	0
V4	59	0	59	44	16
VW	0	0	0	0	0
VE	0	0	0	0	0
MM	22	0	22	16	7
ME	13	0	13	8	4
MW	13	0	13	9	4
P3	0	0	0	0	0
P4	0	0	0	0	0
P5	0	0	0	0	0
P6	0	0	0	0	0
P7	0	0	0	0	0
P8	3	0	3	2	1
P9	0	0	0	0	0
P10	0	0	0	0	0
P11	0	0	0	0	0
P12	1	0	1	1	0
P13	0	0	0	0	0
P14	2	0	2	1	1
P15	0	0	0	0	0
P16	0	0	0	0	0
Totals	256	24	232	161	95

Table D-7. Calculations for surface and subsurface bar deposit particle-size distribution.

Bar sample ID	D10	D16	D50	D84	D90
Gravel sample 1	13	16	31	51	61
Gravel sample 2	13	16	36	62	66
Gravel sample 3	6	10	26	59	71
Gravel sample 4	4	7	26	57	63
Gravel sample 5	4	7	16	33	50
Gravel sample 6	4	7	16	38	44
mean	7	10	25	50	59
std. dev.	4	4	8	12	10

Particle-size distribution descriptor	Mean pebble count values (mm)	Conversion factor	Character of subsurface sediment
D10	7	18.0	0.4
D16	10	9.4	1
D50	25	2.1	12
D84	50	1.2	42
D90	59	1.2	50

	Greater than 8 mm (%)	Less than 8 mm (%)
Surface D_{90} layer	88	12
Subsurface layer	63	37

Table D-8. Particle size distribution of sand-bar deposits.

Sieve Opening (mm)	Sand bar deposit 1		Sand bar deposit 2	
	Cumulative Weight retained (g)	Culmulative Percent Finer Than	Cumulative Weight retained (g)	Culmulative Percent Finer Than
2.000	6.2	99.3	13.9	98.6
1.000	11.7	98.6	24.9	97.5
0.850	13.9	98.3	30.1	97.0
0.425	50.8	93.9	125.6	87.6
0.150	590.4	29.0	810.0	20.2
0.075	764.9	8.0	962.2	5.2
Pan	831.6	0.0	1014.9	0.0

Particle-size distribution descriptor	Sand bar deposit 1 (mm)	Sand bar deposit 2 (mm)	Average (mm)
D10	0.41	0.53	0.47
D16	0.38	0.41	0.40
D50	0.24	0.27	0.26
D84	0.10	0.13	0.12
D90	0.08	0.10	0.09